Accelerated Weathering of Traffic Control Materials by Laboratory Testing

Final Report

FDOT Agreement No. BE717

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DISCLAIMER

METRIC CONVERSION TABLE

Approximate Conversions to SI Units				
Symbol	Known	Conversion Factor	Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
Area				
in^{2}	square inches	645.2	square millimeters	mm^{2}
ft^{2}	square feet	0.093	square meters	m^{2}
yd^{2}	square yard	0.836	square meters	m^{2}
Volume				
ft^{3}	cubic feet	0.028	cubic meters	m^{3}
yd^{3}	cubic yards	0.765	cubic meters	m^{3}
gal	gallons	3.785	Liters	L
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
Temperature				
ºF	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	ºC
Force and Pressure or Stress				
lbf	poundforce	4.45	Newtons	N
lb/in^{2}	poundforce/square inch	6.89	kilopascals	kPa
Illumination				
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^{2}	cd/m^{2}
Approximate Conversions from SI Unites				
Symbol	Known	Conversion Factor	Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	yards	yd
Area				
mm^{2}	square millimeters	0.0016	square inches	in^{2}
m^{2}	square meters	10.764	square feet	ft^{2}
m^{2}	square meters	1.195	square yard	yd^{2}
Volume				
m^{3}	cubic meters	35.314	cubic feet	ft^{3}
m^{3}	cubic meters	1.307	cubic yards	yd^{3}
L	liters	0.264	gallons	gal
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Temperature				
ºC	Celsius	1.8C+32	Fahrenheit	ºF
Force and Pressure or Stress				
N	Newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	lb/in^{2}
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m^{2}	candela/m^{2}	0.2919	foot-Lamberts	fl

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16. Abstract

This project was undertaken to identify the appropriate accelerated laboratory testing procedures and conditions for predicting weathering deterioration of coating materials for steel structures and retroreflective sign sheeting materials for traffic control. The current standard test methods specified by state transportation departments, FHWA, and manufacturers were reviewed. The effects of test parameters, including irradiance, temperature, moisture, chloride ion concentration, and exposure duration, were discussed. The correlation of various laboratory accelerated test methods with outdoor testing were evaluated and analyzed. The acceleration factors of different accelerated laboratory tests were calculated using the corresponding published test data. Test protocols for the coating materials and sign sheeting materials were recommended. For the coating materials, test conditions of ASTM D5894 were modified by increasing the UV irradiance, temperature, chloride ion concentration, and test duration to shorten the testing time to 10% of the outdoor exposure. For the sign sheeting materials, irradiance levels during xenon light-on periods of the test procedure according to ASTM D7869 were increased to accomplish the testing time of 16% of the outdoor testing duration.

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EXECUTIVE SUMMARY

To ensure the long-term performance of traffic materials (such as structural coatings and sign sheeting), products have been exposed to outdoor weathering testing in South Florida for up to 5 years, according to Florida Department of Transportation (FDOT) specifications. The long testing time has been a challenge for developing and approving new products. Therefore, identifying appropriate accelerated laboratory test methods to replace outdoor testing is desirable for FDOT and for corresponding industries.

This project was undertaken to develop accelerated laboratory test (ALT) protocols using laboratory instruments to predict acceptable performance of traffic materials under climatic conditions similar to those of the Miami area of South Florida. The goal is to reduce the testing duration to 10% of the corresponding outdoor exposure time, allowing for approval of traffic control materials for use on state roadways in less time and enabling anticipated performance of products in a more controlled environment.

An extensive literature review compiled information on the weathering behavior of coating materials for steel structures and retroreflective and non-retroreflective sign sheeting materials. The standard practices and acceleration and outdoor test methods implemented standard test methods for weathering evaluation were identified from the specifications of state departments of transportation (DOTs) and federal agencies. The correlation between ALTs and outdoor tests was analyzed, and the acceleration factor (AF) was determined using published test data. Models of the effects of UV irradiance, temperature, and moisture on material degradation rates were reviewed and applied to calculate the equivalent testing times based on the climatic conditions of Miami, Florida.

Two new ALT methods were developed to achieve a testing time of 10% and 16% of the natural exposure time for coating materials and retroreflective sheeting, respectively. Both new ALT methods were built on the current ASTM test procedures with modifications to provide the desirable acceleration. They are described as follows:

- Coating materials and systems for steel structures:

  The new test protocol is based on ASTM D5894. Modifications include the NaCl concentration, temperature, the segment's duration for the fog/dry cycle, and the irradiance of the UV cycle. The 336-hour test cycle consists of Step 1 (21 cycles of UV/condensation: 4 hours UV at 1.55 $W/(m^2 \cdot nm)$ at 340 nm at 60^oC, followed by 4 hours condensation at 50^oC) and Step 2 (21 cycles of fog/dry: 4 hours 5-wt% NaCl spray at 49 ± 2^oC, relative humidity (RH) > 95%, followed by 4 hours dry at 60 ± 2^oC, RH $\leq$ 30%).

- Retroreflective sign sheeting materials:

  The new test protocol is based on ASTM D7869. The modification focuses on the UV irradiance by increasing irradiance at 340 nm from 0.4 to 0.8 $W/(m^2 \cdot nm)$ in Steps 2, 4, 7, and from 0.8 to 1.2 $W/(m^2 \cdot nm)$ in Steps 3 and 8 of the 10-step test cycle.

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1. INTRODUCTION

Florida Department of Transportation (FDOT) requires outdoor testing to evaluate the long-term performance of structural coating materials and retroreflective and nonreflective sign sheeting materials. Currently, the test protocols specify exposing the traffic control materials to tropical weather conditions in South Florida for up to 5 years. The goal of the outdoor testing is to assess how meteorological conditions (sunlight, heat, moisture) affect traffic control materials' ability to meet the FDOT standards over their expected service lives. Similar requirements with different exposure durations are specified by other DOTs around the United States. However, the long outdoor testing time can be a hurdle for approving new materials and formulations.

The objective of this project is to identify and develop appropriate test protocols for accelerated weathering methods using laboratory instruments along with material testing methods to be implemented according to FDOT specifications. The recommended test protocols should be able to predict acceptable performance of traffic materials (such as structural coatings and sign sheeting) within reasonable time frames if exposed to similar or more aggressive climatic conditions than those of the Miami area of South Florida. The laboratory accelerated weathering methods shall reduce the testing duration to about 10% of the corresponding outdoor exposure time, allowing approval of the traffic control materials for use on state roadways in less time and enabling estimation of products' performance and their compliance with specifications in a more controlled environment.

The objective of this project was accomplished through two tasks. Task 1 focused on the review of specifications from DOTs and federal agencies, product quality control test methods specified by the manufacturers, and published reports and papers, resulting in a summary of the-state-of-practice for weathering evaluation of coating materials and retroreflective sign sheeting materials. Task 2 was to perform in-depth analyses of the reviewed test protocols and experimental data so that appropriate test conditions for the accelerated laboratory test (ALT) can be identified together with the acceleration factors.

This final draft report is the Deliverable of Task 3(a) of the project. The report consists of two parts: (1) coating materials for steel structures and (2) retroreflective sign sheeting materials for traffic control.

1.1 Background on Accelerated Weathering Tests

The photodegradation behaviors of polymeric materials and coating materials have been well studied. The extensive publications can be categorized into two general topics: 1) assessing the weathering behavior and mechanism using different accelerated laboratory weatherometers and 2) comparing the degradation behaviors between outdoor exposure and accelerated laboratory weathering.

A review paper on the design of the accelerated weathering test was published by Jacques (2000). The design concept of an accelerated test is illustrated in Figure 1. The basic principle is that the degradation mechanisms of the tested polymers must be the same in the weatherometer and at the field site.

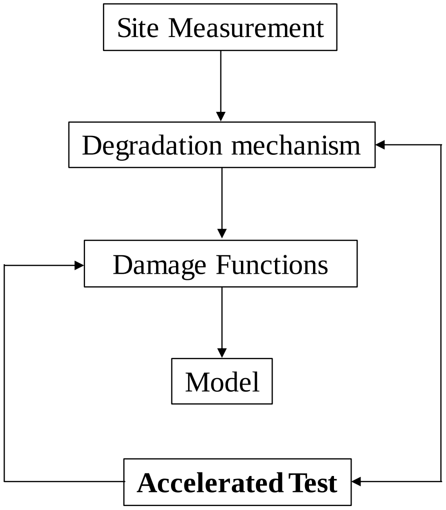


Figure 1 – A flow chart to illustrate the design of an accelerated test

Several standard test practices and methods have been established by ASTM International, the standard organization. Table 1 summaries the current standard practice for weathering tests which include outdoor tests and ALTs. ASTM G90, *Standard Practice for Performing Accelerated Outdoor Weathering of Materials Using Concentrated Natural Sunlight* refers to a concentrated natural sunlight test practice that is not commonly specified because of the sophisticated test apparatus and test location requirements. ASTM D7869 "*Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings is Designed for Transportation Coating*" is a weathering test for coating materials applied to automobiles and airplanes, but this method is considered in this project. The other five methods have been referenced in many state and federal specifications and are discussed in this report.

Table 1 – Summary of ASTM Accelerated Outdoor and Laboratory Weathering Tests

Type	Test Method	Title	Comment	Relevant to This Project
Outdoor	ASTM G7	Practice for Atmospheric Environmental Exposure Testing for Nonmetallic Materials	5°, 45° or 90° from the horizontal facing equator	Yes
	ASTM G90	Practice for Performing Accelerated Outdoor Weathering of Materials Using Concentrated Natural Sunlight	Dual axis tracking: one to control the azimuth rotation of the machine and the other to control the tilt elevation.	No
Laboratory Accelerated Test	ASTM G154	Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials	Equipped with UV lamps with irradiance that varies with lamp types.	Yes
	ASTM G155	Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic	Inner and outer filters can be an important factor.	Yes
	ASTM D4587	Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings	Define test cycles with UV lamps and test conditions	Yes
	ASTM D5894	Practice for Cyclic Salt Fog/UV Exposure of Painted Metal	A cycling salt fog/dry cabinet (ASTM G85) and a fluorescent UV/condensation cabinet (ASTM D4587)	Yes
	ASTM D7869	Practice for Xenon Arc with Enhanced Light and Water Exposure for Transportation Coatings	Use irradiances of 0.4 and 0.8 W/(m^2·nm) at 340 nm, and long wetting period	Yes

1.2 Laboratory Weathering Apparatus

ASTM G155 and ASTM D4587 describe the test procedure using a xenon arch weathering apparatus and a UV-fluorescent/condensation weathering apparatus, respectively. These two apparatuses are commercially available and are made in the United States. The designs of the apparatus vary by manufacturer, but they conform to the standard requirements.

The xenon arc weatherometer (ASTM G155) uses a long arc, water cooled xenon lamp equipped with inner and outer filters as the light source. The irradiance spectrum can be varied by the types of inner and outer filters used. For example, when borosilicate inner and outer filters are used, the irradiance spectrum closely resembles natural daylight (sunlight spectrum at noontime in Miami, Florida), as can be seen in Figure 2. The irradiance level can be adjusted to increase radiation energy, although the typical setting is 0.35 W/(m^2·nm) at 340 nm. The moisture is introduced as water spray onto the surface of the test samples, and the temperature can be controlled by the black panel temperature.

The UV-fluorescent/condensation weathering device (ASTM G154) equips with eight UV fluorescent lamps. The spectral output of the lamps only emits a light spectrum in the UV region (< 400 nm), where the energy is high enough to cause polymer degradation. The UVA-340 lamp represents light from 300 to 400 nm, as shown in Figure 3. The typical setting for the irradiance is 0.85 W/(m^2·nm) at 340 nm. Moisture is introduced in the form of condensation; thus, the temperature during the condensation period is always lower than the temperature during the UV period. The temperature is controlled by the black panel temperature.

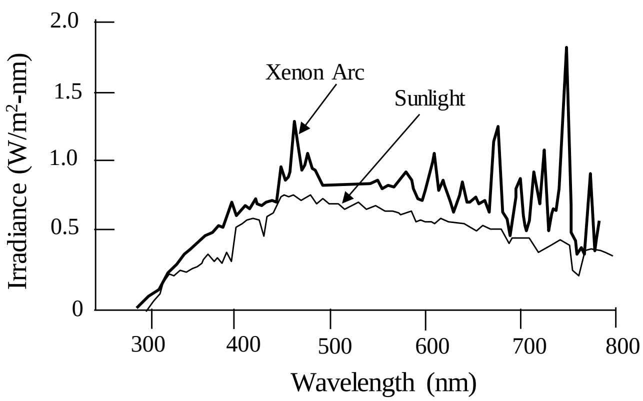


Figure 2 – Spectrum of xenon arc with borosilicate filters and sunlight spectrum

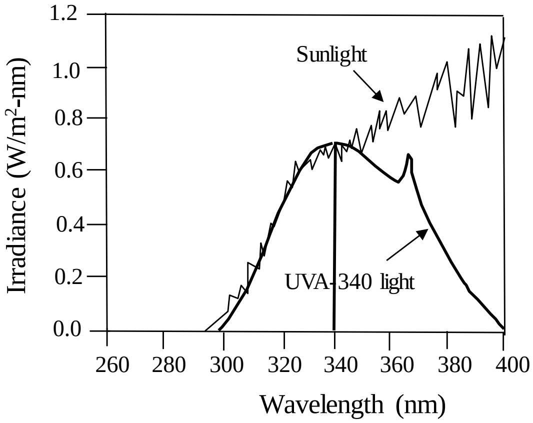


Figure 3 : Sunlight and UVA-340 lamp spectrum and sunlight spectrum

1.3 Factors Affecting the Sunlight Degradation Reaction Rate

In the two types of laboratory weatherometers, the controllable test parameters that can enhance the degradation rate are *temperature* and *irradiance*. The moisture effect is either “on” or “off” and is not varied.

- Temperature: The degradation rate is related to the temperature based on the Arrhenius Equation, Eq. (1) (Hsuan and Koerner, 1998; Gu et al., 2009).

$$k_T = A * exp\left(\frac{-E}{RT}\right) \tag{1}$$

where: k_T = degradation rate in terms of temperature (%/day),
E = thermal activation energy (kJ/mol),
R = gas constant (8.314 J/mol-K),
T = incubation temperature (K), and A is a constant.

Koerner et al. (2017) performed a 12-year long laboratory weathering test on geotextiles and geomembranes made from either polyethylene or polypropylene. The tests were carried in four UV/florescent weatherometers at temperatures of 55, 65, 75 and 85°C, while the irradiance and moisture were kept the same. The degradation was measured using tensile break strength and elongation, and the reaction rate was fitted with the Arrhenius equation to predict the service life.

- Irradiance: The effect of irradiance on the sunlight degradation rate follows one of the three relationships of the reciprocity law, Schwarzschild's law, or the power law:

i). The law of reciprocity is expressed in Eq. (2) (Chin et al., 2005; Martin et al., 2009).

$$I * t = constant, \tag{2}$$

where: the rate of degradation corresponds to (*1/t*); thus, the slope of the straight line is the reaction rate under sunlight at a constant temperature.

ii). Schwarzschild's law is expressed in Eq. (3), where the degradation rate exhibits a non-linear response to the irradiance (Schwarzschild, 1900):

$$I * t^p = constant \tag{3}$$

where: p is a constant less than 1 and the value depends on the material, wavelength, and intensity.

iii). The power law is expressed in Eq. (4) is another non-linear response of the degradation rate, (Jorgensen et al. 2002; Hardcastle, 2005).

$$I^q * t = constant \tag{4}$$

where: q is constant ranging between 1 and 0.5 and the value depends on the material.

When $p = 1$ in Schwarzschild's law, the equation becomes the reciprocity law. For the power law, the degradation rate decreased at high irradiance, which may be caused by the cage effect limiting the reaction rates. Martin et al. (2002) found the degradation of an epoxy coating material according to the reciprocity law. Also, Vahidi et al. (2018) confirmed that the reciprocity law can be applied to oxidative induction time test data of a black high density polyethylene sample under irradiance levels of 41.5, 60, and 80 W/m^2 in a xenon arc weatherometer.

For predicting the outdoor degradation in Miami, Florida, the laboratory accelerated weathering test data must be converted to the equivalent Florida time. To perform the conversion, the annual solar energy at Miami is required (Vahidi et al., 2018). The equivalent outdoor exposure time was calculated according to Eq. (5):

$$t_{outdoor} = \frac{E_{total,Weatherometer}}{E_{total,Outdoor}} * 12 \qquad (5)$$

where: $t_{outdoor}$ = equivalent outdoor exposure time in Months,
$E_{total.weatherometer}$ = total absorbed energy in the weatherometer (MJ/m^2);
$E_{total.outdoor}$ = total absorbed energy in the outdoor environment (MJ/m^2).

- Moisture: This is the most challenging parameter to be simulated in the weathering device. As stated previously, moisture is introduced in the form of water spray or condensation, depending on the type of weatherometer, resulting in a wet or dry period. For polymers that are susceptible to hydrolysis, the rate of the hydrolytic reaction is affected by the temperature and RH, as expressed in Eq. (6) (Pickett and Coyle, 2013).

$$Reaction\ Rate = A * exp\left(\frac{-E_a}{RT}\right)[RH]^n \qquad (6)$$

where: E_a = activation energy of hydrolytic reaction (kJ/mol);
R = gas constant (8.314 J/mol-K);
T = incubation temperature (K);
A = constant;
RH = Relative humidity (%).

2. COATING MATERIALS FOR STEEL STRUCTURES

2.1 Review Specifications of State DOTs and Federal Agencies for Coating Materials

The review started from FDOT and then extended to other state DOTs and federal agencies. FDOT Sections 560 (2013) and 561 (2013) are two documents specifying coating for new and existing structural steel, respectively. They describe the surface preparations and applications of different coating systems. The performance of coating materials and systems included in the two documents must be compiled with FDOT specification Section 975 (Florida DOT 2013) requirements. Six coating systems are included: (1) structural steel coating systems; (2) galvanized steel coating system; (3) painting strain poles, mast arms and monotube assemblies; (4) elastomeric coatings; (5) Class 5 applied finish coating; and (6) anti-graffiti coating materials, among which three include specific weathering tests and requirements. Information regarding ALTs and outdoor testing relevant to the durability of coating systems is summarized in Table A-1 of Appendix A.

Additionally, specifications of 11 state DOTs, AASHTO, and NASA on coatings of structural steel were reviewed. The 11 reviewed DOTs are either states along coastal areas or that have been referenced in the technical reports discussed in the next section. The coating systems and weathering testing defined in these specifications are summarized in Table A-2 of Appendix A.

The majority of the DOTs have implemented AASHTO R31 (2014) "*Standard Practice for Evaluation of Protective Coating Systems for Structural Steel*" and/or AASHTO M300 (2017) "*Standard Specification for Inorganic Zinc-Rich Primer*" to evaluate the weathering/corrosion resistance of coating materials and systems. In these two standards, the conditions for ALTs and outdoor testing are described. For ALTs, three test methods are specified: the salt spray Test (ASTM B117 (2018), "*Standard Practice for Operating Salt Spray (Fog) Apparatus*"), the ultraviolet (UV) resistance test (ASTM D4587 (2011) "*Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings*"), and the cyclic weathering resistance Test (ASTM D5894 (2016) "*Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet*)). The salt spray test targets the corrosion resistance of the coating systems, the UV test assesses the photodegradation of the coating systems, and the cyclic weathering resistance test examines the combined effects of ultraviolet light and corrosion resistance of the coating systems. The methods used to evaluate the performance of coating systems after the weathering tests include blistering and rust creepage at the scribe mark for the corrosion test, and color and gloss changes for the appearance effect due to UV exposure. For the outdoor weathering, AASHTO R31 requires the scribed test samples to be exposed at a coastal site for 2 years, and then inspected for rust creepage and blister according to ASTM D1654 (2016) "*Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosion Environments*", ASTM D610 (2019) "*Standard Practice for Evaluation Degree of Rusting on Painted Steel Surfaces*", and ASTM D714 (2017) "*Standard Test Method for Evaluating Degree of Blistering of Paints*". On the other hand, AASHTO M300 requires field performance of the primer after 3 years of service in a coastal or marine environment, and the coating must exhibit less than 1% rust.

For the state DOTs that adopt AASHTO M300, the current consensus is to evaluate the performance of 3-component coating systems with inorganic zinc primer by exposure to the salt spray test (ASTM B117) and cyclic weathering resistance test (ASTM D5894). The performance of the exposed samples is evaluated using the blistering test (ASTM D714), and rust creepage at scribe (AASHTO R31). For FDOT, color retention (ASTM D2244 (2016) "*Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*") and gloss loss (ASTM D523 (2014) "*Standard Test Method for Specular Gloss*") are also required after the cyclic weathering test. The details of the testing and required performance after exposure for different coating systems are included in Table 2.

Table 2 – DOT Specified Test Methods, Conditions, Durations and Performance Requirements for Coating Systems for Steel Structures

Coating System	Coating Material	Exposure Method	Exposure Condition	Duration	Performance Requirement
3-coating systems specified by FDOT CALTRANS, MoDOT, AASHTO-M300	Inorganic zinc primer (Type I and II) with various types of intermediate and finish coating	ASTM B117	Continuous spray of salt solution with 5% NaCl at pH range of 6.5-7.2 at 35 ±2°C.	5,000-h (208-d or ~ 7-mon)	• No blistering (ASTM D714) or rusting (AASHTO R31) of the coated portion • No undercutting from the scribe, but FDOT allows average rust creep at the scribe ≤ 0.1-in.
		ASTM D5894 (ASTM D4587-Cycle 2 and ASTM G85-A5)	A test cycle takes 336-h consisting of: 21 UV/condensation cycles based on 4-h UV at 0.89 $W/(m^2 \cdot nm)$ at 340 nm at 60°C followed by 4-h condensation at 50°C, and then expose to 84 fog/dry cycles based on 1-h fog at ambient condition (24±3°C and RH < 75%) and 1-h dry-off at 35°C using electrolyte made of 0.05% NaCl and 0.35% ammonium sulfate by mass.	15 test cycles in 3, 6, 9 12, and 15 intervals. Total testing time is 5,040-h (210-d or 7-mon)	• No blistering or rusting of the coated portion • No undercutting from the scribe, but FDOT allows average rust creep at the scribe ≤ 0.2-in. • FDOT requires color and gloss tests: - Color retention (ASTM D2244) - ΔE ≤ 8 - Gloss loss (ASTM D523) - less than 30 units
3-coating systems specified by MoDOT	Inorganic zinc primer/epoxy/ polyurethane	ASTM B117	Continuous spray of salt solution with 5% NaCl at pH range of 6.5-7.2 at 35 ±2°C.	3,000-h (208-d or ~ 7-mon)	• No blistering (ASTM D714) or rusting (AASHTO R31) of the coated portion. • No undercutting from the scribe,
		ASTM G155 or ASTM G154	• G155-xenon weatherometer: daylight filter, 0.35 $W/(m^2 \cdot nm)$ at 340 nm, 102-min light at 63°C black panel and 18-min light and water spray, repeating nine times for a total of 18-h followed by 6-h dark at 95% RH at 24°C black panel. • G154-florescent UV/condensation weatherometer using 0.89 $W/(m^2 \cdot nm)$ @340 nm. 4-h UV at 60°C/4-h condensation at 50°C.	4,000-h	• Color change ≤ 3 ΔE for white and light color and ≤ 5 ΔE for darker color • Brown color, change ≤ 4 ΔE

Table 2 – Cont.

Coating System	Coating Material	Exposure Method	Exposure Condition	Duration	Performance Requirement
3- or 2-coating systems specified by TxDOT	Water-borne acrylic latex appearance coating primed with epoxy zinc primer with or without epoxy intermediate	ASTM G155	• G155-xenon weatherometer using quartz inner filter and borosilicate outer filter Cycle 1 - daylight filter, 0.35 W/(m^2·nm) at 340 nm, 102-min light at 63°C black panel and 18 min light and water spray.	3,000-h	• Color change ≤ 3 ΔE for white and light color and ≤ 5 ΔE for darker color • Pull-off strength > 400 psi and maximum of 20% adhesion failure of the coating from the primer or cohesive failure.
Finished coating	FDOT Class 5 Applied Finish Coatings	ASTM B117	Continuous spray of salt solution with 5% NaCl at pH range of 6.5-7.2 at 35 ±2°C.	2,000-h	• No disbondment
		ASTM D4587	Use UVA lamp at irradiance of 0.89 W/(m^2·nm) at 340 nm. 4-h UV at 60°C/4-h condensation at 50°C (dark)	2,000-h	• No blistering – ASTM D714 • No observable cracking or delamination, chalking • Chalking no less than 8 – ASTM D4214-Method D
	CALTRANS: Waterborne Acrylic Latex Vehicle (Light and Dark Green, and Leafing and Non-Leafing Aluminum)	ASTM B117	Continuous spray of salt solution with 5% NaCl at pH range of 6.5-7.2 at 35 ±2°C.	100-h	• Rust rate > 10 Grade (ASTM D610) • Blistering < 8F (ASTM D714)
		ASTM D4587	Use UVA Lamp at irradiance of 0.89 W/(m^2·nm) at 340 nm. 4-h UV at 60°C/4-h condensation at 50°C (dark)	300-h	• Color change: ≤ 4 ΔE for light green color and ≤ 10 ΔE for dark green color.

The longest test duration is up to 5,000 hours (7 months), which is approximately one third as long as the 2 years (24 months) required for outdoor exposure. In comparison, Missouri Department of Transportation (MoDOT) Section 1045 specifies a shorter testing time (3,000 hours) for 3-component coating system (inorganic zinc primer/epoxy/polyurethane) using ASTM B117. Instead of implementing the cyclic weathering test ASTM D5894, it requires either a UV-florescence and condensation test (ASTM G154 (2016) "*Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials*" Cycle 2 with UVA lamps) or a xenon arc test (ASTM G155 (2013) "*Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*" Cycle 2) to evaluate the color change and gloss loss after 4,000 hours. Similar requirements have been implemented by Texas Department of Transportation (TxDOT) to evaluate the water-borne acrylic latex appearance coating with epoxy zinc primer and with and without epoxy intermediate. The sunlight test is specified using a xenon arc weatherometer (ASTM G155-Cycle 1) fitted with a lamp using a quartz inner filter and borosilicate outer filter. The maximum allowable color change is specified together with a minimum pull-off strength and failure behavior (adhesion or cohesion).

For finished coating materials, the UV-fluorescence test (ASTM D4587, Cycle 2) is specified instead of the cyclic weathering test. The test condition of Cycle 2 is the same as that used in the UV-fluorescence and condensation cycle of ASTM D5894. However, the testing time and performance requirements vary by states. In FDOT Section 975, 2,000 hours of testing time is specified, and no blistering and cracking should show. The minimum chalking is 8, while color change testing is not required. On the other hand, 300 hours is specified by California Department of Transportation (CALTRANS), and maximum color changes are defined for different colors. The corrosion resistance based on ASTM B117 has been specified by CALTRANS and FDOT, although the test duration is substantially different. FDOT specified no disbondment after 2,000 hours of testing, while rust rate and blistering levels after 100 hours are defined by CALTRANS.

NASA requires 3-component inorganic zinc coating systems to be exposed at the Kennedy Space Center outdoor corrosion testing site for 18 months for initial acceptance and 5 years for final acceptance. For ALT, ASTM D5894 was specified, and the test duration is 60 days for every 3 months of outdoor exposure, an AF of 1.5.

In summary, the testing methods used to evaluate the weathering behavior of coating systems are largely the same. Some states are still using two separate tests to evaluate corrosion and sunlight resistance. When the same test method is specified, the required exposure duration varies by agency.

2.2 Published Reports on Coating Materials and Systems for Steel Structures

Since the 1990s, many studies have been supported by DOTs and FHWA on the assessment and investigation of corrosion protection of steel bridges. Twelve reports were reviewed in this project and they can generally be divided into two types. One type comprises synthesis reports that compiled the state-of-the-practice technologies on coating, corrosion prevention, and recommended areas of research needs. Information related to weathering resistance evaluation from this group of reports is shown in Table B-1 of Appendix B. The other type comprises reports of research studies investigating the corrosion resistance of the coating systems on steel structures. These research studies included assessing and comparing different coating systems using ALT and/or outdoor exposure testing. Some reports included comparison between results obtained from ALTs and outdoor testing or field testing on the in-service bridges. The key findings of each report are summarized in Table B-2 of Appendix B.

Chang and Chung (1999) published a comprehensive report on the protection policy of bridge coating systems. Their report was highly referenced in many coating projects. In their report, Azizinamini et al. (2013) described the function of UV absorbers and hindered amine light stabilizers to preserve the gloss and color of the coating. Kogler (2015) described the challenges of the long testing required to assess the coating materials, particularly 3-component zinc-based coating systems.

The experimental data included in some of the reports are further analyzed in this report to identify the critical acceleration mechanism and AFs for weathering and corrosion of coated steel structures.

2.3 Product Specifications for Coating Materials and Systems for Steel Structures

The approved coating materials were retrieved from the FDOT’s Approval Product List (APL). There are five groups of products: elastomeric coating, structural steel coating systems for new structures, structural steel coating systems for existing structures, anti-graffiti coating (non-sacrificial), and anti-graffiti coatings (sacrificial). For most products, the type of polymer is indicated together with the weathering testing and test conditions. The polymer types include acrylic, polyester, aliphatic acrylic polyurethane, aliphatic urethane, polyamide epoxy, and polysiloxane. The testing methods and conditions used to evaluate the durability vary with polymer types and products, while ASTM B117 is the most commonly required testing method with a test duration ranging from 1,000 hours for ethyl silicate material to 15,000 hours for polyurethane and polyamide epoxy. For a more rigorous weathering test (ASTM D5894), which combines salt spray and ultraviolet light exposure, a 9,072-hours (27s cycles of 336 hours) duration is required for some products. Other tests include water resistance (ASTM D1735, *Standard Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus*), accelerated laboratory weathering (ASTM G26, *Practice for Operating Light-Exposure Apparatus (Xenon Type) With and Without Water for Exposure of Nonmetallic Materials* or ASTM D4587), and salt solution immersion (ASTM D870, *Standard Practice for Testing Water Resistance of Coatings Using Water Immersion*). Collected information on the approved coating materials and systems is included in Table C-1 of Appendix C.

2.4 Weathering Behavior of Coating Materials

From FDOT's APL, the types of polymers used for each coating system are summarized in Table 3. The topcoat is pivotal to the protection of the intermediate coat and primer layers during service. Kline (2008) reported that the service life of the 3-component coating systems (zinc-rich primer/epoxy/polyurethane) is approximately 30 years when the topcoat is touched-up or repainted as required.

Table 3 – Summary of Coating Materials from the FDOT Approval Product List

Coating System	Primer	Intermit	Top
3-coat	Zinc Rich Epoxy	Epoxy	Acrylic Latex
	Zinc Rich Polyamide Epoxy	Polyamide Epoxy	Aliphatic acrylic Polyurethane
2-coat	Organic Zinc	-	Acrylic
	Organic Zinc	-	Polyester modified aliphatic acrylic polyurethane
	Inorganic Zinc	-	Polysiloxane
1-coat	Polyamide Epoxy		
	Cycloaliphatic Amine Epoxy		

In this section, the sensitivity of the top-coat materials to UV irradiance, temperature, oxygen, and moisture is discussed.

- Acrylic and acrylic latex:

  Acrylic coating can be made from a wide variety of monomers, and the photo-degradation mechanism depends on the pendant group, such as carboxylic or ester group (Wypych, 2013). Generally, polymer degradation via chain scission takes place at the ester and alkane groups forming free radicals that react with oxygen to form hydroxyl and carbonyl. In the presence of moisture, acrylic coating is susceptible to the hydrolysis of the hydrophilic ester groups (Nguyen et al., 2016). Christensen et al. (2000) used an infrared (IR) spectrometric method to measure the amount of CO_2 emitted from the photo-oxidation of acrylic films using a xenon arc device and found that the degradation rate (R) was proportional to the square root of UV intensity ($R \propto I^{0.5}$), according to the power law, as expressed in Eq. (7):

  $$Reaction\ Rate\ \left(\frac{1}{t}\right) = Constant * I^{0.5}, \tag{7}$$

  where I is irradiance and t is exposure time

- Polyamide epoxy and cycloaliphatic amine epoxy:

  Under UV-A irradiance and oxygen, amine-cured epoxy forms carbonyl and hydroxyl groups through chain scission and hydrogen abstraction from the polymer backbone (Mailhot et al., 2005; Tesser et al., 2018). Gu et al. (2009) evaluated the weathering behavior of a non-UV-stabilized amine-cured epoxy using a uniquely designed weathering device that can apply specific UV wavelengths, relative humidity (RH) and temperatures. They found that the level of photodegradation can be expressed by the reciprocity law in Equation (2). The rate of degradation corresponds to (*1/t*); thus, the slope of the straight line is the reaction rate under sunlight at a constant temperature.

  The presence of moisture has a strong effect on the degradation of epoxy because of polar hydroxyl (–OH) groups formed during curing and the increasing formation of photooxidation products with moisture (Woo et al., 2007). Vanlandingham et al. (1999) demonstrated that the moisture absorbed into the polymer is governed by the fraction of two phases: a high crosslink density nodular and a low-density phase. Such heterogeneous degradation was also observed by Rezig et al. (2006). They investigated the relationship between the surface roughness and photodegradation of a non-UV-stabilized epoxy using laser scanning confocal microscopy after exposure to 120 days of xenon light at 50°C and RH = 9% and 75%, as well as to an outdoor environment in Gaithersburg, Maryland. The highest roughness and greatest photodegradation were observed on the outdoor samples, followed by the laboratory test at RH = 75% and then the 9%. The high moisture in the outdoor test accelerated the photodegradation, forming random nano-scale depressions and pits.

- Aliphatic acrylic polyurethane and polyester modified aliphatic polyurethane:

  Aliphatic polyurethane underwent chain scission, cross-linking and oxidation (growth of carbonyl) near the exposure surface when exposed in a UV and moisture environment (Kim and Urban, 2000; Merlatti et al., 2008; Wilhem and Gardette, 1997). The effects of moisture and temperature were studied by Shi et al. (2005). They exposed samples to six different temperatures with and without condensation cycle. The moisture in the condensation cycles of the UV/condensation test enhanced the degradation of the coating and the degradation rate increased with temperature.

In commercial coating products, photodegradation mechanisms of the three groups of coating materials described above can be delayed by incorporating UV absorber (UVA) and hindered amine light stabilizer (HALS). Pickett (1997) reviewed the types and functions of UVA in acrylic film and coating materials. He identified three pathways for the UVA loss: (1) physical loss through migration, volatility and/or extraction, which is more vulnerable at temperatures above the glass transition temperature of the polymer; (2) consumption through reactions with free radicals that are generated by photolysis of the coating material; and (3) undergoing photodegradation itself. Since minimizing the free radical formation in the polymer can reduce the chemical loss of UVA through Pathway 2, incorporation of a free radical scavenger, such as HALS, into the coating materials will convert free radicals to stable chemical compounds. Kiil (2015) modeled the reduction of the oxidation zone by adding UVA to the epoxy-amine coating, as illustrated in Figure 4. Data from Mailhot et al. (2004) were analyzed to determine the thickness reduction of the oxidation zone from about 250 to 60 μm with the presence of UVA. The author hypothesized that any free radial species generated at or near the exposed surface can be reacted and stabilized by HALS, though verification by experimental data would be required.

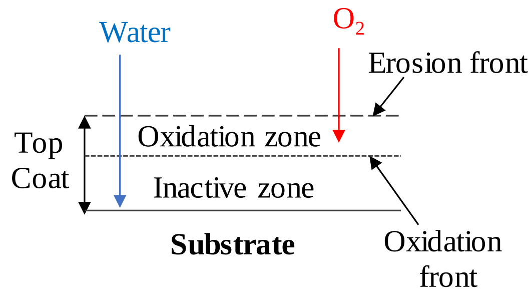


Figure 4 – Schematic illustration of photo-oxidation

The stabilization of polyurethane coating materials against photodegradation has been well studied (Decker et al., 1991, 2004; Merlatti et al., 2008; Forsthuber and Grull, 2010; Nguyen et al., 2018). Decker et al. (1991 and 2004) evaluated the effects of UVA and HALS on the photodegradation of aliphatic polyurethane-acrylate using UV/fluorescent UVB-313 lamps. Using UVA alone provided less light resistance than HALS, while the combination of UVA and HALS yielded the best performance. The presence of HALS was found to reduce the degradation of UVA as well as polyurethane. The benefit of HALS for inhibiting the photo-degradation of UVA was also demonstrated by Forsthuber and Grull (2010) in acrylic coating using a xenon weathering device. Nguyen et al. (2018) studied the benefit of UVA in an acrylic polyurethane coating material by exposure to a UV/fluorescent device with UVB313 lamps and outdoor exposure in Ha Long City, Vietnam. The UVA stabilized material exhibited significantly greater weathering resistance than the unstabilized material. The gloss loss of the stabilized coating was less than 95% after 72 cycles in the UV weathering device, while the unstabilized coating dropped to 80% after only 48 cycles of exposure. Similar observations were obtained in the outdoor exposure testing. The gloss loss of the unstabilized coating reached 20% after 5 years, while 60% was measured after 10 years for the stabilized coating.

2.5 Discussion of Laboratory Test Methods for Coating Materials for Steel Structures

The test methods specified by the state DOTs and coating product manufacturers are shown in Table 4. ASTM B117 and ASTM D5894 are widely used to assess corrosion and appearance retention.

Table 4 – Summary of Specified Test Methods for Coating Systems

Method	Exposure	Test Condition
ASTM B117	Continuous Spraying	5% NaCl solution at pH range of 6.5-7.2 at 35 ± 2ºC.
ASTM D5894	Cycles of UV/condensation and fog/dry	21 cycles of 4-h UV at 0.89 W/(m^2·nm) at 340 nm at 60ºC / 4-h condensation at 50ºC, followed by 84 cyclers of 1-h fog using 0.05% NaCl and 0.35% ammonium sulfate at 24 ±3ºC and RH < 75% / 1-h dry-off at 35ºC.
ASTM G155	Simulating sunlight using Xenon arc device	Daylight filters 0.35 W/(m^2·nm) at 340 nm. 102-minute of light at 63ºC black panel and 18-min light and water spray.
ASTM G154	Simulating UV light using UV- florescent /condensation device	UVA lamp at irradiance of 0.89 W/(m^2·nm) at 340 nm. 4-h UV at 60ºC/4-h condensation at 50ºC.
ASTM D4587	Simulating UV light using UV- florescent /condensation device	Use UVA Lamp at irradiance of 0.89 W/(m^2·nm) at 340 nm. 4-h UV at 60ºC/4-h condensation at 50ºC (dark)
ASTM D1735	Continuous fog exposure	Water at 38 ± 2ºC.
ASTM D870	Immersion	Specified solution modified from water to 5% NaCl at 24ºC.

Note: ASTM D1735 (2014) "*Standard Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus*"
ASTM D870 (2015) "*Standard Practice for Testing Water Resistance of Coatings Using Water Immersion*"

The corrosion test in ASTM B117 requires test specimens to be subjected to continuous sodium chloride solution (5 wt.-% NaCl at pH of 6.5-7.2) spraying at 35ºC. The specified testing time varies greatly ranging from 100 hours for finishing coatings to 70,000 hours for inorganic zinc primer. Testing times between 200 and 5,000 hours are commonly specified for 2- and 3-component coating systems. However, it is known that results obtained from ASTM B117 do not correlate well with those from the outdoor exposure test (Roberge, 1995; Baldwin and Smith, 1999). Pathak et al. (2010) applied ASTM B117 to evaluate the corrosion effect of magnesium-rich primer on aluminum alloys. They found that magnesium hydroxide was formed on the surfaces of the test specimens in the laboratory test while magnesium carbonate was formed in the outdoor exposure testing. The formation of different corrosion products was hypothesized by the limited amount of CO_2 inside the test chamber. The continuous salt spray was also considered to cause the different corrosion degradation mechanisms.

Lyon et al. (1992) studied the wet/dry cycle effect on the corrosion of aluminum alloys. The test cycle comprised 1 hour of solution spray at about 28^{o}C and 1 hour of dry air at 35^{o}C. The electrolyte solution contained NaCl at 0.05% with $(NH_4)_2SO_4$ at 0.35%. After 16 weeks of testing, the corrosion rate under wet/dry cycles was found to be greater than that under ASTM B117 (NaCl at 5%). (It should be noted that the formulation of the electrolyte solution used in this study is the same as that defined in ASTM D5894). Furthermore, their study also measured the corrosion rate using an electrolyte solution with NaCl at 0.35% and $(NH_4)_2SO_4$ at 0.05%, and the rate was about 25% faster than with the low chloride solution (NaCl at 0.05% with $(NH_4)_2SO_4$ at 0.35%).

Lau (2015) performed a correlation study to investigate the corrosion resistance of two new coating systems: chemically bonded phosphate ceramic coating and thermal diffusion galvanizing coating together with a 3-coat system (IOZ/Cycloaliphatic Amine Epoxy/Aliphatic Acrylic-Polyester Polyurethane) and metallizing (85/15 Zinc Aluminum + Urethane). The laboratory test was performed in accordance with ASTM B117 for 5,800 hours, and the outdoor exposure took place at Islamorada, FL and Florida International University in Miami for 8 months. The coating thickness and pull strength were used to assess corrosion resistance. Large variations in both properties made it difficult to a perform quantitative comparison between laboratory and outdoor testing. However, the pull strength of 5,800 hours (8 months) in laboratory samples was lower than that of the 8-month outdoor samples. This study further verifies that test results obtained from ASTM B117 do not represent outdoor performance.

Properly assessing the corrosion resistance of metallic materials is critical to the automobile industry. General Motors developed a wet/dry cyclic corrosion laboratory test, GMW 14872 (2013), "*Test Procedure for Cyclic Corrosion Laboratory Test*". The electrolyte solution used in the test is a 1% complex salt solution consisting of 0.9%-NaCl+0.1%-$CaCl_2$+0.075%-$NaHCO_3$. The test cycle consists of three 8-hours segments, as follows:

Step 1 – 8 hours ambient Stage (25 ± 3^{o}C, 45% ± 10% RH),
salt spray at the beginning of this stage.

Step 2 – 8 hours humid Stage (49 ± 2^{o}C, 100% RH)

Step 3 – 8 hours dry Stage (60 ± 2^{o}C, $\leq$ 30% RH)

The US Army Research Laboratory recommended GMW 14872 in conjunction with ASTM B117 and ASTM G50 (2015) "*Standard Practice for Conducting Atmospheric Corrosion Tests on Metals*" for the accelerated corrosion testing of the coated metal samples (Considine, 2017).

Outside the United States, ISO 16701 (2015), "*International Standard for Corrosion of Metals and Alloys – Corrosion in Artificial Atmosphere Accelerated Corrosion Test Involving Exposure under Controlled Conditions of Humidity Cycling and Intermittent Spraying of a Salt Solution*" requires an intermittent spray of salt solution consisting of 1% NaCl at 35^{o}C and pH of 4.2 to provide a better correlation with the field environments on the influence of chloride ions. The pH of 4.2 shall be achieved by adding diluted sulfuric acid (H_2SO_4) solution (1 ml of 0.05 ml/L H_2SO_4 is added to 1 liter of NaCl solution. The slight acidic solution simulates the precipitation in the industrialized areas. Cycle A of the standard requires salt solution spray in the beginning of the test cycle, as follows:

Cycle A – a 12-hours test cycle consisting of a 6-hours wet cycle followed by a 6-hours dry cycle.

Step 1 – Spraying 1% NaCl solution for 15-min

Step 2 – Exposure at 35^{o}C for 1 hour and 45-min with RH set point at 95% - 99%.

Repetition of Step-1 and Step-2 two more times, making the total period of wetness of 6 hours.

Step 3 – Drying the test specimens at RH of 50% and at a temperature of 35^{o}C over a period of 4 hours.

Step 4 – Exposure at 35^{o}C to a linear increase of RH with time from 50% to 95% over a total period of 2 hours.

Although both GMW 14872 and ISO 16701 include wet/dry cycles and at chloride ion of 1% in the electrolyte solution, the testing temperature of GMW 14872 is 15^{o}C-25^{o}C higher. Therefore, samples exposed in the GMW 14872 test conditions would corrode faster than those in ISO 16701.

The corrosion tests conducted with salt solutions focus on the electrochemical reactions, while the impact of sunlight, particularly UV light, is not considered. This may be acceptable for metals and metallic coatings but not for coating systems made of polymeric materials. It was demonstrated that steel samples coated with epoxy or polyester corroded under a UV/condensation cycle even without exposure to a fog/dry cycle (Quill, 2013). Simpson et al. (1991) compared the corrosion weathering behaviors of three one-coat systems (Alkyd, Acrylic Latex, and Polyamide Epoxy) after exposure to three ALTs and outdoor testing. The outdoor testing took place at the eastern shore of Florida for 27 months and in downtown Cleveland, Ohio, for 12 months. The three ALTs included salt spray, cyclic wet/dry, and cyclic between wet/dry and UV/condensation, for a duration of 2,000 hours. Ranking from 0 to 10 was used to represent failure-to-good performance regarding blister, rust-through, and undercut. The ranking from the cyclic wet/dry with UV/condensation test was found to be the most consistent with findings from the outdoor testing.

ASTM D5894 was developed to achieve the combined effect of UV and corrosion. The test cycle of ASTM D5894 is described as follows:

Step 1 – 8 hours of UV/condensation cycle, repeating for 21 times

4 hours UV at 0.89 W/(m^2·nm) at 340 nm at 60^{o}C followed by 4 hours of condensation at 50^{o}C.

Step 2 – 2 hours of fog/dry cycles, repeating 84 times

1 hour fog at laboratory ambient condition (24±3^{o}C and RH < 75%) using electrolyte made of 0.05% NaCl and 0.35% ammonium sulfate by weight followed by 1 hour dry-off at 35^{o}C.

Repetition of Steps 1 and 2 two more times, making a total of three test cycles

Specifications usually require the number of test cycles to be 15. However, the electrolyte solution used during the fog/dry cycle contains lower amount of chloride ions than the solution used in GMW 14872 and ISO 16701, which, however, may not be appropriate for predicting the corrosion behavior near or in a marine environment.

The significance of the UV/condensation cycle in the formation of blistering was investigated with a coating system with epoxy polyamide primer and polyurethane topcoat by Yang et al. (2002). The samples were exposed to two accelerated weathering test conditions: (1) QUV consisted of 24 weeks of 4 hours UVA radiation at 60^{o}C/4 hours of condensation at 50^{o}C; and (2) ASTM D5894 for 27 weeks of QUV/prohesion with 7-d of QUV, then moving to a prohesion chamber for 7 days of 1 hour salt fog and 1 hour dry-off (i.e., 14 weeks of QUV and 13 weeks of prohesion test). Samples exposed to QUV showed fewer and coarser blisters than samples from the QUV/prohesion cycle test at equal durations of UV exposure. Yang et al. (2002) confirmed that a UV/condensation cycle is an important influencing factor in the corrosion of a coating system on steel structures. However, the mechanisms forming the blisters were different between QUV and QUV/prohesion tests.

In ISO 20340 (2003), "*International Standard for Paints and Varnishes – Performance Requirements for Protective Paint Systems for Offshore and Related Structures*", the annex A test cycle is similar to ASTM D5894, including a UV/condensation cycle and a salt spray cycle. but a freeze period at the end of each test cycle is added:

Step 1 – 8 hours of UV/condensation cycle, repeating for 72 hours

4 hours UV at 0.76 W/(m^2·nm) at 340 nm at 60°C followed by 4 hours condensation at 50°C

Step 2 – Continuous salt spray using 5% NaCl solution cycles for 72 hours at 35°C

Step 3 – Freeze at -20°C for 24 hours.

In this ISO method, a 5% NaCl is used, which is significantly higher than that used in ASTM D5894 (0.05%). The test temperature is 35°C throughout Step 2 without a drying period.

2.6 Correlation of Accelerated Laboratory Testing and Outdoor Testing for Coating Materials for Steel Structures

The effects of the NaCl concentration in electrolyte solutions and including a freeze period in the salt spray test procedure were investigated by LeBozec et al. (2015). They evaluated the corrosion resistance of 15 coating systems on steel substrates using seven ALT methods, as shown in Table 5. The corrosion damage was determined by measuring the scribe growth. Results obtained from ISO 9227 (2009), "*International Standard for Corrosion Tests in Artificial Atmospheres – Salt Spray Test*", which uses 1% NaCl solution, did not correlate well with those obtained from the field test and ALTs using 5% NaCl solution. Also, no difference was observed between samples exposed to a temperature of -20°C and those exposed to ambient temperature for 24 hours. The acceleration factors (AFs) of four ALTs in comparison to the field test of the five coating systems were calculated using Eq. (8), which was taken from LeBozec et al.; the values are shown in Table 6. The materials of the five coating systems, however, were not identified in that paper. The AF of Method 4 with 5% NaCl solution is 1.4 times higher than that of Method 5 with 1% NaCl. The high salt spray frequency (Method 5 vs Methods 6 and 7) did not change the acceleration factors.

$$Accleration\ Factor\ (FA) = \frac{X(Lab.Test)}{X(Field)} * \text{Constant}; \qquad (8)$$

where $X$is the maximum delamination (or other quantitative measurement) and $Constant = \frac{Exp.Duration\ (Field)}{Exp.Duration\ (Lab.Test)}$

Table 5 – Summary of Test Methods Used by LeBozec et al. (2015)

No.	Method Name	Condition
1	ISO 9227	Continuous 1% NaCl solution spray for 1440-h
2	ISO 16701	6-h of 15-min. of 1% NaCl solution spray and then maintain at 35ºC for 1-h and 45-min. at 95% to 99% RH. Dry sample to 50% RH for 4-h; Increase to 95% RH in 2-h
3	ISO 20340	72-h of 4-h UV at 60ºC/4-h Condensation at 50ºC, 72-h of 5% NaCl solution spray at 35ºC once time only, 24-h of freeze at -20ºC
4	BS5/S0/C50/FBS1/-20	72-h of 4-h 60ºC/40% RH – 4-h 50ºC/95% RH, 72-h of 5% NaCl solution spray at 35ºC once every 4-h 24-h of freeze at -20ºC
5	BS1/S0/C50/FBS1/-20	72-h of 4-h 60ºC/40% RH – 4-h 50ºC/95% RH, 72-h of 1% NaCl solution spray at 35ºC once every 4-h 24-h of freeze at -20ºC
6	BS1/S0/C50/FBS3/-20	24-h of 4-h 60ºC/40% RH – 4-h 50ºC/95% RH, 72-h of 1% NaCl solution spray at 35ºC once every 24-h 24-h of freeze at -20ºC
7	BS1/S0/C50/FBS3/amb.	24-h of 4-h 60ºC/40% RH – 4-h 50ºC/95% RH, 72-h of 1% NaCl solution spray at 35ºC once every 24-h Repeating for 2 more times; 24-h at ambient
8	BS1/S0/amb. /FBS1/amb.	24-h of ambient, 24-h of 1% NaCl solution spray at 35ºC once every 4-h Repeating for 2 more times; 24-h of freeze at -20ºC

amb. = ambient (23ºC, 50% RH)

Table 6 – Acceleration Factor of Four Coating Systems from LeBozec et al. (2015)

Coating Sample Code	**Test Method**			
	4	**5**	**6**	**7**
S1	28.43	24.96	22.19	18.03
S2	8.32	5.94	5.35	4.56
S3	14.91	10.75	12.83	10.19
S8	10.19	6.59	6.59	6.24
S9	10.62	7.33	7.53	6.93
Average	**11.01**	**7.65**	**8.07**	**6.98**
CV	**25%**	**28%**	**41%**	**34%**

Note CV = Coefficient of Variation

Weathering testing was carried out in three DOT research studies in which ASTM D5894 was used to evaluate the resistance of different coating systems and which compared the results with those from outdoor weathering.

- ***Chong and Yao (2000)*** studied the weathering behavior of three types of zinc-rich moisture-cured urethanes (MCU) coating systems on two types of steel surfaces (SSPC-SP10 and SSPC-SP 3) after 4,000 hours of laboratory testing using ASTM D5894 and 2 years exposure at Sea Isle, New Jersey, with daily seawater spray. The material compositions of the three systems are shown in Table 7. The authors found that the rust creepage length increased linearly with exposure time. For coating systems on SSPC-SP3, the rust creep data were reanalyzed in this report to determine FAs of the laboratory tests. The time to reach 2-mm rust creepage was calculated using the linear creepage rates, as shown in Table 8. The concept of this analytical approach is the same as that of Eq. (8). The two sets of data (1 and 2) represent samples with and without sealer prior applying the coating. Also, chloride contamination was applied to half of the test samples for each set, but it has very little effect on AFs of the samples in both sets. For samples without sealer, AFs of A1, B1, and C1 are 2.8, 4.1, and 9.3, respectively. In contrast, for coating systems with sealer, the disparity of AFs is relatively small, with values of 3.0, 5.1, and 3.7 for A2, B2, and C2, respectively. Coating systems A and B have relatively similar AFs regardless of the sample preparation conditions, whereas system C behaves differently between samples with and without sealer. As the outdoor exposure holds the true weathering behavior, the three MCU coating systems corroded differently under the test conditions according to ASTM D5894.

Table 7 – Composition of Zinc-Rich Moisture-Cured Urethane (MCU) Coating Systems

System	Coating System
A	Zinc-rich MCU/MIO-filled MCU/MCU
B	Zinc-rich MCU/MIO-filled MCU/MIO-filled MCU
C	Zinc-rich MCU/MIO & Al-filled MCU/MIO-filled MCU

MIO = micaceous iron oxide
Al = aluminum

Table 8 – The Creepage Growth with Exposure Time of Three Moisture-Cured Urethanes (Data from Chong and Yao, 2000)

Coating Code	Relationship between creepage rate (mm) with time (year or		Creepage (mm)	Outdoor (year)	Outdoor (hour)	Lab (hour)	Acceleration Factor (Outdoor/Lab)
	Outdoor test	Lab. test					
A1	y = 1.98x-0.5	y = 0.0006x-0.3544	2	1.263	11060.6	3924.0	**2.8**
A1-Cl	y = 3.98x-1.95	y = 0.0006x-0.3689	2	0.741	6493.0	2281.5	**2.8**
A2	y = 5.88x-0.95	y = 0.0015x-0.448	2	0.332	2905.1	965.3	**3.0**
A2-Cl	y = 7.84x-0.9	y = 0.0017x-0.6509	2	0.242	2123.0	971.1	**2.2**
B1	y = 1.9x-1.05	y = 0.0007x-0.4044	2	1.605	14062.1	3434.9	**4.1**
B1-Cl	y = 1.92x-1	y = 0.0007x-0.3904	2	1.042	9125.0	1986.3	**4.6**
B2	y = 3.12x-0.8	y = 0.0012x-0.0742	2	0.577	5053.8	895.2	**5.6**
B2-Cl	y = 6.02x-1.75	y = 0.0016x-0.442	2	0.457	4001.7	901.3	**4.4**
C1	y = 2.22x-1	y = 0.0012x-0.5207	2	1.351	11837.8	1267.3	**9.3**
C1-Cl	y = 3.62x-1.75	y = 0.0012x-0.2096	2	0.760	6654.7	1008.0	**6.6**
C2	y = 3.36x-0.45	y = 0.0012x-0.2358	2	0.432	3780.4	1029.8	**3.7**
C2-Cl	y = 3.46x-0.5	y = 0.0016x-0.5607	2	0.434	3797.7	975.4	**3.9**

Note: Coating codes with 1 have no sealer; coating codes with 2 have sealer prior to coating. Samples with chloride contamination are noted as -Cl.

- ***Yao et al. (2011)*** evaluated nine coating systems for their gloss loss, color change, and mean creepage. Information on the coating systems is in Table 9. The test condition of ALT was modified from ASTM D5894 by adding a freeze period to each test cycle which consisted of 24 hours freeze, 4 hours/4 hours of UV/condensation cycle for total of 168 hours, and 1 hour wet/1 hour dry salt-fog cycle for total of 168 hours. The 24 hours freeze period was to simulate the cold temperature during the winter season in the northern states and induced bending stress on the coating layer due to different thermal expansion coefficients between the coating layer and the metal substrate. The mean creepage values were measured throughout the 9.5 months of ALT. Figure 5 shows a plot of creepage value versus time from the report. Not all creepage linearly relates to the exposure time. For some coating systems, the creepage rate gradually decreases as exposure time increases, except for urethan mastic (UM) and SLX which exponentially increase with time. Figure 6 is a plot of mean creepage versus time of the 18-month outdoor test at the McLean, Virginia site (coded as NW) and samples with intermittent salt spray (coded as NWS). The trends of creepage changing with time are generally similar to those of ALT. The creepage value varies with coating systems and exposure conditions, as shown in Table 10. A very small amount of creepage was measured from the outdoor tests; some of the coating systems did not even have measurable creepage. On the other hand, creepage lengths ranging from 0.7 to 35.6-mm were measured after ALT. The effect of daily salt spray was assessed by comparing the creepage value of NWS to NW. Four of the one-coat systems were accelerated by the salt spray, particularly UM. The daily salt spray condition created a harsher corrosion condition than the marine environment (ME) for some of the coating systems, as indicated by the >1 ratio value of NWS/ME. The AFs between ALT and outdoor tests were calculated using Eq. (8), and they varied significantly among different coating systems and different outdoor conditions. Many of the AFs are well above 10 or even 100, making the correlation questionable.

Table 9 – Information of the Nine Coating Systems

No.	**System**	**Coating Type**		
		Primer	**Intermediate**	**Top**
1	3-coat	Zinc-rich epoxy	Epoxy	Polyurethane
2	2-coat	Zinc-rich moisture-curing urethane		ASP*
3	1-coat	ASP		
4		Epoxy mastic (EM)		
5		High-ratio calcium sulfonate alkyd (HRCSA)		
6		High-build waterborne acrylic (HBAC)		
7		WBEP**		
8		SLX***		
9		Urethane mastic (UM)		
*ASP – ester compounds (a types of secondary aliphatic amine with aliphatic polyisocyanate **WBEP – waterborne coating ***SLX – inorganic silicon-oxygen in combination with organic binders.				

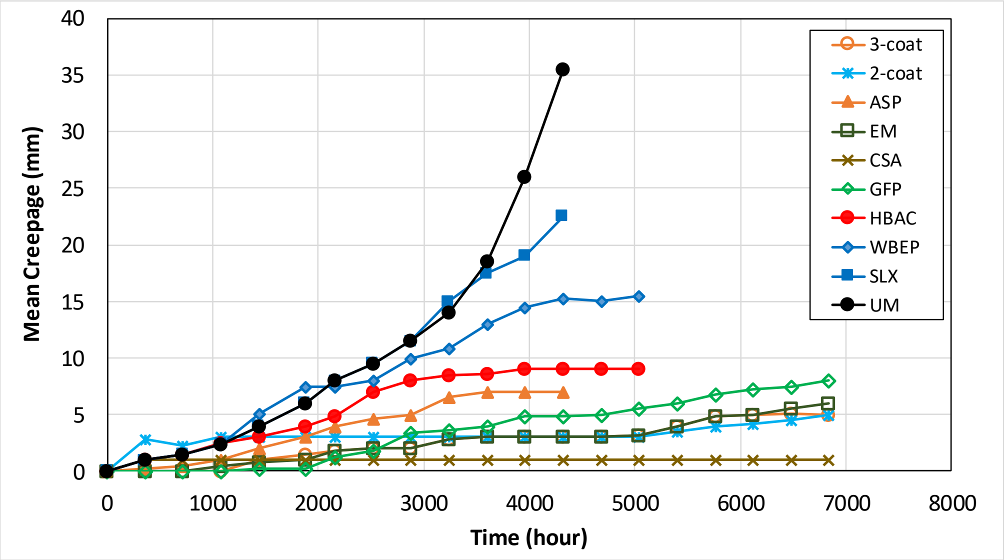


Figure 5 – Mean creepage versus exposure time in an accelerated laboratory test according to ASTM D5894 (replotted from Yao et al., 2011)

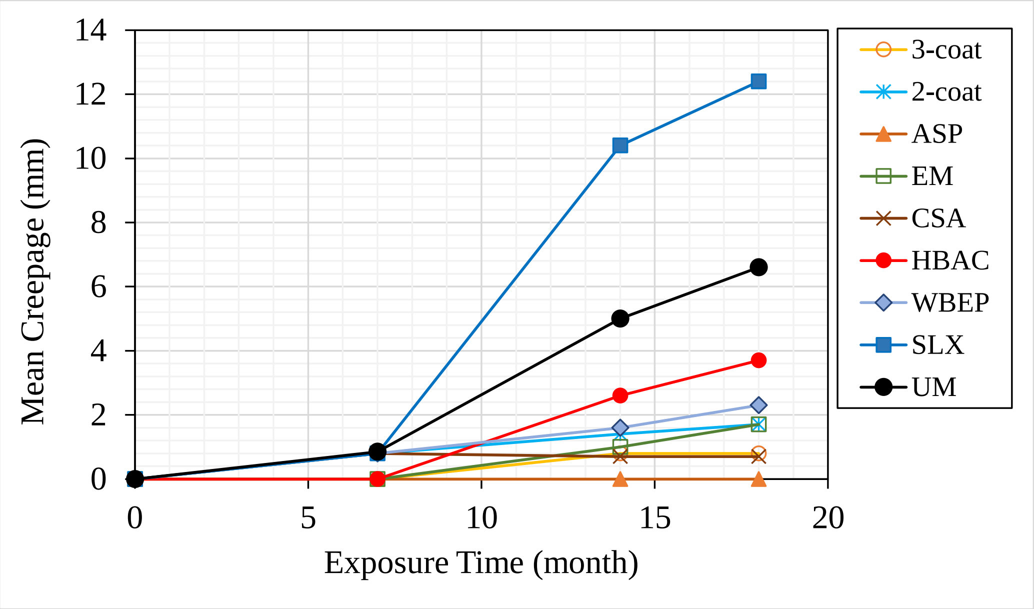


Figure 6 – Mean creepage value versus outdoor exposure time at McLean, Virginia, site. (reproduced from Yao et al., 2011)

Table 10 – Acceleration Factor and Salt Effect Based on the Mean Creepage Data from Yao et al. (2011)

Coating System	Outdoor Creepage (mm)			ALT		Salt Effect		Acceleration Factor		
	NW (18-mon)	NWS (18-mon)	ME (24-mon)	Time (mon)	Creepage (mm)	NWS/ME	NWS/NW	ALT/NW	ALT/NWS	ALT/ME
3-coat	0.0	0.5	0.0	9.5	5.3	NA	NA	NA	20.08	NA
2-coat	1.6	1.5	1.6	9.5	4.7	0.94	0.9	5.6	5.94	5.57
ASP	0.0	0.0	1.8	6.0	6.8	NA	NA	NA	NA	11.33
EM	0.6	1.6	0.9	9.5	6.5	1.78	2.7	20.5	7.70	13.68
HRCSA	0.7	0.7	1.0	9.5	0.7	0.70	1.0	1.9	1.89	1.33
HBAC	0.0	3.7	1.3	7.0	9.3	2.85	NA	NA	6.46	18.40
WBEP	0.6	2.3	1.1	7.0	15.9	2.09	3.8	68.1	17.78	37.17
SLX	2.2	12.5	30.5	6.0	21.9	0.41	5.7	29.9	5.26	2.15
UM	0.7	6.6	5.2	6.0	35.6	1.27	9.4	152.6	16.18	20.54

NA = Not Applicable

The gloss loss and color change test data were taken from the report by Yao et al. (2011) and are presented in Tables 11 and 12. The AF values were calculated using Eq. (8). For the gloss loss, AFs varied with outdoor conditions for each coating system. Most of the AF values are less than 5.0, but UM has factors well above 10. Such high values raise the question whether the laboratory testing condition truly reflects the outdoor weathering for this material. The daily salt spray of the outdoor testing did not lead to greater gloss loss, except for the ASP sample, and it also poorly simulated the ME condition. For the color change, AFs range between 1.0 and 9.0 for most of the coating systems, whereas the values for the SLX and UM systems are above 10, particularly for UM. The daily salt spray (NWS/NW) did not introduce additional effects on color change, and it also did not simulate the ME condition.

Table 11 – Acceleration Factor of Gloss Loss after Exposure in ALT and Outdoor Environment Using Data from Yao et al. (2011)

Coating System	Outdoor			ALT	Acceleration Factor			Salt Effect	
	NW	NWS	ME		ALT/NW	ALT/NWS	ALT/ME	NWS/ME	NWS/NW
3-coat	29.5	14.2	28.9	50.9	3.3	6.8	4.4	0.5	0.5
2-coat	39.0	34.5	91.5	60.3	2.9	3.3	1.7	0.4	0.9
ASP	10.1	15.0	52.7	27.6	5.2	3.5	1.3	0.3	1.5
EM	96.9	97.3	97.7	99.0	1.9	1.9	2.6	1.0	1.0
HRCSA	81.9	74.1	30.6	66.7	1.5	1.7	5.5	2.4	0.9
HBAC	24.4	16.5	29.2	79.5	6.2	9.1	6.9	0.6	0.7
WBEP	59.3	63.8	66.9	77.8	2.5	2.3	2.9	1.0	1.1
SLX	20.6	12.4	32.8	18.5	1.7	2.8	1.4	0.4	0.6
UM	1.5	0.5	4.3	23.8	30.1	90.2	14.0	0.1	0.3

Table 12 – Acceleration Factor of Color Change after Exposure in ALT and Outdoor Environment Using Data from Yao et al. (2011)

Coating System	**Outdoor**			**ALT**	**Acceleration Factor**			**Salt Effect**	
	NW	**NWS**	**ME**		**ALT/NW**	**ALT/NWS**	**ALT/ME**	**NWS/ME**	**NWS/NW**
3-coat	1.0	1.0	1.0	1.2	2.3	2.3	3.0	1.0	1.0
2-coat	0.5	0.3	3.5	1.4	5.3	8.8	1.0	0.1	0.6
ASP	0.3	0.4	1.6	1.4	8.8	6.6	2.2	0.3	1.3
EM	14.4	15.3	9.6	8.6	1.1	1.1	2.3	1.6	1.1
HRCSA	6.3	8.2	9.8	6.3	1.9	1.5	1.6	0.8	1.3
HBAC	3.3	3.3	2.2	10.9	6.3	6.3	12.5	1.5	1.0
WBEP	1.7	1.7	1.9	4.7	5.2	5.2	6.2	0.9	1.0
SLX	0.4	0.4	0.4	3.1	14.7	14.7	19.6	1.0	1.0
UM	0.2	0.2	0.4	3.7	35.1	35.1	23.4	0.5	1.0

- ***Kodumuri and Lee (2012)*** evaluated eight coating systems, including two 3-coat systems, four 2-coat systems and a 1-coat system, as listed in Table 13. The coating preparation was according to the SSPC standard number 5 condition. The coated samples were exposed to ALT according to ASTM D5894 for 3,600 hours (10 test cycles) and at the McLean, Virginia, outdoor testing site for 10 months. The outdoor exposure conditions were coded as NW and NWS for natural weathering and natural weathering with daily salt spray, respectively.

Table 13 – Coating Systems Evaluated by Kodumuri and Lee (2012)

System	**Coating Type**		
	Primer	**Intermediate**	**Top**
3-coat	Inorganic zinc-rich epoxy (IOZ)	Epoxy (E)	Aliphatic Polyurethane (PU)
	Zinc-rich epoxy (ZE)	E	PU
	Moisture-cured urethane zinc (MCU)	E	Fluorourethane (F)
2-coat	ZE		PU
	Inorganic zinc (Zn)		Polysiloxane (PS)
	Thermally sprayed zinc (TSZ)		Linear epoxy (LE)
	Experimental zinc		LE
1-coat	High-ratio calcium sulfonate alkyd (HRCSA)		

Tables 14 and 15 show the test data and AFs of gloss loss and color change, respectively. Some of the AFs for gloss loss and color change are less than 1.0, indicating that a greater change was measured after exposure to the outdoor environment than was measured in the ALT. The

Zn/PS system exhibited an unusual gloss loss under ALT and salt spray outdoor conditions, while the color change was enhanced under ALT.

Table 14 – Acceleration Factor of Gloss Loss after Exposure in ALT and an Outdoor Environment Using Data from Kodumuri and Lee (2012)

Coating System	**Outdoor**			**Acceleration Factor**		**Salt Effect**
	NW	**NWS**	**ALT**	**ALT/NW**	**ALT/NWS**	**NWS/NW**
IOZ/E/PU	9.5	27.6	13.0	2.7	0.9	2.9
ZW/E/PU	14.5	8.9	17.8	2.4	4.0	0.6
MCU/E/F	3.7	2.1	0.8	0.4	0.8	0.6
ZE/PU	10.1	9.8	14.7	2.9	3.0	1.0
Zn/PS	1.4	-0.6	-6.9	-9.7	22.6	-0.4
TSZ/LE	92.6	92.5	94.7	2.0	2.0	1.0
ZnE/LE	92.6	96.2	75.6	1.6	1.6	1.0
HRCSA	66.9	50.6	24.4	0.7	1.0	0.8

Table 15 – Acceleration Factor of Color Change After Exposure in ALT and an Outdoor Environment Using Data from Kodumuri and Lee (2012)

Coating System	**Outdoor**			**Acceleration Factor**		**Salt Effect**
	NW	**NWS**	**ALT**	**ALT/NW**	**ALT/NWS**	**NWS/NW**
IOZ/E/PU	1.3	0.6	0.1	0.1	0.3	0.4
ZW/E/PU	1.0	0.5	0.3	0.6	1.4	0.4
MCU/E/F	1.1	0.4	0.1	0.2	0.5	0.4
ZE/PU	1.2	0.4	0.2	0.3	0.9	0.3
Zn/PS	0.7	1.3	1.3	3.6	2.1	1.8
TSZ/LE	3.3	4.6	3.9	2.4	1.7	1.4
ZnE/LE	2.6	4.0	2.9	2.2	1.4	1.5
HRCSA	5.1	7.2	2.7	1.0	0.7	1.4

For the three coating systems with PU as topcoat, AFs of approximately 2.7 were obtained for gloss loss when compared with NW; however, when compared with NWS, one of the PU systems has AF less than 1.0. The color change was greater in the outdoor test (NW) than in ALT, as all three AFs were less than 1.0. Only one sample showed AF > 1 in color change between ALT and NWS. For the LE topcoat on the 2-component coating systems, AFs of approximately 2.0 were calculated for both gloss loss and color change. The daily salt spray has no effect on the gloss loss while lower AFs were obtained for color change.

To assess corrosion resistance, the mean creepage was measured throughout the ALT test duration and the data are reproduced in Figure 7. Except for the MCU/E/F system, all systems developed rust creepage less than 1.5 mm. Interestingly, coating systems ZE/E/PU and ZE/LE seem to possess an incubation period. The comparison between ALT and outdoor wreathing was not feasible because no rust creepage was developed after 10 months outdoor exposure, except for the ZE/LE coating, which had a 0.16-in (4-mm) rust creepage and is significantly greater than 3,600 hours of ALT.

The 3-component and 2-component coating systems evaluated in this study probably possess high corrosion resistance properties, as indicated by the small creepage values after 10 months of outdoor testing. Comparing the gloss loss and color change measurements, the color change values are too small for 3-component and PU coating systems to obtain reliable AFs. A longer testing time for both ALT and outdoor testing would be required to provide a more meaningful correlation.

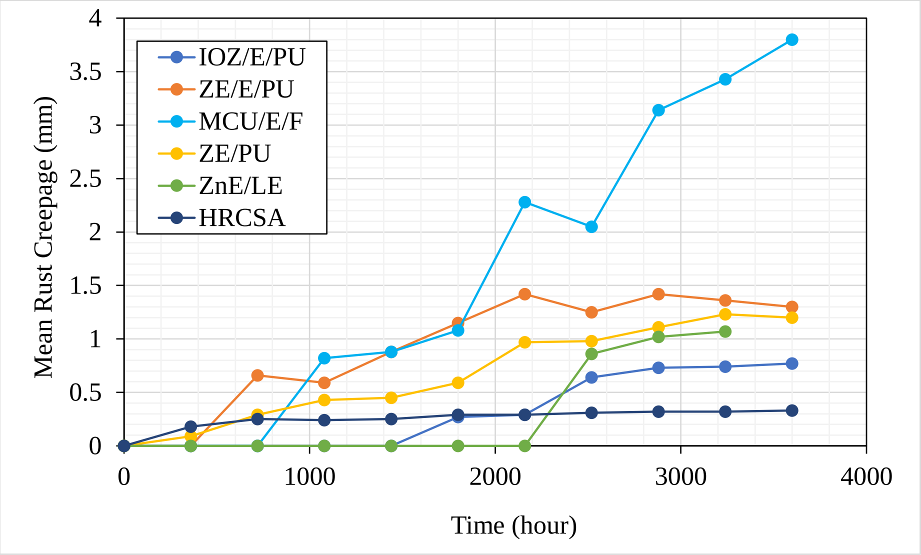


Figure 7 – Mean creepage value versus ALT time.
(reproduced from Kodumuri and Lee, 2012)

- ***Balaguru et al. (2018)*** used a modified ASTM D5894 to evaluate six coating systems for their weathering resistance. The six coating systems are given in Table 16. The test conditions of the modified method and the standard method are provided in Table 17. The total UV light time was shorter (8 hours vs 12 hours per day), while the UV irradiance and sample temperature were not provided. The salt solution with 5% NaCl, which is higher than the standard method, was used in this study. Each test cycle took 24 hours to complete instead of 336 hours as in the standard. Figure 8 shows a plot of percentage reduction of tensile strength versus test cycle number using data from the report. After 100 cycles (100 days), the two 3-coat systems (Systems 5 and 6) with zinc primer performed better than the epoxy mastic systems (Systems 1 to 4), suggesting that the zinc primer formed a stronger bond with steel substrate than the epoxy primers. Similar behavior was observed on the corrosion creep measurement, as shown in Figure 9. The field data reported in this report were obtained from the Thomas Mathis Bridge, located over the saltwater of Barnegat Bay of the Atlantic Ocean. A total of 47 coating systems from 18 manufacturers were applied to the bridge spans in the period from November 1986 to June 1987. The 47 coating systems were categorized into eight types. Inspection was performed after 1, 8, and 20 years. The performance was ranked in the order from good to poor: Metallizing systems > Inorganic Zinc systems > Organic Zinc systems > Miscellaneous systems > Alkyd systems > Urethane systems > Aluminum systems > Epoxy systems. Although AFs could not be determined due to different evaluation matrices, the ranking for the corrosion resistance is the same for ALT and outdoor exposure. Except for the metallizing systems, both inorganic zinc and organic zinc systems have a better corrosion resistance than the other five types of coating. The worst performance was for the epoxy systems.

Table 16 – Coating Systems Evaluated by Balaguru et al. (2018)

System	Primer Layer	Intermediate Layer	Top Layer
1	Phenalkamine Epoxy (epoxy mastic system)	NA	Aliphatic Acrylic-Polyester Polyurethane
2	Polyamine Bisphenol-A Epoxy (epoxy mastic system)	NA	Acrylic Polyurethane
3	Carbomastic Epoxy (epoxy mastic system)	NA	Aliphatic Acrylic-Polyester Polyurethane
4	Epoxy (Alkalyd)	NA	Aliphatic Urethane
5	Polyamide Epoxy-Organic Zinc Rich	Polyamide Epoxy	Aliphatic Acrylic Polyurethane
6	Solvent Based Inorganic Zinc	Cycloaliphatic Amine Epoxy	Aliphatic Acrylic-Polyester Polyurethane

Table 17 – Comparison of Modified ASTM D5894 with ASTM D5894

Modified ASTM D5894	ASTM D5894
16-h of 1-h wet and 1-h dry cycle at undefined temperature Followed with 8-h freeze	168-h of 4-h UV at 60°C/4-h condensation cycle at 50°C Followed with 168-h of 1-h salt/1-h fog cycle
UV light on during 1-h dry cycle	UV light on during 4-h UV dry environment
Not defined in the report	UV irradiance = 0.89 W/m^2·nm
NaCl concentration = 5%	NaCl concentration = 0.05%
Test cycle = 24-h	Test cycle = 336-h

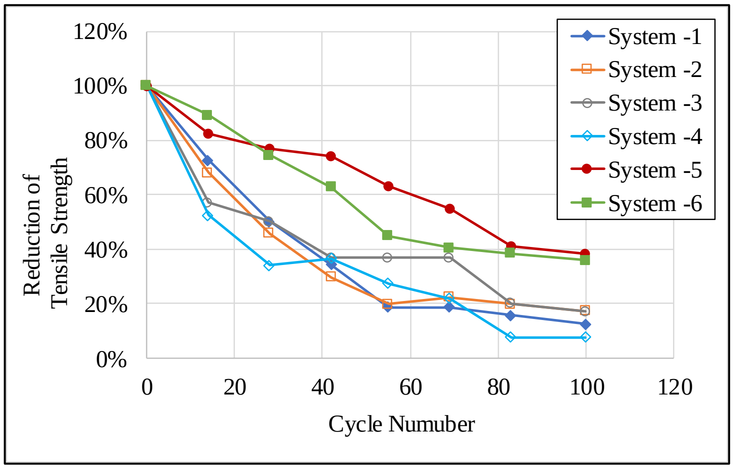


Figure 8 – Tensile strength percentage reduction versus exposure cycle, Balaguru et al. (2018)

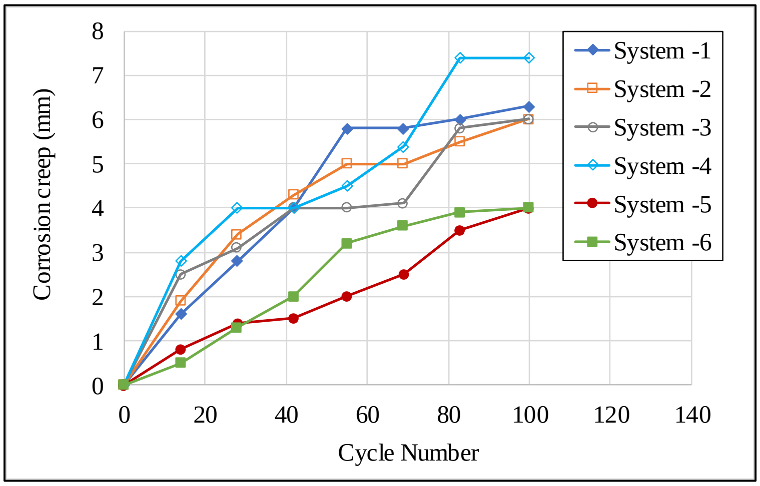


Figure 9 – Corrosion creep growth versus exposure cycle, Balaguru et al. (2018)

- ***Cocuzzi and Pilcher (2013)*** performed a comprehensive study to investigate the effectiveness of ALTs for assessing the weathering behavior of coil coating materials. The study was a joint effort between ASTM International and the National Coil Coating Association. The weathering behavior of 23 coating materials between two outdoor tests and four ALTs were correlated. The two outdoor testing sites were Arizona and Florida for a duration of 10 years. Test samples were retrieved at the intervals of 2, 3, 5, 7 and 10 years. The four ALTs and their test durations were Fresnel Test for 1680 MJ, QUA-340A lamps for 9,000 light-hours, QUB-313B lamps for 2500-light hour, and a dew cycle (unfiltered carbon arc) for 100 light-hours. The gloss retention, color change, and chalking were measured after exposure and the data were analyzed using the Spearman rank correlation to obtain the rho value, as shown in Eq. (9).

$$rho = 1 - \frac{6 * \sum(rank_{outdoor\ site} - rank_{ALT})^2}{N(N^2) - 1} \tag{9}$$

where N is number of samples, which is 23 in this case.

The study defined a rho value greater than 0.9 to be an acceptable level of correlation. However, none of the ALTs reached a rho value greater than 0.9 when compared with the 10-year exposure. The chalking showed the worst correlation in the three properties. Also, the carbon arc device generated the lowest rho values in the four ALTs. The best rho values were obtained for the 7-year outdoor data. However, data were not available for comparing the rho values between the four ALTs and the 7-year outdoor testing. The color change behaved linearly with outdoor exposure time for the first 5 years, but then slowed afterward. This suggests that linear extrapolation from the earlier data would overestimate the photo-degradation rate.

The Spearman rank is a qualitative method to distinguish the performance of different materials after a given testing time. In this paper, the light times (or energy) of the four ALTs did not match well with the 10-year outdoor exposure. A quantitative analysis based on a fitted mathematical model for the changing rate of the property would yield a more conclusive comparison.

2.7 Recommendation of Laboratory Accelerated Test Method for Coating Materials for Steel Structures

As indicated in the previous section, many standard test methods and modified test methods have been used to evaluate weathering resistance of coating systems. These test methods can be categorized into three types, as shown in Table 18. Even though the continuous spray methods have been proven not well correlated with the corrosion occurring in the outdoor environment, they are still included in many DOT specifications. The spray/dry cycle methods are mainly used by the automotive industry, or in some research studies for bridge coatings. The cyclical tests with UV/condensation and fog/dry are the most widely specified methods by DOTs and are used by the manufacturers to qualify their coating products. AFs in the range of 2 – 6 were obtained for the corrosion creepage and gloss loss of 3-coat and 2- coat systems using ASTM D5894. However, there is no reliable AF for color change.

Table 18 – Summary of Test Methods for Coating Weathering Evaluation

Exposure	Method	Test Condition
Continuous Spraying	ASTM B117	5% NaCl solution at pH range of 6.5-7.2 at 35 ± 2ºC.
	ISO 9227	
Spray/dry cycles	GMW 14872	Electrolyte solution: 0.9%-NaCl+0.1%-$CaCl_2$+0.075%-$NaHCO_3$ 8-h at 25 ± 3ºC, 45 ± 10% RH 8-h at 49 ± 2ºC, 100% RH 8-h at dry stage (60 ± 2ºC, ≤ 30% RH)
	ISO 16701	Electrolyte solution: 1% NaCl at pH 4.2 15-min. spray salt solution at ambient temperature 1-h 45-min. at 35ºC and 95 to 99% RH 4-h drying at 50% RH at 35ºC 2-h increasing the RH to 95% at 35ºC
Cycles of UV/condensation and fog/dry	ASTM D5894	21 cycles of 4-h UV at 0.89 W/(m^2·nm) at 340 nm at 60ºC / 4-h condensation at 50ºC, following by 84 cycles of 1-h fog using 0.05% NaCl and 0.35% ammonium sulfate at 24 ±3ºC and RH < 75% / 1-h dry-off at 35ºC.
	ISO 20340	72-h of 4-h UV at 0.76 W/(m^2·nm) at 340 nm at 60ºC / 4-h condensation at 50ºC, followed by 72-h of 1-h spray using 5% NaCl solution at 35ºC and finishing with 24-h of freezing at -20ºC.

ASTM D5894 is a comprehensive test method to challenge both the photodegradation via the UV/condensation cycle and the corrosion through the fog/dry cycle. The complex multi-degradation mechanism however is difficult to model, particularly with unknown types and amounts of UV stabilizers and absorbers. On the other hand, the test parameters of the method can be modified to further increase the degradation rate, as described in the following:

- Salt concentration

  In the fog/dry cycle, the salt concentration can be increased from the current 0.05% to 5% NaCl which can better simulate the marine environment, such as found in Miami, Florida. The acceleration effect of high salt content in electrolyte solution on the corrosion has been demonstrated by LeBozec et al. (2015). Also, Balaguru et al. (2018) used 5% NaCl solution to distinguish between the corrosion behaviors of six coating systems, and the ranking found in ALT is similar to that found in the marine environment.

- Temperature/moisture

  The current temperature in the fog/dry cycle is 35^{o}C. A higher temperature similar to those used in GMW 14872 (49 ± 2^{o}C, RH = 100% for the fog cycle and 60 ± 2^{o}C, RH $\leq$ 30% for the dry cycle) can be adopted to accelerate the chemical reaction rates, such as corrosion, oxidation, and hydrolysis. The test temperatures at 50^{o}C and 60^{o}C are closer to the sample surface temperature in Miami, Florida. Also, the high RH during the fog segment of the cycle allows coating absorption of the saltwater to reach a pseudo-saturated condition.

- Duration in each cycle

  The current defined duration, 1h fog/1h dry, is long enough for the chamber to dry off from < 75% RH and to reach temperature equilibrium between 24^{o}C and 35^{o}C. However, a longer duration is required to reduce RH from 100% to less than 30%. A cycle with 4 hours fog/4 hours dry is more appropriate which is the same drying period in ISO 16701 for RH between 99% and 50%.

- Ultra-violet (UV) irradiance

  Matching the spectral power distribution (SPD) between natural sunlight at Miami, Florida and UV light in weathering devices is an essential part of the weathering test, particularly for the photo-chemical reactions. The SPDs of a UV-340 lamp with intensities of 0.89 W/(m^2·nm) and 1.55 W/(m^2·nm) at 340 nm are compared with the noon summer light in Miami, Florida in Figure 10 (Fedor and Brennan, 1994). The cut-off wavelength matches well with sunlight around 295 nm. A higher irradiance, 1.55 W/(m^2·nm), can be considered in the UV cycle of the test to accelerate the photo-chemical reactions.

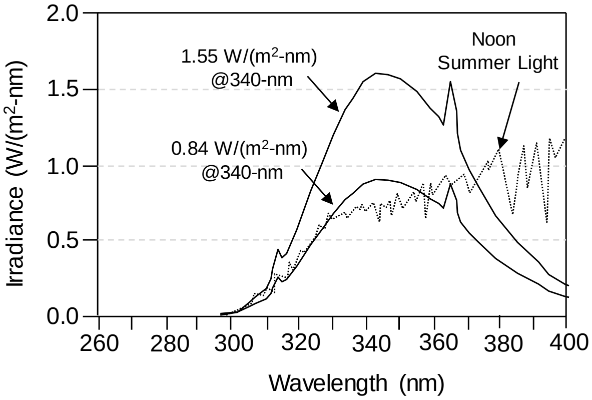


Figure 10 – Comparison of spectral power distribution between noon summer sunlight and UVA-340 lamps at two intensities. (Fedor and Brennan, 1994)

In summary, a modified ASTM D5894 with more aggressive test conditions is recommended, as follows:

Step 1 – 21 cycles of UV/condensation cycles: 4 hours UV at 1.55 W/(m^2·nm) at 340 nm at 60°C follows by 4 hours of condensation at 50°C.

Step 2 – 21 cycles of fog/dry cycles: 4 hours 5-wt% NaCl spray at 49 ± 2°C, RH > 95% followed by 4 hours of dry at 60 ± 2°C, RH ≤ 30%.

The testing time for each cycle remains the same as the current standard, 336 hours. The elevated temperature in the fog/dry cycle is 25°C higher than the current standard. Based on the Arrhenius equation (recall Eq. (1)), the reaction rate doubles with an approximate 10°C increase in temperature for a simple chemical reaction (White and Forman, 2015). Therefore, the chemical reactions governed by the Arrhenius equation (such as diffusion and corrosion) would be 2.5 times faster during fog/dry cycle. For the UV/condensation cycle, increasing the UV irradiance from 0.84 to 1.55 W/(m^2·nm) at 340 nm can enhance the photodegradation rate 1.84 times according to the reciprocity law. If using the power law with a power function of 0.5 (as observed by Christensen et al., 2000, on acrylic films), the reaction rate will be 1.48 times faster. Increasing the NaCl concentration to 5% can further accelerate the weathering degradation. Although no data are available for NaCl effect from 0.05% to 5%, 1.5 times was obtained from 1% to 5% by LeBozec et al. (2015). The combined effect is obtained by multiplying 2.5 (temperature), 1.48 (UV irradiance), and 1.5 (salt concentration) which is 5.55 faster than the current standard test method. Taking a conservative AF of 2.0 for ASTM D5894 in correlating with outdoor conditions, a 5-year outdoor testing in Miami, Florida can be shortened to a 5.4-month testing time (i.e., AF = 11) using the modified ASTM D5894.

2.8 Test Protocol to Evaluate the Weathering of Coating Materials for Steel Structures

Currently, the physical and mechanical properties of the coating materials are evaluated after weathering testing. The physical properties are measured using non-destructive tests so fewer samples are required while more measurements can be obtained to achieve statistical variation. These properties include gloss loss, color change, blister, and creepage rate. For the mechanical property, which is obtained from a destructive test, tensile test is used to assess the adhesive property of the coating to the substrate. The variation of this test tends to be large and more test samples are required to achieve statistical significance.

On the base of the reviewed literature, the Zn-rich primers exhibit a good weather/corrosion resistance when the substrate surface is probably prepared. The weathering is focused on the performance of the topcoat, which plays a critical role in protecting the primer and /or intermit layers. Therefore, methods to monitor changes of physical properties are recommended in this study.

Analytical methods (such as FTIR or UV absorption tests) are not recommended to be used for monitoring the weathering behavior of the coating materials because interpreting the results can be challenging. Commercial coating products with proprietary additives can make the spectrum even more difficult to analyze.

3. RETROREFLECTIVE SIGN SHEETING MATERIALS

3.1. Review Specifications of State DOTs and Federal Agencies for Retroreflective Sign Sheeting Materials

Specifications from state DOTs for retroreflective and nonreflective sign sheeting material were reviewed. However, most of the specifications address the performance properties of the signs. For the weathering evaluation, many specifications refer to the state's PALs. The weathering test was found in five DOTs' specifications and they are summarized as follows:

- ***Florida Department of Transportation (FDOT) – Specification Section 994 (2013):***

  FDOT Specification Section 994 (Florida DOT, 2013) specifies the requirements for retroreflective and nonreflective sheeting and sign panel fabrication. The classifications of retroreflective and nonreflective sheeting materials are in accordance with ASTM D4956 (2017) "*Standard Specification for Retroreflective Sheeting for Traffic Control*" in which the properties of nine types of retroreflective sheetings and five adhesive backing classes are specified. Each type of retroreflective sheetings must conform to the minimum requirements for retroreflectance, color, and durability. The retroreflectance is determined by the minimum coefficient of retroreflection (R_A) for each color at defined observation and entrance angles, and the minimum and maximum daytime luminance factor ($Y\ \%$) for each color. For the rotational sensitivity property, FDOT requires the sheeting and sheeting systems to be tested in accordance with AASHTO M268 (2015) "*Standard Specification for Retroreflective Sheeting for Flat and Vertical Traffic Control Applications*".

  In Section 994, the outdoor weathering is stated to be performed in accordance with and to meet the requirements of ASTM D4956 for each system, color and classification. The one exception is Type VI, fluorescent pink. The outdoor exposure site shall be at Miami, Florida or at a location with equivalent climatic conditions. The outdoor testing procedure shall follow ASTM G7 using opened back panels and oriented at an angle of 45° from the horizontal and facing the equator. The duration and requirements after the exposure are shown in Table 19.

  Additional to Section 994, a standard test protocol FDOT FM 5-571 (2015) "*Test Method for Sign Sheeting Materials*" was developed to evaluate sign sheeting materials. The test method includes laboratory and outdoor testing for non-retroreflective and retroreflective sheeting, transparent and opaque process inks for retroreflective sheeting materials, and film overlays. The outdoor testing procedure refers to ASTM D4956 Section 7.6 using a procedure according to ASTM G7. However, the method noted that artificial weathering will not be accepted as a substitute for the outdoor weathering requirement.

Table 19 –Requirements after Outdoor Exposure for Each Type of Retroreflective Sheeting (taken from ASTM D4956)

Type	Grade	Duration* (month)	R_A** at 0.2^o, -4^o and +30^o ($cd/fc/ft^2$)	Observation
I	Engineering	24	50% of values in table 1§	No appreciable cracking, scaling, pitting, blistering, edge lifting, or curling or more than 1/32-in. shrinkage or expansion.
II	Super engineering	36	65% of values in table 3§	
III	High-intensity	36	80% of values in table 4§	
IV	High-intensity	36	80% of values in table 5§	
V	Super high-intensity	36	80% of values in table 6§	
VI	N/A	6	50% of values in table 7§	
VII	Reclassified as Type VIII			
VIII	N/A	36	80% of values in table 8§	
IX	N/A	36	80% of values in table 9§	
X	Reclassified as Type VIII			
XI	N/A	36	80% of values in table 10§	

Note: Taken from ASTM D4956. *When sheeting is specified for construction work zone application, the outdoor weathering shall be 12 months; ** According to ASTM D4956, and N/A = not available; (§) Referring to tables in ASTM D4956, *Standard Specification for Retroreflective Sheeting for Traffic Control*.

- ***Hawaii Department of Transportation (HiDOT) – Specification Section 750 (2013)***

HiDOT Specification Section 750 (Hawaii DOT, 2013) specifies retroreflective sheeting of Types I, II, III, IV, VII (now VIII) and IX. The specification does not reference ASTM D4956 for any of the performance property tests and outdoor testing. For assessing the weathering resistance, outdoor testing is required for Type IX and Type VII (now Type VIII) retroreflective sheeting. Test samples shall be unprotected facing the equator and inclined 45^o from vertical. The exposure samples shall show no appreciable cracking, blistering, crazing or dimensional change after 3 years for Type IX and after 1 year for Type VIII. Laboratory accelerated testing is permitted for Type VIII products by exposure in a xenon arc weatherometer in accordance with ASTM G155, Type B, Method A for a duration of 1,500 hours. (It should be noted that the Type B and Method A were referred to ASTM G26 which was replaced by ASTM G155 in the year 2000.) ASTM G26, Method A corresponds to

Cycle 1 in ASTM G155 using daylight filters with 340 nm irradiance controlled at 0.35 W/(m^2·nm), which is Method II in the Supplementary S3 section of ASTM D4956. A 3-year field performance is also required for the Type VIII products.

- ***Kansas Department of Transportation (KDOT) – Specification Section 2201 (2015)***

  KDOT Specification Section 2201 (Kansas DOT, 2015) specifies Type I, Type III, and Type IV retroreflective sign sheeting. For the outdoor exposure test, the specification refers to the requirements of ASTM D4956. For ALT, the test shall be conducted according to ASTM G155, Cycle 1 which corresponds to Method II in the Supplementary Requirement S3 of ASTM 4956. However, test samples shall be placed in a cold cabinet at 0°F for 1 hour after 20 hours of Cycle 1, and then placed back into the weatherometer for an additional 20 hours of exposure using Cycle 1 conditions. The cold period is designed for large temperature differences during the spring and fall seasons in Kansas.

- ***Pennsylvania Department of Transportation (PENNDOT) (2003) – Retroreflective Sheeting Materials and Process Inks***

  The PennDOT specification (Pennsylvania DOT, 2003) covers Types III, IV, VI, VIII, IX, and XI of retroreflective sheeting. The outdoor weathering and requirements should be performed according to ASTM D4956. The outdoor testing site should use NTPEP test decks in Arizona, Louisiana, and Virginia for all sheeting except Type VI, which shall be tested in Arizona and Louisiana. However, the specification does not include a statement regarding the laboratory accelerated weathering testing.

- ***Texas Department of Transportation (TxDOT) DMS-8300 (2013) – Sign Face Materials***

  TxDOT specification Section 8300 (Texas DOT, 2013) covers the prequalification, material, testing requirements, warranty, and approval procedures for sign face materials, which include reflective sheeting, nonreflective sheeting, screen inks, electronically cuttable transparent films, and anti-graffiti films and coatings. The specification includes both outdoor testing and ALT. The outdoor testing follows the procedure described in Section 7.6 of ASTM D4956, and is performed at the test site in Austin, Texas. For ALT, the test condition refers to Supplementary Requirement S3 in ASTM D4956, but the testing method regarding the irradiance intensity is not defined. Without defining the method (i.e., the irradiance level), there is a gap in the artificial accelerated weathering procedure. The test durations and results are specified as follows:

(a) Nonconstruction zone –

- 2,200 hours
- Meeting a minimum of 80% of the minimum specified initial retroreflectivity values for the material.

(b) Construction zone (used for temporary construction work zone applications) –

- 500 hours
- Meeting a minimum of 60% of the minimum specified initial retroreflectivity values for the material.

At the federal level, AASHTO M268 (2015) was developed to evaluate retroreflective sheeting for flat and vertical traffic control applications. The specification establishes four types of retroreflective sheeting, Types A, B, C, and D, which are as follows:

Type A – Retroreflective sheeting materials meeting Type A are typically constructed of encapsulated microscopic glass bead lens construction.

Type B – Retroreflective sheeting materials meeting Type B are typically constructed of unmetallized microprismatic optics. These triangular microprismatic materials do not have a significant 1° observation angle performance.

Type C – Retroreflective sheeting materials meeting Type C are typically constructed of unmetallized microprismatic optics. These triangular microprismatic materials have a significant 1° observation angle performance.

Type D – Retroreflective sheeting materials meeting Type D are typically constructed of unmetallized microprismatic optics. These materials have 0.5° and 1° observation angle performance two times greater than Type C materials.

The correlation between these four types of retroreflective sheets to those classified in ASTM D4956 is based on the charts presented in “Traffic Sign Retroreflective Sheeting Identification Guide” (FHWA, 2014). There is no Type C listed on the chart, but the description of Type C is the same as for Type B.

- Type A ~ Type III
- Type B and C ~ Type III, IV, VIII, IX
- Type D ~ Type XI

The specification describes both outdoor and laboratory accelerated weathering tests. The outdoor weathering shall be performed in climates equivalent to Phoenix, Arizona and Miami, Florida. Sheeting material shall be placed on open-backed panels at a 45^o angle to horizontal and facing the equator. The sheeting shall be examined annually for 3 years. The exposed samples shall not exhibit appreciable discoloration, cracking, streaking, crazing, blistering, or dimensional change, and a minimum 80% of the minimum specified initial retroreflectivity values for the material.

The accelerated laboratory weathering test shall be performed for 2,200 hours according with ASTM G151 and G155, Cycle 1 which is equivalent to Method II in ASTM D4956 (0.35 $W/(m^2 \cdot nm)$ at 340 nm). The exposed samples shall not exhibit appreciable discoloration, cracking, streaking, crazing, blistering or dimensional change, and a minimum 80% of the minimum specified initial retroreflectivity values for the material.

3.2. Published Reports on Retroreflective Sign Sheeting

Projects supported by state DOTs to study the long-term performance of traffic signs were carried out so that comprehensive maintenance plans were developed to meet the requirements of FHWA Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009). Even though, these studies do not directly address the weathering behavior of the traffic signs, information related to the field deterioration rates could be useful for the correlation evaluation with artificial accelerated laboratory weathering.

- **Pennsylvania Department of Transportation – "*Retroreflectivity of Existing Signs in Pennsylvania*" (Pennsylvania DOT, 2013)**

  In this study, retroreflectivity (R_A) levels of 1,000 traffic signs were measured in three locations of Pennsylvania. The measured signs were limited to Type III with service time $\geq$ 10 yr. Linear regression was used to correlate the measured R_A values with service times for four colors: yellow, white, red and green. The coefficient of determination (R^2) values of the four regression lines ranged from 0.05 to 0.25. The low coefficient value indicates that the variability in $\mathrm{R_A}$ values cannot be confidently correlated with the aging of the signs in the field. The study found the performance of Type III well beyond the manufacturer's warranty of 10-year; thus, a 15-year service life was proposed for Type III traffic signs in Pennsylvania.

- **Minnesota Department of Transportation (MnDOT) – "*Traffic Sign Life Expectancy*" (Minnesota DOT, 2014)**

  The project collected service life data of traffic signs that are not yet available to Mn DOT, especially for the ASTM Types XI and IX, prismatic sheeting materials. The report summarizes previous studies on ASTM Types I and II sheeting materials. The key conclusions are as follows: (1) linear regression equations were the best fit for forecasting retroreflectivity degradation, (2) the prediction based on linear regression equations did not account for environmental factors, (3) color fading can have strong inference to the retroreflectivity measurement, and (4) no long-term measurement data verify the predicted values.

  Additional sign measurements were carried out during the project for ASTM Type I, IV, IX, and XI sheeting. While the results were inconclusive due to insufficient creditable data, they suggested a service life of 12 to 20 years. for beaded sheeting, and 15 to 30 years. for prismatic sheeting for all colors. Furthermore, an outdoor deck was established in June 2013 at a site near Albertville, Minnesota to test traffic signs under a controllable environment by eliminating vandalism and physical damage.

- **Oloufa (2017) – "*Development of a Sign Sheeting Sampling Protocol for the Determination of Service Life of Traffic Signs*"**

  The report investigated the sampling protocol for sign sheetings in four districts of Florida. The report includes publications relevant to this project. For example, the report summaries two studies by Ketola (1989, 1999) on artificially accelerated tests versus outdoor exposure tests. These two papers are discussed in a later section of this report.

3.3. Product Specifications for Retroreflective Sign Sheeting Materials

Product information regarding retroreflective and nonreflective sign sheeting was reviewed and retrieved from the FDOT's APL. Currently, products of Types IV, V, VI, and XI are included on the list, and compiled information is shown in Table D-1 of Appendix D. Many products do not include the polymer types in the technical data sheets. For those products listing the polymer types, acrylic, vinyl, and polycarbonate are included. Also, no information regarding the weathering test is available in the product's technical data sheet. Instead, manufacturer's warranty is provided with duration ranging from 7 to10 years. for Type IV and 7 to12 years. for Type XI.

3.4. Weathering Behavior of Retroreflective Sign Sheeting Materials

Based on the compiled information from FDOT-APL, the retroreflective signs are made from acrylic, vinyl, and polycarbonate. However, it is not certain whether the polymer is used for the entire product or part of the product. Figure 11 shows a prismatic retroreflective sheet structure. In this multilayer structure, the plastic film is an exterior layer exposed to the ambient environment and serves as a protective layer for the interior structure. The weathering resistance of the plastic film would play an important role in the long-term field performance of the product.

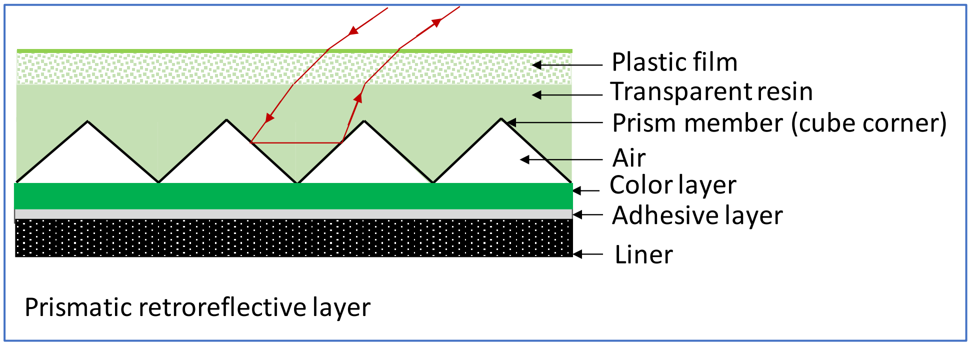


Figure 11 – A schematic of a retroreflective cube corner sheet

Benson (2003) indicated that the cube corner element of a retroreflective sheeting is usually made from a polymer with a refractive index of about 1.5, and such a polymer can be acrylic, polycarbonate, polyethylene-based ionomers, polyester and cellulose acetate butyrates.

Polycarbonate with a refractive index of 1.6 is an ideal material for retroreflective products. However, polycarbonate made from bisphenol-A monomer is susceptible to photooxidation forming hydroxyl and chain scissions (Wypych, 2013). In addition, polycarbonate can undergo hydrolysis which is accelerated by increasing of temperature (Ghorbel et al., 1995).

In the commercial products, UVA and HALS are added to the polymers, particularly the top plastic film, to prevent photo-oxidation. The functions of UVA and HALS in protecting the polymer against photodegradation were described in Section 2.4. For hydrolysis, there are no inhibitors to delay the reaction, but it depends on the concentration of carboxyl end groups in polyester or phenolic end groups in polycarbonate. As indicated in Eq. (6) in Section 1.3, the rate of hydrolysis is affected by the temperature and RH. The *"n"* value in the equation was found to be "2" for polycarbonate and polyester (Pickett and Coyle, 2013).

3.5 Test Methods Specified by State and Federal Agencies for Retroreflective Sign Sheeting Materials

For the retroreflective sign sheeting, the evaluation of the weathering resistance refers to ASTM D4956 in which the outdoor test requirement is specified together with ALTs. The correlation between ALT and outdoor testing based on irradiance is described in the standard. The standard defined that the outdoor weathering procedure shall be performed according to ASTM G7 (2013). The required exposure times for each type of retroreflective product can be seen in Table 19. The locations of the outdoor exposure test are recommended to be Miami, Florida representing a tropical summer rain climate, and Phoenix, Arizona representing the desert climate. Additionally, ALT can be considered in preliminary judgment until outdoor weathering results are available. Three ALT methods were recommended using a xenon arc apparatus, as described in Table 20. Methods I and II have been specified by state DOTs and AASHTO. The test durations of ALTs together with the required outdoor test duration for each type of retroreflective sheeting are shown in Table 21. The two laboratory test durations (2,000 hours for Method-I and 2,915 hours for Method -II) are equivalent to 12 months of outdoor exposure based on total UV radiation dosage. (The calculation for the equivalent outdoor exposure is included as Appendix E.) Also included in Table 21 are the minimum retention of coefficient of retroreflection (R_A) values, which are the same for the outdoor testing and ALTs, suggesting that ALT can achieve an AF of 3.

As indicated in Section 3.1, ALT is specified by HiDOT, TxDOT and AASHTO M268 with a test duration of 1,000, 2,000, and 2,200 hours, respectively, using Method-II in ASTM D4956. It should be noted that these testing durations are all shorter than the value defined in ASTM D4956 for Method-II.

Table 20 – Xenon Weatherometer Operating Conditions and Set Points in ASTM D4956

Exposure Parameters	Method		
	I	II	III
Irradiance set point at 340 nm	0.51 W/(m^2·nm)	0.35 W/(m^2·nm)	0.51 W/(m^2·nm)
Light/dark panel temperature set point	Continuous light	Continuous light	Continuous light
Filters for xenon lamp	Boron inner and Boron outer		
Uninsulated black panel	63°C	63°C	na
Black standard thermometer temperature	na	na	65°C
Water spray cycle	Alternating periods of 102 minutes light only and 18 min light + water spray		
Relative humidity set point	50% during the light only period (optional)		50% during the light only period
Chamber air temperature	38°C (optional)		38°C

Note: na = not applicable

Table 21 – Requirement for Radiant Exposure in Xenon Weatherometer and Outdoor Exposure Duration

Type	Outdoor Exposure Time* (months)	R_A** at 0.2°, -4° and +30° (cd/fc/ft^2)	Exposure Time (hours)		R_A** at 0.2°, -4° and +30° (cd/fc/ft^2)
			Methods I & III	Method II	
I	24	50% of values in Table 1§	1,000	1,460	50% of values in Table 1§
II	36	65% of values in Table 3§	2,000	2,915	65% of values in Table 3§
III	36	80% of values in Table 4§	2,000	2,915	80% of values in Table 4§
IV	36	80% of values in Table 5§	2,000	2,915	80% of values in Table 5§
V	36	80% of values in Table 6§	2,000	2,915	80% of values in Table 6§
VI	6	50% of values in Table 7§	250	365	50% of values in Table 7§
VIII	36	80% of values in Table 8§	2,000	2,915	80% of values in Table 8§
IX	36	80% of values in Table 9§	2,000	2,915	80% of values in Table 9§
XI	36	80% of values in Table 10§	2,000	2,915	80% of values in Table 10§

Note: When sheeting is specified for construction working zone applications, the outdoor exposure time is 12 months, and the minimum radiant exposure shall be 920 kJ/m^2-nm (equivalent to 500 hours using Methods I and III for 730 hours exposure using Method II.)

* When sheeting is specified for construction work zone application, the outdoor weathering shall be 12 months; ** According with ASTM D4956; § Referring to tables in ASTM D4956, *Standard Specification for Retroreflective Sheeting for Traffic Control*.

3.6 Discussion of Laboratory Test Methods for Retroreflective Sign Sheeting Materials

FDOT approved retroreflective sign sheeting products include Types IV, V, VI, and XI from four manufacturers. However, most of the technical data sheets do not include testing methods for weathering assessment. Only one of the Type V products indicates the weatherability property meeting the requirement of ASTM D4956, Section 7.6, and the minimum coefficient of retroreflective (R_A) percentage after outdoor exposure. Communication with representatives of three manufacturers (3M, Averydennison, and Nikkalite) revealed that the weathering resistances of their products are evaluated in accordance with ASTM D4956, using both outdoor testing and accelerated weathering testing. For ALT, Method I and/or II has been used, depending on the product.

In ASTM D4956, ALT shall be performed using a xenon arc apparatus. The three ALT methods shown in Table 20 are further discussed in this section. Method-I is equivalent to ISO 4892-2 (2013) "*International Standard for Plastics – Methods of Exposure to Laboratory Light Sources, Part 2: Xenon-Arc Lamps*", Cycle 10; Method-II is equivalent to ASTM G155, Cycle 1; and Method-III is equivalent to ISO 4892-2 Plastics Cycle 1. All three methods specify the xenon lamp filter type to be daylight (i.e., the filtered spectra should be close to daytime sunlight spectra in Miami, Florida). The borosilicate for inner and outer filtering has been commonly used to simulate outdoor sunlight, but its UV cutoff wavelength is slightly lower than that of the noon-time sunlight in Florida, as shown in Figure 12. Such a mismatch in the low wavelengths can induce degradation that does not take place under natural outdoor exposure for some polymers (Nichols, 2013; Berry et al., 2018). For that reason, alternative filters have been developed to improve the cutoff wavelength, for example, 3M adopted a quartz inner filter and a 3M proprietary outer filter for a xenon lamp to simulate the daylight spectrum (White et al., 2015), and Nichols et al. (2013) used Right-Light™ inner and quartz outer filters for a water-cooled xenon lamp.

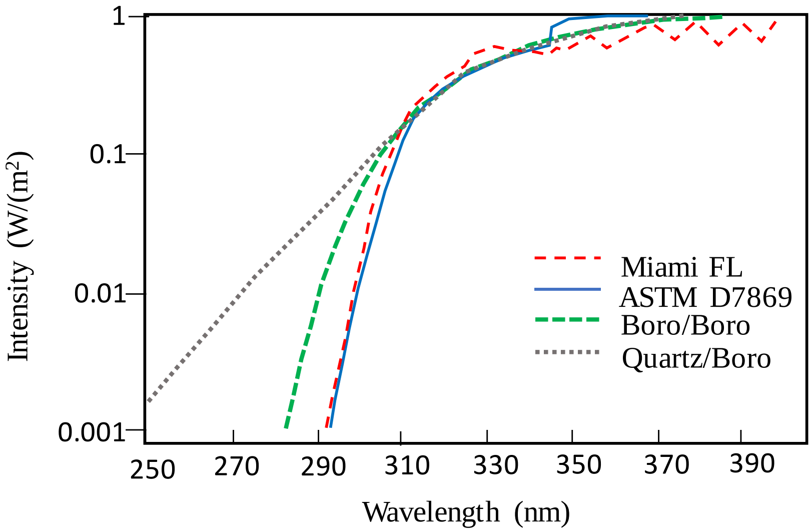


Figure 12 – The spectral power distribution of xenon lamp with different types of filters together with the noon-time sunlight in Miami, Florida.
(replotted from Berry et al., 2018)

Nichols et al. (2013) developed an accelerated weathering test protocol for automotive coating systems. In their method, two long water spray cycles at zero irradiance, one long water spray cycles with higher irradiance, and no water spray were implemented in the xenon weathering test. Using the changing of (–OH) and (–NH) absorption peaks in FTIR, they calculated the AFs to be 8 and 16 for the two coating systems, in comparison to the Florida outdoor exposure. The long water spray period was to ensure the coating absorbed enough water as it would occur during the nighttime period in Florida.

Based on the study by Nichols et al. (2013), a standard method, ASTM D7869 (2017), was established. The xenon spectrum conforms with the standard also shown in Figure 12 (replotted from Berry et al., 2018), in which spectra obtained from different filters are included for comparison. The ASTM D7869 xenon spectrum matches well with the noontime sunlight spectrum in Miami Florida. The standard test procedure involves a 24-hours test cycle that consists of a 10-step procedure. Each step is designed to imitate the material exposed to the Florida climate, as described in Table 22.

Table 22 – Summary the 10 Steps of a Test Cycle and the Corresponding Field Environment

Step	Duration at % RH	Temperature (Chamber/ Black Panel)	Irradiance at 340 nm W/(m^2·nm)	Corresponding Field Environment
1	240-min. at 95%	40ºC	Light-off and spray	To achieve similar water uptake in a normal day outdoors in South Florida, inducing failures such as cracking, delamination, loss of stabilizers.
2	30-min. at 50%	42ºC/50ºC	0.4	To remove the water from within the coating layers before sun rises high enough in the sky.
3	270-min. at 50%	50ºC/70ºC	0.8	To simulate the bright sunlight: the irradiance is higher than Florida noon sunlight to generate acceleration and the 70ºC is the average maximum panel temperature between light and dark color.
4	30-min. at 50%	42ºC/50ºC	0.4	Transitional step between highly stressed day time period and cool/wet dark night period.
5	150-min. at 95%	40ºC	Light-off and Spray	Simulate water uptake, but less than maximum.
6	30-min. at 95%	40ºC	Light-off and Spray	Short duration of wetting to simulate shower.
7	20-min. at 50%	42ºC/50ºC	0.4	Short drying period following the short wetting period.
8	120-min. at 50%	50ºC/70ºC	0.8	High irradiance at a shorter period is to achieve accumulated photochemical degradation.
9	10-min. at 50%	40ºC	Light-off	Total relaxation from all stresses
10	Repeat Steps 6 – 9 three more times			

The accumulated radiation energy per each test cycle (24 hours) is calculated to be 39.36 kJ/m^2 at 340 nm. To compare the UV radiation energy between the accelerated test and at Miami, Florida, the average annual irradiation of 295 MJ/m^2 at 295-385 nm is used for Miami (Vahidi et al., 2018). The value is then converted to 3245 kJ/m^2 at 340 nm per year or 8.9 kJ/m^2 at 340-nm/day. Therefore, the accumulated UV radiation of ASTM D7869 is 4.4 times higher than the sunlight in Florida per day. Most importantly, long wetting periods are incorporated into the test cycle to ensure moisture absorption of the test samples.

In Table 23, the test conditions of Methods I and II in ASTM D4956 and ASTM D7869 together with the corresponding AFs are listed for comparison. Considering UV alone, Method I in ASTM D4956 generates the highest AF. However, the duration of the moisture cycles in Methods I and II of ASTM D4956 is very short (18-min) not long enough for the test sample to absorb water. (The short period of wetting is intense to wash away the degraded materials.)

Therefore, Methods I and II in ASTM D4956 do not mimic the moisture effect on the retroreflective materials in the outdoor environment, particularly for materials susceptible to hydrolysis. The higher testing temperature defined in ASTM D7869 also accelerates water absorption and the rate of hydrolysis, as indicated in Eq. (6).

Table 23 – Comparison of Three Laboratory Acceleration Test Methods and Their Calculated Acceleration Factors

ASTM Test	**Duration at % RH**	**Temperature (Chamber/ Black Panel**	**Irradiance at 340 nm (W/(m^2·nm))**	**Accumulated UV radiation at 340 nm/day (kJ/m^2)**	**Acceleration Factor Based on UV Radiation**
D4956, Method-I	1440-min. at 50% (light on), and 216-min. at 100% (light on)	63°C	0.51	44.06 kJ/m^2	5.0
D4956, Method-II	1440-min. at 50% (light on), and 216-min. at 100% (light on)	63°C	0.35	30.24 kJ/m^2	3.4
D7869	420-min at 95% (light off) and 890-min at 50% (light on)	40°C (light off) and 50°C/70°C (light on)	0.4 and 0.8	39.36 kJ/m^2	4.4

Wood (2018) compared the gloss retained and color change (ΔE) of poly(vinylidene fluoride) coating between 250 days of ASTM D7869 and 81 months of outdoor exposure in Florida. The Spearman ranking correlations for both properties are greater than 0.9 which is considered to be a good correlation. It should be noted that ASTM D7869 has also been used to evaluate the weathering resistance of photovoltaic modules (Spataru et al., 2018; Hacke et al., 2019).

3.7 Correlation of Accelerated Laboratory Testing and Outdoor Testing for Retroreflective Sign Sheeting

Compared to coating materials, very few publications focus on the weathering of retroreflective sheeting materials. The majority of the DOT reports focused on the field performance of the products and service life prediction using the linear regression analysis on the collected field data. Several reports have already recognized the lack of data on the acceleration testing on this group of products and suggested the need for such a study.

Ketola (1989, 1999) are two earlier papers to investigate the durability of retroreflective sheeting materials in both outdoor exposure and ALTs. He pointed out that multilayer composite retroreflective sheeting products would exhibit different failure modes depending on the design (enclosed lens, encapsulated lens, or cube corner), and the products' materials. Some failure modes were identified in Ketola (1999):

- Destruction of the metallic reflector coat
- Disruption or distortion of the optical elements within the sheeting, reducing the reflectivity
- Degradation or destruction of outermost polymer layer
- Fading of dyes or color pigments
- Failure of bonds between layers.

In these two papers, the author indicated that the credibility of accelerated laboratory weatherometers (UV/condensation, xenon and carbon arc) was questionable because of the poor reproducibility of test results. To compare results of eight reflective sheeting samples after exposure to three ALTs for 2,500 to 3,000 hours to two outdoor tests at Florida and Arizona for 5 years (Ketola,1989), a ranking from 1 to 8 was used. Four of the tested samples exhibited similar ranking for the three laboratory tests, but the correlation between the laboratory and outdoor testing was inconsistent. The author recommended to use the outdoor test method according to ASTM D4956 to assess the weathering properties of retroreflective sheeting products. However, the ranking method used may not be the appropriate method for comparison because there was no common denominator.

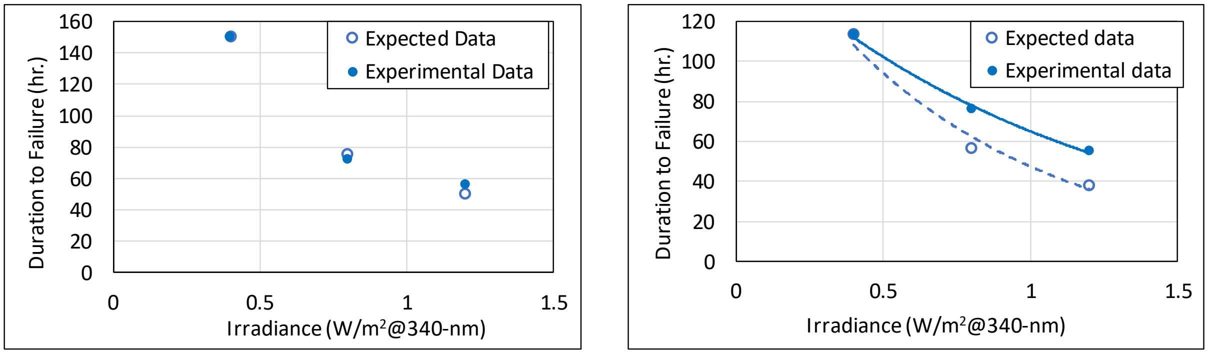
More recently, Mohan et al. (2012) studied the deterioration of reflective sheets (ASTM Type III) of different colors under natural weathering at Delhi, India, and a xenon arc weatherometer with irradiance of 60 $W/m^2 \cdot nm$ at 400 nm (or equivalent to 550 W/m^2 (290-385 nm). (It should be noted that this irradiance level is extremely high and covers greater than the UV range (295-385 nm). Their results indicate that the required duration for each color to reach the minimum allowable coefficient of retroreflection is not the same. Based on this single measurement parameter, acceleration factors ranging from 80 to 327 were obtained from the laboratory tests. Such high acceleration factors are questionable because it is uncertain that the same degradation mechanism took place in both testing conditions.

Immaneni et al. (2009) synthesized the deterioration rates of Type I and III retroreflective sign sheeting products from field inspection data compiled by FHWA, North Carolina State University, Oregon DOT, and Purdue University. A linear regression was used to analyze the deterioration rate of each product. The R^2 value of the regression lines ranges from 0.19 to 0.52, which indicates that the model does not adequately explain the variability of degradation with time. Although the field measurement represents the true performance of the sheeting, the large variability of the field condition makes it difficult to determine the governing degradation mechanism.

3.8 Recommendation of Laboratory Accelerated Test Method for Retroreflective Sign Sheeting

Based on the discussion in Section 3.6, ASTM D7869 is a more appropriate accelerated weathering test for retroreflective sign sheeting materials than Methods I and II in ASTM D4956. When only considering the UV irradiance, it will take 8.2 months testing time using ASTM D7869 to achieve the equivalent TUV of 36 months outdoor exposure required for Types IV, V, and XI retroreflective products. The 8.2 months is too long under the objective of this project.

To shorten the testing time, the irradiance of the test procedure in ASTM D7869 needs to increase while keeping the temperatures and the total wetting duration the same. The 70^{o}C black panel temperature is probably the highest temperature that does not change the properties of polymers to avoid exceeding the glass transition temperatures of some polymers. Assuming the reciprocity law is valid, changing the irradiance in Steps 3 and 8 of the test cycle from 0.8 W/(m^2·nm) to 1.2 W/(m^2·nm) and from 0.4 W/(m^2·nm) to 0.8 W/(m^2·nm) in Steps 2, 4 and 7 can shorten the total testing time to 5.3 months for the equivalent TUV of 36 months. Scott and Hardcastle (2009) exposed the polycarbonate and polystyrene samples to three irradiance levels at 0.4, 0.8 and 1.2 W/(m^2·nm) using a xenon arc device. The nominal specimen temperature was 77^{o}C. The yellowness results indicate that the reciprocity law was applicable to the polycarbonate but was not valid for polystyrene, as illustrated in Figure 13.



(a) Polycarbonate (b) Polystyrene

Figure 13 – Expected and experimental data for exposure samples
(Scott and Hardcastle, 2009)

As described previously, the relationship between the reaction rate and irradiance can also follow a power law, as expressed in Eq. (4). Considering $q = 0.5$, the accumulated UV radiation at 340 nm per day becomes 56.8 kJ/m^2. The laboratory xenon testing time to achieve equivalent 36-month outdoor exposure in Florida is 5.7 months, which is about 16% of the outdoor testing time. To achieve the 10% of the outdoor testing time, an irradiance of 3.2 W/(m^2·nm) at 340 nm in Steps 3 and 8 would be required. However, the lifetime of the xenon lamp would be significantly shortened at such high irradiance. Also, there would be a large uncertainty for adopting such high irradiance in the test protocol without verification. In summary, the test procedure of ASTM D7869 is modified by following the 10 steps listed in Table 24. The modified ASTM D7869 can substitute the supplementary requirement S3 of ASTM D4956.

Table 24 – The 10 Steps of a Modified Test Cycle in ASTM D7869

Step	Duration at % RH	Temperature (Chamber/Black Panel)	Irradiance @ 340 nm W/(m^2·nm)
1	240-min. at 95%	40ºC	Light-off + Spray
2	30-min. at 50%	42ºC/50ºC	0.8
3	270-min. at 50%	50ºC/70ºC	1.2
4	30-min. at 50%	42ºC/50ºC	0.8
5	150-min. at 95%	40ºC	Light-off + Spray
6	30-min. at 95%	40ºC	Light-off + Spray
7	20-min. at 50%	42ºC/50ºC	0.8
8	120-min. at 50%	50ºC/70ºC	1.2
9	10-min. at 50%	40ºC	Light-off
10	Repeat Steps 6 to 9 three more times		

3.9 Methods to Evaluate the Weathering of Retroreflective Sign Sheeting Materials

The methods specified in ASTM D4956 are recommended to evaluate the retroreflective sign sheeting materials. The key nondestructive test used to assess the weathering resistance of retroreflective sheeting, inks and cover films is the coefficient of retroreflection (R_A) based on the test procedure in accordance with ASTM E810 (2003) "*Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry*". In addition, daytime color is determined on the exposed and washed exposed samples (colorfastness) in accordance with ASTM E308 "*Standard Practice for Computing the Colors of Objects by Using the CIE System*" (colorimeters shall have 45º/0º or 0º/45º viewing angle), nighttime color in accordance with ASTM E811 (2018) "*Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors under Nighttime Conditions*", and shrinkage. Destructive mechanical tests include adhesion, flexibility, liner removal, and impact resistance.

4. CONCLUSION AND RECOMMENDATIONS

Extensive review compiled information on the weathering behavior of coating materials for steel structures and retroreflective and non-retroreflective sign sheeting materials. The standard test methods that have been implemented by state DOTs and federal agencies were identified and discussed. The published test results obtained from these tests were reanalyzed and correlated to the outdoor test data using known equations to obtain the AFs. The photodegradation mechanisms of the polymers used in FDOT's APL were described. The effects of UV irradiance, temperature, and moisture on the degradation rate were identified from the published literature and applied to the calculation to predict the equivalent testing times based on the climatic conditions in Miami, Florida.

The recommended ALT methods were developed from the relevant ASTM test procedures with appropriate modifications to provide the desirable acceleration. The proposed test protocol for accelerated weathering of coating materials for steel structures is built on the test procedure according to ASTM D5894, the cycles of UV/condensation and fog/dry test. The modification involves increasing the duration of the fog/dry cycle from 1 hour to 4 hours each, raising the temperature from 35^{o}C to 50^{o}C, and changing the NaCl concentration from 0.05% to 5% in the electrolyte solution. Also, the irradiance in the UV/condensation cycle increases from 0.85 to 1.55 W/(m^2·nm) at 340 nm. The new test protocol shortens the testing time to 10% of the outdoor testing. The modified test conditions are described in Appendix F.

For the retroreflective sign sheeting materials, the recommended accelerated weathering test adopts the 10-step test procedure according to ASTM D7869. Modifications focus on the UV irradiance at 340 nm by changing them from 0.8 to 1.2 W/(m^2·nm), and from 0.4 to 0.8 W/(m^2·nm). The new test protocol shortens the testing time to 16% of the outdoor testing. The modified test conditions are described in Appendix G.

REFERENCES

1. AASHTO M268-15, "*Retroreflective Sheeting for Flat and Vertical Traffic Control Applications*", Technical Section: 4d, Safety Devices, (AASHTO), Washington, D.C., 2000.
2. AASHTO M300, "Standard Specification for Inorganic Zinc-Rich Primer", American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., (2017)
3. AASHTO M268, "Standard Specification for Retroreflective Sheeting for Flat and Vertical Traffic Control Applications", American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., (2015).
4. AASHTO R31, "Standard Practice for Evaluation of Protective Coating Systems for Structural Steel", American Association of State Highway and Transportation Officials, (AASHTO), Washington, D.C., (2014).
5. ASTM B117, *Standard Practice for Operating Salt Spray (Fog) Apparatus*, ASTM International, West Conshohocken, PA, (2018).
6. ASTM D523, *Standard Test Method for Specular Gloss*, ASTM International, West Conshohocken, PA, (2014).
7. ASTM D610, *Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces*, ASTM International, West Conshohocken, PA, (2019).
8. ASTM D714, *Standard Test Method for Evaluating Degree of Blistering of Paints*, ASTM International, West Conshohocken, PA, (2017).
9. ASTM D870, *Standard Practice for Testing Water Resistance of Coatings Using Water Immersion*, ASTM International, West Conshohocken, PA, (2015).
10. ASTM D1654, *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments*, ASTM International, West Conshohocken, PA, (2016).
11. ASTM D1735, *Standard Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus*, ASTM International, West Conshohocken, PA, (2014).
12. ASTM D2244, *Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*, ASTM International, West Conshohocken, PA, (2016).
13. ASTM D4587, *Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings*, ASTM International, West Conshohocken, PA, (2011).
14. ASTM D4956, *Standard Specification for Retroreflective Sheeting for Traffic Control*, ASTM International, West Conshohocken, PA, (2017).

15. ASTM D5894. *Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet*, ASTM International, West Conshohocken, PA, (2016).

16. ASTM D7869, *Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings*, ASTM International, West Conshohocken, PA, (2017).

17. ASTM E308 *Standard Practice for Computing the Colors of Objects by Using the CIE System*, ASTM International, West Conshohocken, PA, (2018).

18. ASTM E810 *Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry*, ASTM International, West Conshohocken, PA, (2003).

19. ASTM E811 *Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors under Nighttime Conditions*, ASTM International, West Conshohocken, PA, (2018).

20. ASTM G7 *Standard Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials*, ASTM International, West Conshohocken, PA, (2013).

21. ASTM G50 *Standard Practice for Conducting Atmospheric Corrosion Tests on Metals*, ASTM International, West Conshohocken, PA, (2015).

22. ASTM G90, *Standard Practice for Performing Accelerated Outdoor Weathering of Materials Using Concentrated Natural Sunlight*, ASTM International, West Conshohocken, PA, (2017).

23. ASTM G154, *Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials*, ASTM International, West Conshohocken, PA, (2016).

24. ASTM G155, *Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*, ASTM International, West Conshohocken, PA, (2013).

25. Azizinamini, A., Power, E.H., Myers, G.F., Ozyildirim, C., Kline, E.S., Whitmore, D. W., and Mertz, D. R., "Design Guide for Bridges for Service Life", Washington, D.C., (2013), 629 pgs.

26. Balaguru, P., Najm, H., and Caronia, D., "*Evaluation of Different Paint Systems for Over-Coating Existing Structural Steel*", FHWA-NJ-2018-006, New Jersey Department of Transportation Bureau of Research and U.S. Department of Transportation Federal Highway Administration (2018), 69 pages.

27. Baldwin, K.R., Smith, J.E., "Accelerated Corrosion Tests for Aerospace Materials: Current Limitations and Future Trends", *Aircraft Engineering and Aerospace Technology*, Vol. 71, Issue 3, 1999, pp. 239-248.

28. Benson, G. M. "Retroreflective Cube Corner Sheeting, Molds Therefore, and Methods of Making the Same", European Patent Specification, EP 0993363B1, (2003)

29. Berry, D.H., Hinderliter, B., Sapper, E.D., Seebergh, J.E., and Schultz, K.A., “Spectral Power Distributions in Accelerated and Natural Weathering Tests and Their Impact on Aerospace Coating Service Life Prediction”, Chapter 8 in Service Life Prediction of Polymers and Plastics Exposed to Outdoor Weathering, White, C.C., White, K.M., Pickett, J.E., Editors, Elsevier Inc., (2018), 328 pages.

30. Cocuzzi, D.A., and Pilcher, G.R., “Ten Year Exterior Durability Test Results Compared to Various Accelerated Weathering Devices: Joint Study between ASTM International and National Coil Coating Association”, *Progress in Organic Coating,* 76, (2013), pp. 979-984.

31. Considine, T.A., *Standard Operating Procedure for Accelerated Corrosion Testing at ARL*, US Army Research Laboratory, ARL-TN-0855, November 2017.

32. Chang, L.M. and Chung, S., “*Steel Bridge Protection Policy, Volume II of V, Evaluation of Bridge Coating System for INDOT Steel Bridges*”, FHWA/IN/JTRP-98/21-II, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, (1999), 95 pgs.

33. Chin, J., Nguyen, T., Byrd, E., and Martin, J. "*Validation of the Reciprocity Law for Coating Photodegradation.*" *JCT research*, 2, no. 7 (2005): 499-508.

34. Chong, S-L. and Yao, Y. “*Laboratory and Test-Site Testing of Moisture-Cured Urethanes on Steel in Salt-Rich Environment*”, FHWA-RD-00-156, Federal Highway Administration Research and Technology, McLean, Virginia, (2000), 72 pages.

35. Christensen, P.A., Dilks, A., Egerton, T.A., and Temperley, J., “Infrared Spectroscopic Evaluation of the Photodegradation of Paint, Part II: The effect of UV intensity and wavelength on the degradation of acrylic films pigmented with titanium dioxide”, *Journal of Materials Science*, 35, (2000) pp. 5353-5358.

36. Decker, C., Moussa, K., and Bendaikha, T., “Photodegradation of UV-Cured Coatings, II. Polyurethane-Acrylate Networks”, *Journal of Polymer Science: Part A: Polymer Chemistry*, Vol. 29 (1991), pp. 739-747.

37. Decker, C., Masson, F., and Schwalm, R., “Weathering Resistance of Waterbased UV-Cured Polyurethane-acrylate Coatings”, *Polymer Degradation and Stability*, 83 (2004), 309-320.

38. Fedor, G.R., and Brenna, P., “Irradiance Control in Fluorescent UV Exposure Testers” Accelerated and Outdoor Durability Testing of Organic Materials, ASTM STP 1202, Warren D. Ketola and Douglas Grossman, Eds., ASTM, Philadelphia, 1994, pp. 199-214.

39. FDOT “Specification Section 560, Coating New Structural Steel”, Florida Department of Transportation, Tallahassee, Florida, (2013).

40. FDOT “Specification Section 561, Coating Existing Structural Steel”, Florida Department of Transportation, Tallahassee, Florida, (2013).

41. FDOT FM 5-571, “*Test Method for Sign Sheeting Materials*”, Florida Department of Transportation, State Materials Office, Gainesville, Florida, (2015).

42. Florida DOT “Specification Section 975, *Structural Coating Materials*”, Florida Department of Transportation, Tallahassee, Florida, (2013).

43. Florida DOT “Specification Section 994, Retroreflective and Nonreflective Sheeting and Sign Panel Fabrication”, Florida Department of Transportation, Tallahassee, Florida, (2013).

44. FHWA *Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways*, US Department of Transportation, Federal Highway Administration, Washington, D.C., (2009).

45. FHWA, *Traffic Sign Retroreflective Sheeting Identification Guide*, FHWA-SA-14-022, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., (2014).

46. Forsthuber, B., and Grull, G., “The Effects of HALS in the Prevention of Photo-degradation of Acrylic Clear Topcoats and Wooden Surfaces”, *Polymer Degradation and Stability*, 95, (2010), pp. 746-755.

47. Ghorbel I., Thominette, F., Spiter, P., and Vergu, J., “Hydrolytic Aging of Polycarbonate. I. Physical Aspects”, *Journal of Applied Polymer Science*, Vol. 55, (1995), pp. 163-171.

48. GMW 14872 “Test Procedure for Cyclic Corrosion Laboratory Test”, GM Worldwide Engineering Standards, General Motors Company, March 2013.

49. Gu, X., Stanley, D., Byrd, W.E., Dickens, B., Vaca-Trigo, I., Meeker, W.Q., Nguyen, T., Chin, J.W., Martin, J.W., “Linking Accelerated Laboratory Test with Outdoor Performance Results for a Model Epoxy Coating System”, Service Life Prediction of Polymeric Materials: Global Perspectives, Jonathan, M. W., Rose A., R., Chin, J., and Ray Dickie, Editors, Springer Science, (2009), 537 pages.

50. Hacke, P. Owen-Bellini, M., Kempe, M., Tanahashi, T., Sakurai, K., Gambogi, W., Trout, J., Felder, T., Choudhury, K., Philips, N., Koehl, M., Weiss, A., Spataru, S., Monokroussos, C., Mathiak, G., “Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules”, *Micro and Nano Technologies*, (2019), pp. 279-313.

51. Hardcastle, H.K. “*Service Life Prediction: Challenging the Status Quo*” Edited by Martin, J.W., Ryntz, R.A., Dickie, R.A., *Federation of Societies for Coatings Technology*, Blue Bell, PA, (2005) p. 217.

52. Hawaii DOT “Specification Section 750 Traffic Control Sign and Marker Materials”, Hawaii Department of Transportation, Honolulu, Hawaii, (2013).

53. Hsuan, Y. G., and R. M. Koerner. "*Antioxidant Depletion Lifetime in High Density Polyethylene Geomembranes.*" Journal of Geotechnical and Geoenvironmental Engineering 124, no. 6 (1998): 532-541.

42. ISO 4892-2 “International Standard for Plastics – Methods of Exposure to Laboratory Light Sources, Part 2: Xenon-Arc Lamps”, Geneva, Switzerland, (2013).

43. ISO 9227 "International Standard for Corrosion Tests in Artificial Atmospheres – Salt Spray Test", Geneva, Switzerland, (2009).

44. ISO 16701 "International Standard for Corrosion of Metals and Alloys – Corrosion in Artificial Atmosphere_ Accelerated Corrosion Test Involving Exposure under Controlled Conditions of Humidity Cycling and Intermittent Spraying of a Salt Solution" Geneva, Switzerland, (2015).

45. ISO 20340 "International Standard for Paints and Varnishes – Performance Requirements for Protective Paint Systems for Offshore and Related Structures", Geneva, Switzerland, (2003).

46. Immaneni, V. P. K., Hummer, J. E., Rasdorf, W., Harris, E.A., Yeom, C., "Synthesis of Sign Deterioration Rates Across the United States", *Journal of Transportation Engineering,* ASCE, 135 (3), (2009), 94-103.

47. Jacques, L.F.E., "Accelerated and Outdoor/Natural Exposure Testing of Coatings", *Progress in Polymer Science*, 25, (2000), 1337-1362.

48. Jorgensen, G., Bingham, C., King, D., Lewandowski, A., Netter, J., Terwilliger, K., and Adamsons, K. "*Service Life Prediction: Methodology and Metrologies*", Edited by Martin, J.W., and Bauer, D.R., ACS Symposium Series 805, American Chemical Society, Washington, D.C., (2002), p. 100.

49. Ketola, W. D., "Durability Testing for Retroreflective Sheetings", *Transportation Research Record* 1230, (1989), pp. 67-76.

50. Ketola, W. D., "Laboratory-Accelerated Versus Outdoor Weathering for Retroreflective Sheeting Specifications", *Transportation Research Record*, 1657, (1999), pp. 63-70.

51. Kansas DOT "Standard Specifications for State Road and Bridge Construction, Section 2201, Retroreflective Sheeting", Kansas Department of Transportation, Topeka, Kansas, (2015).

52. Koerner, R.M., Hsuan, Y.G., and Koerner, G.R., "Lifetime Predictions of Exposed Geotextiles and Geomembranes" *Geosynthetics International*, 24, No. 2, (2017), pp. 198–212.

53. Kogler, R., "*Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges*", FHWA-HIF-16-002-Vol. 19, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., (2015), 83 pgs.

54. Kiil, S., "Quantitative Mapping of Mechanisms for Photoinitiated Coating Degradation", Chapter 12, Service Life Prediction of Exterior Plastics: Vision for the Future, White, C.C., Martin, J., and Chapin, J.T., Editors, Springer International Publishing, Switzerland, (2015), 262 pages.

55. Kim, H., and Urban, M.M., "Molecular Level Chain Scission Mechanisms of Epoxy and Urethane Polymeric Films Exposed to UV/H_2O. Multidimensional Spectroscopic Studies", *Langmuir*, 16, (2000), pp. 5382-5390.

56. Kline, E., "Corrosion Steel Bridges", *Journal of Protective Coatings and Linings*, May 2008, pp. 20-31.

57. Kodumuri, P. and Lee, S-K, "*Federal Highway Administration 100-Year Coating Study*", FHWA-HRT-12-044, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., (2012), 62 pages.

58. Lau, K. "*Corrosion Evaluation of Novel Coatings for Steel Components of Highway Bridges*", FDOT Project BDV29 977-02, Florida Department of Transportation, Tallahassee, Florida, (2015), 217 pages.

59. LeBozec, N. Thierry, D., Le Calve, P., Favennec, C., Pautasso, J.-P., and Hubert, C. "Performance of Marin and Offshore Paint Systems: Correlation of Accelerated Corrosion Tests and Field Exposure on Operating Ships", *Materials and Corrosion*, 66, No. 3, (2015), pp. 215-225.

60. Lyon, S.B., Thompson, G.E., and Johnson, B. "Materials Evaluation Using Wet-Dry Mixed Salt-Spray Tests", New Methods for Corrosion Testing of Aluminum Alloys, ASTM STP 1134, V. S. Agarwala and G. M. Ugiansky, Eds., American Society for Testing and Materials, Philadelphia, 1992, pp. 20-31.

61. Mailhot, B. et al., "Depth Profiling by AFM Nanoindentations and Micro-FTIR Spectroscopy for the Study of Polymer Ageing", *Macromolecular Rapid Communications*, 25, (2004), pp. 436-440.

62. Mailhot, B., Morlat-Therias, S., Ouahioune, M., and Gardette, J., "Study of the Degradation of Epoxy/Amine Resin: Photo-and Thermo-Chemical Mechanism", *Macromolecular Chemistry and Physics*, 206, (2005), pp. 575-584.

63. Martin, J. W., Nguyen. T., Byrd, E., Dickens, B., and Embree, N. "Relating Laboratory and Outdoor Exposures of Acrylic Melamine Coatings: I. Cumulative Damage Model and Laboratory Exposure Apparatus." *Polymer degradation and stability*, 75, no. 1 (2002): 193-210.

64. Martin, J.W., Ryntz, R.A., Chin, J., Dickie, R.A. (Editors) "*Service Life Prediction of Polymeric Materials, Global Perspectives*", 4th International Symposium on Service-Life Prediction, December 3-8, 2006 in Key Largo, Florida, Springer, (2009), 537 pgs.

65. Merlatti, C., Perrin, F.X., Aragon, E., and Margaillan, A., "Natural and Artificial Weathering Characteristics of Stabilized Acrylic-urethane Paints", *Polymer Degradation and Stability*, Vol. 93, Issue 5, (2008), pp. 896-903.

66. Minnesota DOT, "*Traffic Sign Life Expectancy*", Howard Preston, CH2M Hill, Minnesota Department of Transportation, Research Services and Library, Office of Transportation System Management, St. Paul, Minnesota, (2014).

67. Mohan, S., "Deterioration of Retro-Reflective Sheet Under Outdoor Weathering and Weather-O-Meter", *International Journal of Transportation Science and Technology*, Vol. 1, No. 1, 2012, 61-72.

68. Nichols, M., Boisseau, J., Pattison, L., Campbell, D., Quill, J., Zhang, J., Smith, D., Kenderson, K., Seebergh, J., Berry, D., Misovski, T., and Peters, C., "An Improved Accelerated Weathering Protocol to anticipate Florida Exposure Behavior of Coatings", *J. Coat. Technol. Res.*, 10 (2), (2013), pp. 157-173.

69. Nguyen, T.V., Tri, P.N., Nguyen, T.D., Aidani, R.E., Trinh, V.T., and Decker, C., "Accelerated Degradation of Water Borne Acrylic Nanocomposites used in Outdoor Protective Coatings", *Polymer Degradation and Stability*, 128, (2016), pp. 65-76.

70. Nguyen, T.V., Le, X.H., Dao, P.H., and Decker, C., "Stability of Acrylic Polyurethane Coatings under Accelerated Aging Tests and Natural Outdoor Exposure: The Critical Role of the Used Photo-Stabilizers", *Progress in Organic Coatings*, 124, (2018), pp.137-146.

71. Oloufa, A. "*Development of a Sign Sheeting Sampling Protocol for the Determination of Service Life of Traffic Signs*", Florida Department of Transportation, Tallahassee, Florida (2017).

72. Pathak, S.S., Blanton, M.D., Mendon, S.K., Rawlins, J.W., "Investigation on Dual Corrosion Performance of Magnesium-rich Primer for Aluminum Alloys Under Salt Spray Test (ASTM B11&) and Natural Exposure" *Corrosion Science*, Vol. 52, Issue 4, (2010), pp. 1453-1463.

73. Pennsylvania DOT, "*Specification for Retroreflective Sheeting Materials and Process Inks*" Commonwealth of Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, (2013).

74. Pickett, J.E., "Review and Kinetic Analysis of the Photodegradation of UV Absorbers", *Macromolecules Symposium*, 115 (1997), pp. 127-141.

75. Pickett, J.E., and Coyle, D.J., "Hydrolysis Kinetics of Condensation Polymers under Humidity Aging Conditions" *Polymer Degradation and Stability*, 98, Issue 7, (2013), pp. 1311-1320.

76. Quill, J., Gauntner, J., Fowler, S., and Regan, J., "Combined Corrosion and Weathering: Validating a Concept with Over a Decade of Research", Technical Article, LF-8160, Q-Lab Corporation, Westlake, Ohio, (2013), 5 pages.

77. Rezig, A., Nguyen, T., Martin, D., Sung, L., Gu, X., Jasmin, J., and Martin, J., "Relationship Between Chemical Degradation and Thickness Loss of an Amine-Cured Epoxy Coating Exposed to Different UV Environments", *JCT Research*, Vol. 3, No. 3, (2006), pp. 174-184.

78. Roberge, P.R., "What is Accelerated in Accelerated Testing: A Framework for Definition", Cyclic Cabinet Corrosion Testing, ASTM STP 1238, Gardner S. Haynes, Ed., American Society for Testing and Materials, Philadelphia, (1995), pp. 18-30.

79. Schwarzschild, K. "*On the Deviations from the Law of Reciprocity for Bromide of Silver Gelatine*", *Astrophysical Journal*, Vol. 11, (1900), p. 89.

80. Scott, K.P., and Hardcastle III, H.K., "A new Approach to Characterizing Weathering Reciprocity in Xenon Arc Weathering Devices", Chapter 6, Service Life Prediction of Polymeric Materials: Global Perspective, Martin, J.W., Ryntz, R.A., Chin, J., Dickie, R.A., Editors, Springer Science, New York, New York, (2009), pp. 83-92.

81. Shi, A., Koka, S., Ullett, J., "Performance Evaluation on the Weathering Resistance of Two USAF Coating Systems (Standard 85285 Topcoat Versus Fluorinated APC Topcoat) via Electrochemical Impedance Spectroscopy", *Progress in Organic Coatings*, Vol. 52, Issue 3, (2005), pp. 196-209.

82. Simpson, C.H., Ray, C.J., and Skerry, B.S., "Accelerated Corrosion Testing of Industrial Maintenance Paints Using A Cyclic Corrosion Weathering Method", *Journal of Protective Coating and Linings*, Vol. 8, No. 5 (1991), pp. 28-36.

83. Spataru, S., Hacke, P., and Owen-Bellini, M., "Combined-Accelerated Stress Testing System for Photovoltaic Modules", IEEE 7th World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, (2018), pp. 3943-3948.

84. Texas DOT "Specification, Section 8300, Sign Face Materials", Departmental Materials Specification (DMS), Texas Department of Transportation, Austin, Texas, (2013).

85. Tesser, E., Lazzarini, L., and Bracci S., "Investigation on the Chemical Structure and Aging Transformations of the Cycloaliphatic Epoxy Resin EP2101 Used as Stone Consolidant", Journal of Cultural Heritage, 31, (2018), pp. 72-82.

86. Toubia, E. and Emami, S. "Performance Comparison of Structural Steel Coating Systems", State Job Number 135004, The Ohio Department of Transportation, Columbus, Ohio, (2016), 107 pages.

87. Vahidi, S., ElSafty, A., and Hsuan, Y.G., "Predicting the depletion of antioxidants in high density polyethylene (HDPE) under sunlight using the reciprocity law", 11th International Conference on Geosynthetics, Seoul, South Korea, September 16-21, (2018).

88. Vanlandingham, M.R., Eduljee, R.F., Gillespie, Jr. J.W., "Moisture Diffusion in Epoxy Systems", Journal of Applied Polymer Science, Vol. 72, Issue 5, (1999), pp. 787-798.

89. White, K.M, Burns, D.M., and Gregar, T.Q., "Laboratory-Based Predictions of Weathering in Outdoor Environments Over the Entire Degradation Pathway", Chapter 2, Service Life Prediction of Exterior Plastics: Vision for the Future, White, C.C., Martin, J., and Chapin, J.T., Editors, Springer International Publishing Switzerland, (2015), pp. 21-40.

90. White, K., and Forman, J., "Accelerated Testing: Understand Experimental Design and Error Propagation", Chapter 6, Service Life Prediction of Exterior Plastics: Vision for the Future, White, C.C., Martin, J., and Chapin, J.T., Editors, Springer International Publishing, Switzerland, (2015), pp. 87-94.

91. Wilhem, C., and Gardette, J-L., “Infrared Analysis of the Photochemical Behavior of Segmented Polyurethanes: 1. Aliphatic Poly(ester-urethane), Polymer, Vol. 38, No. 16, (1997), pp. 4019-4031.

92. Woo, R.S.C., Chen, Y., Zhu, H., Li, J., Kim, J-K., and Leung, C.K.Y., “Environmental Degradation of Epoxy-organoclay Nanocomposites due to UV Exposure. Part I: Photo-degradation”, Composites Science and Technology, 67, (2007), pp. 3448-3456.

93. Wood, K., “New Tools for Service Life Prediction and Risk Minimization for Exterior Building Product Finishes”, Chapter 5, Service Life Prediction of Polymers and Plastics Exposed to Outdoor Weathering, White, C.C., White, K.M., Pickett, J.E., Editors, Elsevier Inc., (2018), pp. 65-78.

94. Wypych, G., Handbook of Material Weathering, 5th edition, ChemTec Publishing, Toronto, 2013, 827 pages.

95. Yang, X.F., Tallman, D.E., Bierwagen, G.P., Croll, S.G., and Rohlik, S., “Blistering and Degradation of Polyurethane Coatings under Different Accelerated Weathering Tests”, *Polymer Degradation and Stability*, 77, (2002), pp. 103-109.

96. Yao, Y., Kodumuri, P., and Lee, S-K, “*Performance Evaluation of One-Coat Systems for New Steel Bridges*”, FHWA-HRT-11-046, U.S. Department of Transportation, Federal Highway Association, Washington, D.C., (2011), 104 pages.

APPENDIX – A

Table A-1 and Table A-2 on Specifications of Coating Materials for Steel Structures

Table A-1 – Summary of the Laboratory and Outdoor Testing of Coating Materials for Steel Structures in FDOT Specification Section 975

Structural Steel Coating Systems				
Laboratory Testing				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Salt Fog Resistance	AASHTO R31 (ASTM B117)	5,000 hrs.	ASTM D714	Blister Size = 10, Average Rust Creep at the Scribe ≤ 0.1 inches
Cyclic Weathering Testing	AASHTO R31 (ASTM D5894)	15 – 336 hr. cycles	ASTM D714	Blister Size = 10, Average Rust Creep at the Scribe ≤ 0.2 inches
			ASTM D2244	Color Retention ΔE ≤ 8
			ASTM D523	Gloss loss less than 30 units
Outdoor Testing				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Blistering	ASTM G7	5 years	ASTM D714	Blister Size = 10,
Color Retention	ASTM G7	2 years	ASTM D2244	Color Retention ΔE ≤ 8
Gloss	ASTM G7	2 years	ASTM D523	Glass loss ≤ 30 units
Class 5 Applied Finish Coatings				
Laboratory Testing				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Salt Spray (fog) Resistance	ASTM B117	2,000 hrs.	Not Defined	No disbondment
Fluorescent UV-Condensation Exposure	ASTM D4587	2,000 hrs. 4-h UV, 4-h cond.	ASTM D714 (blistering only)	No blistering, No observable cracking or delamination, chalking
			ASTM D4214 -Method D)	Rating no less than 8

Note:
AASHTO R31 *“Standard Practice for Evaluation of Protective Coating Systems for Structural Steel”*
ASTM B117 *“Standard Practice for Operating Salt Spray (Fog) Apparatus”*
ASTM D714 *“Standard Test Method for Evaluating Degree of Blistering of Paints”*
ASTM D5894 *“Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet)”*
ASTM D2244 *“Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates”*
ASTM D523 *“Standard Test Method for Specular Gloss”*
ASTM G7 *“Standard Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials”*
ASTM D4587 *“Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings”*
ASTM D4212 *“Standard Test Method for Evaluating the Degree of Chalking of Exterior Paint Films”*

Table A-1 – Cont.

Anti-Graffiti Coating Materials				
Laboratory Testing – Non-Sacrificial				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Cyclic Weathering Testing	AASHTO R31 (ASTM D5894)	15 – 336 hr. cycles	Not Defined	No blistering, cracking, chalking, or delamination. Color ≤ 3 ΔE CIE Lab units Retention of 60° Gloss ratio ≥ 0.8
Outdoor Exposure Test – Non-Sacrificial				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Graffiti Resistance	ASTM G7	6 Months at FDOT test site. 2500 psi pressure washer	Not Defined	Complete removal of solvent based acrylic, polyurethane, and alkyd-based spray paint. No delamination or visual defects.
Laboratory Testing –Sacrificial				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Cyclic Weathering Testing	AASHTO R31 (ASTM D5894)	No salt fog, at 95°F, 0-90% RH, 500 hrs. Alternating RH every 100 hrs.	Not Defined	No melting or disbondment
Outdoor Exposure Test – Sacrificial				
Property	Test Method	Condition	Property Test Method	FDOT Requirement
Sacrificial Coating Removability	ASTM G7	6 Months at FDOT test site.	Not Defined	Complete removal of solvent based acrylic, polyurethane, and alkyd-based spray paint from substrate.

Table A-2 – Summary of Specifications for Structural Steel Coating Materials from State DOTs and Federal Agencies

#	Title	Date	Coating Materials and Tests
1	AASHTO/NSBA Steel Bridge Collaboration S8.1-2014, Guide Specification for Application Coating Systems with Zinc-Rich Primers to Steel Bridges,	2014	The document describes the material acceptance, surface preparation, and paint application. For material acceptance: Coating products shall meet the test requirements of AASHTO M300, and AASHTO R31. AASHTO maintains a testing protocol and database of testing results as part of AASHTO National Transportation Product Evaluation Program (NTPEP).
2	Virginia DOT Road and Bridge Specifications – Section 231 Paint	2016	• 3-component systems: zinc/epoxy/urethane systems approved by NEPCOAT* or in accordance with AASHTO R-31 • 2-component systems: modified epoxy mastic and aluminum in color. – Weathering test – ASTM G23, Type D for 1000 hr. – No rust, loss of adhesion to steel test panel or blistering. – Salt Fog test – ASTM B117 for 1000 hr. – An X mark having 2-in legs down to base metal. No rusting or blistering beyond 1/16 in. from the center of the scribe mark or a loss of bond. • Water reducible paint: acrylic water borne paint. No defined test methods.
3	Pennsylvania DOT Publication 408 Specification – Section 1060 Shop Painting Structure Steel	2016	• Coating system for plain carbon steel: self-curing inorganic zinc primer/epoxy or urethane intermediate/aliphatic urethane topcoat. • Coating system for galvanized steel: two coat paint system (epoxy polyamide intermediate coat and aliphatic urethane as topcoat. • Required materials are listed in Bulletin 15.
	Pennsylvania DOT Publication 408 Specification – Section 1070 Painting Existing Structural Steel	2016	Painting for existing bridges using a three-coat system (organic zinc primer/epoxy or urethane intermediate/aliphatic urethane topcoat. Required materials are listed in Bulletin 15.
	Pennsylvania DOT – Bulletin 15 Qualified Products List for Construction	2019	Materials required in Section 1060 and Section 1070 are approved and maintained by Northeast Protective Coating Committee (NEPCOAT). The NEPCOAT qualified Products are compiled with AASHTO R-31.

* NEPCOAT – North East Protective Coating Committee (members are Connecticut, Delaware, Massachusetts, Maine, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island and Vermont)

Note:		
	AASHTO M300	*"Standard Specification for Inorganic Zinc-Rich Primer"*
	AASHTO R31	*"Standard Practice for Evaluation of Protective Coating Systems for Structural Steel"*
	ASTM G23	*"Operating Open Flame Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials"*
	ASTM B117	*"Standard Practice for Operating Salt Spray (Fog) Apparatus"*

Table A-2 – Cont.

#	Title	Date	Coating Materials and Tests
4	California State Transportation Standard Specifications – Section 59 Structural Steel Coatings	2018	For inorganic zinc primer, it should comply with AASHTO M300 Type I or II. For waterborne coating system used for existing structural steel, specification PWB coating should be implemented. For finish coat: • Color Tolerance: after 300 hr. UV exposure using ASTM D4587, Cycle 2 (4 hr. UV at 60ºC/4 hr. condensation, dark at 50ºC), irradiance of 0.89 W/m^2·nm at 340 nm. Maximum 4 ΔE for PWB 171 and Maximum 10 ΔE for PWB 172 by ASTM D2244. • Salt Fog exposure: 100 hr. using ASTM B117, Rust rating must be minimum 10 by ASTM D610, and Blistering cannot be more than 8F by ASTM D714.
5	Texas DOT Departmental Materials Specification – DMS 8101 Structural Steel Paints – Performance	2007	• Inorganic zinc primer: a solvent-based inorganic zinc coating of the self-curing ethyl-silicate type. • Epoxy zinc primer: a polyamide-cured epoxy containing > 84% of Zn • Epoxy intermediate coating: a polyamide-cured or polyamide/amine-cured epoxy with inhibitive type pigments. • Urethane appearance coat: a glossy, acrylic-cured aliphatic urethane-appearance coat • Acrylic latex appearance coat: a water-borne acrylic latex coating. For testing appearance coatings with epoxy zinc prime – 3000 hr. in an Atlas xenon weatherometer according with ASTM G155, using exposure Cycle 1 with a quartz inner filter glass and Type "S" Borosilicate outer filter glass. The acrylic latex must not show any serious failure (no peeling, chipping, blistering discoloring, cracking, crazing or eroding with thickness loss, splitting, or disbanding.) After 3000 hr. - Color change must less than 3 ΔE for white and light colors and less than 5 ΔE for darker colors After 3000 hr. – pull-off test must have a minimum 400 psi strength and maximum of 20% adhesion failure of coating from the primer or a cohesive failure using ASTM D4541 Type II.

Note: ASTM D4587 *"Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings"*
ASTM D2244 *"Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates"*
ASTM D610 "*Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces*"
ASTM D714 *"Standard Test Method for Evaluating Degree of Blistering of Paints"*
ASTM G155 *"Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials"*
ASTM D4541 *"Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesive Testers"*

Table A-2 – Cont.

#	Title	Date	Coating Materials and Tests
6	Missouri DOT Standard Specifications for Highway Construction – Section 1081 Coating of Structure Steel	2019	Five paint systems for coating new and existing bridges and structures made of structure steel are included. System G: Inorganic zinc silicate/epoxy/polyurethane; System H: Inorganic zinc silicate/waterborne acrylic intermediate/waterborne acrylic; System I: Inorganic zinc silicate-polysiloxane; Calcium sulfonate system; Aluminum & gray epoxy-mastic Primer.
	Missouri DOT Standard Specifications for Highway Construction – Section 1045 Paint for Structural Steel	2019	Specific test protocols for each coat of the five paint systems specified in Section 1081. • Inorganic Zinc Silicate coating: should comply with AASHTO M300 Type 1A • Epoxy System G intermediate coating and Polyurethane System G finish coating: - Weathering resistance: 4000 hr. using ASTM G153, Cycle 1, ASTM G155, cycle 2, or ASTMG154, cycle 2 – Color change no greater than 3 ΔE using ASTM D2244. - Salt fog resistance: 3000 hr. using ASTM B117 and D1654 – no rusting, undercutting, discoloration, fading, blistering, chalking, loss of gloss or change in color. • Waterborne Acrylic System H intermediate and finish coating: Same as System G, except for Brown color of the finish coat which shall show a color difference less than 4 ΔE. • Polysiloxane System I finish coating: same as system G. • Aluminum Epoxy-Mastic primer: - Weathering and salt fog resistance: ASTM G154 Type A lamps for 300 hr. (4 hr. UV/4 hr. condensation), afterward the panel shall be scribed with an “X” of at least 2-in. legs down to base metal. The scribed panel shall be tested according with ASTM B117 for 1000 hr. The tested panel shall show no loss of bond, rusting or blistering beyond 1/16 in. from the center of the scribe mark. • Gray Epoxy-Mastic Primer: same as Aluminum Epoxy-Mastic primer • Calcium Sulfonate System: Salt fog resistance: 500 hours ASTM B117 – no more than 1% rust undercutting, blistering or peeling.

Note:
ASTM G153 *“Standard Practice for Operating Enclosed Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials”*
ASTM G154 *“Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials”*
ASTM D1654 *“Standard Test Method for Evaluation of Painted for Coated Specimens Subjected to Corrosion Environments”*

Table A-2 – Cont.

#	Title	Date	Coating Materials and Tests
7	Louisiana DOT, Section 09910 Painting	Unknown	Section includes approved paint manufacturers. Under the field quality control section, a series of tests is required including accelerated weathering. However, the required specification is not included in this section.
8	Georgia DOT, Section 870 Paint	Unknown	Section includes the compositions of nine types of paints for structure steel, but the testing is not included in this section.
9	South Carolina, Section 710 Paint for Structural Steel	2004	A list of qualified products is included in Qualified Product List (QPL) 19, but the material specification requirement seems to be contract dependent.
10	Indiana DOT, Approval Procedures for Coating Formulations and Coating Systems, ITM No. 606-19	2015	The document lists AASHTO M300 for Inorganic Zinc-Rich Primer. No material specification is included in this document.
11	New Jersey DOT, Standard Specifications for Road and Bridge Construction	2019	Paints systems should be approved by NEPCOAT and list on the QPL. • Inorganic-zinc/epoxy/urethane for coating new structures • Organic/epoxy/urethane for re-coating existing structures • Epoxy mastic, urethane for over-coating existing structures
12	NASA Technical Standard, Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment	2016	The minimum material requirement is specified. Materials include Inorganic zinc coatings, primer and intermediate coatings, finish coatings, epoxy mastic coatings, coal tar-epoxy (other listed coatings are not commonly used for steel structures). • Inorganic Zinc Coatings: - Greater than 83% zinc by weight. - Rating not less than 9 based on ASTM D610; and ASTM D1654. - Exposed to Kennedy Space Center (KSC) Beach Corrosion Test Site for a) 18 months for initial acceptance and 5 yr. for final acceptance. • Finish Coatings - Rating not less than 8 based on ASTM D610 and ASTM D1654, and a rating of not less than 9F based on ASTM D714. - Exposed to KSC Beach Corrosion Test Site for 18 months for initial acceptance and 5 yr. for final acceptance.

Table A-2 – Cont.

#	Title	Date	Coating Materials and Tests
13	NASA Technical Standard, Corrosion Protection for Space Flight Hardware	2012	Test methods are specified for 6 classes: 1) seawater, 2) seacoast, 3) inland (≥ 50 miles from seacoast, 4) corrosive chemical or microbial induced corrosion, 5) indoor/uncontrolled humidity environments, and 6) indoor temperature and controlled humidity environment. For these 6 classes, Classes 1, 2, and 3 are more relevant to steel structures in transportation. • Class 1 – ASTM G52, 2X maximum allowed exposure • Class 2 – one of the following tests - Beach exposure at KSC beach corrosion test site. - ASTM D5894, alternate 7-day UV exposure with 7-day salt spray (starting with UV testing followed by cyclic corrosion testing). The testing duration is 60 days for every 3 months of beach exposure. - 7-day alternating cycles, starting with UV testing followed by salt spray (fog) testing according with ASTM D5894 and ASTM B117. The testing duration is 1000-h for every 45 days of beach exposure. • Class 3 – one of the following tests - Beach exposure at KSC beach corrosion test site for 9 months. - Atmospheric exposure for coating materials is according with ASTM G7. - ASTM D5894, alternate 7-day UV exposure with 7-day salt spray (starting with UV testing followed by cyclic corrosion testing). The total duration of slat cyclic corrosion is 60 days - 7-day alternating cycles, starting with UV testing followed by salt spray (fog) testing according with ASTM D5894 and ASTM B117. The total duration of salt spray is 500-h.

Note: ASTM G52 *“Standard Practice for Exposing and Evaluation Metals and Alloys in Surface Seawater”*

APPENDIX – B

Table B-1 and Table B-2 on Information of Coating Materials and Systems for Steel Structures

Table B-1 – Summary of Information from Reports on Coating Materials and Systems for Steel Structures (State-of-Practice Review)

#	Title and Author	Date	Summary on Weathering Resistance Properties
1	Maintenance Issues and Alternate Corrosion Protection Methods for Exposed Bridge Steel NCHRP Synthesis 257 By T. Neal	1998	• Coatings are increasingly selected based on accelerated laboratory weathering tests as opposed to the compositional type of specification. • Salt fog testing has been used as the accelerated test for long lasting coating. It is now replacing by Cycle UV/Condensation cycle and salt fog/dry.
2	Steel Bridge Protection Policy – Volume II Evaluation of Bridge Coating Systems for INDOT Steel Bridges FHWA/IN/JTRP-98/21 By L.M. Chang and S. Chung	1999	• The report describes the INDOT coating system in late 1990 and new coating systems at that time. The new coating systems included: - three-layer coating -Inorganic/organic zin, epoxy and urethane coating system - Two-layer coating – inorganic zinc and waterborne acrylic coating - Moisture cure urethan coating system • Specification for coating systems was included in Appendix C of their report: - Waterborne Acrylic – ASTM D4587, UV 340 bulbs for 3000-h and Cyclic salt fog resistance - ASTM G85 Annex A5, for 4000-h. - Urethane – ASTM 4587, UV 340 bulbs for 3000-h and Salt fog resistance – ASTM B117, for 3000-h. • Factors affecting performance and durability of overcoating systems: 1) Adhesion/cohesion and 2) surface contamination.
3	Design Guide for Bridges for Service Life SHRP 2 Report S2-R19A-RW-2 By A. Azizinamini, et al.	2013	In Chapter 6 “Corrosion Prevention of Steel Bridges”, it indicates the moisture barrier property of the topcoat is essential to prevent corrosion. The chemical compositions of the coating materials were included. The additives in the vehicle part include UV absorbers which is essential the weathering resistance of the coating. Polyurethane coatings were formulated with hindered amine light stabilized to preserve gloss and color. • Other methods and materials to prevent bridge corrosion were described in this chapter, but the weathering testing of coating systems was referred to other FHWA studies.

Note: ASTM G85 *“Modified Salt Spray (Fog) Testing”*

Table B-1 – Cont.

#	Title and Author	Date	Summary on Weathering Resistance Properties
4	Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges FHWA-HIF-16-002-Vol.19 By R. Kogler	2015	The report presents the corrosion protection methods for steel bridges. The coatings for abrasive-blasted steel and the zinc-rich paint systems have been used for new and existing steel structures. Challenges on the curing time of the zinc primers were discussed. The weathering of the coating systems was included. Challenge of long testing time in natural marine exposure condition was stated, particularly to discriminate between high performance systems. Alternatively, laboratory accelerated weathering tests to rank the durability of paint formulation was suggested.
5	Successful Preservation Practices for Steel Bridge Coatings NCHRP Project 20 68A, Scan 15-03 By P. Vinik, et al.	2016	• The report synthesized the recent systems include: - inorganic zinc primers for shop painting, while for field painting both inorganic and organic zinc primers have been used. Zinc primers are commonly coated with epoxy mind-coat with a polyurethane topcoat. - three-coat polyurethane systems – two coats of moisture-cured polyurethane (including a zinc-based primer) with a two-component aliphatic polyurethane as the topcoat. - inorganic zinc primer coated with waterborne acrylic. - spot applications include coatings such as epoxy mastics, moisture-cured polyurethanes, calcium sulfonate modified alkyds, low-VOC alkyds, and direct-to-metal acrylics. • Identify the importance for testing high-performance coating systems, which are 100% solids technology (epoxy and polyurea), fluoropolymers, and powder coatings, in both outdoors and modified accelerated weathering testing. • Recommend testing different color of coating by NTPEP to better differentiate performance of topcoats and incorporate colorimetry into the evaluation. • Identify three approaches to evaluate coatings: 1) use data from NTPEP for approved product list, 2) in house characterization of coating for chemical composition, and 3) specify in-house formulations. • Recommend two new coating systems: 1) thermal spray and 2) ultra-weatherable coating. Identify the better performance of inorganic zinc primers than organic zinc primers based on NASA's beachside exposure test site.

Table B-2 – Summary of Information from Reports on Coating Materials and Systems for Steel Structures (Experimental Projects)

#	Title and Author	Date	Summary on Weathering Resistance Properties
1	Laboratory and Test-Site Testing of Moisture-Cured Urethanes on Steel in Salt-Rich Environment FHWA-RD-00-156 By S-L Chong and Y. Yao	2000	The report presents the test results of three moisture-cured urethane (MCU) formulae using laboratory test and outdoor exposure. MCU was applied to three 3-layer coating systems (zinc-rich MCU/ MCU/MCU) with different metal fillers in the intermediate and top coating layers. The laboratory test procedure was freeze /UV-condensation/salt-fog-dry-air cycle for 4000-h. The outdoor test took place at Sea Isle, NJ; test panels were inclined 45^o facing south and sprayed with natural seawater daily for 2-year. • Directly comparing total color difference of topcoat after 4000-h cycle test and 2-yrear outdoor exposure indicated a lesser color change in the laboratory cycle test than the outdoor. However, the color change ratios between lab. test and outdoor exposure vary with the coating systems. A linear growth rate for rust creepage was found in the laboratory cycle test for all coating systems, suggesting that the cycle test can be shortened to 2000 to 3000-h.
2	Are Two Coats as Effective as Three? FHWA-HRT-06-006 By S-L Chong and Y. Yao	2006	Comparing a 2-coat system (zinc-rich primer with a thick layer of polyaspartic, polyurethane or polysiloxane topcoat) with a 3-coat system (zinc-rich primer/epoxy/polyurethane or zinc-rich primer/moisture-cured urethane (MCU)/MCU-polyurethane. Weathering resistance were evaluated using laboratory and outdoor tests: • Laboratory test – freeze/UV condensation/salt-fog dry air for 5000-h. • Outdoor test at Sea Isle city, NJ, at 45^o facing south for 2-year. Results of laboratory and outdoor test: • A greater gloss reduction in 2-coating systems after 5000-h. • The gloss reduction after 2-year outdoor exposure is significantly higher than 5000-h laboratory test. • A linear growth of rust creepage after 1500-h in 2-coating and 3-coating systems. • Adhesion strength remained nearly constant for 11 systems, but the inorganic zinc alkyl silicate primer has lower strength than others. • Comparison between 5000-h laboratory test and 2-year outdoor exposure, the mean scribe creepage length is higher in laboratory test than outdoor. The ratio is very similar for the 3-coating systems, while it varies significantly among the 2-coating systems. • Conclusion: - the tested 2-coating systems are comparable with the tested 3-coating systems in this study.

Table B-2 – Cont.

#	Title and Author	Date	Summary on Weathering Resistance Properties
3	Performance Evaluation of One-Coat Systems for New Steel Bridges FHWA-HRT-11-046 By Y. Yao, P. Kodumuri, and S-K Lee	2011	Comparing eight types of one-coat systems with one 2-coating system and one 3-coating system for their weathering resistance using laboratory and outdoor tests: • Laboratory test – freeze/UV condensation/salt-fog dry air for 5000-h. • Outdoor test at Sea Isle city, NJ, at 45° facing south and in McLean, VA, at 30° facing south for 2-year. Half of the test panels at McLean site were exposed to 15 wt.% of sodium chloride one a day 5 days a week starting 3-mon after the exposure. Results of laboratory and outdoor test: • After 5000-h of lab. test, ΔEs of one-coat systems are higher than 2- and 3-coating systems. • The 3-coating system showed similar color changes in four exposure conditions. • The 2-coating system showed the highest value at NJ site while similar lower values were measured from McLean sites. • The ΔE value varied greatly among the one-coat systems. In four systems, the lab. test yielded a greater ΔE value than the corresponding outdoor tests. • High uncertainty in the gloss reduction data of the 10 coating systems after exposed to four conditions. • Accumulated rust creepage is greater in the lab. test than the outdoor conditions for most of the coating systems. Four of the one-coat systems have similar creepage length as 2- and 3-coating systems. A one-coat system showed a much lower length. • The correlation between defects and adhesive strength is poor for all tested coating systems. • Conclusion: - the 3-coating system performed the best in this study.

Table B-2 – Cont.

#	Title and Author	Date	Summary on Weathering Resistance Properties
4	Federal Highway Administration 100-year Coating Study FHWA-HRT-12-044 By P. Kodumuri and S-K Lee	2012	Assessing the 100-year maintenance-free service life for steel bridge. Three 3-coating systems, four two-coating systems and a single one-coat system were evaluated using laboratory test and three outdoor test conditions. • Laboratory test – freeze/UV condensation/salt-fog dry air for 5000-h. • Outdoor test in McLean, VA, at 30° facing south for 2-year. Half of the test were exposed to 15 wt.% of sodium chloride once a day 5 days a week starting 3-mon after the exposure. Results of laboratory and outdoor test: • The color %-change of the laboratory test showed lower values than those from outdoor for all coatings. Two of the 2-coating systems and the one-coat system showed large color change. • The difference in mean gloss reduction between lab. test and McLean site varied with coating systems. The same 2-coating systems and the one-coat system that showed large color change also showed high gloss loss. • The accumulated rust creepage growth in lab. test did not all exhibit linear relationship with exposure time. Some ceased to grow after 2000-h. • Conclusion: - none of the tested coating systems will provide 100-year service life.
5	Corrosion Evaluation of Novel Coatings for Steel Components of Highway Bridges FDOT Project BDV29 977-02 By K. Lau	2015	Two new coating systems, chemically bonded phosphate ceramic coating and the thermal diffusion galvanizing coating, were evaluated for their long-term weathering performance together with a 3-coat painting system (inorganic Zn+Cycloaliphatic Amine Epoxy+Aliphatic Acrylic-Polyester Polyurethane) and a thermal spray metallizing system as control references. Weathering test was performed in laboratory and outdoor sites: • Laboratory test – salt-fog chamber ASTM B117 for 2200-h and 5800-h • Outdoor test at Florida International University for Inland Site and at Islamorada, FL. for Beach Site. Test racks were facing south at an incline angle of 45° with the horizon for 4-months and 8 months. • Evaluation tests – visual observation, coating thickness and pull-off strengths • Conclusions: - the salt-fog test was found to be a harsher condition than the outdoor test. - after 5800-h salt-fog testing, the two new coating systems exhibited more corrosion than two reference systems. - the phosphate ceramic coatings were found not durable in salt fog environment. - a robust topcoat is essential for the duration thermal diffusion galvanizing system.

Table B-2 – Cont.

#	Title and Author	Date	Summary on Weathering Resistance Properties
6	Spot Painting to Extend Highway Bridge Coating Life: Volume 2: Research Overview NCHRP Web-only Document 251 By: T. Hopwood II, et al.	2018	One of the 3 objectives of the report is to develop method to identify suitable spot coatings using accelerated laboratory testing procedures, ASTM D5894, and ASTM B117. The report presents the accelerated testing and field testing of spot coating systems performed at Kentucky Transportation Center: • Coating systems were tested: - three coating systems – 1) two acrylic coatings, 2) two alkyd coatings and 3) an epoxy primer with a two-component polyurethane topcoat. - six liquid-applied coating systems – 1) calcium sulfonate alkyd, 2) two-coat alkyd system, 3) a two-coat acrylic system, 4) a two-coat moisture cure urethane system including MIO-aluminum primer and UV resisting topcoat, 5) an epoxy penetrating sealer with two-component polyurethane topcoat, and 6) a micaceous iron oxide (MIO) pigmented epoxy primer with two-component polyurethane topcoat. • Test procedures: - 5000-h ASTM B117 - 15 two-week-long (5040-h) using ASTM D5894 – 1 week in UV/condensation device followed by 1-week in fog/dry chamber. - two field test sites located in Kentucky – Bluegrass Parkway bridge and twin bridges at KY 922 over KY 4. Six types of liquid-applied coatings were tested on these two sites. • Conclusions: - the liquid applied coating MIO-pigmented epoxy primer with a polyurethane topcoat performed the best in the laboratory tests. - both laboratory test methods should be used because different coating systems performed differently in each of the test methods. - the coating system in the field performed as anticipated after 14 months based upon the laboratory tests.

Table B-2 – Cont.

#	Title and Author	Date	Summary on Weathering Resistance Properties
7	Evaluation of Different Paint Systems for Over-Coating Existing Structural Steel FHWA-NJ-2018-006 By P. Balaguru, H. Najm, and D. Caronia	2018	The research study was to develop new protocol for evaluating durability and corrosion resistance of new systems in a timely manner. • Coating systems being tested: - four 2-coating systems and two 3-coating systems • Test procedures: - laboratory test used a modified ASTM D5894 which was based on a test cycle of 24-h (1-day) consisted of 1-h wet/1-h dry for total of 16-h (total of 8-h dry and 8-h wet). Wetting was used 5% salt by weight and dry period was exposure to UV irradiance. Following the 16-h wet/dry cycle, samples were exposed to deep freeze for 8-h. A total of 100-test cycle (i.e., 100-d) was carried out for the testing. - exposed laboratory samples were tested for their pull-strength. - the field data were taken from a study on NJDOT Mathis Bridge. 47 coating systems were applied onto 66 spans. the 47 coatings were grouped into 8 systems: 1) Metallizing, 2) Inorganic Zinc, 3) Organic Zinc, 4) Miscellaneous, 5) Alkyd, 6) Urethane, 7) Aluminum systems, and 8) Epoxy. - condition of the field coating systems was evaluated in 8- and 20-year using rating based on ASTM D610. • Correlation of lab. and field test results: - systems with zinc primers performed well in both field and lab. tests. - Epoxy mastic systems performed poorly in both field and lab. tests. - systems without zinc primer performed better than epoxy mastic systems but worse than systems with zinc primer. - metallizing systems performed the best in the field, but they were not tested in the lab.

APPENDIX – C

Table C-1 Summary of Information of FDOT Approved Coating Products

Table C-1 – Summary of Information of FDOT Approved Coating Products

Elastomeric Coating	BASF C C Building Systems	MasterSeal Traffic 1500 (Sonoguard)	APL No. 462-000-001	polyurethane	Not available
	Pilgrim Permocoat Inc.	Uroflex 65		saturated polyester & aliphatic urethane	Not available
Structural Steel Coating Systems for New Structures	Carboline Company	Carbozinc 11HS		Solvent Based Inorganic Zinc	ASTM B117 - 70,000 hr.
		Carboguard 893		Cycloaliphatic Amine Epoxy	ASTM B117 - 4000 hr. ASTM D1735 - 5000 hr. ASTM G26 - 4000 hr.
		Carbothane 133LH System		Polyester & Aliphatic Acrylic-Polyurethane	Not available
		Carbothane 134 Clear Coat		Aliphatic Acrylic Polyurethane	Not available
	Sherwin Williams	Zinc Clad II LV	B69VZ12	Ethyl silicate, Zinc rich	ASTM B117 - 1000 hr.
		Macro epoxy 646	B58W610 B58V600	Polyamide Epoxy	ASTM B117 - 2000 hr.
		Acrolon 218 HS	B65W611 B65V600	Polyester modified, aliphatic acrylic polyurethane	ASTM D5894 - 27 cycles, 9072 hr. ASTM B117 - 15000 hr.
		Zinc Clad II Plus-Fast Clad HB Acrylic	B66W411	Acrylic	ASTM D5894 - 6 cycles, 2016 hr. AASHTO R31, Section 8 Test 3 - 15 cycles, 5040 hr. ASTM B117 - 5000 hr.
Structural Steel Coating Systems for Existing Structures	PPG Protective & Marine Coatings	Amercoat 68HS		Zinc rich Epoxy	Not available
	Carboline Company	Carbozinc 859		Organic Zinc-Rich Epoxy	ASTM D870 - 5% NaCl at 24^{o}C for 30 days
		Carboguard 893		Cycloaliphatic Amine Epoxy	ASTM B117 - 4000 hr. ASTM D1735 - 5000 hr. ASTM G26 - 4000 hr.
		Carbothane 133 VOC		Polyester & Aliphatic Acrylic-Polyurethane	ASTM B117 - 4000 hr.
	Sherwin Williams	Zinc Clad III HS	B69A100 B69V100	Polyamide Epoxy zinc rich	ASTM D5894 - 27 cycles, 9072 hr. ASTM B117 - 15000 hr.
		Macro poxy 646	B58V600 B58W610	Polyamide Epoxy	ASTM B117 - 2000 hr.
		Acrolon 218 HS	B65W611 B65V600	Polyester modified, aliphatic acrylic polyurethane	ASTM D5894 - 27 cycles, 9072 hr. ASTM B117 - 15000 hr.
Galvanizing Repair Materials	PPG Protective & Marine Coatings	Amercoat 68HS		Zinc rich Epoxy	Not available
	Carboline Company	Carbozinc 859		Organic Zinc-Rich Epoxy	ASTM D870 - 5% NaCl at 24^{o}C for 30 days
	Sherwin Williams	Zinc Clad III HS		Polyamide Epoxy zinc rich	ASTM D5894 - 27 cycles, 9072 hr. ASTM B117 - 15000 hr.
Anti-Graffiti Coatings (non-Sacrificial)	Sherwin Williams	2K WB Urethan Anti-Graffiti Coating	B65T194-Gloss B65V190-Gloss B65T195-Satin B65V195-Satin	Hydrophobic polyurethane	ASTM D4587 (QUV-A) - 2000 hrs.
	The Euclid Chemical Co.,	Euco AG 563		Polysiloxane	Not available
	Textured Coatings of America	Graffiti Guard S	180102-045 clear	Polysiloxane	Not available
	Raptor USA, LLC.	Raptor-Co/AC		Polysiloxane	Not available
Anti-Graffiti Coatings (Sacrificial)	IMRAE Corp.	CoatMasters	CM 2007 NSC-AG	Siloxane/Silane	Not available
	The Euclid Chemical Co.,	Euco AG 100	254AG 05	not define	Not available
	Textured Coatings of America	Tex-Cote Sacrificial Graffiti Guard	180102-045 clear	not define	Not available

APPENDIX – D

Table D-1 Summary of Information of FDOT Approved Retroreflective Sign Sheeting Materials

Table D-1 – Summary of Information of FDOT Approved Retroreflective Sign Sheeting Materials

Product Type	Supplier	Product Name	Product Code	Polymer	Warranty or Weathering Test
ASTM Type IV	Avery Dennison Corp.	T-6500	4930 Ink Over	Acrylic/Polypropylene	10 yr. Warranty
		T-9500	4931 Ink Over	Vinyl/Polyester	11 yr. Warranty
		T-7500	OL-2000	Acrylic/Polypropylene	12 yr. Warranty
		SC900 Overlay film		not defined	not available
	Nippon Carbide Industries	5000 Series Hi-S	Cal Black Vinyl	not defined	not available
		Nikkalite Crystals 92800		not defined	not available
	3M	3930	880I (Color series)	3930 - Polycarbonate cubic coner technology	7-10 yr. Warranty
		3930	1170 (Electrocut film)	880I - polyester monofilament screen fabric	7-10 yr. Warranty
		3920		Polycarbonate cubic coner technology	7-10 yr. Warranty
		3940		Polycarbonate cubic coner technology	10 yr. Warranty
		3980, Doa,pmd Grade VIP RS		Polycarbonate cubic coner technology	7-10 yr. Warranty
ASTM Type V	ORAFOL Americas Inc.	Oralite AR 1000		not defined	ASTM D4956-outdoor and Xenon-arc
	Avery Dennison Corp.	V-9700		not defined	not available
ASTM Type VI	3M	Diamond Grade Flourescent RS24	Lightweight flexible material	Material is not defined on the website	not available
	ORAFOL	Oralite 5935		not defined	not available
		Oralite Super Bright Roll Up Sign		not defined	not available
	Signs and Safety Equip.	SBC Roll up sign		not defined	not available
ASTM Type XI	3M	Series 4000 DG3		polycarbonate cubic corner technology	8-12 yr. Warranty
		4090	880I		
		4090	1170		
	Avery Dennison Corp	T-11500	4930 ink	Acrylic	7 yr. Warranty 12 yr. Warranty for vertical exposure
		T-11500	OmniCube		
		T-11500	OL-2000		
		T-11501	SC900 overlay film		

APPENDIX - E

Equivalent of Outdoor Exposure based on Irradiance Used in a Xenon Arc Apparatus

Equivalent of Outdoor Exposure based on Irradiance used in a Xenon Arc Weatherometer:

In ASTM D4956 Supplement S3, the required testing duration in a Xenon Arc Apparatus using irradiance of 0.51 W/(m^2·nm) to generate sunlight energy that is equivalent to one year of outdoor exposure in Miami or Arizona: *"A test specimen exposed to 3670 kJ/(m^2·nm) at 340 nm in a typical xenon weatherometer with daylight filters will have received a total UV (295-385 nm) radiant dosage on the order of 330 MJ/m^2."* The radiant dosage of 330 MJ/m^2 value is obtained using the conversion factor provided by the Atlas Company (in a xenon weatherometer, the I_{340nm} is approximately 1.1% of $I_{UV\ (295\text{-}385\ nm)}$).

3,670 kJ/(m^2·nm) at 340 nm = 3,670/1.1% = 333 kJ/(m^2·nm) at 295-385 nm. which is approximately 330 MJ/m^2

<u>Irradiance of 0.51 W/(m^2·nm)</u>

To reach *3,670 kJ/(m^2·nm) at 340 nm* radiant dosage, the required exposure time in a Xenon Arc Apparatus with irradiance of 0.51 W/(m^2·nm) is 2,000 hours according to Table 2 in the report:

*0.51 W/(m^2·nm) * 2,000 hr. * 3,600 sec/hr. =* 3,670 *kJ/(m^2·nm)*

<u>Irradiance of 0.35 W/(m^2·nm)</u>

To reach *,3670 kJ/(m^2-nm) at 340 nm* radiant dosage, the required exposure time in a Xenon Arc Apparatus with irradiance of 0.35 W/(m^2·nm) is 2,915 hours according to Table 2 in the report:

*0.35 W/(m^2·nm) * 2,915 hr. * 3,600 sec/hr. =* 3673 *kJ/(m^2·nm)*

APPENDIX – F

Test Protocol for Accelerated Weathering Test for Coating Materials for Steel Structures

Test Protocol
For
Accelerated Weathering Test for Coating Materials for Steel Structures

The recommended Accelerated Weathering Test for Coating Materials for Steel Structures is based on the test procedure in accordance with ASTM D5894 "*Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet)*". The test conditions are modified to enhance the degradation rate in both Fog/Dry cycle and UV/Condensation cycle.

In this document, only the modified sections of ASTM D5894 are presented, and the changes are shown in red.

Summary of Practice (Section 4.0 in ASTM D5894)

4.1 The test specimens are exposed to alternating period of one week in a fluorescent UV/condensation chamber followed by one week in a cyclic salt fog/dry chamber. The fluorescent UV/condensation cycle is 4 hours UV at 1.55 W/(m^2·nm) at 340 nm at 60^{o}C followed by 4 hours condensation at 50oC using UVA-340 lamps. The fog/dry chamber runs a cycle of 4 hours fog at 49 ± 2^{o}C and 4 hours dry-off at 60 ± 2^{o}C. The fog electrolyte solution consists of 5% sodium chloride.

Procedure (Section 8.1 in ASTM D5894)

8.1 *Fluorescent UV-Condensation Exposure*

8.1.3 For irradiance-controlled devices and unless otherwise specified, se the irradiance level to 1.55 W/(m^2·nm) at 340 nm; the maximum allowable deviation from the set point at the control point indicated by the readout of the calibrated control sensor during equilibrium operation is ± 0.02 W/(m^2·nm) for irradiance.

8.2 *Cyclic Salt Fog/Dry Exposure*

8.2.2 Program a fog/dry cycle of 4 hours fog at 49 ± 2^{o}C followed by 4 hours dry-off at 60 ± 2^{o}C at the chamber's reference temperature sensor.

8.2.3 Prepare the salt solution with 5% sodium chloride by weight.

8.2.4 Expose the specimens for 21 cycles in the fog/dry chamber before transferring back to the fluorescent UV-condensation chamber. These 21 cycles equal a total of 168 h (1 week)

Report (Section 10 in ASTM D5894)

10.1.1 Test cycle

10.1.1.2 Fog/dry cabinet cycle (for example, 4 hours fog at 49 ± 2^{o}C and 4 hours dry-off at 60 ± 2^{o}C)

10.1.3 Electrolyte solution (for example, 5% sodium chloride by mass).

APPENDIX – G

Test Protocol for Accelerated Weathering Test Using Xenon Arc Device with Enhanced Light and Water Exposure for Sign Sheeting Materials

Test Protocol

For

Accelerated Weathering Test Using Xenon Arc Device with Enhanced Light and Water Exposure for Sign Sheeting Materials

The recommended Accelerated Weathering Test for Sign Sheeting Materials is based on the test procedure in accordance with ASTM D7869 "*Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings*". The test conditions are modified to enhance the degradation rate during light-on periods of the test.

In this document, only the modified sections of ASTM D7869 are presented, and the changes are highlighted in red.

Scope (Section 1.0 in ASTM D7869)

1.2 This practice uses a xenon arc light source with specified optical filter(s). The spectral power distribution (SPD) for the lamp and special daylight filter(s) is as specified in ANNEX A1. The irradiance level used in this practice varies between 0.8 and 1.2 W/(m^2·nm) at 340 nm. Water is sprayed on the specimens during portions of several dark steps. The application of water is such that the coatings will absorb and desorb substantial amounts of water during testing. In addition, the cycling between wet/dry and warm/cool will induce mechanical stresses into the materials. These test conditions are designed to simulate the physical and chemical stresses from environments in a subtropical climate, such as southern Florida.

Test Procedure (Section 9.0 in ASTM D7869)

9.3 Program the xenon arc light and water apparatus to run the exposure cycle shown in Table 1 and in accordance with manufacturer's instructions. The duration of the test in terms of number cycles, hours, or radiant dosage shall be agreed upon by contractual parties.

Table 1 – Exposure Cycle

Step	Duration (minute)	Function	Irradiance Set Point[A] at 340 nm (W/m^2·nm)	Black Panel Temperature Set Point	Chamber Air Temperature Set Point	Relative Humidity Set Point
1	240	Dark + spray	-	-	40ºC	95%
2	30	Light	0.80	50ºC	42ºC	50%
3	270	Light	1.2	70ºC	50ºC	50%
4	30	Light	0.80	50ºC	42ºC	50%
5	150	Dark + spray	-	-	40ºC	95%
6	30	Dark + spray	-	-	40ºC	95%
7	20	Light	0.80	50ºC	42ºC	50%
8	120	Light	1.2	70ºC	50ºC	50%
9	10	Dark	-	-	40ºC	95%
10	Repeat subcycle steps 6 to 9 (shown in bold) in additional 3 time (for a total of 24 hours = 1 cycle					

[A] – The set point is the target condition for the sensor used at the operational control point and is programmed by
the user. When the exposure cycle calls for a particular set point, the user programs the apparatus to use that exact number. Operational fluctuations are deviations from the indicated set point during equilibrium operation. The maximum allowable operational fluctuation during equilibrium conditions for the exposure cycle above is ±0.02 W/(m^2·nm) for irradiance, ±2.5°C for black panel temperature, ±2°C for chamber air temperature, and ±10 % for relative humidity.

Explanation of Rationale for Steps in the Cycle Defined in Table 1 (X2 in ASTM D7869)

X2.3.1 Step 2:

30 min, light, 0.80 W/(m^2·nm) irradiance, BP 50ºC, CA 42ºC, RH 50%

X2.3.1 The purpose of this step is to totally remove all of the water from within the coating layers. In a typical Florida day, the sun comes up and dries out the coating completely by mid morning.

X2.3.2 The irradiance is set at a relatively low level, 0.80 W/(m^2·nm) because Florida data has shown that all the water was driven off from the coating before the sun ever got high enough in the sky to produce higher irradiances.

X2.3.3 The black panel temperature is set at 50°C because Florida data has shown that by the time the sun heats the specimen to 50°C almost all of the water has been removed from the coating.

X2.3.4 Unnatural effects can be produced if the test does not remove all of the water before the start of the high-temperature, high-irradiance step. For instance, excessive cracking and micro cracking can be produced if water inside the coating is heated up too quickly.

X2.3.5 A time of 30 min was chosen because data has shown that 30 min at 50°C is the time required to take the water content to near zero.

X2.3.6 The RH of 50 % was chosen because a higher humidity will require too long a time to remove all of the water. Perhaps a lower humidity could have been chosen. But 50 % is a realistic outdoor humidity that works for this step. The important thing is that the RH is in fact controlled because different humidities will cause different rates of drying.

X2.4 Step 3:

270 min, Light, 1.20 W/(m^2·nm) irradiance, BP 70°C, CA 50°C, RH 50 %

X2.5 Step 4:

30 min, Light, 0.80 W/(m^2·nm) irradiance, BP 50°C, CA 42°C, RH 50 %

X2.9 Step 7:

20 min, Light, 0.80 W/(m2·nm) irradiance, BP 50°C, CA 42°C, RH 50 %

X2.10 Step 8:

120 min, Light, 1.20 W/(m^2·nm) irradiance, BP 70°C, CA 50°C, RH 50 %