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Fire performance of multi-layer fire-retardant systems for exterior wood products

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Abstract
Intumescent paints could be used in exterior applications and provide beneficial fire protection for structures located in wildfire-prone areas if the paints were more durable to weathering. A limited number of studies have evaluated the effectiveness of intumescent paints on wood post-weathering, and they have shown that the service life is relatively short, on the order of about one year. None of the previous studies assessed the effects of applying multiple coatings, including an acrylic latex color, bonding primer, and acrylic topcoat, over an intumescent paint. The effects of proper versus improper coating application have also not been evaluated. Here we used a cone calorimeter at three heat fluxes to investigate the fire performance of multiple combinations of coatings applied to cedar shingles. Depending on coating combination, specimens were subjected to either natural or accelerated weathering. The results showed after one year of natural weathering that no char expansion of the intumescent paint occurred, indicating all coating systems failed with UV and moisture degrading the topcoat(s). With similar thickness, application method had little effect on overall fire performance of the coating systems both before and after accelerated weathering.

Keywords
Cone calorimeter, intumescent paint, natural weathering, accelerated weathering, wildland-urban interface

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Introduction

Background on wildland urban interface

Fire plays a fundamental, positive ecological role in the health of America's forests, shrublands, grasslands, and other wildlands.[1,2] However, wildfires also pose threats to people, property, and communities and have been the cause of significant economic and ecological losses.[3] Wildfires can occur anywhere where vegetation is found provided the right conditions (e.g. low moisture, wind, etc.) are present. In addition, because firebrands (also referred to as embers) are transported by wind, structures not immediately adjacent to wildland are at risk of ignition and damage during a wildfire.[4] The United States Forest Service has identified the wildland urban interface, or WUI, as any area where humans and their development meet or intermix with wildland fuel,[5] including communities that are within a 0.8 km (0.5 miles) of the intermixed land. As the number of people that live in and around the WUI increases, so do the fire-related challenges of managing wildlands and reducing the vulnerability of the nearby built environment. Reducing the loss of lives, property, infrastructure, and costs of wildfire management requires individuals in communities to act. Communities that are prepared for wildfire referred to as "fire adapted." Being fire adapted involves implementing and maintaining a variety of strategies to reduce their risk.[6–8]

Being fire adapted requires active support and participation from all stakeholders in a community, including mitigation strategies that individual homeowners implement to reduce their risk. These mitigation strategies can be divided into active and passive fire protection methods.[9,10] Active methods include intervention from a person (e.g. fire fighters or resident) or device (e.g. exterior sprinklers) when the wildfire is imminently threatening structures while passive methods require no intervention or activity at the time when a wildfire is threatening a structure. Passive methods include creating a noncombustible zone immediately adjacent to structures (i.e. the home and any out-buildings) and the use of ignition-resistant or noncombustible materials and certain design features. Ignition-resistant materials that pass an extended, 30-minute flame spread tunnel test[11] or materials that comply with a performance-based test method may be used for new construction in areas that have adopted a WUI building code. As per the International Wildland Urban Interface Code (IWUIC), fire-retardant-treated wood materials are required to be pressure-impregnated with an exterior-rated fire-retardant chemical.[12] As of right now, the California Building Code is an exception and a nominally combustible material can comply for use if it meets specified fire penetration criteria.[13] With a predictable effective service life, intumescent paints could be an easily-applied and financially-feasible option for homeowners to passively protect existing structures.[10]

Fire-retardant coatings and weathering

It has been suggested that fire-retardant-treated (FRT) systems may provide protection of existing structures located in the WUI, particularly where wood products are installed. These systems may be applied to building components to minimize flame spread or increase fire resistance, depending on end-use. For wood products, FRTs are commonly pressure-impregnated such that the chemicals penetrate into the wood fibers. A 1970s study by Holmes[14] examined the potential of exterior fire protection options applied to wood shingles. In this study, 21 pressure-impregnated FRTs were screened after being exposed to a 28-day weathering protocol. Only four pressure-impregnated treatments based on leachability were further evaluated with fire testing after weathering in accordance with ASTM D2898 Method B.[15] To evaluate the fire performance, burning-brand, Schlyter, and eight-foot tunnel tests were conducted. Ultimately, the results showed increased flame spread after weathering, indicating further work was needed to ensure sufficient fire-retardant effectiveness.

Alternatively, surface FRTs do not penetrate wood fibers. One type of surface FRT is intumescent paint which contains additives that improve fire performance of the substrate by expanding up to 20 times the original dry-film thickness when exposed to elevated radiant heat levels or flames, acting as heat insulation and minimizing the access of oxygen to the underlying substrate.[9] These intumescent paints are commonly used for interior building applications, such as steel structural members,[16] but others have investigated the potential used of exterior applications for steel[17–20] and polymeric materials.[21] More recently, Bahrani et al.[9] investigated the effects of natural weathering on the fire properties of intumescent paint on wood. Three intumescent paints applied to southern yellow pine plywood were exposed to natural weathering conditions for three, six, and twelve months. After weathering, flammability was evaluated using a cone calorimeter at three different heat fluxes to provide information on performance for different fire scenarios. At 30 kW/m^2, two of the intumescent paints retained their fire protection properties despite weathering conditions. However, at the 50 and 70 kW/m^2, all the weathering regimes reduced the fire protection effectiveness of all intumescent paints. Bahrani et al.[9] also evaluated the intumescence expansion and observed that two of the coatings showed minimal or no intumescence expansion for the post-weathered specimens.

Markert et al.[22] investigated the potential to use solvent-based intumescent paints for protecting wood pre-treated with phosphate or a silicate-based flame-retardant before and after UV and corrosion aging. Utilizing a cone calorimeter with heat fluxes between 25 and 50 kW/m^2, they showed UV exposure (irradiance of 0.71 mW/cm^2 and the spectral passband wavelength was 254 nm) up to 72 hours did not negatively affect the fire properties of the intumescent paint applied to plywood and spruce. For corrosion aging, the specimens were immersed in a hydrochloric acid solution, resulting in little to no char formation, which was attributed to washing out of water-soluble components of the intumescent paint.

Dubrulle et al.[10] investigated dual-coated FRT systems with both film-forming and non-film-forming water-based intumescent paints in combination with topcoats applied to wood species commonly used for fences and decking located within the WUI. Wood topcoats are typically the finish coats that provide the final protective barrier from the elements and minimize dimensional instability by retarding moisture changes within the product. In the Dubrulle et al.[10] study, a cone calorimeter with the application of one heat flux (50 kW/m^2) was used to characterize the fire performance both pre- and post-accelerated weathering. Prior to weathering, four of the intumescent paints evaluated reduced the flammability of the western redcedar wood substrate with substantial decreases in the heat-release rate and total heat released but only two of the intumescent paints maintained intumescent char expansion when a topcoat was applied. After accelerated weathering for an estimated equivalent outdoor time of 14 days to 28 days, the tested intumescent paints were ineffective and the fire performance of the two dual-coated systems that maintained char expansion pre-weather had similar heat-release rate results to uncoated red cedar. In addition, Dubrulle et al.[10] noted that topcoat failures after weathering were potentially due to incompatibility between the intumescent paints and acrylic topcoats and warned users to evaluate a product's fire test data post-weathering and confirm the expected service life for exterior application.

The limited previous studies found intumescent coatings would not be sufficient for exterior used in the WUI alone or with one topcoat. Building on the previous work, this study expands on the use of a compatible dual-coated system by including a combination of acrylic latex color, bonding primer, and/or an acrylic topcoat over an intumescent paint (multi-layer FRT system) applied to cedar shingles and then naturally weathered. These multi-layer FRT systems were varied to identify potential methods to maintain the fire performance properties of the underlying intumescent paints. In addition, we note that application of these FRT systems in the field may not always follow the manufacturer's specifications, which could impact the intended fire performance. To address this, a dual-coated system (topcoat with intumescent paint) was both properly and improperly applied to cedar shingles and the flammability and durability evaluated. Ultimately, this study was conducted to determine suitability of different coating combinations to be used with intumescent paints for application in wildfire-prone areas.

Materials and methods

Naturally weathered specimens

In this study, two different intumescent paints were evaluated; a brush-on water-based paint and a spray-on paint. Western red cedar (*Thuja plicata* Donn ex D. Don) shingles were chosen by the homeowner. The application techniques were different for the specimen types. The water-based intumescent paint was brushed on to the specified total dry thickness of 508 microns. The acrylic protective topcoat, primer, and latex color were all applied with a roller to total dry thicknesses of approximately 154.4, 127, and 35.5 microns, respectively. The water-based intumescent paint was originally intended for interior use but, per the manufacturer, when used in an exterior environment, the intumescent paint should be covered with a specified (compatible) water-based acrylic topcoat. The number of coatings varied along with the use of topcoats, primer, and an exterior acrylic latex color paint (denoted with P). The FRT systems for the naturally weathered specimens were applied in the field with the final configurations summarized in Table 1 and illustrated in Figure 1.

The naturally weathered specimens were located on the exterior of a residential home in Mill Valley, California (Figure 2). The application of the coatings occurred between June 28 and July 1, 2019, and the specimens were removed on July 1, 2020. The exterior walls that the specimens were installed on had either a south or southwest exposure as identified in Table 1. Figure 2 shows the shingles after application of the coating on the structure. The tan shingles included the exterior acrylic latex color paint (AP, BP, CP, D, and E) while the white shingles did not (A, B, C). The control specimens were uncoated, cedar shingles, which were installed on the exterior walls of the residential home after a few coated shingles were removed.

The meteorological conditions provided in Table 2 were obtained from NREL National Solar Radiation Database.[23] Multiple readings were taken per day and the data presented are average readings $\pm$ standard error over the course of each month. The station collects the following meteorological variables: Clear Sky Direct Horizontal Irradiance (DHI), Clear Sky Global Horizontal Irradiance (GHI), dewpoint, precipitable water, temperature, and relative humidity (RH). Weather records showed that there were 145 rainy days ($\sim$37%), and the average precipitation for the 12 months of the study was 1.56 mm (0.06 in) per

Table 1. Naturally weathered specimen configuration.

ID	Intumescent type	Number of layers	100% acrylic protective topcoat[b]	Number of acrylic topcoats	Water-based bonding primer[c]	Exterior acrylic latex color[d]	Exposure
Control	None	N	N	N	N	N	Natural
AP	Brush-on water-based intumescent paint[a]	2	Y	1	Y	Y	Southern exposure 202° S, top of wall
A	Brush-on water-based intumescent paint[a]	2	Y	1	Y	N	Southern exposure 202° S, bottom of wall
BP	Brush-on water-based intumescent paint[a]	2	Y	1	N	Y	Southern exposure 202° S, top of wall
B	Brush-on water-based intumescent paint[a]	2	N	1	N	N	Southern exposure 202° S, bottom of wall
CP	Brush-on water-based intumescent paint[a]	2	N	N	N	Y	Southern exposure 202° S, top of wall
C	Brush-on water-based intumescent paint[a]	2	N	N	N	N	Southern exposure 202° S, bottom of wall
D	Clear, spray-applied intumescent paint[e]	1	N	N	N	Y	Southwest exposure 233° SW, whole wall
E	Exterior acrylic latex color paint	N	N	N	N	Y	Southwest exposure 207° SW, whole wall

[a]Proprietary formulation.
[b]Titanium dioxide (15–20%); Mica (0–5%).
[c]Water-based acrylic; kaolin clay (2.5–10%), hydrous magnesium silicate (1–2.5%), aliphatic petroleum distillates (0.1–1%), oxirane 2-methyl polymer with oxirane monobutyl ether (0.1–1%); 224 trimethyl 1 3 pentanediol monoisobutyrate (0.1–1%), 2 2 ethylenedioxydiethyl bis 2 ethylhexanoate (0.1–1%), zinc oxide (0.1–1%).
[d]Titanium dioxide (10–25%), zinc oxide (3%), cristobalite (0.3%).
[e]Proprietary formulation.

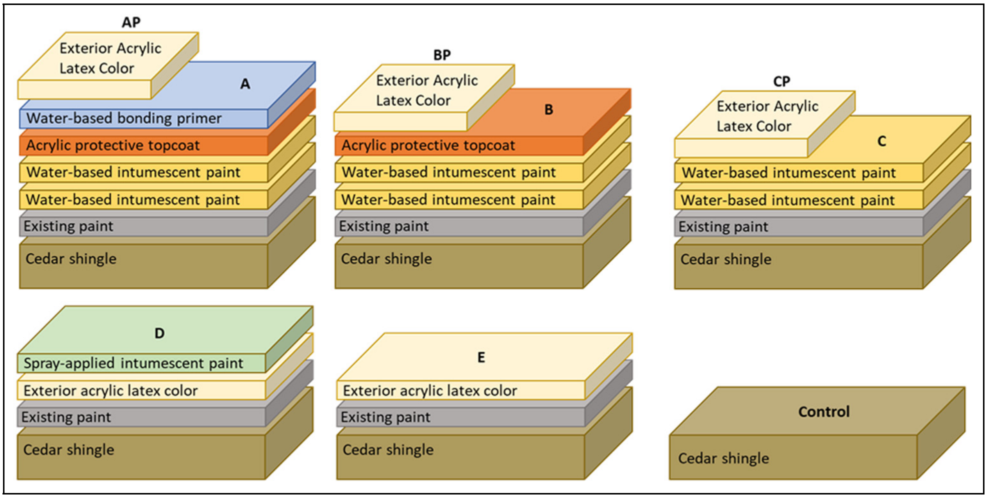

Figure 1. Diagram of natural weathering specimen configurations (not to scale).

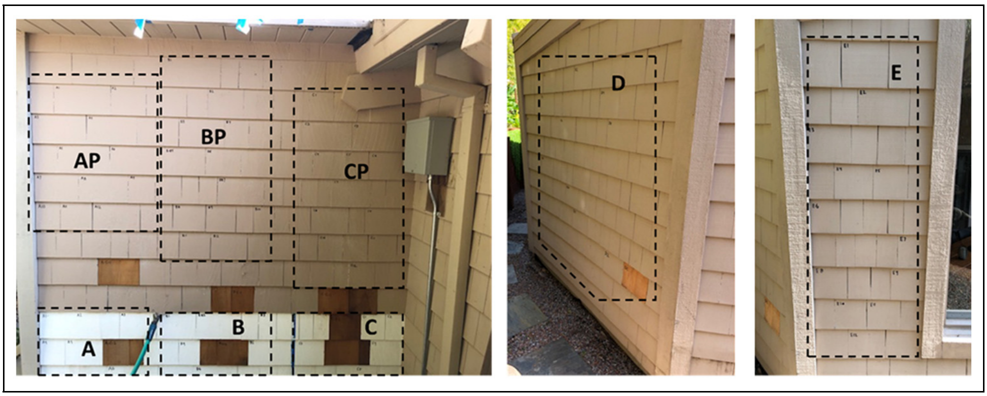

Figure 2. Images of field-applied coatings after one year of natural weathering. The letters correspond to the specimen configurations in Table 1, which were grouped within the dashed rectangles. The control specimens are uncoated and were incorporated within the specimen configuration groups.

month. Note that rainfall in this part of northern California occurs primarily between October and April, with typically no rainfall occurring during summer months.

Accelerated weathering specimens

The substrate for the accelerated weathering specimens was #2 grade western red cedar (*Thuja plicata* Donn ex D. Don) shingles. The shingles chosen had limited sapwood, knots, and other defects. Each shingle had an average thickness of 8.7 mm and average density of 0.34 g/cm^3. For these specimens, two application procedures were used with all coatings

Table 2. Weather variables for Mill Valley, California over the course of the one-year[a] exposure time.

Year	Month	Avg. Clear Sky DHI[b] (W/m^2)	Avg. Clear Sky GHI[c] (W/m^2)	Avg. Dew Point (°C)	Avg. Precipitable Water (mm)	Avg. Temperature (°C)	Avg. Relative Humidity (%)
2019	July	59.5 ± 2.3	323.8 ± 13.8	11.8 ± 0.1	1.9 ± 0.0	18.4 ± 0.2	70.0 ± 0.8
2019	August	58.1 ± 2.7	287.1 ± 12.8	12.6 ± 0.1	1.9 ± 0.0	20.2 ± 0.2	67.2 ± 0.9
2019	September	46.5 ± 2.4	253.4 ± 11.9	11.9 ± 0.1	1.8 ± 0.0	19.9 ± 0.2	66.6 ± 1.0
2019	October	35.1 ± 1.7	205.7 ± 10.1	5.2 ± 0.2	1.1 ± 0.0	17.3 ± 0.2	53.1 ± 1.1
2019	November	31.2 ± 1.8	131.3 ± 7.6	7.2 ± 0.2	1.4 ± 0.0	14.3 ± 0.2	68.2 ± 0.9
2019	December	32.4 ± 2.0	77.4 ± 5.1	9.2 ± 0.1	1.8 ± 0.0	11.9 ± 0.1	84.5 ± 0.4
2020	January	34.4 ± 2.0	110.8 ± 6.5	8.5 ± 0.1	1.5 ± 0.0	11.0 ± 0.1	86.0 ± 0.4
2020	February	34.5 ± 1.9	180.3 ± 9.6	7.4 ± 0.1	1.1 ± 0.0	12.2 ± 0.2	75.9 ± 0.7
2020	March	71.2 ± 3.9	179.1 ± 9.3	7.6 ± 0.1	1.5 ± 0.0	11.9 ± 0.1	77.0 ± 0.0
2020	April	70.8 ± 3.7	234.8 ± 11.8	9.3 ± 0.1	1.7 ± 0.0	13.7 ± 0.2	76.8 ± 0.7
2020	May	71.3 ± 3.5	296.8 ± 13.1	10.3 ± 0.1	1.7 ± 0.0	16.8 ± 0.2	70.2 ± 0.8
2020	June	66.8 ± 3.1	337.7 ± 14.1	10.6 ± 0.1	1.8 ± 0.0	18.2 ± 0.2	66.5 ± 0.9
2020	July	70.9 ± 3.3	296.9 ± 13.1	10.8 ± 0.1	1.5 ± 0.0	18.2 ± 0.2	67.34 ± 0.9

[a]Mill Valley, California (2019–2020) was determined to have drought throughout the year these specimens were installed.
[b]Modeled solar radiation on a horizontal surface received from the sky excluding solar disk.
[c]Modeled solar radiation on a horizontal surface received from the sky.

being applied in a lab setting rather than the field. The first procedure followed the manufacturer's specifications (FG specimen group) which included brushing on two individual coats of both products, each with the thickness per the manufacturer's instruction (Table 3 and Figure 3). The intumescent paint was specified to have a total dry thickness of approximately 508 microns and the topcoat has a specified total dry thickness of 152.4 microns such that the overall total dry thickness of the dual-coated FRT system was approximately 660.4 microns. The second procedure did not follow the manufacturer's specifications (FB specimen group) and instead a single coat of each product was brushed on. The overall total dry thickness of the dual-coated FRT system applied improperly was measured to be between 500 and 600 microns.

Accelerated weathering parameters

Accelerated weathering, a technique used in a laboratory setting, allows for specific ultraviolet exposure (UV), moisture, and temperature conditions to be applied on a 24-hour schedule. Even though this procedure is faster than natural weathering, a definite correlation between natural weathering and accelerated weathering exposure times has not been ascertained.[10]

The accelerated weathering specimens (100 mm × 100 mm × 10 mm) were exposed to UV and water in a QUV/spray accelerated weatherometer (Q-Lab, Westlake, OH) following ASTM D2898.[15] The weathering protocol followed the cycle outlined in Method B, which consisted of repeat cycles of 4 hours of wetting (12.2 ± 0.8 L/min•m^2), 4 hours of drying (66 ± 3°C), 4 hours of wetting (12.2 ± 0.8 L/min•m^2), 4 hours of drying (66 ± 3°C), and 8 hours of dark. Water was recirculated after 72 hours with a circulating volume of at least 19 L of fresh water through each spray nozzle for the 4 hours of wetting periods. Ultraviolet sun lamps (UVA-340+) were used during the drying periods with an irradiance of 5.0 W/m^2 at a wavelength of 315 to 400 nm. Specimens changed position weekly in the apparatus to allow exposure to all locations. Sampling occurred after weathering durations of 336 hours, 672 hours, and 1,008 hours (Table 3). A set of specimens were not weathered and served as controls (FG_control and FB_control). Uncoated cedar shingles were not included in the accelerated weathering series as ASTM D2898 assesses the durability of the fire-retardant treatment (e.g. paints, sprays, etc.) and not the wood itself. Prior to surface analysis, all specimens were conditioned (27°C and 30% RH) for two weeks pre- and post-weathering. Specimens were weighed pre- and post-weathering to determine weight loss.

Surface analysis

A series of surface analyses were conducted for specimens prior to and following exposure to accelerated weathering. Coating failure was evaluated by comparison with photographic depictions to reference standards for checking (slight breaks in the coating that do not penetrate through the last applied coating layer), cracking (breaks in the coating that penetrate through the last applied coating layer exposing the wood surface), and blistering (a bubbling of the coating layer). Degree of checking, cracking, and blistering range from 10 (no defect) to 0 (complete failure). Checking of the coating was determined following ASTM D660, *Standard Test Method for Evaluating Degree of Checking of Exterior Paints*.[24] The types of checking were documented for all specimens. Cracking of the coating was determined following ASTM D661, *Standard Test Method for Evaluating Degree of Cracking of Exterior*

Table 3. Accelerated weathering specimen configurations and exposure duration.

Specimen ID	Intumescent type	Number of Intumescent paints	100% acrylic protective topcoat	Number of Acrylic Topcoats	Water-based bonding primer	Exterior acrylic latex color paint	Weathering Procedure
FG_control	water-based intumescent paint	2	Y	2	N	N	None
FG336	water-based intumescent paint	2	Y	2	N	N	Lab 336 hours
FG672	water-based intumescent paint	2	Y	2	N	N	Lab 672 hours
FG1008	water-based intumescent paint	2	Y	2	N	N	Lab 1,008 hours
FB_control	water-based intumescent paint	1	Y	1	N	N	None
FB336	water-based intumescent paint	1	Y	1	N	N	Lab 336 hours
FB672	water-based intumescent paint	1	Y	1	N	N	Lab 672 hours
FB1008	water-based intumescent paint	1	Y	1	N	N	Lab 1,008 hours

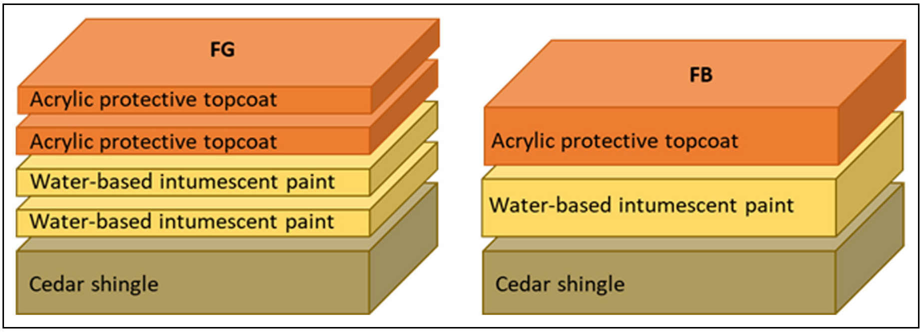

Figure 3. Diagram of accelerated weathering specimen configurations (not to scale).

Paints.[25] The types of cracking were documented for all specimens. Blistering of the coatings was determined following ASTM D714, *Standard Test Method for Evaluating Degree of Blistering of Paints*.[26] The size and frequency of blisters was documented for all specimens.

Color and gloss measurements. Color (CIE—International Commission on Illumination) was measured using a handheld spectrophotometer (CM-2300d, Konica Minolta, Osaka, Japan). Two readings were obtained for each specimen pre- and post-weathering. Specimen measurements were made at 60°. These measurements were taken for each specimen using color parameters (L^*, a^*, and b^*), where L^* represents lightness from 0 (black) to 100 (white), a^* represents chromaticity coordinates red (+) or green (−), and b^* represents chromaticity coordinates yellow (+) or blue (−). Color change (ΔE) was determined using Equation 1.

$$E^*_{ab} = \sqrt{\Delta L^{*2} + a^{*2} + b^{*2}} \quad (1)$$

Specular gloss was measured using a handheld glossmeter (ETB-0686) following ASTM D523, *Standard Test Method for Specular Gloss*.[27] Gloss retention (%) was calculated for all specimens (Equation 2).

$$Gloss\,Retention = 100 \cdot \left(\frac{final\,gloss}{initial\,gloss}\right) \quad (2)$$

Flammability

Flammability tests to evaluate the fire performance of the specimens were conducted using a cone calorimeter (Fire Testing Technology, iCone mini, East Grinstead, West Sussex, UK) in accordance with ASTM E1354: *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*.[28] After weathering (either naturally or accelerated) and prior to fire testing, the specimens were conditioned for a minimum of 30 days in a chamber maintained at a set point for a RH of 56.4 ± 1.3% and an ambient temperature of 21.5 ± 0.3°C. Three different heat fluxes were used to evaluate the fire performance of the specimens: 25, 50, and 75 kW/m^2. For all tests, the spark igniter was used, and the tests were terminated two minutes after flaming combustion ceased.

Table 4. Number of cone calorimeter specimens per coating configuration and heat flux.

		Number of replicates at a prescribed heat flux		
Weathering procedure	Specimen ID	25 kW/m^2	50 kW/m^2	75 kW/m^2
Natural	AP	3	3	3
	A	2	3	2
	BP	3	3	3
	B	2	3	2
	CP	3	3	3
	C	2	2	1
	D	3	3	3
	E	3	3	3
	Control	3	3	2
Accelerated	FG_control	3	3	3
	FB_control	3	3	3
	FG336	2	3	2
	FB336	3	3	3
	FG672	-	3	-
	FG672	-	3	-
	FG1008	-	3	-
	FB1008	-	3	-

The number of replicates per specimen type and heat flux are provided in Table 4. The time to ignition (t_{ig}), heat-release rate (HRR), and total heat released (THR) were measured. For HRR, the peak (pHRR), time to pHRR, and average for the first 120 seconds after ignition (HRR_{120}) were calculated to evaluate the ignition characteristics of the multi-layer FRT systems. Due to the low number of replicates ($n \leqslant 3$), two-tailed t-tests (assuming equal variances) were used to determine significant differences ($P \leqslant 0.05$) between specimen types.

Results and discussion

Natural weathering

The naturally weathered specimens were not visually evaluated for coating breakdown prior to fire testing. This is because surface analysis was not conducted immediately after installation on the residential home such that a comparison of before and after the one year of exterior exposure was not possible. Figure 3 shows the specimens and configurations for each naturally weathered specimen type after one-year of outdoor exposure. The pre-fire test images (Figure 4) indicated there was no obvious breakdown of the coatings or microbial growth on the surface of the coatings.

Natural weathering flammability

The average flammability parameters, based on replicates, for each naturally weathered specimen type are provided in Table 5. As expected, higher heat fluxes resulted in lower t_{ig}, higher pHRR, and increased THR regardless of the combination of multi-layer FRT systems.

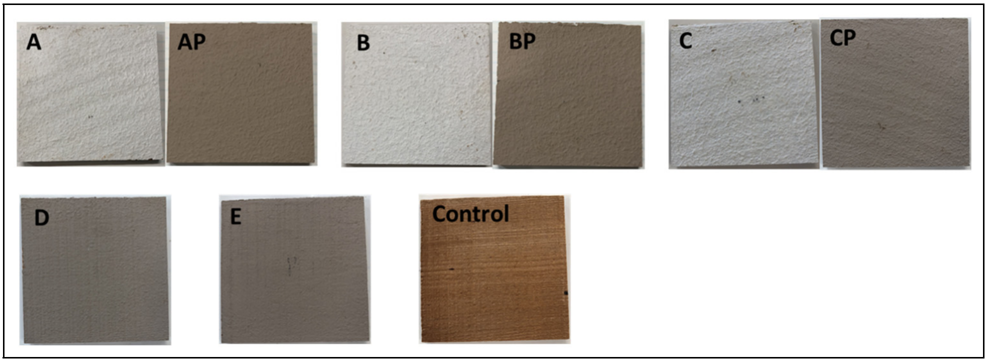

Figure 4. Naturally weathered specimens cut to 100 mm × 100 mm. Specimen configurations can be found in Table 1 and Figure 1. Specimens in service can be seen in Figure 2.

Table 5. Summary of cone calorimeter results for naturally weathered specimens, averaged over the number of specimens for each type and rounded to the nearest whole number.

Specimen group	Heat flux [kW/m^2]	t_{ig} [s]	pHRR [kW/m^2]	time to pHRR [s]	HRR_{120} [kW/m^2]	THR [MJ/m^2]
AP	25	88	208	98	74	35
	50	17	283	25	111	45
	75	8	362	15	132	44
A	25	121	214	132	72	33
	50	20	271	30	107	43
	75	10	332	18	133	41
BP	25	118	181	129	67	38
	50	16	276	23	110	43
	75	10	336	14	146	46
B	25	77	205	91	67	33
	50	17	265	27	105	38
	75	9	353	16	126	36
CP	25	60	202	76	74	34
	50	16	263	22	92	39
	75	7	293	12	96	42
C	25	126	150	329	57	39
	50	17	293	27	106	39
	75	10	205	17	92	35
D	25	98	240	102	76	37
	50	15	326	21	111	43
	75	7	363	11	144	44
E	25	108	229	114	76	33
	50	16	310	21	97	39
	75	9	371	13	134	43
Control	25	78	168	88	93	38
	50	12	224	26	137	47
	75	7	322	16	175	41

Visual expansion of the intumescent paint was not observed during heat exposure for any of the multi-layer FRT configurations. This indicates natural weathering for one year diminished the ability of the acrylic latex color, bonding primer, and/or topcoat to protect the intumescent paint. This is consistent with the findings of Bahrani et al.[9] who either did not observe visual expansion on naturally weathered specimens or, when expansion occurred, the height was too small to be accurately determined.

The average t_{ig} and pHRR are presented in Figure 5. For naturally weathered specimens exposed to 25 kW/m^2, the average t_{ig} ranged from 60 to 126 seconds. The ranges decreased to 11 to 20 seconds (~83% reduction) and 6 to 11 seconds (~91% reduction) for the exposures at 50 kW/m^2 and 75 kW/m^2, respectively. At the lower heat flux of 25 kW/m^2, the differences in specimens with the exterior acrylic latex color paint versus those without were more noticeable than at the higher heat fluxes. At 25 kW/m^2, specimens B and CP ignited, on average, 1.3 and 18 seconds faster than the uncoated control while all other specimens were slower to ignite than the control by 10 to 47 seconds. At 50 and 75 kW/m^2, the average t_{ig} was lower than the uncoated control by 3.3 to 8.7 seconds and 0.5 to 4 seconds, respectively.

Figure 6 compares the average heat-release rate curves for the naturally weathered specimens compared to the results of the uncoated controls. The curves exhibit features typical of wood materials, showing two distinct peaks. The first peak is attributed to the ignition of the material with a decrease due to the formation of char, followed by a second peak which is generally believed to be a result of material burn-through.[29] The initial pHHR values were similar for the different combinations of multi-layer FRT systems. While the initiation of the second peak occurred at similar times when compared to the uncoated controls, the actual second peak occurred at later times and was often lower for the multi-layer FRT systems. The delay in the second pHRR observed suggests a delay in burn-through, which may be attributed to the general presence of coatings.

T-tests were performed to evaluate the effects of multi-layer FRT systems versus uncoated controls. The t-tests also allowed comparison between the presence or absence of an exterior acrylic latex color (AP, BP, CP) as applied to a combination of bonding primer, and/or an acrylic topcoat over a brush-on intumescent paint (A, B, C, D and E). In addition, we compared the results from the brush-on (A, B, C) and spray-applied intumescent paints (D). The P-values used to determine significant difference ($P \leqslant 0.05$) obtained from the t-test are provided in Table 6.

It was anticipated that an intumescent paint would increase the t_{ig} and the time to pHRR while decreasing the pHRR, HRR_{120}, and THR. In addition, the hypothesis was that including a combination of acrylic latex color, bonding primer, and/or an acrylic topcoat would aid in protecting the intumescent paint. However, no significant differences were observed for the specimens between combinations of coatings. There were some instances where the t-test results showed significant differences between the uncoated control and certain combinations of specimens with multi-layer FRT systems. At 25 kW/m^2, E and BP had longer t_{ig} than the control. At 50 kW/m^2, most of the multi-layer FRT systems took longer to ignite when compared to the uncoated control with the exception of BP. It is difficult to determine which layer had an effect here because when comparing the multi-layer FRT systems, the only significant difference was between A and AP, with A having the longer time to ignition and time to pHRR. The improvement noted for A may be attributed to the kaolin clay[30] and hydrous magnesium silicate[31] in the primer, which have been reported as having fire-retardant properties. However, we did not observe improved fire performance when

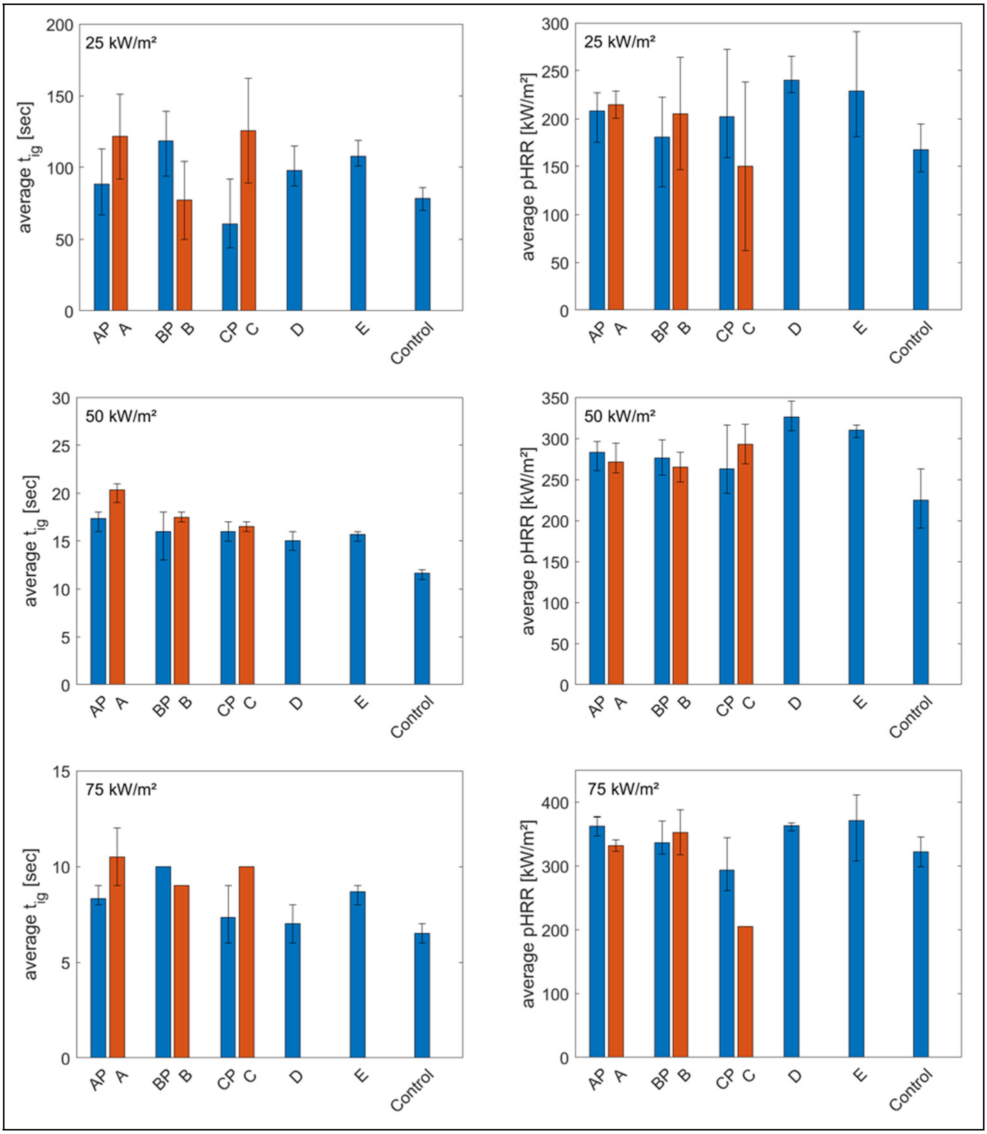

Figure 5. Results at each heat flux for naturally weathered specimens with an exterior acrylic latex color paint compared to those without. The plots on the left provide average time to ignition data and the plots on the right provide the average peak HRR data. The control values are provided for reference. The error bars represent the maximum and minimums for the specimen group.

comparing A to B or C. At 75 kW/m^2, B, BP, and E were different from the control with greater t_{ig}. Unexpectantly, none of the multi-layer FRT systems were significantly different from each other at both 25 kW/m^2 and 75 kW/m^2. Regarding the pHRR, the uncoated control was significantly lower from D and E at 25 and 50 kW/m^2. This is potentially due to the additional fuel source of the exterior acrylic latex color layer.[10] However, the other specimens with the exterior acrylic latex color (AP, BP, and CP) did not have significantly higher

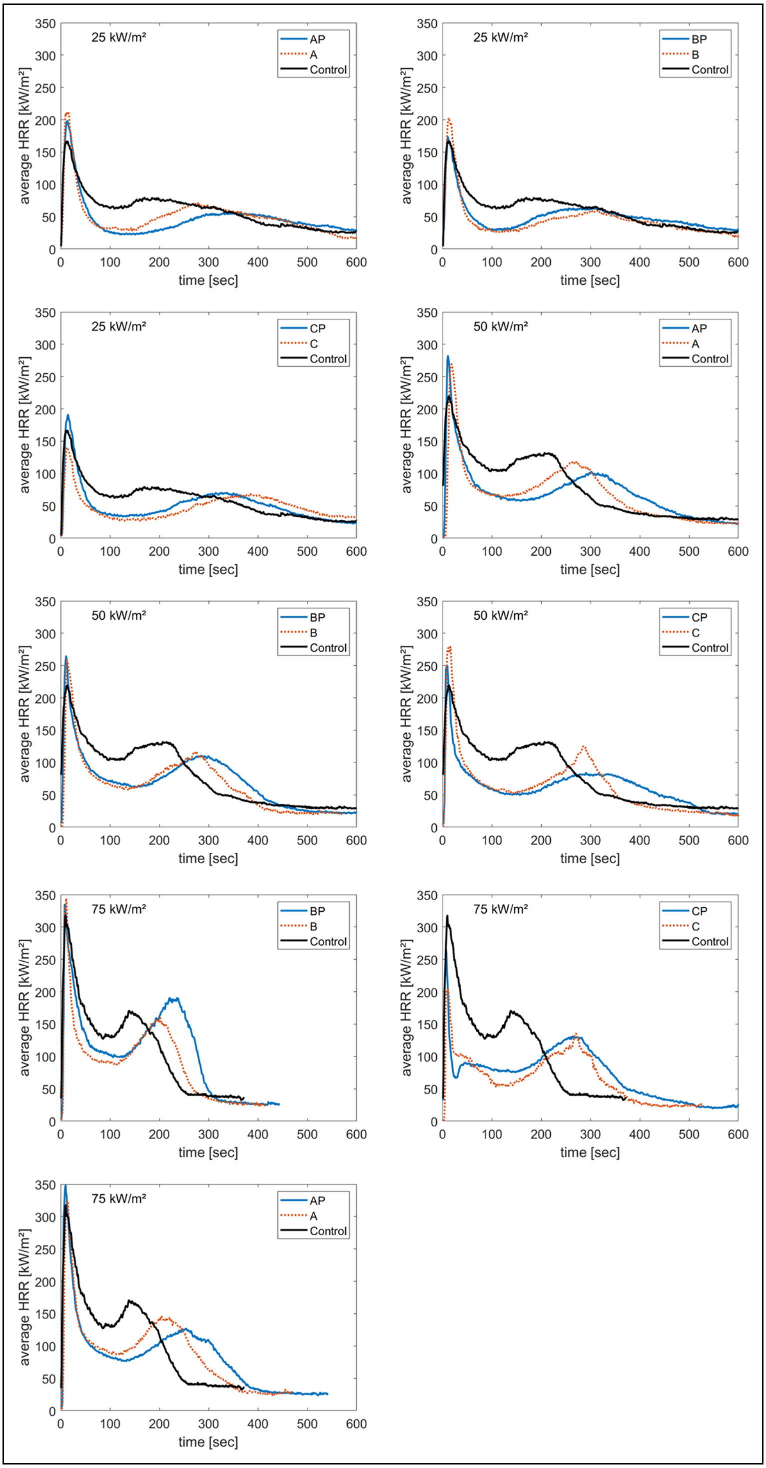

Figure 6. Average heat-release rate curves for the naturally weathered specimens. The average heat-release rate curve for the uncoated control specimens is provided as a reference.

pHRR when compared to the uncoated control. This could be attributed to the failure of the acrylic latex color when applied over a primer, topcoat and/or intumescent paint. It is unclear if this failure is due to UV and hygrothermal degradation of the multi-layer systems or incompatibility of the acrylic latex color with the underlying layers. At 75 kW/m^2 the HRR_{120} was observed to be significantly lower for AP, B, BP, CP, and D when compared to the uncoated control. This indicates that the multi-layer FRT systems may have initially offered some protection to the cedar shingle, however the results from the t-test showed no significant differences for the THR for any of the specimens. The lack of difference in the THR suggests that each multi-layer FRT system failed to protect the cedar shingle, which contributed to the combustion process. This aligns with the findings of Bahrani et al.,[9] which showed that natural weathering reduced effectiveness of the intumescent paint with efficacy expected to decrease between three and six months of weathering.

Accelerated weathering

Accelerated weathering occurred for 336 hours (Figure 7), 672 hours (Figure 8), and 1,008 hours (Figure 9) for the dual-coated FRT systems following the work done by LeVan and Holmes[32] and White.[33] In Figures 7–9, A and C are images of the samples before weathering while B and D are images after weathering at each respective weathering duration. Results from the 336 hour accelerated weathering show structurally sound specimens for both specimen groups (FG and FB); however, medium, and large blisters (red circles in Figure 7(b) and (d)) formed across the coated surface on all specimens regardless of proper (FG) versus improper (FB) application (Table 6).

Results from 672 hours of accelerated weathering are provided in Figure 8. Both the FG672 and FB672 specimens had medium and large blisters (red circles in Figure 9(b) and (d)). More notably, the blisters were denser on the FB672 specimens (Table 6). In addition, checking (Table 6) was present on some FB specimens (Figure 8(d), black arrows).

Results after 1,008 hours of accelerated weathering are provided in Figure 9. Both FG1008 and FB1008 a dense amount of medium and large blisters (red circles in Figure 9(b) and (d)) on the surface of the specimens. Checking was also present on both FG1008 and FB1008 specimens (Figure 9(b) and (d), black arrows). Similar to the other weathering durations, the checking type presented as shrinkage for both application methods after 1,008 hours of weathering (Table 6).

The test specimens underwent additional changes during the accelerated weathering process. Due to the wetting and UV exposure, specimens lost between 1 g and 5 g during the test, with the greater weight loss corresponding to longer test durations (Table 7). However, there were no notable differences in weight loss between the FG and FB specimen groups. Rain and UV exposure showed differences in gloss retention (%) between the FG and FB specimen groups (Table 7). The FG specimen group retained 73.2%, 94.3%, and 52.3% gloss after 336, 672, and 1,008 hours, respectively. The FB specimen group performed better retaining 91.5%, 81.8%, and 75.6% gloss after 336, 672, and 1,008 hours, respectively.

Color (CIE) data is provided in Table 8. Changes in Lightness (ΔL^*), which represents changes from black to white, and changes in red or green chromaticity (Δa^*) occurred in both FG and FB test specimens, but these changes were similar between FG and FB. There were differences in the yellow or blue chromaticity (Δb^*) and color(ΔE) between the FG and FB specimen groups with FB672 and FB1008 showing the larger changes. The greatest change in color (>5) was for FB1008.

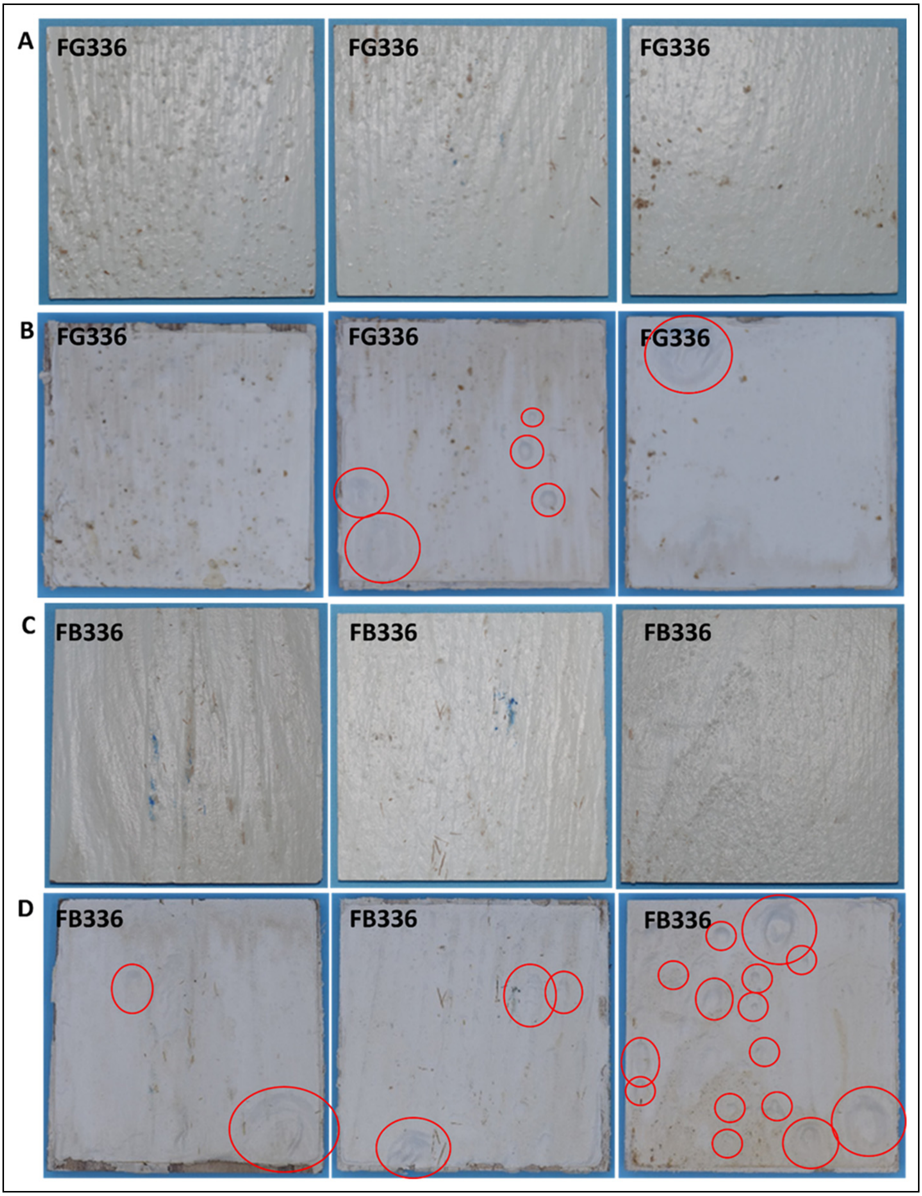

Figure 7. Dual-coated FRT systems before (a, c) and after (b, d) accelerated weathering for 336 hours in a QUV/spray accelerated weatherometer following Method B of ASTM D2829.[16] Specimens surfaces are 100 mm by 100 mm. Blisters are circled.

Blistering, the most common form of paint failure,[34] was present following accelerated weathering regardless of application method and weathering duration. Blistering is often a precursor to peeling or complete removal of the painted surface, likely due to a buildup of fluid pressure underneath the painted surface forcing it to detach from the cedar shake. Both

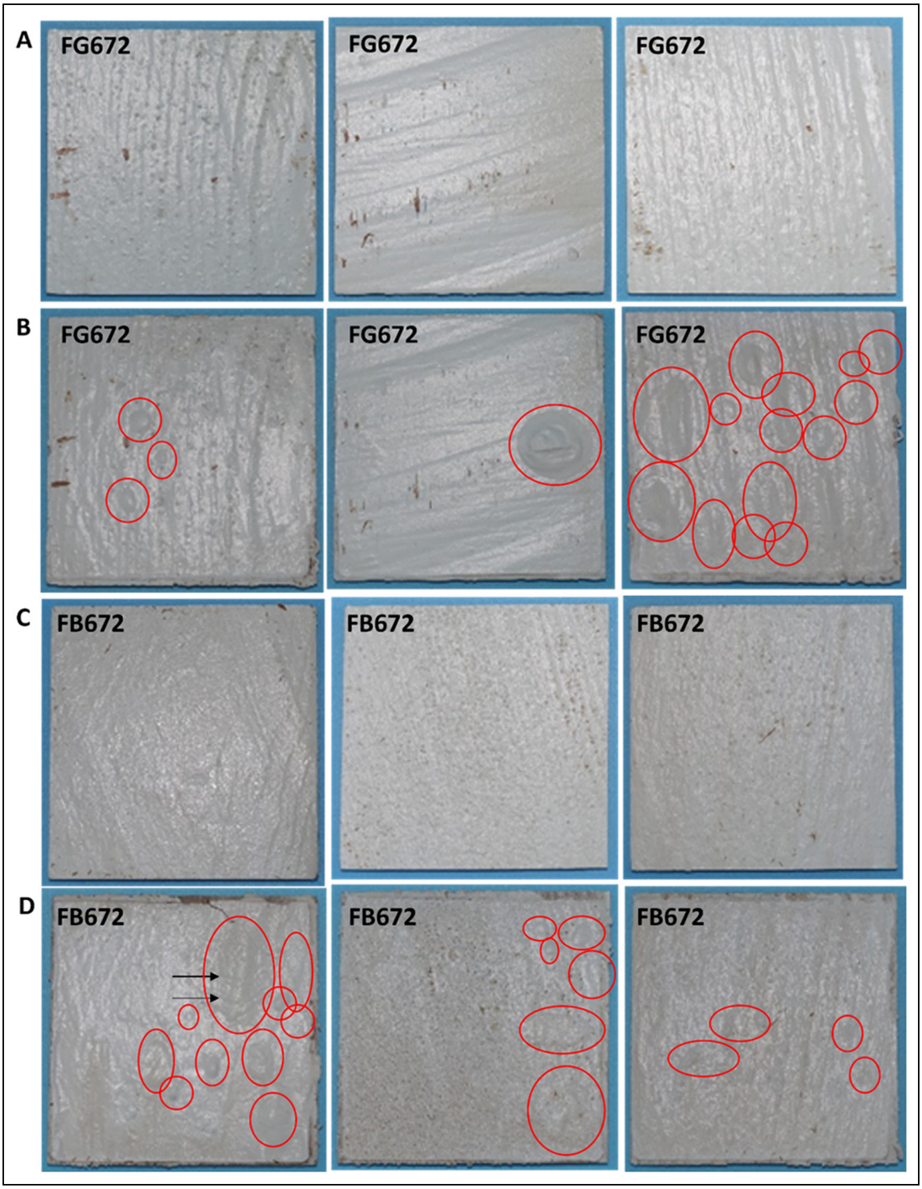

Figure 8. Dual-coated FRT systems before (a, c) and after (b, d) accelerated weathering for 672 hours in a QUV/spray accelerated weatherometer following Method B of ASTM D2829.[16] Blisters are circled, and arrows represent checking on the surface of the paint.

frequency and density of blistering increased with longer weathering duration indicating active breakdown of the coated specimen. The composition of the coating can also play a role in the formation and type of blistering while the wood species plays no role in blistering. Dubrulle et al.[10] exposed coated red cedar specimens to 8 hours of UV, 0.25 hours of

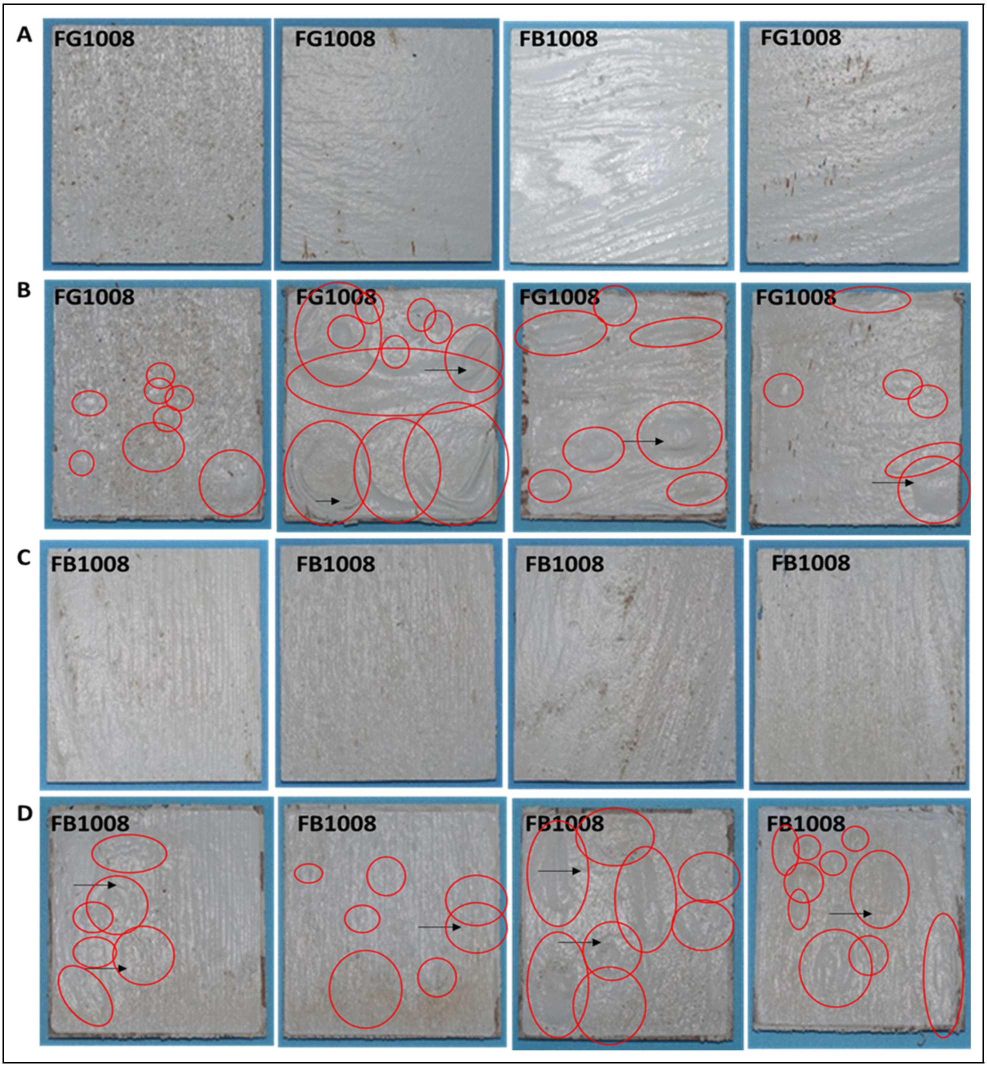

Figure 9. Dual-coated FRT systems before (a, c) and after (b, d) accelerated weathering for 1,008 hours in a QUV/spray accelerated weatherometer following Method B of ASTM D2829.[16] Blisters are circled, and arrows represent checking on the paint surface.

wetting, and 3.75 hours of condensation for up to 28 days (672 hours),[10] which is different from the 4 hours of wetting, 4 hours of UV, 4 hours of wetting, 4 hours of UV, and 8 hours of dark for up to 1,008 hours that were employed for this study. After 672 hours of accelerated weathering, Dubrulle et al.[10] noted blistering and cracking at the coating surface, which aligns with what we observed with our test specimens.

Checking was present regardless of application type after 672 hours and 1,008 hours of accelerated weathering. The type of checking seen was classified as shrinkage which forms short irregular breaks often progressing at right angles. In all cases, the checking present on the specimens in this study was associated with large blisters. This was likely due to UV

Table 6. P-values of naturally weathered specimens that showed significant differences for flammability parameters ($P \leq 0.05$) based on t-test results.

t_{ig}	pHRR	time to pHRR	HRR_{120}	THR
25 kW/m^2				
Control to E*: 0.01 Control to BP*: 0.04	Control* to D: 0.01	Control to E*: 0.04	None	None
50 kW/m^2				
AP to A*: 0.03 Control to A*: 0.0003 Control to B*: 0.002 Control to C*: 0.003 Control to D*: 0.007 Control to E*: 0.001 Control to AP*: 0.001 Control to CP:* 0.001	Control* to D: 0.01 Control* to E: 0.01	AP to A*: 0.003	C to E*: 0.03	None
75 kW/m^2				
Control to B*: 0.03 Control to E*: 0.03 Control to BP*: 0.01	None	Control* to D: 0.02	BP to B*: 0.04 Control to B*: 0.01 Control to D*: 0.03 Control to AP*: 0.02 Control to BP*: 0.04 Control to CP*: 0.0007	None

*This specimen had better fire performance results than the comparison for the given flammability parameter.

exposure and the buildup of moisture (liquid and water vapor) as a result of the severity of the accelerated weathering protocol.

Changes in gloss post-weathering can indicate surface-level degradation, like the checking present at 672 hr and 1008 hr, regardless of application type. Gloss reductions may indicate chemical changes in the coating,[35] however, these were not measured in this study. Gloss reduction can be variable with respect to coating type and wood species.[36] Color changes happen rapidly when wood is subjected to UV and moisture and can be influenced by coating type (i.e. transparent, semi-transparent, paint, etc.). Longer exposure times often results in larger color changes, as seen in all specimens weathered for 1008 hr. Similarly, Bahrani et al.[9] observed a reduction in glossiness, cracks in coating, and presence of mold after weathering of their southern pine plywood specimens coated with intumescent paint.

Accelerated weathering flammability

The flammability parameters for each accelerated weathered specimen type (averages based on replicates) obtained from the cone calorimeter tests are provided in Table 9 and compared in Figure 10. As expected, the higher the heat flux, the lower the t_{ig} and higher the pHRR, regardless of the coating type, application method, or weathering.

T-tests were performed to evaluate the effects of application methods of the dual-coated FRT systems. We also compared the results from unweathered controls to the accelerated weathered dual-coated FRT systems. For the accelerated weathering specimens, the

Table 7. Surface analyses results for dual-coated FRT systems pre- and post-accelerated weathering for 336, 673, and 1,008 hours. Cracking, Checking, Checking Type (i.e. shrinkage, irregular, parallel, switch, crow foot, etc.), Gloss Retention, Blistering Size and Frequency results are presented below and represent an average (± standard error) of three for FG336, FG672, FB336, and FB672 and an average of four for FG1008 and FB1008.

Specimen	Weight loss (g)	Cracking ASTM D660[21]	Checking ASTM D661[22]	Checking type ASTM D661[22]	Gloss retention (%) ASTM D523[24]	Blistering size[a] ASTM D714[23]	Blister frequency ASTM D714[23]
FG336	1.1 (2.7)	10 (0)	10 (0)	-	73.2	2 (0)	*Few to Medium*
FG672	3.5 (3.1)	10 (0)	8 (3.5)	*Shrinkage*	94.3	2 (0)	*Medium Dense*
FG1008	5.3 (3.6)	10 (0)	6 (3.3)	*Shrinkage*	52.3	2 (0)	*Medium Dense to Dense*
FB336	3.1 (2)	10 (0)	10 (0)	-	91.5	2 (0)	*Few to Medium*
FB672	4.1 (0.7)	10 (0)	7.3 (2.3)	*Shrinkage*	81.8	2 (0)	*Medium Dense*
FB1008	5.1 (3)	10 (0)	6 (3.3)	*Shrinkage*	75.6	2.5 (1)	*Medium Dense to Dense*

[a] 10 represents no blistering; 8 represents smallest blisters visualized; 6, 4, 2 represent progressively larger size blisters

Table 8. Changes in color after accelerated weathering for lab-applied, water-based intumescent paint

Specimen	ΔL*	Δa*	Δb*	ΔE*
FG336	2.8 (1.6)	0.4 (0.4)	0.6 (1)	3.0 (1.7)
FG672	1.7 (1.9)	0.3 (0.5)	0.4 (1.3)	2.1 (1.9)
FG1008	3.3 (2)	0.6 (0.5)	0.3 (1.1)	3.5 (2.1)
FB336	3.3 (2.9)	0.5 (1)	0.7 (3.2)	4.5 (3)
FB672	1.8 (2.1)	0.2 (0.9)	−1.7 (1.9)	3.5 (1.2)
FB1008	2.8 (3.5)	0.3 (0.9)	−2.1 (3.7)	5.7 (1.8)

The numbers reported are an average of nine readings (error in parenthesis).

Table 9. Summary of cone calorimeter results for dual-coated FRT systems, averaged over the number of specimens for each specimen type and rounded to the nearest whole number.

	Heat Flux [kW/m^2]	t_{ig} [s]	pHRR [kW/m^2]	time to pHRR [s]	HRR_{120} [kW/m^2]	THR [MJ/m^2]
FG_control	25	82	166	93	36	4
	50	16	237	31	89	45
	75	7	330	19	106	53
FB_control	25	82	146	89	25	3
	50	18	213	31	50	17
	75	9	317	20	93	48
FG336	25	92	200	100	60	36
	50	13	217	26	96	55
	75	7	349	19	130	60
FB336	25	82	154	94	50	29
	50	18	228	30	79	51
	75	9	345	19	123	60
FG672	50	13	250	27	98	49
FB672	50	18	248	29	98	60
FG1008	50	15	319	27	126	54
FB1008	50	14	260	22	108	59

significant differences are provided in Table 10. Based on observations by Dubrulle et al.,[10] accelerated weathering negatively impacts the effectiveness of the dual-coated system. From the t-test results, we see the negative effects of the accelerated weathering with significantly lower HRR_{120} and THR for unweathered controls regardless of application type. In addition, it would be anticipated that the dual-coated FRT systems applied properly would have better fire performance when compared to the improperly applied dual-coated FRT system, as was observed at 75 kW/m^2 when the t_{ig} for FG_control was significantly higher than the FB_control. However, overall, there was little difference between the effectiveness of the application methods and, surprisingly, a few cases where the improperly applied specimens performed better than the properly applied specimens. At 50 kW/m^2, FB336 had a significantly higher t_{ig} than FG336 and FB1008 had a lower pHRR than FG1008. This indicated

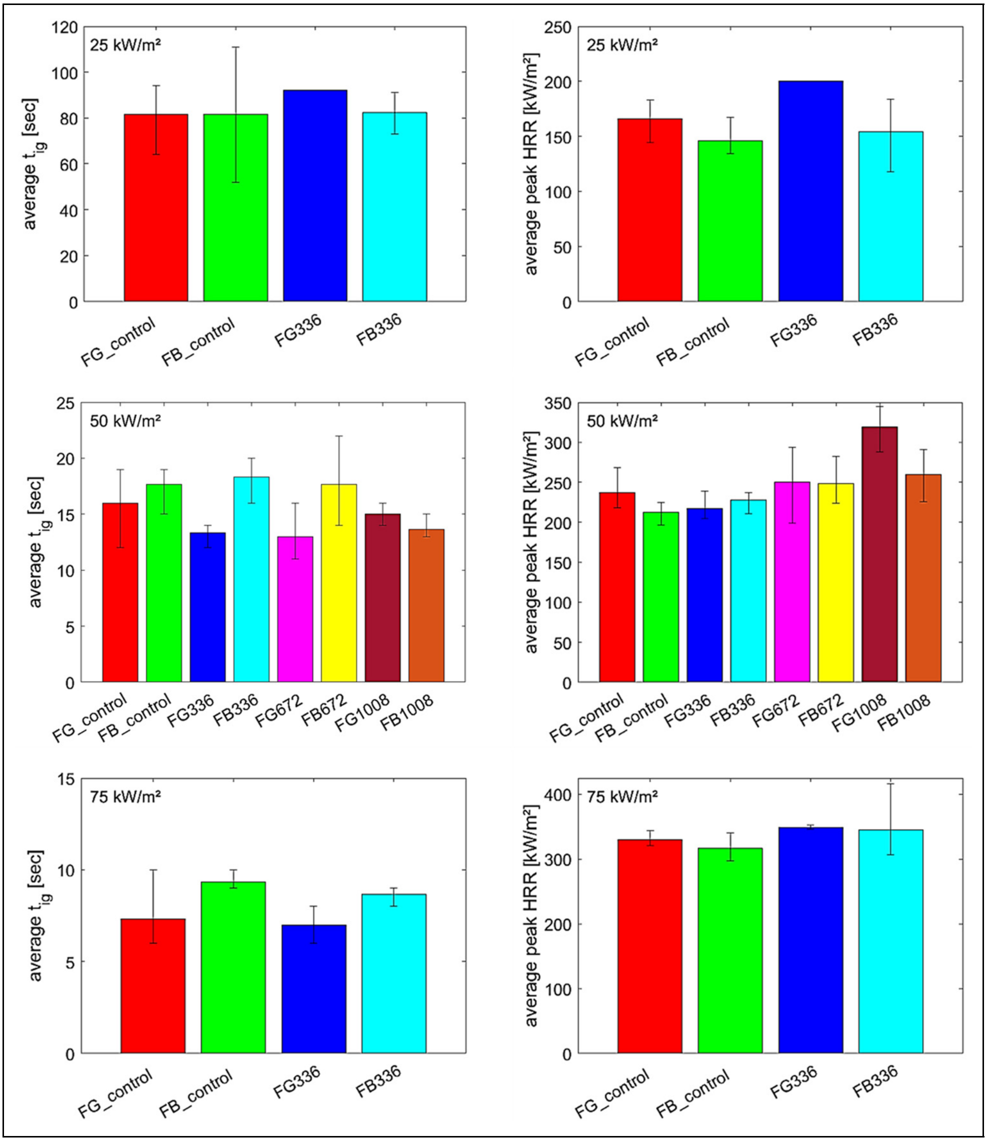

Figure 10. Results at each heat flux comparing dual-coated FRT systems applied properly (FG-) and improperly (FB-). The plots on the left are the average t_{ig} and the plots on the right provide the average pHRR. The control values are provided for reference. The error bars represent the maximum and minimums for the specimen group.

that accelerated weathering, and subsequently checking and blistering, negatively impacted the fire performance, regardless of application methods.

Table 10. P-values of accelerated weathered specimens that showed significant differences for flammability parameters ($P \leqslant 0.05$) based on t-test results.

t_{ig}	pHRR	Time to pHRR	HRR_{120}	THR
25 kW/m^2				
None	None	None	FG_control* to FG336: 0.04 FB_control* to FB336: 0.03	FG_control* to FG336: 0.001
50 kW/m^2				
FG336 to FB336*: 0.02 FB336* to FB1008: 0.02	FG1008 to FB1008*: 0.03 FG336* to FG1008: 0.006	FB336* to FB1008: 0.006 FB672* to FB1008: 0.01	FB_control* to FB672: 0.007 FB_control* to FB1008: 0.03 FG_control to FB_control*: 0.02	FG_control* to FG336: 0.002 FB_control* to FB1008: 0.04 FB336* to FB672: 0.03
75 kW/m^2				
FG_control* to FB_control: 0.004	None	None	FG_control* to FG336: 0.03	None

*This specimen had better fire performance results than the comparison for the given flammability parameters.

Dual-coated FRT weathering comparisons

Conducting t-tests with the results from both the naturally weathered (B) and accelerated weathered (FG and FB) specimens, we gain insight into potential differences of weathering type on the dual-coated FRT systems. In addition, to understand the efficacy of the dual-coated FRT systems before weathering, we compared the unweathered controls (FG_control and FB_control) to the uncoated control from the naturally weathered specimen group, which was weathered for one year. While natural weathering of uncoated wood will impact the surface qualities such as color, the overall ignition and burning rates of uncoated wood have been shown to not be affected by weathering.[37] The P-values used to determine significant difference ($P \leqslant 0.05$) from these comparisons are provided in Table 11.

Based on the durations of the QUV accelerated weathering, we would expect the naturally weathered dual-coated specimen (B) to be similar to the specimens exposed to accelerated weathering for 336 hours (FG336 and FB336), which was representative of one year.[32] This was true for most instances except that B, which was naturally weathered for one year, had a significantly greater t_{ig} than FG336 at 50 kW/m^2 and significantly lower THR than FG336 and FB336 at both 50 and 75 kW/m^2. This suggests that the accelerated weathering protocol used was a more severe exposure than the natural weathering.

In certain instances, the unweathered control specimens with the dual-coated FRT system, regardless of application, performed better than the uncoated, naturally weathered control. Surprisingly, this did not hold true for all flammability parameters measured where either there was no significant difference or the uncoated control performed better than the dual-coated FRT unweathered control (t_{ig} at 75 kW/m^2). This lack of difference is additionally supported by the fact the visual expansion of the intumescent paint nor that self-

Table 11. P-values of dual-coated specimens that showed significant differences for flammability parameters ($P \leqslant 0.05$) based on t-test results.

t_{ig}	pHRR	time to pHRR	HRR_{120}	THR
25 kW/m^2				
None	None	None	FG_control* to Control: 0.02 FB_control* to Control: 0.01	FG_control* to Control: 0.001 FB_control* to Control: 0.001
50 kW/m^2				
FG336 to B*: 0.02 FB1008 to B*: 0.02 FB_control* to Control: 0.01	None	None	None FB_control* to Control: 0.01	FG336 to B*: 0.03 FB336 to B*: 0.008 FB672 to B*: 0.004
75 kW/m^2				
FB_control to Control*: 0.01	None	None	FG_control* to Control: 0.008 FB_control* to Control: 0.005	FG336 to B*: 0.0006 FB336 to B*: 0.006

*This specimen had better fire performance results than the comparison for the given flammability parameters.

extinguishment was observed for the unweathered dual-coated FRT systems. This could be a result of mechanical restriction or thermal shielding by the topcoat affecting expansion of the underlying intumescent paint or chemical incompatibility[10] of the two products. If thermal shielding of the topcoat occurred, it is more likely that the expansion would have been delayed rather than nonexistent for the samples tested here. Furthermore, the two products that formed the dual-coated FRT system were specified to be used together by the manufacturer so chemical incompatibility is less likely. As previously noted by Bahrani et al.,[9] Dubrulle et al.,[10] Wang et al.,[18] Jimenez et al.,[38] and Xu et al.[39] topcoat interactions with intumescent coatings are nuanced, requiring careful evaluation of compatibility and end-use application.

General remarks

This study utilizes a cone calorimeter at three different heat fluxes that represented ignition, a developing fire, and a fully developed fire.[40] However, the cone calorimeter represents radiation-driven ignition and does not specifically address convective heating or direct flame impingement that may occur in the WUI, nor do the heat fluxes used encompass all potential ranges of radiative exposures. Regardless, the cone calorimeter provides a way to screen materials for flammability and allowed comparison of the reaction to fire between each multi- and dual-layer FRT system investigated here.

In addition, products intended for use in exterior locations are commonly weathered per ASTM D2898 Method B and evaluated in a tunnel per ASTM E2768.[11] A heat flux level of 50 kW/m^2 applied in the cone calorimeter may represent the burner exposure in the tunnel test; however, recent models utilize results from the cone calorimeter at lower 25 kW/m^2 to predict tunnel test results.[41–43] As such, we used both heat flux levels. Ultimately, while the cone calorimeter may not accurately predict the flame spread outcome from the tunnel test, the flammability results do demonstrate the negative effect both accelerated and natural weathering had on the multi- and dual-layer FRT systems.

While important findings have been presented regarding the use of multi-layer FRT systems in the WUI, future work to address the limitations of this study are recommended. We evaluated multi-layer FRT coating combinations after natural weathering, but visual ratings were not recorded; we recommend conducting surface analysis tests both before and after natural weathering. In addition, measuring the chemical composition of the coatings both before and after weathering is recommended to allow assessment of chemical changes. Evaluation of different coating thickness and coating adhesion should be taken into consideration. Finally, while it is common to test triplicates in the cone calorimeter, a greater number of samples are recommended to improve the statistical analysis.

Conclusions

The primary objective of this study was to assess various coating combinations (multi-layer FRT systems) to be applied on top of intumescent paints for exterior application in wildfire-prone areas. It was anticipated that certain combinations would provide a barrier against UV and hygrothermal degradation, preserving the fire performance of the intumescent paints after weathering. The following conclusions are obtained for this objective:

- After one year of natural weathering, all multi-layer FRT systems investigated failed to protect the intumescent paint layer indicating the UV and moisture were able to penetrate the topcoat(s).
- Regardless of the presence of a topcoat or acrylic latex color, the UV and moisture intrusion negatively affected the intumescent paints tested, all of which showed no visual expansion or self-extinguishing characteristics.
- The use of a primer with kaolin clay and hydrous magnesium silicate may improve the t_{ig} though not statistically significant for all cases and further testing should be conducted.
- Largely, the presence of a multi-layer FRT system was not beneficial over the entirety of the cone calorimeter test, however most combinations did offer improvement to the t_{ig} when compared to the uncoated cedar shingle.

A secondary objective of the study was to evaluate the impact of proper versus improper application of dual-coated FRT systems with the expectation that improper application would negatively affect the fire performance. The following conclusions are obtained for this objective:

- Accelerated weathering caused significant breakdown of the coating and resulted in no visual expansion of the intumescent paints.
- Overall, applying the dual-coated FRT systems properly or improperly had little effect on the fire performance.

Finally, to gain insight into the differences between weathering methods, we compared the results of the dual-coated FRT systems that were both exposed to natural and accelerated weathering. In addition, the fire performance of the unweathered dual-coated FRT system was compared to uncoated cedar shingle. From this we found:

- The naturally weathered specimens showed greater t_{ig} and lower THR when compared to the accelerated weathering specimens, suggesting that the accelerated weathering protocol implemented in the QUV was more severe than the natural weathering that occurred in Mill Valley, CA.
- The flammability parameters of the unweathered dual-coated FRT systems were not significantly different from the uncoated cedar shingle, indicating that coating combinations should be assessed at a wide a range of heat fluxes and weathering conditions when the intended end-use is for exterior applications in the WUI.

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This article does not contain any studies with human or animal participants.

Consent to participate

There are no human participants in this article and informed consent is not required.

Consent for publication

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Statements and declarations

The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. The findings and conclusions also do not necessarily reflect the official policies or views of the Forest Service or IBHS.

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