Courtney Magill
University of Pennsylvania

Performance Assessment and Evaluation of Hydrophobic and Ultraviolet Protective Treatments for Historic Log Structures

ABSTRACT

This paper focuses on the evaluation of the durability of traditional and modern sustainable hydrophobic and ultraviolet resistant treatments for historic log structures such as those found at the Bar BC Dude Ranch in Grand Teton National Park, WY. These treatments are evaluated on a variety of criteria including performance in accelerated weathering, ecological sustainability, and impact on aesthetic and heritage character. Like many log structures in the American West, Grand Teton National Park's historic structures are exposed to a large amount of ultraviolet radiation. In addition to problems delineated from contact with water, the physical fabric of wood is damaged by ultraviolet light through degradation of lignin. Exposed wooden members are often affected by this damage in a matter of days. The small depth of penetration restricts damage to surface area. However, when combined with shrinkage and swelling of water sorption or abrasion from weathering, surface material delaminates, exposing untreated surfaces for further delignification and loss of fabric.

Accelerated weathering was conducted using a QUV Weatherometer in the Architectural Conservation Laboratory which simulates weathering by subjecting samples to cycles of UV-B light, heat, condensation, and sprayed water. While artificial weathering occurs in more intense, concentrated cycles than those in nature, results can be a good indicator of the longer-term performance of the treatments. Five modern and two historically-used treatments were chosen for testing on samples of lodgepole pine (*Pinus contorta latifolia*), a common building material in the area, obtained from a supplier in the region. Samples were monitored every 100 hours to observe surface degradation and were then evaluated pre- and post-weathering using microscopic analysis, Fourier Transform Infrared Spectroscopy (FTIR), contact angle measurements, and color measurements with a spectrophotometer. Supplementary natural weathering will be conducted on site this summer in order to verify lab results, and the combined results of the lab and field testing programs will inform the Park's conservation and maintenance program for the many historic log structures in their care. This testing was performed in cooperation with the National Park Service and the Western Center for Historic Preservation.

1. INTRODUCTION

This paper examines the durability of some chosen traditional and modern synthetic clear and lightly tinted protective treatments for historic log structures. The selected treatments have been conducted on new samples of the western species Lodgepole pine (*Pinus contorta latifola*), a coniferous softwood used widely in historic construction throughout the Rocky Mountain region. After artificial weathering, the coatings were assessed primarily on their hydrophobic and UV-resistant qualities and secondarily on aesthetic appearance in an effort to make recommendations for use in the preservation and maintenance of log structures found in northwestern Wyoming, focusing on historic sites found in the National Parks.

1.1 HISTORIC LOG STRUCTURES

Grand Teton National Park was established in northwest Wyoming on February 26, 1929 and was later expanded into the valley called Jackson Hole in 1950. It is only ten miles south of Yellowstone National Park, the first national park established in the United States in 1872, and the combined area protected by the National Park Service in both parks constitutes over 18,000,000 acres.

While these parks have traditionally been known for their natural resources, the new goal set by management is to establish the area as a cultural resource as well. A plethora of historic log structures originating first in Westward expansion and later in the Great Camp Movement survive in both parks ranging in size and complexity from small guest cabins on dude ranches to the Old Faithful Inn, a pinnacle monument in western log construction. These buildings form a rich cultural landscape for the public to explore.

Figure 1. Barn on Mormon Row in Grand Teton National Park

One such site, the Bar BC Dude Ranch, located on the banks of the Snake River in Grand Teton National Park, is a focal point for conservation and site restoration. The ranch was founded in 1912 by Struthers Burt and Horace Carncross, both prominent Philadelphians, and catered to western fantasies of elite guests from the east coast. The cabins and other log buildings on site were built in the so-called "cowboy style," a rustic form of construction that was both economical for the owners and exactly what guests expected to encounter on their long vacations to the Wild West. The romanticized ideal was forwarded by Burt and his wife Katherine, both prominent authors; the ranch was even featured in the early Hollywood movie, "Snowblind," from a screenplay adapted from one of Katharine's Western romance novels. The logs at the many ranches like the Bar BC were usually left undressed or treated with linseed oil, allowing the wood to weather and aesthetically become part of the landscape.

Figure 2. Cabin 1368 (left) and 1369 (right) on the Bar BC Dude Ranch, Bar BC Condition Assessment and Report conducted by the Architectural Conservation Laboratory of the University of Pennsylvania.

The parks are located in a semi-arid mountain climate with mild summers and long, very cold winters. The climate is very dry with a low relative humidity throughout most of the year and most precipitation occurs during winter months. Heavy snow loads from November to April can create problems both with overloading the unstable historic structures as well as establishing constant water exposure through daily cycles of freezing and thawing on the lower portions of these structures for months at a time. However, because of the high elevation at about 6,800 feet in the valley alone, ultraviolet (UV) radiation remains one of the main forms of wood deterioration in the park.

1.2 RESEARCH APPROACH

Research for this paper mainly focused on investigation of finishes used for the protection of wood, particularly on those that are similar to the finishes seen on the log structures throughout the two Park systems. Generally, a good deal of these treatments have historically served more to express the materials and methods of log cabin construction rather than to protect the wood to the fullest extent especially due to the lack of continued maintenance over their lifetimes. In order to better understand the deterioration mechanisms of wood, I will later be exploring the natural weathering process on site as compared to the high stress environment created in a QUV Weatherometer.

Preservative treatments for wood derive from four basic methods: pretreatment of wooden members before installation in the structure, usually by impregnation -- biocidal washes -- one-time biocidal treatments delivered during repairs -- and more permanent protective systems of paints, stains and coatings. The treatments selected for this experiment consist of this last method of treatment, striving for longer-lasting protection through protective surfaces. Thus, it addresses treatments that can be applied to largely prevent the conditions conducive to wood decay rather than treat those symptoms that can occur once decay conditions have been reached. However, most finishes do require some sort of fungicide to prevent the formation of mildew on the surface.

Wood has a hydrophilic character due to the hydroxyl groups contained in its structure. These hydroxyl groups allow for the movement of water along with other nutrients throughout the body of the tree. However, once these wood cells die, excess of water can create a climate of decay. Thus, hydrophobic treatments can be especially significant in wood conservation due to the detrimental effects that extensive water absorption can have on the material, for wood is only safe from decay when kept dry. At moisture contents above the fiber saturation point, various agents of decay such as insects, fungi, and water-soluble impurities can begin to degrade the material. The speed of attack of organisms depends on various combinations of moisture content, temperature, relative humidity, and different chemicals present in the wood. Most of these decay agents cannot tolerate moisture levels below 18%, some as low as 8%. Thus, prevention of moisture content higher than this level can be an effective way to limit wood decay.

Ultraviolet light can also damage the physical fabric of wooden members through degradation of lignin in the material. This photo-oxidation leads to colored decomposition products that results in the lightening or darkening of the wood surface, depending on the species. This process can happen rather quickly, affecting the exposed wooden member in a matter of days. Due to a small depth of penetration however, this damage is restricted to surface areas. However, when combined with the shrinkage and swelling of water sorption or abrasion from weathering, surface material can begin to delaminate, exposing untreated surfaces for further delignification.

Figure 3. Degradation by UV Radiation on Cabin 1379 at the Bar BC Dude Ranch, Bar BC Condition Assessment and Report conducted by the Architectural Conservation Laboratory of the University of Pennsylvania.

Additionally, coatings that do not protect against UV radiation can also face accelerated polymer degradation from the release of free radicals in the wood caused by substrate surface breakdown, causing them to be rendered ineffective. In the field, it is important that coatings have as long of a life as possible, even under harsh weathering conditions, because often historic structures, especially largely disused ones, can receive preservation attention only sporadically over their lifetimes. It is vital to note that decay in wooden members can occur due to a variety of factors inherent to the substrate and that wood is an incredibly variable material. The degree of decay in certain conditions can be affected by the species of tree, the type of that species (hardwood or softwood), the density of the wood and the ring structure (old growth or new growth), the portion of the tree the member was cut from (heartwood or sapwood), and the natural resins, gums, and extractives found in the wood which may promote water-repellence or fungicidal qualities.

1.3 HISTORICALLY USED TREATMENTS

Cultures that have traditionally used wood as a building material have developed various techniques for its protection from rot and decay. The evolution and success of these treatments depended on the environmental conditions of the area as well as the available resources, but most treatments for wood involve regular maintenance and reapplication in order to ultimately be successful. Wood will last longer if it is regularly treated with finishes that add water repellency and prevent cracking and weathering while inhibiting fungal growth.

Due to a preponderance of pine trees in the area, Scandinavian cultures traditionally protected buildings using pine tar resin. Prominent buildings of wooden shingle construction, such as the Viking stave churches of Sweden and Norway, were usually the recipients of this treatment. The product was collected using carefully built kilns which would distill down the resins in the heartwood of old pine trees over a period of a few days as operators skillfully manipulated air flow, heat, and material. This process has been carried out in Norway since the early medieval period and small batches are still made every few years. Mandates in medieval law required that peasants produced this tar every three years and coat the church. This regular maintenance and effective coating have protected the stave churches for over eight hundred years with minimal replacement of wood material. The tar coating is very distinctive and tends to form a shiny appearance, so it is not necessarily an appropriate choice for use on Rocky Mountain cabins that were traditionally uncoated or treated with just linseed oil. However, some more recent products out of Sweden incorporate the pine tar resin into a thinner coating that has less impact on the visual appearance of the wood and could be worthy of future testing.

Linseed oil was commonly used, and is still used, for its hydrophobic properties and deep penetration into wood surfaces for protection from water and rot. Even a thin layer can reduce wood movement and cracking by preventing rapid surface absorption and avoiding steep surface moisture gradients. Surfaces must be cleaned before application, however, or dirt and debris can become engrained in the finish and turn the wood black, and once linseed oil has cured then it is very hard to remove. It is a drying oil, so it dries through the chemical process of oxidation and can polymerize into a solid form. Upon exposure to oxygen, the large amount of alpha-linolenic acid in the oil reacts to form polymer chains that crosslink and results in the increased rigidity of the oil.

Linseed oil is the product of cold-pressing seeds from the flax flower. The raw oil never fully dries and is much fattier, so professionals utilize boiled linseed oil, a product resulting from the refinement of raw linseed oil through the addition of oxygen. This "cooking" process reduces the amount of proteins and impurities in the oil, improving drying time and shine and reducing the fat content of the oil. Linseed oil products can often include chemical dryers as well to speed up the drying process. In more modern finishes, linseed oil is often modified to form alkyd resins to make them less prone to mildew as well. Unfortunately, because of its fatty acids, linseed oil is especially attractive to insects and thus, if not successfully boiled, can encourage infestations even as it acts as a hydrophobic barrier to water. Therefore oil treatments have often been mixed with anti-fungal agents or pesticides. This led to treatments such as the Madison Formula later in the mid-20th century trying to find an effective coating that embodied many different ingredients to create the perfect finish. The treatment combined a linseed oil base and mineral spirits for penetration with the fungicide pentachlorophenol, paraffin wax for waterproofing, pigments for stain colors, and zinc stearate for pigment suspension. However, this finish is no longer widely available due to its high toxicity.

Historically, natural waxes such as beeswax have been used more often in waterproofing objects and building materials. However, as technology has progressed, waxes with slightly different properties have been developed. Paraffin wax is a petroleum byproduct and is a fairly inert mixture of hydrocarbons that form a slightly brittle wax with a melting point around 99 ˚F. This higher melting point and the brittle quality make it a much better for exterior waterproofing because, except under very high heat, the wax will not melt and hold any dirt or soiling products kicked up by wind changing the appearance of the building. The wax alone does not penetrate deeply into the wood surface, so waxes have been mixed with mineral spirits, turpentine, mineral oil, and many other solvents and media in order to achieve greater penetration. Additionally, most recipes call for the mixture to be lightly heated in order for the treatment to permeate the wood. Subsequent applications can also be applied once the first coat dries. One of the main benefits of the wax and mineral spirits treatment is that, like linseed oil, it is nontoxic to the environment.

Later commercial products sprung out of the greater reach of coating companies and the increasing chemical technology after WWI and WWII. Architectural styles such as the Arts & Crafts movement made exposed, natural wood very appealing aesthetically. The desire for exposed wood surfaces continues today, and the wood decking industry especially drives the widespread market for longer-lasting, low-maintenance, UV resistant stains.

2. METHODOLOGY

2.1 PRODUCT SELECTION

Because of the abundance of products available on the market for wood protection, I developed a list of criteria in order to select products for testing. Included below is a small table of the seven products I chose after a careful selection process, with some of the more important properties I considered in the process. Because an oil finish had been historically applied to the logs on site at the Bar BC Dude Ranch and likely on other buildings in the area, I used linseed oil as a traditional finish as well another historically used treatment for water repellency, paraffin wax melted into mineral spirts.

	UV Protection	Water Repellence	Pigmentation	Color	Base	VOC content	Biocidal / Fungicidal	Availability & Cost
Allbäck Linseed Oil	None	Yes	None	Lightly yellow tint	Oil	None	No	Sweden or New York supplier ($21.50/L)
Paraffin Wax with Mineral Spirits	None	Yes	None	Clear	Mineral spirits	772 g/L (low odor) 276 g/L (odorless)	No	Widely available (wax $4.42/lb) (spirits $16.44/gal)
DEFY Extreme Wood Stain	Zinc oxide Nanopartic les	Yes	Yes, fine white nano particles	Clear	Waterborne	Less than 250 g/L	Yes	Available at certain retailers or on the web ($42.71/gal)
Armstrong Wood Stain, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	No more than 50 g/L	Yes	Available at certain retailers or on the web ($36.95/gal)
TWP 1500, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	350 g/L	Yes	Available at certain retailers or on the web ($37.99/gal)
Flood CWF UV-5, Clear	Yes	Yes	Yes	"Clear" tone, lightly tinted	Oil-based (linseed)	332 g/L	Yes	Widely available ($18.98/gal)
Messmer's UV Plus, Natural	Yes	Yes	Yes	Natural tone, lightly tinted	Oil-based	Less than 250 g/L	Yes	Available at certain retailers or on the web ($37.99/gal)

Table 1. The Products Chosen for Testing and some of their Properties Considered in Selection.

I evaluated a variety of commercial products that are commonly available so that the National Park Service might have an easily attainable and relatively inexpensive option for maintenance. Many of these commercial products are proprietary and do not divulge their formulations because of trade secrecy; however, some key information such as class of coating, solvent type, percent solids by weight, and hazardous materials are available along with other logistical information in technical data sheets and material safety data sheets. In the process of selection, some of the standards were deemed more important than others depending on the needs of the site. Due to the high UV radiation in the Rocky Mountains, ultraviolet protection for the wood is a paramount concern; additionally, due to the decay mechanisms caused by high moisture content, water repellence was also prioritized. Also, because the coatings of such regional log structures in the past were historically clear or only lightly colored, selected products had to be as such with very little impact on the aesthetic appearance of the wood. Another important consideration is the changing product market due to increasingly strict laws on volatile organic compounds, or VOC's, from the enforcement of the Clean Air Act. States such as California have increased their restrictions past the federal limits, requiring that products have 250 g/L or less of volatile organic compounds in clear and semi-transparent stains while the federal limits require 550 or less. While Wyoming currently has no state limits, federal limits may change swiftly in the future causing higher VOC products to become illegal and are no longer available. Other criteria were considered in final selection, but I deemed these the most important.

2.2 SAMPLE PREPARATION

All of the trees harvested from Timbered Island and the surrounding area for use in erecting homesteads and ranches like the Bar BC were lodgepole pine, a species of tree known for its tall, straight stature and relatively little branches, making them perfect for building. Logs used currently by the Park Service in repairs and replacements for historic structures are still lodgepole pine, though the trees must be sourced from outside of the park. In order to best represent the wood that was historically used and is still being used today for repairs, samples for the experiment were obtained from a recurrent supplier, Willmore Lumber Company out of Idaho. In an effort to imitate the outer sapwood that would be most affected by the exterior weathering, Willmore sent scrap material that was cut off of logs while making dimensional lumber using a technique called plain or cant sawing; the rounded edge is cut off to produce a cant that is further cut to produce boards. This edge material consists of the outer 1-2 inches of the lodgepole pine logs roughly the same size as those used at the Bar BC, comprising of the bark and cambium along with sapwood. Samples were cut from this material in the Fabrication Laboratory at the University of Pennsylvania to standardized sizes measuring 9 ¼" long, 1 ¾" wide, and ½" deep, removing the outer bark and creating a flat surface in order to fit into the stainless steel sample brackets of the weathering apparatus. Additionally, each long sample was separated into two smaller samples with the insertion of a neoprene strip coated in epoxy.

Figure 4. Preparation of Samples on the Lab Bench.

The seven products were applied to these wood samples according to instructions given by the manufacturer. These instructions were found on the can as well as on the websites of each individual product. In the case of the linseed oil and paraffin with mineral spirits, further investigation was carried out on the historic application of these treatments in order to apply them with the best results. The samples were measured for moisture content using a Wagner MMC 210 Moisture Meter before treatment and all contained less than 10% moisture. Product application was carried out a week before the samples were inserted into the machine to allow time for curing, especially for the oil-based products. These samples were weighed before and after treatment to indicate how receptive each sample was to the treatment. Additionally, before the products were inserted into the brackets for weathering, a sample 5/16 inch deep was cut off the end of each samples and labelled for the purpose of comparison before and after accelerated weathering.

The samples were then fit into stainless steel brackets for the Weatherometer that had been retrofitted to hold six samples rather than two in order to utilize more space within the machine using aluminum T-bar to prevent cross-contamination across the samples; Chicago Binder Posts inserted into the frames along with coated wire was used to hold samples in place.

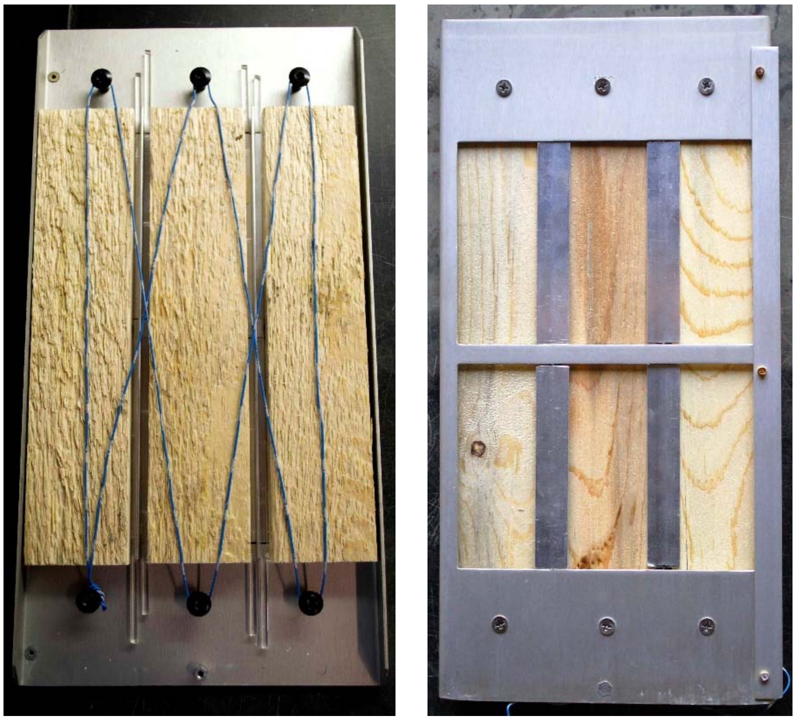

Figure 5. Assembled Testing Brackets from the back (left) and front (right).

2.3 WEATHERING

Accelerated weathering was conducted using a QUV Weatherometer in the Architectural Conservation Laboratory at the University of Pennsylvania. The Weatherometer was set to a fifteen minute spray followed by a three hour and forty five minute condensation period. The samples were then exposed to four hours of ultraviolet radiation before undergoing the spray and condensation again in a continuing cycle.

The experiment was carried out over an 800 hour period in a QUV Weatherometer to come as close to industry standards for testing as possible with the limited amount of time available.[1] UV-B-313 lights were used instead of UV-A to further accelerate the process. Though they are more intense and project some wavelengths that are not seen in nature, the purpose of the experiment was to push the treatments to their limits to see how they might break down under extreme circumstances. Accelerated weathering by nature is an extreme process because of the small cycles of wetting and drying along with the radiation, so natural weathering testing is always recommended in the field to evaluate results.

Figure 6. The QUV Weatherometer in the Architectural Conservation Laboratory both closed (left) and opened with specimen brackets inserted (right).

2.4 MONITORING

Samples were removed from the machine every 100 hours for photography along with weight and color measurements in an effort to monitor the degradation of the material. The weights varied depending on the point in the weathering cycle when the samples were removed from the machine, but inspection of the surfaces led insight into how each treatment behaved as time passed. Surfaces were monitored for symptoms of degradation such as wooling, checking, graining, and warping.

3. OBSERVATIONS

In order to monitor the changes that may have occurred at the surface of the samples during accelerated weathering in both the wood fabric and the penetrating treatment, a variety of testing methods derived from ASTM standards were utilized to test for certain properties of the wood before and after the weathering process. Ultraviolet resistance was monitored through inspection of surface morphology using a Leica MZ16a Microscope, sample weight change,

[1] Time was limited both by the semester as well as by another student performing weathering testing with the QUV Weatherometer in the ACL.

color change measured by a Konica Minolta Spectrophotometer CM-2500d, and Fourier Transform Infrared Spectroscopy (FTIR). Water repellence properties were monitored through contact angle measurements of water droplets on sample surfaces. Treatment retention was also analyzed using FTIR. These tests along with the monitoring periods every 100 hours throughout testing gave insight into the performance of each product in protecting the wood substrate. [2]

3.1 SURFACE INSPECTION

Wood surfaces as well as cured stains on glass slides were examined more closely at low magnification to examine changes that occurred during weathering, in the case of the wood samples, and to better understand composition, in the case of the stains. Photographs were taken at the same location before and after weathering for the most part.

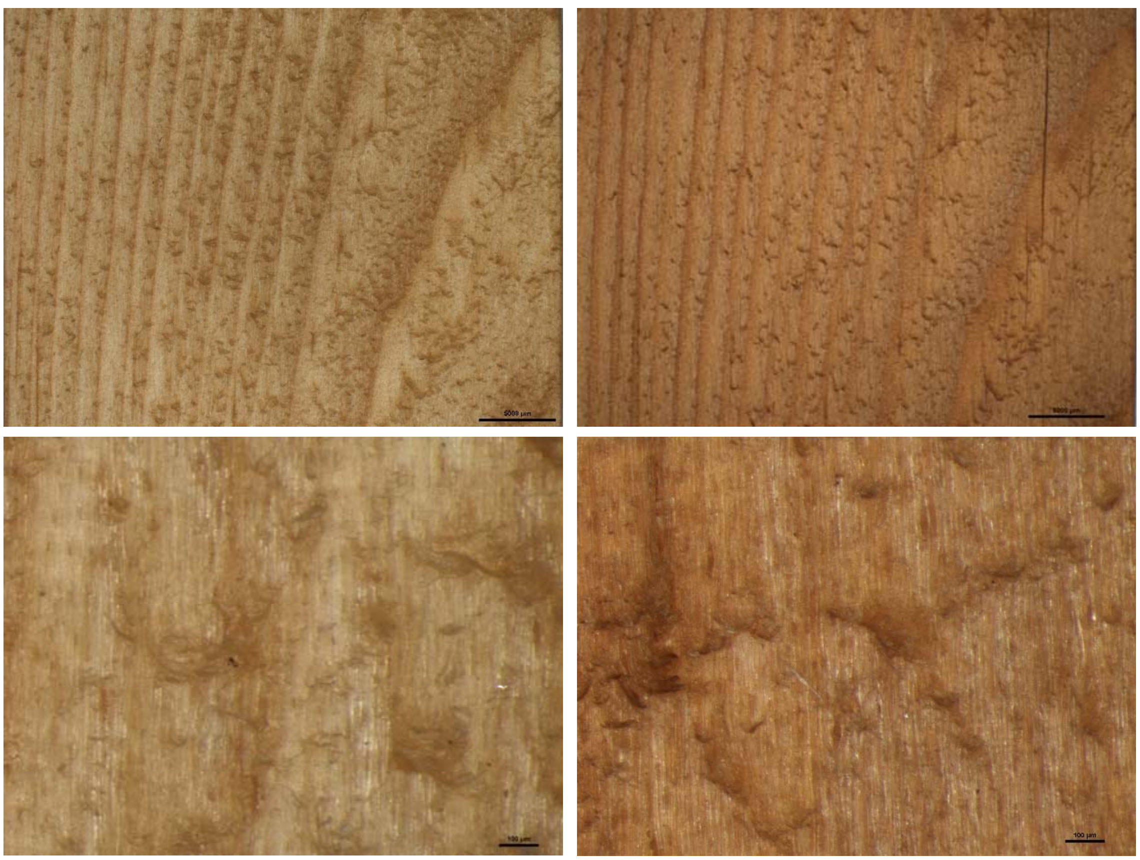

Figure 7. Messmer's UV Plus Sample 1 before (left) and after (right) weathering at 1x magnification (above) and 10 x magnification (below).

[2] For more detailed information on the results of each test, refer to the full thesis *Performance Assessment and Evaluation of Hydrophobic and Ultraviolet Protective Treatments for Historic Log Structures* by Courtney Magill (2015).

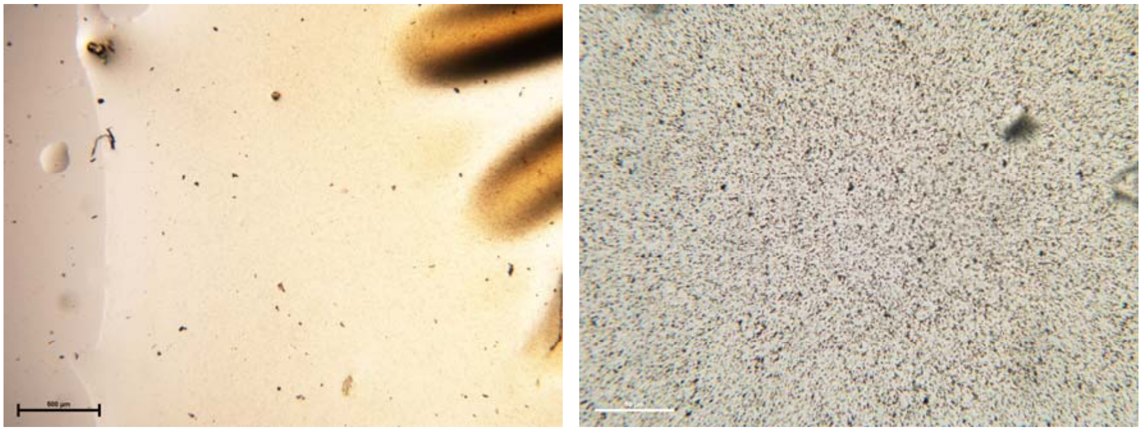

Figure 8. Messmer's UV Plus deposited on a glass slide and inspected at 4x magnification (left) and 40x magnification (right).

3.2 WEIGHT CHANGE

Weight changes from pre- to post-weathered samples can serve as a good indicator of physical degradation of the wood surface as well as the penetrating treatments. Each full length sample, containing two samples each (1-2, 3-4, 5-6), was weighed after treatment before weathering and after weathering; the samples were measured for moisture content at both times of measurement to ensure that each weight was a good representation of the wood fabric rather than for excess water. Moisture content was measured using a Wagner MMC 210 Moisture Meter and the samples were weighed on an Adventurer OHaus Analytical Balance.

There was a range in the weights of each sample due to the variability of the wood fabric, but weight change measurements and percentage values in table 5 reflect relatable degradation of fabric and treatments between the products. Some products had a greater range of percent weight loss between the three long samples, while others varied very little. Though there was an effort to regularize the samples as much as possible, this irregularity could be due to conditions in certain samples such as ratio of earlywood to latewood, how much treatment was accepted into the wood fabric, any abnormalities in the wood fabric, moisture content, etc.

Sample		Weight (Post-Treatment, Pre-Weathering)	Moisture Content (Pre-Weathering)	Weight (Post-Weathering)	Moisture Content (Post-Weathering)	Mass of Treatment Absorbed	Weight Change	Percent (%) Weight Loss
Control								
	CON-1 & CON-2	72.77	8.9 / 8.4	71.71	8.6 / 8.7	n/a	**1.06**	**1.46**
	CON-3 & CON-4	70.27	8.0 / 7.6	69.14	7.4 / 7.6	n/a	**1.13**	**1.61**
	CON-5 & CON-6	74.46	8.9 / 8.9	72.49	7.3 / 7.5	n/a	**1.97**	**2.65**
Linseed Oil								
	LIN-1 & LIN-2	74.93	8.5 / 8.3	73.30	8.3 / 8.3	1.84	**1.63**	**2.18**
	LIN-3 & LIN-4	64.45	7.2 / 7.8	62.65	7.1 / 7.4	2.17	**1.80**	**2.79**
	LIN-5 & LIN-6	77.71	9.5 / 9.5	75.67	9.1 / 9.5	1.15	**2.04**	**2.63**
Paraffin and Mineral Spirits								
	PAR-1 & PAR-2	77.18	8.2 / 8.7	75.55	9.2 / 9.8	0.77	**1.63**	**2.11**
	PAR-3 & PAR-4	65.01	7.5 / 7.1	63.35	6.8 / 7.1	1.19	**1.66**	**2.55**
	PAR-5 & PAR-6	76.86	9.8 / 9.6	74.67	9.2 / 8.6	0.19	**2.19**	**2.85**
DEFY Extreme								
	DEF-1 & DEF-2	78.22	7.6 / 8.1	76.48	8.2 / 8.6	1.35	**1.74**	**2.22**
	DEF-3 & DEF-4	62.15	7.3 / 6.9	60.77	7.9 / 7.7	1.58	**1.38**	**2.22**
	DEF-5 & DEF-6	67.57	7.9 / 8.5	65.65	8.1 / 8.2	0.82	**1.92**	**2.84**
Armstrong's Wood Stain								
	ARM-1 & ARM-2	76.02	8.9 / 9.5	74.16	8.7 / 8.9	1.72	**1.86**	**2.45**
	ARM-3 & ARM-4	75.51	8.0 / 7.8	73.95	8.4 / 8.2	2.23	**1.56**	**2.07**
	ARM-5 & ARM-6	81.18	9.1 / 8.7	79.78	9.8 / 9.8	2.05	**1.14**	**1.40**
TWP 1500 Natural								
	TWP-1 & TWP-2	59.27	6.8 / 6.6	57.47	6.2 / 6.6	1.26	**1.80**	**3.04**
	TWP-3 & TWP-4	73.87	8.6 / 9.0	72.08	8.7 / 8.6	0.86	**1.79**	**2.42**
	TWP-5 & TWP-6	74.59	7.9 / 8.4	72.80	7.9 / 8.1	0.76	**1.79**	**2.40**
Flood CWF UV-5								
	FLO-1 & FLO-2	77.21	8.7 / 9.2	75.58	8.7 / 9.3	1.10	**1.63**	**2.11**
	FLO-3 & FLO-4	73.72	9.7 / 9.8	71.60	8.5 / 9.0	0.88	**2.12**	**2.88**
	FLO-5 & FLO-6	79.27	9.8 / 9.8	77.38	9.2 / 9.8	0.61	**1.89**	**2.38**
Messmer's UV Plus								
	MES-1 & MES-2	69.56	7.9 / 8.4	67.82	6.8 / 7.1	0.88	**1.74**	**2.50**
	MES-3 & MES-4	67.88	7.6 / 7.3	66.24	7.2 / 7.4	1.14	**1.64**	**2.42**
	MES-5 & MES-6	69.10	7.3 / 7.3	67.32	6.6 / 7.1	1.22	**1.78**	**2.58**

Table 2. Weight changes from pre-weathering to post-weathering showing weight gained during treatment, amount of weight lost during weathering, and the percentage of weight lost.

3.3 COLOR CHANGE

Absorption of ultraviolet radiation and the subsequent degradation of lignin in the wood substrate is the primary cause of color change in the weathering of wood. The wood gets darker with the accumulation of the lignin degradation products, and, as these product wash away, becomes lighter and more silvered due to the accumulation of cellulose fibers at the surface.

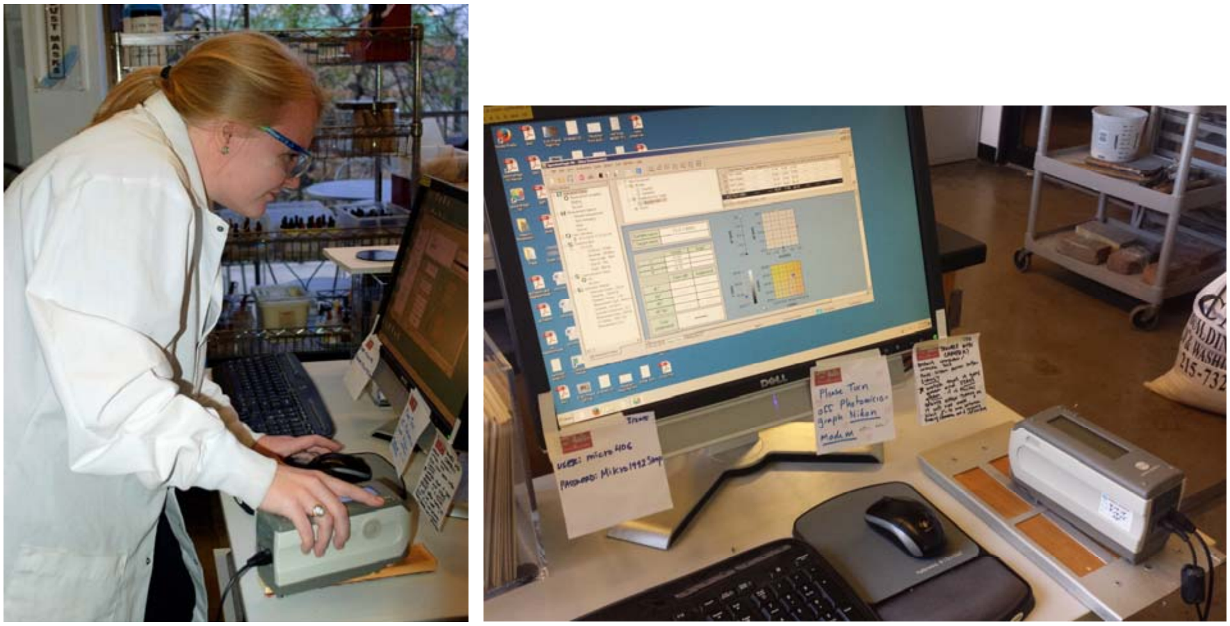

Figure 9. Taking color measurements using the Konica Minolta Spectrophotometer in the Architectural Conservation Laboratory.

A Konica Minolta Spectrophotometer CM-2500d was used to observe changes in the wood fabric and coatings in three different scenarios: from before treatment to after treatment, before weathering to after weathering, and comparison of the weathered control sample to the weathered coated samples. These three scenarios were chosen to better understand the aesthetic changes that occur when a sample is coated with a certain product, how that product weathers and whether it is protecting the wood, and how that product compares to the weathering of the uncoated wood substrate. As previously mentioned in the methodology, the CIE 1976 L*a*b* system was used for evaluation using SpectraMagic NIX software for processing changes (L*Δa*Δb* and ΔE* overall) in each scenario. A target sample was first taken using the spectrophotometer to obtain the values for the standard to which the sample is being compared and then the actual sample was measured for comparison. The software then generated color values as well as calculated the overall difference (ΔE) and the shifts in the axes L*, a*, and b* for comparison purposes.

Sample	Before and After Treatment (ΔE) (Average)	Before and After Weathering (ΔE) (Average)	Weathered Sample to Weathered Control (ΔE) (Average)
Control	n/a	24.69	n/a
Linseed	17.23	29.25	13.99
Paraffin	2.59	25.75	5.69
Defy	4.12	30.04	8.30
Armstrong	21.27	20.48	8.92
TWP	26.89	15.43	14.22
Flood	22.88	26.30	22.64
Messmer's	29.55	20.05	20.75

Table 3. Average values of color change for each scenario.

3.4 FTIR

Fourier Transform Infrared Spectroscopy sampling by transmission was conducted at the labs of the Philadelphia Museum of Art using a Nexus 670 FTIR and OMNIC Processing. The samples were inspected in the middle region of the spectrum, ranging from 500 – 4000 wavenumbers. Due to limits on testing time, only one sample of each treatment could be tested, so sample 1 was used for the whole range of treatments for continuity. A very small amount of surface material was carefully removed using a clean scalpel and deposited in a diamond cell where it was further pressed into the cell with a metal roller. The cell was then placed under the microscope and background measurements were taken 200 times before material analysis to ensure that the diamond cell did not interfere with the bands of the wood and the products.

Once an acceptable sample was found with initial readings, the spectra was generated 200 times to form the resulting graphs. The spectra for un-weathered and weathered lodgepole pine was first inspected in order to confirm peaks listed in previous papers that used infrared spectroscopy to monitor wood and paper degradation (Lionetto et al., 2012; Proniewicz et al., 2002; Schmalzl and Evans, 2003). Each of these papers listed a variety of peaks for wood components, but all listed the small peak at about 1508 wavenumbers (cm-1) as an indicator for lignin that can be monitored to detect wood fabric degradation. Spectra of the un-weathered surface and several areas of the weathered surfaces confirmed the presence of the peak from the fabric before weathering and its subsequent absence in the three sampling locations of weathered fabric.

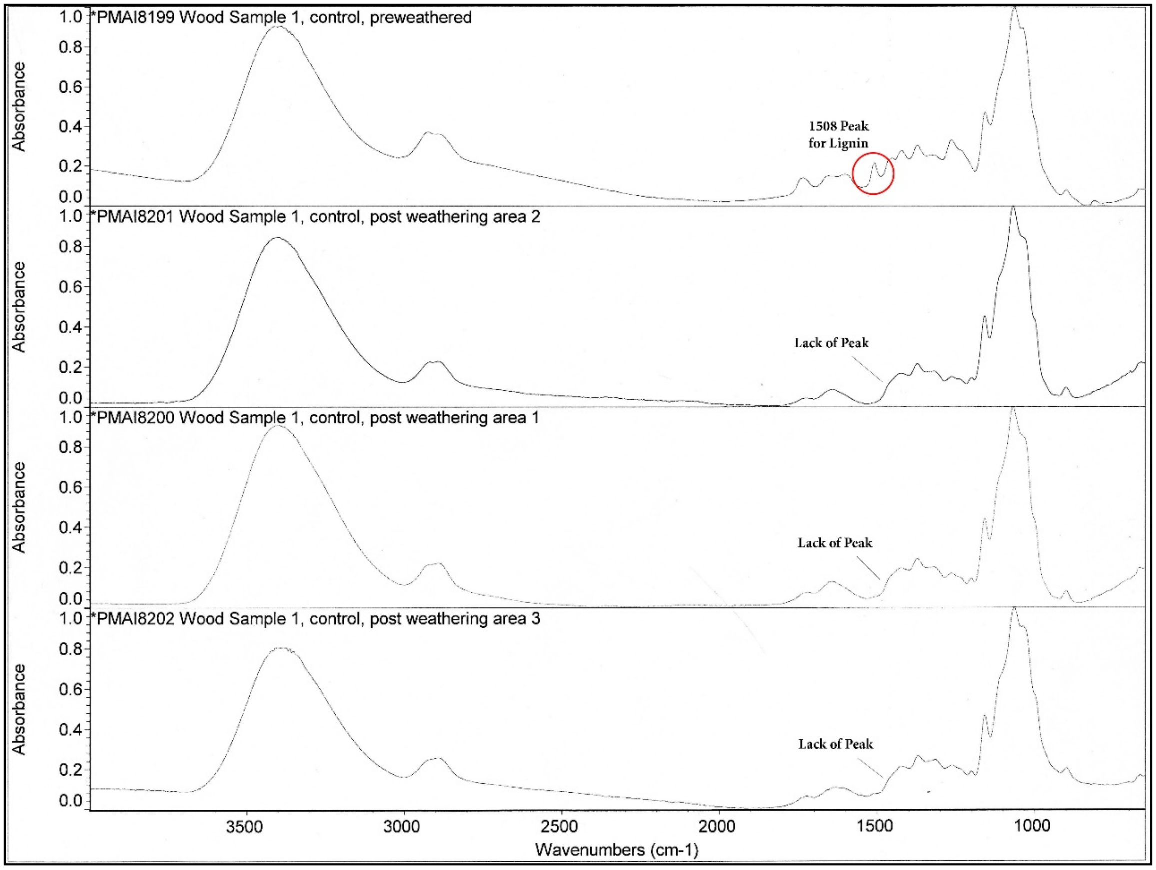

Figure 10. Spectra for Control Sample 1 before and after weathering confirmed that the peak for lignin at 1508 wavenumbers was a good indicator for weathering and subsequent loss of lignin. Spectra generated at the Philadelphia Museum of Art.

3.5 WATER REPELLENCY

This test dealt with measurement of the angle of contact when a drop of liquid is applied to a coated surface. This angle is the interior angle that a drop makes between the substrate and a tangent drawn at the intersection between the drop and the substrate. These angles are governed by surface tension, an effect that arises from unbalanced molecular cohesive forces at a surface that cause the surface to contract and behave like a membrane, but cannot be used to measure surface tension directly (ASTM D7334 – 08). By measuring the advancing contact angle, the angle immediately after the drop is deposited on the surface, the hydrophobicity of the coating and wood surface can be determined; for water, an angle less than 45˚ indicates a hydrophilic surface, greater than 90˚ indicates a hydrophobic surface, and anywhere between 45-90˚is intermediate.

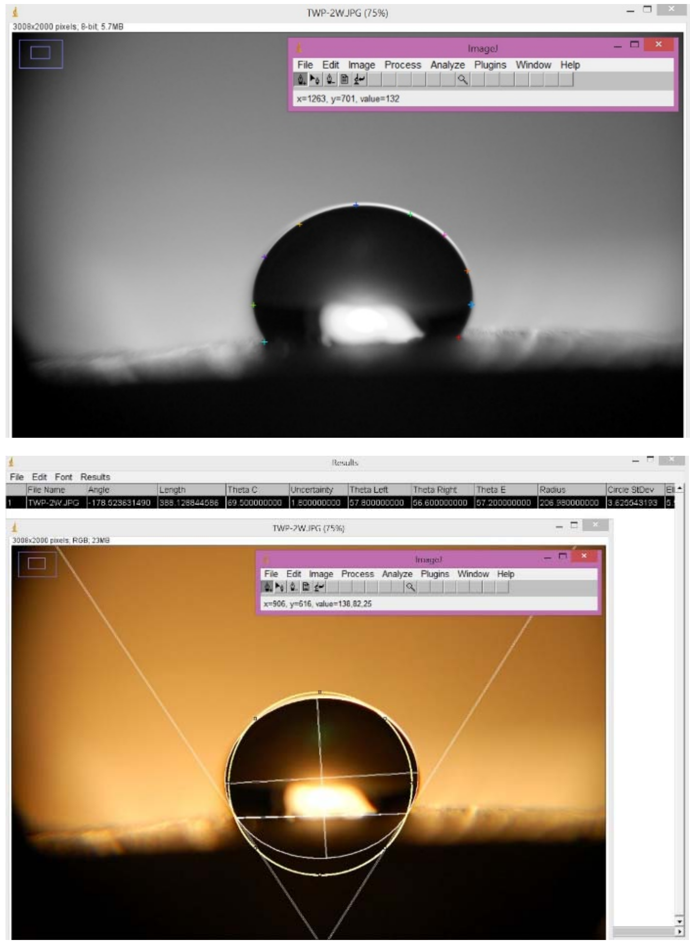

Figure 11. Droplet processing using the Contact Angle plug-in on ImageJ. Points are selected around the edges of the drop to create the most accurate fit (above) and the software subsequently processes the best-fit ellipse or circle and calculates the angle of interaction with the axis of the surface to generate the contact angles on both sides of the droplet (below).

The set up for the experiment included a horizontal stage on which the sample was placed. In order to focus the camera lens on the distilled water droplet, a mounted plano-convex lens with a focal length of 50 mm was placed between the camera and the sample area, held in place with another clamp and stand. The lens was located one inch from the sample stage and two inches from the camera lens, focusing the image on the droplet. A light source, was placed behind the sample stage facing the camera in order the illuminate the contact region from behind and allow greater contrast in the image for more accurate measurement. The water drop was dropped ¼" deep in the sample plane away from the lens and towards the light. Photographs were taken no more than ten seconds after the drop had been deposited in order to gain the most accurate reading of the contact angle. These photographs were then fed into ImageJ, an open source analytical software, with a Contact Angle plugin in order to read measurements.

	Sample	Pre-Weathering Left Angle (˚)	Pre-Weathering Right Angle (˚)	Post-Weathering Left Angle (˚)	Post-Weathering Right Angle (˚)
Control					
	CON-1	97.9	87.6	135.9	132.1
	CON-2	95.9	88.4	127.5	134.7
	CON-3	94.5	90.4	149	140.2
	CON-4	107.4	104.8	141.9	151.1
	CON-5	80.3	80.3	109.3	67.9
	CON-6	96.2	91.1	100.7	96.8
Linseed Oil					
	LIN-1	84.9	84.9	85	82.1
	LIN-2	81.3	78.9	71.6	78.5
	LIN-3	85.6	86.7	83.5	85.2
	LIN-4	77.7	73.8	66.9	65.9
	LIN-5	71.9	68.7	72.4	72.1
	LIN-6	86.4	81.9	70.1	78.7
Paraffin and Mineral Spirits					
	PAR-1	77.9	80.4	n/a	n/a
	PAR-2	74.4	74.2	n/a	n/a
	PAR-3	93.9	88	n/a	n/a
	PAR-4	67.7	64.7	146.7	70.7
	PAR-5	84.8	88.7	76.9	113
	PAR-6	75.2	76.9	131.4	132.5
DEFY Extreme (Clear)					
	DEF-1	107.8	99.9	86.2	82.1
	DEF-2	93.1	97.6	79.9	80.5
	DEF-3	74.9	72.8	76.8	78.4
	DEF-4	57	58.8	81.2	86.6
	DEF-5	64.2	61.8	88.4	86.4
	DEF-6	61.4	61.2	77.7	81.3
Armstrong (Natural)					
	ARM-1	63	66.4	76.6	73.6
	ARM-2	67.6	65.6	82.2	88.3
	ARM-3	74.2	72	68.6	69.5
	ARM-4	64.7	64.5	69.3	69.5
	ARM-5	75.7	74.8	84.2	79.6
	ARM-6	67.8	69.9	78.9	74.8
TWP 1500 (Natural)					
	TWP-1	67.4	69	71.2	73.3
	TWP-2	59.9	59.1	57.8	56.6
	TWP-3	68.6	69.2	60.1	63.1
	TWP-4	47.7	49.1	61.4	67.5
	TWP-5	67.4	69.5	67.1	72.2
	TWP-6	65.5	65.5	65.1	65.6
Flood CWF UV-5 (Natural)					
	FLO-1	74.2	74.4	92.4	109.9
	FLO-2	79.7	80.6	101.3	100.5
	FLO-3	78.9	77.5	106.4	107.5
	FLO-4	96.4	96.5	94.4	97.2
	FLO-5	83.1	84.1	94.9	95.8
	FLO-6	80.2	88.2	98.3	97.1
Messmer's UV Plus (Natural)					
	MES-1	81.8	80.3	71.5	69.8
	MES-2	80.3	77.9	80.2	88.8
	MES-3	76.2	77.4	78.5	80.3
	MES-4	92.5	88.4	72.3	73.6
	MES-5	72.8	71.2	62	60.8
	MES-6	68.8	69.4	70.2	70.7

Table 4. Contact Angle Measurements of both sides of the water droplet on samples before and after weathering

3.6 TREATMENT RETENTION

For this test, FTIR was used as a qualitative rather than a quantitative analysis. This judgement stems from the unknown compositions of most of the treatments. Though the relative concentrations and identities of the components are still unknown, by appraising the spectra of the un-weathered and weathered treated samples, the existence, or lack thereof, of the treatment in the surface fabric can be indicated through the presence or absence of peaks.

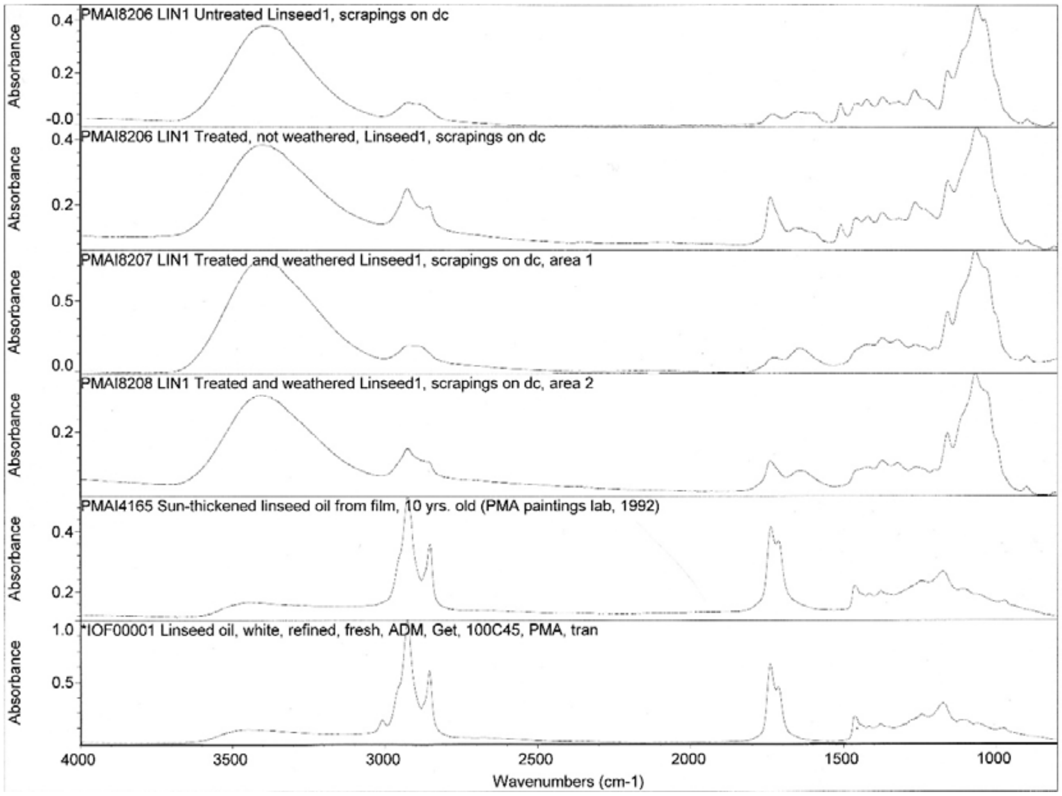

Figure 12. The spectra for the linseed oil treatment before and after weathering with standard spectra for both fresh and 10-year-old linseed oil for comparison shows retention of the treatment. Generated at the Philadelphia Museum of Art.

3.7 PRODUCT PERFORMANCE

At the end of the experiment, the weathered samples were evaluated within their cohorts to determine how each performed. Each sample was given a rating out of five relative to the other samples within its cohort: 1 bad, 2 poor, 3 fair, 4 good, and 5 excellent.

Figure 13. Example of the typical symptoms exhibited by a weathered sample. This sample has checks ranging from very small to large, a roughened earlywood surface, and raised latewood grain. Color change is apparent at the bottom of the photograph from where the bracket covered the sample and protected it from UV degradation.

4. CONCLUSIONS

In creating a long-term maintenance plan for log structures, both the efficacy of the treatment against degradation and the aesthetics of the site have to be considered. The treatments must allow the new log replacements to weather and match the extant fabric while also protecting that historic fabric from degrading further. The ideal conservation treatment would create this uniform appearance and be compatible with both weathered and new replacement logs, environmentally-friendly, affordable, and reversible or at least re-treatable. Finding a treatment that fits all of these criteria is difficult, but observations and tests from this accelerated weathering experiment has given insight into the behavior of a small selection of possible solutions.

4.1 PRODUCT PERFORMANCE

4.1.1 Control

The control samples behaved much as uncoated wood is expected to behave upon exposure to the elements: it turned darker and silvered, checks of various sizes formed across the surface as the fabric was stressed, wetting of just the surface caused the samples to cup inward, and the surfaces roughened and lost cellulose fibers mostly in the earlywood due to ultraviolet radiation and abrasion. The control group lost the least amount of weight compared to the other cohorts, but this is likely because the weight loss was purely related to the wood components rather than wood loss as well as product loss. FTIR confirmed the loss of the lignin at the surface and the water repellency showed a significant drop in hydrophobicity of the surface after weathering.

4.1.2 Allbäck Boiled Organic Linseed Oil

The linseed oil treated samples retained much of their hydrophobicity through the weathering process, most likely due to the deep penetration of the product. In examination of the final cohort, the majority of the samples appeared to be in fairly good condition with a stable substrate that did not shift too far in color away from the weathered control. On average these samples lost about the same percentage of weight as the other treated samples. This treatment also has the benefit of a long history of use in the wood industry, and likely on the Bar BC Ranch, as a conditioning and water-repellent treatment and is a very ecological option. The organic boiled linseed oil from Allbäck is more expensive than the other products and has no pigmentation for ultraviolet protection. However, Allbäck's product is very high quality, low viscosity, and has a greater depth of penetration; thus, it tends to have a longer working life than most other linseed oils on the market.

4.1.3 Paraffin and Mineral Spirits

The very small amount of paraffin in the recipe utilized in this experiment appears to have had very little effect on the weathering ability of the sample. It behaved much the same as the control, the surfaces losing much of their hydrophobicity in weathering so that three could not even be measured for contact angles as well as being very close in coloring and surface appearance to the controls. Additionally, the samples lost about the same percentage of fabric as the other treatments, but since there was very little paraffin deposited in the wood substrate, it can be inferred that a greater amount of the fabric lost was the wood itself. It is a very inexpensive treatment and environmentally-friendly when low-VOC mineral spirits are used, but the formulation must be improved in order for it to be effective as a protective treatment and water repellent. Normally paraffin is usually used in combination with linseed oil for greater penetration and water repellency, but in the case of this research, the variables were isolated in two different treatments in order to better understand their performance as single variable components.

4.1.4 DEFY Extreme Exterior Clear Wood Stain

The DEFY product made many claims about its UV protective zinc oxide nanoparticles and their density of deposition on the surface while not affecting the color of the wood. In addition to the low-VOC waterborne formula, this product offered new technology for wood preservation. Indeed, upon inspection of the treatment on a glass slide, there was a large concentration of colorless particles that were much smaller than those seen in the other treatments. The coloring of the wood barely changed upon application of the treatment, and the weathered DEFY samples on average were the closest in coloring to the weathered controls. The average percent weight loss was about the same as with the other products. The lack of oil in the product base appears to have affected the conditioning of the wood, for, when compared to the oil-based products, the samples appear dry and have very roughened surfaces for the most part. However, this lack of oil does not appear to have affected the hydrophobicity, for the dense deposit of nanoparticles appears to act as a water barrier as well. The acrylic-based deterioration product detected in FTIR analysis should be explored further to determine what it is, whether it is actually a result of degradation, and what effect it might have on wood and the environment. An additional downside to this product is its relatively high cost.

4.1.5 Armstrong's Wood Stain for Decks (Natural Tone)

This product strongly advertises its mixture of drying and non-drying oils for better conditioning within the wood substrate with a protective coating at the surface. Treatment retention of the oils at least appears to be quite good, for the samples still left oil marks on any paper they came into contact with even after weathering. Additionally, the percentage of material loss for this product was the lowest of the products tested. The treated samples retained their water repellency as well. The pigmentation of the product is fairly light and more of a warm tone due to the natural iron oxide pigments; the final weathered product was within ten units of the weathered control as well. This product has low VOC and the manufacturers are very environmentally conscious from being based in California where limits are lower than in most states.

4.1.6 TWP 1500 Natural Stain (1530 – Natural Tone)

The water repellency of the TWP product was excellent both before and after weathering, in fact the weathered surfaces were more repellent than many of the pre-weathered surfaces of other products. While the treatment initially appeared very dark compared to the control and had one of the greatest color differences, it eventually weathered to be fairly close to color of the controls. Inspection of the product on a glass slide shows what appears to be two different types of particles, translucent particles as well as clumps of colored particles for pigmentation. FTIR indicated that lignin had degraded out of the surface of the TWP treated samples and also suggested the presence of a calcium-based weathering deposit on the surface, perhaps deriving from product degradation. This phenomena should be investigated further. Fabric loss was slightly higher than the average for the samples.

4.1.7 Flood CWF-UV 5 Penetrating Wood Finish for Fences, Decks, and Siding (Natural Tone (Clear))

Water repellency decreased during the weathering process, though the weathered samples are still hydrophobic. The coloring of the Flood product was much more orange-toned than that of the other products and the weathered surface was the furthest from the weathered control. Likely wood treated with this product would not fit in well with the extant fabric at the Bar BC. Additionally, upon application, the "clear" product had a distinct orange tone and was very thick, appearing to deposit more of a film on the surface rather than penetrate deeply. The oil version of this product may be worth further investigation, but this acrylic product is not recommended for further testing on site.

4.1.8 Messmer's U.V. Plus Exterior Wood Finish (Natural)

This product and the Armstrong stain appear to be very similar in composition and performance, though in evaluations of the individual cohorts the Messmer's samples had a greater amount of samples that were ranked "poor" or "bad". The water repellent qualities of the treated samples remained about the same before and after weathering, and FTIR indicated that the surfaces retained the treatment but that most of the lignin is gone. The percentage of weight loss was about average. The final color comparisons between weathered control samples and samples treated with Messmer's showed that the difference was quite large, though this product may better compared to the dark weathered logs found on many sites in Grand Teton National Park.

4.2 SUMMARY OF RESULTS

After a full review of the treatments, it was apparent that each had strengths and weaknesses in terms of the different properties used for evaluation. A summary of these differences can be found in the following table where each product was ranked on a scale from 1 – 10, where 1 is bad and 10 is excellent.

	Physical Degradation of Surface (Microscopic Inspection)	Treatment Absorbed (Weight Change)	Material Lost During Weathering (Weight Change)	Color Change - Final Result to Control (Spectroph-otometer)	Lignin Degradation at Surface (FTIR)	Water Repellence (Contact Angle Measurement)	Treatment Retention (FTIR)
Control	2	n/a	5	n/a	1	2	n/a
Linseed Oil	8	9	4	6	2	9	7
Paraffin and Mineral Spirits	2	1	5	8	1	2	1
DEFY Extreme	5	8	7	9	5	7	7
Armstrong's Wood Stain (Natural)	7	10	9	9	4	8	9
TWP 1500 Series (Natural)	8	5	4	6	3	10	8
Flood CWF UV-5 (Clear)	4	3	6	2	2	5	4
Messmer's UV Plus (Natural)	6	7	5	4	5	8	9

Table 5. Comparison of Treatments in terms of Testing Properties.

In accordance with this table, the treatments can be ranked by their overall performance in accelerated weathering as follows (from highest ranking to lowest):

Armstrong's Wood Stain (Natural)

DEFY Extreme Exterior Clear Wood Stain

Messmer's U.V. Plus (Natural)

TWP 1500 Series (Natural)

Linseed Oil

Flood CWF UV-5 (Clear)

Paraffin and Mineral Spirits

5. RECOMMENDATIONS

Further field testing is recommended for those products that performed the best during accelerated weathering. In accordance with the rankings on product performance established in the conclusions section, these products are Armstrong's Wood Stain (Natural), DEFY Extreme Exterior Clear Wood Stain, Messmer's UV Plus (Natural), and TWP 1500 Series (Natural). These treatments will be addressed in subsequent natural weathering testing in the summer of 2015 on site at the Bar BC Dude Ranch.

In natural outdoor weathering, wood is affected by a complex combination of chemical, mechanical, and light energies that depend on the local climactic conditions as well as the duration and severity of exposure to the sun and rain. In most cases, the conditions of natural weathering are much less aggressive than those seen in accelerated weathering. Cycles of wetting and drying are less intense, temperatures vary, and the ultraviolet radiation of the sun is not of the same intensity as the UV-B bulbs. Thus, follow up testing on similar samples with these products is extremely necessary to truly understand their working potential for protecting wood surfaces. Logs of both new and weathered material will be available for testing to see how they accept treatments and subsequently weather on tangential orientations. Therefore the aesthetics of treatment for both states of material can be designed to approach the same basic result while still trying to retain as much original fabric as possible.

Further accelerated weathering testing could be used to explore many other aspects of the treatment concerns that were not addressed in this paper. An incredibly large collection of wood treatments are available from a wide variety of manufacturers today. Those appropriate for conservation limits the pool slightly, but there still remains a plethora of new treatments to explore and compare via accelerated and natural weathering. This is especially relevant in the rapidly developing low-VOC coating industry. Additionally, weathered material could be inserted into the machine to test the performance of treatments on these historic samples as well to see how they would further weather and whether the treatments provided enough consolidation and protection for the historic wood in extreme circumstances. This could also provide the opportunity to see how the penetrating treatments are affected by a previously treated wood substrate, especially if the previous treatment was oil based while the new treatment is water-based.

The effects of weathering and treatments on different grain orientations could also be explored as well as experimenting with the effects of different cycle sets in the Weatherometer on similar wood samples. More intricate cycles for material weathering have been explored in recent years and may have very different, and possibly more natural, weathering results. Additionally, conditions in the machine could be manipulated to more closely resemble the climate of Grand Teton National Park. These cycles could also be manipulated to better understand the effects of each degradation mechanism on the lodgepole pine samples in an effort to better correlate certain kinds of damage to each mechanism.

Though the degradation process of wood under ultraviolet exposure is relatively slow compared to other mechanisms of degradation, the surface material of historic log structures is being compromised. If not regularly maintained and protected from such damage, these buildings, especially those located at high altitudes, will fall into ruin and be lost.

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8. AUTHOR BIOGRAPHY

Courtney Magill graduated from the University of Georgia with dual Bachelor of Arts degrees in art history and classical culture in 2011. She continued her research in art conservation through an internship with the Curator of Decorative Arts at the Georgia Museum of Art and an apprenticeship with a private conservator in the Athens, GA area. In the summer of 2012 she attended the Museum of Early Southern Decorative Arts' Summer Institute, concentrating on the decorative arts of the southern backcountry and an AIC workshop located on Ossabaw Island, GA in 2013, learning preventative preservation tactics through implementation in the Torrey Mansion. She recently completed her Master of Science in Historic Preservation at the University of Pennsylvania in May of 2015. Her coursework has concentrated on the theoretical, logistical, and physical approach to the conservation and preservation of historic buildings and sites, and has focused on conservation as it applies to building materials. She is continuing her research on UV resistant protective treatments for the exteriors of historic log structures on-site in Grand Teton National Park in the summer of 2015. Afterwards, she will be continuing as a post-graduate fellow for the Architectural Conservation Laboratory at the University of Pennsylvania. She can be contacted at courtneymagill89@gmail.com.