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WHITE PAPER

Weather Durability Testing of Paints and Coatings

WILL MY COATING LAST OUTDOORS?

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1. Executive Summary

The world of decorative paints and protective or functional coatings has expanded beyond conception since one, if not the first, documented paint weathering test exposure began in 1906 in North Dakota, USA. By every measure – durability, performance, functionality – coatings are used in locations and applications never dreamt possible. From the formulator's perspective, the vast array of natural and synthetic resins, curing and cross-linking agents, performance enhancing and functional additives allows fine tuning coating characteristics to an unbelievable degree.

From a color and appearance perspective, high gloss, metallic, high chroma, and special effects coatings have revolutionized architectural, automotive and interior design. Despite all of these advances, paint failures still occur on a regular basis. While some of these can clearly be attributed to issues such as the choice of the wrong coating, bad installation, incompatible substrate, improper surface preparation, etc., many failures can clearly be linked to improper or incomplete testing.

Weather durability testing is a key aspect for not only understanding coating durability under some reference test method, but also understanding its behavior in various climates and under various conditions of application, substrate type and surface preparation; in other words, the "robustness" of a coating to service use, and under a range of installation (or mis-installation) conditions.

Weather durability testing is also key to understanding the effect of ingredient or formulation changes, new applications, or simply benchmarking the durability of new or competitive products.

But with increasing service life durability comes the problem of prohibitively long outdoor exposure tests. While real time testing should always be performed, business needs usually mandate a necessity for increasingly accelerated testing. Laboratory accelerated fade and weather testing is now in its 100th year, yet many in the industry rely on outdated, inadequate or inappropriate testing methods.

The fact that standards organizations are often a decade or more behind current technology is another matter. It is therefore not surprising that poor correlation or predictive ability is often reported with accelerated weathering tests. However, the industry leaders in coatings and weathering testing have learned much and have shown that reliable testing is indeed possible with the right methodologies and technologies.

This paper will introduce the various natural outdoor, accelerated outdoor, and laboratory accelerated artificial weathering techniques and some issues regarding their use in coatings testing. Also, recent advances in coatings weathering will be highlighted. These include advances in technology such as better solar simulation, higher acceleration, lower testing temperatures, and others. On the methodology side, improvements in test methods such as cyclic corrosion testing and more sophisticated laboratory weathering cycles will be discussed. Finally, some advances in coatings weathering research tools, such as ultra-acceleration, spectral and specimen temperature monitoring will be mentioned.

2. The Challenge

Importance of Coatings Weather Durability

Obviously decorative paints as well as protective and functional coatings are expected to maintain some level of durability, that is to perform to some level of expectations for a given time period in a particular application or location. This is true regardless of whether your product is an interior or exterior house paint, an anodized architectural finish, a protective bridge or marine coating, a traffic marking, a deck stain, a "cool roof" maintenance product, a powder coating, a protective hard coat, an automotive basecoat/clearcoat paint system or any of the myriad of solid, liquid or otherwise applied products that comprise the coatings universe.

There are degradation mechanisms that are internal to almost all coatings (think of it as similar to the human ageing process); these can be exacerbated and accelerated by the stresses of the service environment in which they perform. There are also specific degradation mechanisms and failure modes that are a direct response to exposure to the environment, such as the effects of ultraviolet solar radiation, salt air, temperature cycling, moisture levels, or mold & mildew, for example. It is the resistance or susceptibility to the stresses of the environment (whatever that may be) that we describe as *weatherability*, and the process of product deterioration as *weathering*. We use weathering testing technologies to assess and quantify these effects.

The Need for Weatherability Testing

In many cases you need to demonstrate product weatherability in order to sell a product. Sometimes these are mandated by the customer in bid or procurement specifications, sometimes as de facto "voluntary consensus" standards (such as AAMA 2604 for a 5-year exterior architectural finish), by market needs to match or surpass competitive products, or to provide defensible support for performance or warranty statements.

And, of course, weatherability test data is essential to improve existing or develop new coatings products as well as maintain quality throughout a product's lifecycle (to guard against process or raw materials issues).

The Business Challenge

While coating field life testing is essential, business needs simply cannot wait 5, 10 or more years to generate weatherability data in multiple climates. The question of how best to assess coating performance and durability in a minimum time is the subject of this paper.

3. What is Known?

About Coating Types

When we describe a coating's base resin chemistry we are primarily referring to the film forming binder that makes up the majority of solids in the coating. Acrylics, alkyds, vinyls, polyurethanes, epoxies, aminos and polyester (saturated) are some of the major types of coating resins. In general there is also a solvent, such as an organic or water, which is removed during the drying or curing process upon application. Most, but not all, coatings are of the film-forming variety, that is the solids coalesce or crosslink to form a decorative and/or protective-functional film over the substrate. Non-film-forming products generally penetrate the substrate, often carrying dyes, pigments or protective chemicals.

There is a vast array of basic and specialized coatings chemistries in use today, both in field and factory applied products. These may be in ready to use single component (1K) or two part (2K) mix-at-use formulations, or solids (e.g., powder coatings).

The specific resin chemistry largely determines the functionality and characteristics (such as hardness, moisture resistance, gloss) of a coating and, by virtue of the specific degradation mechanisms that affect it, a coating's overall weatherability. Epoxies, for example, have a known UV sensitivity which results in chalking; hence, epoxy coatings are not generally used in unprotected directly exposed exterior applications. Some resins undergo hydrolysis reactions and are not suited for high moisture environments, and so on. Environmental regulations, such as those limiting VOC solvent content, have forced the reformulation of many products and the need for re-evaluating their weathering performance.

While it may be possible to offer some general durability and performance characteristics based on resin type, the wide variety of curing agents and additives available can greatly affect the attributes of specific formulations. Further, many "hybrid" coatings offer properties that cross base polymer characteristics.

Other Coatings Components

In addition to the binder, there are often one or more colorants, usually an inorganic mineral (such as MMO, mixed metal oxides) or organic pigments (especially "high chroma" colorants), or dyes (stains). Some coatings, such as special automotive finishes, may also use special effects pigments, such as pearlescent, metallic flake or hue-shifting pigments.

Due to environmental legislation around the world (e.g., RoHS Restriction on Hazardous Substances) many traditional pigments, such as those containing cadmium or chrome, are no longer allowed or are pending phase-out. This has required the reformulation of many products, often resulting in changes to light resistance (e.g., color fade) and the need for subsequent testing.

Note that color fade can also result in substantial color hue shift if one (or more) pigment(s) in a multi-pigment paint fades at a different rate. Hue shift can also result from yellowing of the paint film; a blue tinted paint, for example, can shift to green if the paint film yellows even though the blue pigment remains unaffected.

Colorants are not always inert. Some pigments, notably white titanium dioxide (TiO2), are photocatalytic; certain grades are catalyzed by the UV in solar radiation which in combination with moisture actually degrades the binder and shortens life. Conversely, carbon black is an effective UV blocker that helps protect the paint film. Other constituents, such as IR reflecting pigments for "cool roof" applications, can degrade and lose functionality without affecting the coating durability.

Most coatings also contain various stabilizers. For enhanced weatherability, protective additives such as UV absorbers (UVA's), Hindered Amine (Light) Stabilizers (HAS, HALS), antioxidants (AO's), and UV screening pigments are usually used for exterior applications.

Some stabilizer combinations have synergistic effects making them more effective when used together. As stabilizers are expensive, weatherability testing is critical to evaluate lower cost alternatives or changes to formulation additive concentrations.

Mold/mildew and other biological inhibitors are important to prevent microbial growth in wet, high humidity locations which can destroy paint films. Special exposures such as vertical north facing (in the northern hemisphere) in humid environments are used.

It is important to note that anything in a paint or coating can contribute to degradation and a loss of weatherability.

Substrates

The substrate to which a coating is applied is very important for two reasons. First, for primarily decorative coatings (i.e., paints), adhesion loss of the paint film to the substrate is a common failure mechanism. There are many root causes for this, some being specific to the coating, others specific to the substrate itself. Some products require a compatibilizing primer to promote adhesion, while others may require special surface preparation. One example is surface cleaning, such as degreasing, to prevent pinhole formation (adhesion loss in a small localized area).

Natural substrates such as wood present special issues. Not only are the characteristics of the wood species important, but also the 3D geometric cut of the wood in relation to the log, heartwood v. sapwood, early growth v. late growth, moisture content, etc., all can affect adhesion and overall coating performance. Degradation of the wood surface prior to painting can also affect coating lifetime. Lumber left exposed to sunlight for as little as two weeks develops a "sun-burnt" degraded surface that can shorten coating adhesion life by as much as half.

Porous substrates such as concrete, masonry and stone also present special issues regarding moisture transport, "breathability," soluble salts, etc., and the coating characteristics must be properly matched to the substrate.

So a critical aspect of coatings durability testing is to test on all of the actual potential substrates to which it may be applied. Also, a variety of surface preparation methods (or lack thereof) should be used to assess the "robustness" of a coating to misapplication or improper installation.

Since the primary function of protective coatings is to protect the substrate, such as the corrosion protection of a steel bridge or a water sealer on a wood deck, methods for assessing the coating's effectiveness on various substrates needs to be considered when planning weathering testing. The same is true for assessing other functional coatings, such as antimicrobials or moisture barriers, for performance during weather ageing.

Of course, often both substrate protection and aesthetics are important. For example, the State of Florida, which is the top tourism destination in the world, pays particular attention to the aesthetics of their highway bridges and overpasses, even while being in one of the harshest climates for coating weathering.

Weather and Climate

In addition to all of the above issues, the end-use (service) climate of a coating obviously is one of the principle factors affecting its service lifetime. Climates can be incredibly varied across the three main factors of weathering stresses: solar radiation, temperature and moisture. Their upper and lower limits as well as both their short (daily) and long (seasonal) term cycles are important.

The world's major climate zones (and their various subsets) are classified in the Köppen-Geiger Climate Classification system Figure 1. In short, apart from special cases such as alpine, offshore or coastal marine, the three main climate types responsible for the degradation of most coatings are hot arid/semi-arid deserts subtropical/tropical hot/wet conditions and and temperate.

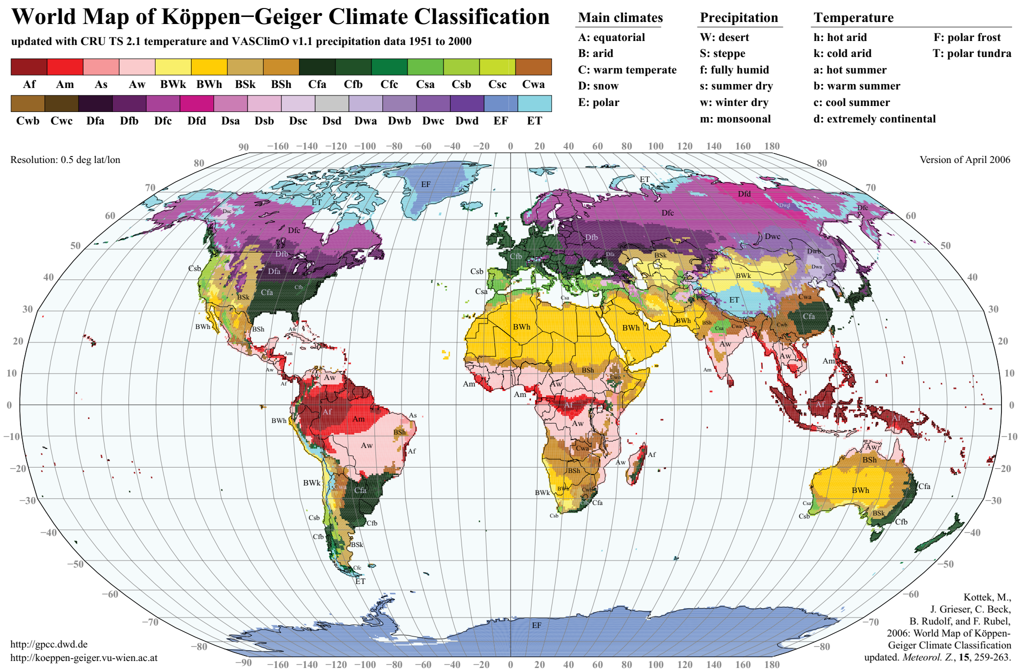


Figure 1 - World climate classifications. http://koeppen-geiger.vu-wien.ac.at/present.htm accessed March 30, 2015

Locations with high amounts solar radiation, high moisture (relative humidity, condensation and rain) and high temperatures (above freezing) are usually the most severe for coatings. These are generally the subtropical or tropical regions. Of these, the subtropical southernmost tip of Florida has historically been a major coating weathering benchmark testing location.

Hot arid locations usually have higher high temperatures and wider temperature swings than the above. Due to the drier air, solar radiation is usually stronger so these locations may see higher rates of color fade.

For these reasons most (but not all) of the commerical and private outdoor weathering exposure test sites are located in bands 15-35 north and south of the equator.

The next most severe climate location is usually a temperate one characterized by moderate solar radiation, relatively high moisture and by seasons of frequent freeze/thaw cycles.

As chemical degradation processes generally are slower at low temperatures, high latitude and polar locations produce the least degradation unless the failure mode is a direct result of thermomechanical changes to the coating or substrate, such as a too-brittle coating on a thermally expanding and contracting substrate, or a moisture-saturated one going through freeze/thaw cycles.

As an anecdotal example, typical coatings weather about half as fast in northern temperate Chicago as they do in South Florida, and about fourfold less in Germany. Of course, these are generalities, but South Florida has become one of the *de facto* global benchmark test locations for presenting and comparing coatings weathering data.

Atlas owns and operates a number of weathering exposure sites globally, and has also created the Worldwide Exposure Network (WEN) of affiliated sites to offer outdoor weathering exposures at approximately 25 global locations (Figure 2).

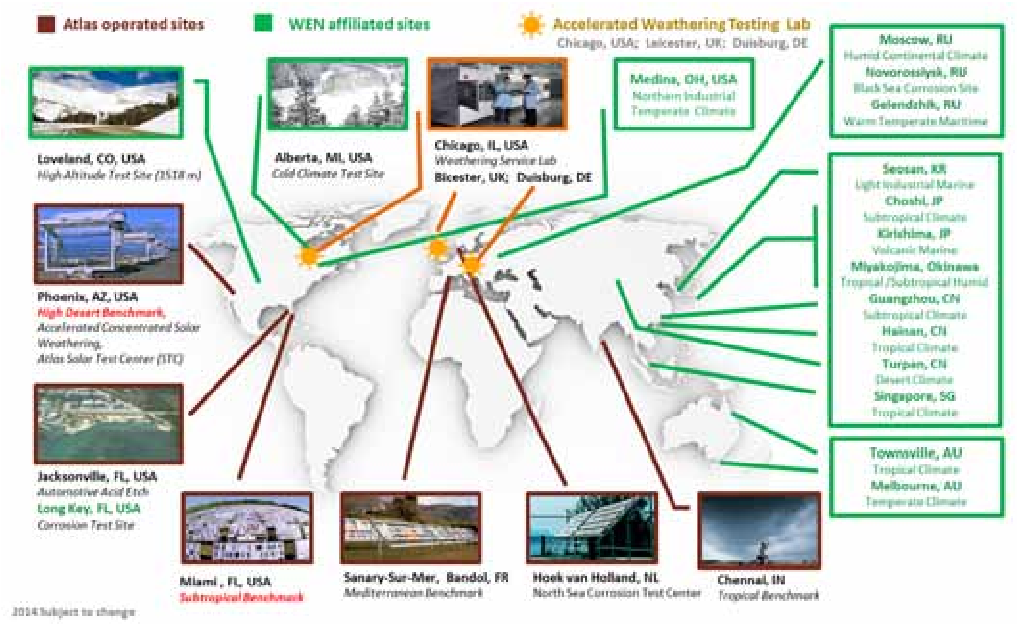


Figure 2 - Atlas' Worldwide Exposure Network of owned or affiliated test sites

Key Factors of Weather

By far, the three most critical stress factors which comprise weather and climate are heat, light and moisture.

Light

Light, specifically terrestrial solar radiation, is comprised of three distinct spectral regions defined in terms of wavelength: the ultraviolet (UV), the visible (Vis) and the infrared (IR):

- UV radiation is particularly damaging to organic materials (including people) because the photons possess sufficient energy to break chemical bonds, a requisite for [bad] chemical reactions.

The UV is subdivided into three zones, UV-A, UV-B, and UV-C. UV-C radiation is blocked by the earth's ozone layer and is not present in terrestrial sunlight in measureable quantities. Some UV-B above ~295 nm does reach the earth. This energy is very damaging to organic materials. UV-A wavelngths, known for causing tanning of human skin, exists above 315 nm to the beginning of [human] visible light ~400 nm. These longer UV-A wavelengths also possess sufficient energy to break certain chemical bonds and damage polymers and organic materials such as coating binders, additives and colorants.

- Visible light occupies the region of ~400 – 800 nm and is a principle component of sunlight. Photons of visible light do possess sufficent energy to cause some photodegradation reactions, especially when a product is photosensitized (such as by a contaminant such as a transition metal) or a reaction is otherwise photocatalyzed.

Many are accustomed to believing that only UV is important in coating photodegradation, but that is not true. While the lower UV wavelengths are usually the most damaging, some polymer photochemical reactions do result from visible light. Some colorants used in coatings, for example, are specifically sensitive to visible wavelengths.

- The near and far infrared spectrum above 800 nm is primarily responsible for surface heating effects. IR reflecting pigments are used in "cool roof" reflective coatings, for example, to lower the heat load into a building. Pigments and resins absorb visible and IR differently; this usually results in different colors of a test specimen achieving different temperatures on exposure.

These temperature differences are important as they alter the rates of chemical reactions, affect moisture levels, etc. Testing to UV light only does not provide the temperature differences colored coatings will reach on outdoor exposure to sunlight and may negatively affect the acuracy and relevance of the testing.

Heat

Heat, or more specifically, temperature (and it's cycles) can influence weathering rates. Heat, by itself, is not generally a significant cause of coating degradation or failure, except perhaps for extreme service applications. Neither does it play a significant role in strictly photolytic (photon initiated) reactions. However, most polymer and coating degradation is caused by a combination of photon-induced chemical bond breaking followed by subsequent free radical reactions. The latter are usually thermally influenced (Arrhenius or Eyring dependency) processes.

Secondly, heat and thermal cycles can cause thermomechanical stress and create stress either between coating layers or with the substrate, especially if coefficients of thermal expansion (COTE) are very different. For example, the frequent freeze-thaw cycles combined with the higher UV levels at high elevations are believed to cause localized "Denver cracking" of automotive coating systems.

Thirdly, temperature and its cycles have a direct influence on the moisture content of many coatings. This movement of moisture can cause differential mechanical stress as the hydrodynamic volume fluctuates.

In short, heat will not increase the rate of light induced damage (which is a function of the number and energy of photons), but heat will increase the rate of the subsequent damaging secondary chemical reactions. Therefore, in order to accurately predict the effects and rate of weathering, test specimens should reach their maximim expected service temperatures (which may differ with color). This is very important from a chemistry standpoint, as important temperature related parameters such as activation energies (Ea) and glass transition temperatures (Tg) are involved in weathering. Automotive coating test samples, for example, are typically mounted to form the top of a black metal box on outdoor exposures. The trapped air simulates the dead space of an automobile body and alters the test specimen temperatures throughout the day for a more accurate temperature-moisture profile.

Most polymers, including coatings, degrade via a classic autocatalytic photo-oxidation mechanisms which involves both bond scissions and oxidatative and free radical reactions.

Temperature cycles are important as they drive moisture migration into and out of coatings and substrates and cause mechanical stress and damage from thermal expansion and contraction, especially when there is a mismatch between the coating and substrate. Temperature also affects moisture condensation (night time dew) and time-of-wetness (TOW). Freeze-thaw cycles can be important as well, especially for coatings that absorb water.

As mentioned, surface temperature is also affected by color and the IR absorptivity of the coating in service or under test.

Moisture

The effects of moisture on coatings degradation has been, and is still today, often underestimated. Moisture can be in the form of vapor (relative humidity), condensation, rain, water immersion, etc. Water is the “universal solvent” and can leach protective additives from a coating. It is an important participant in chemical reactions such as hydrolysis reactions and TiO_2 photocatalytic degradation. It can alter pH (e.g., acid rain), be absorbed and swell a polymer matrix, or carry oxygen and other gases into the paint film. It can collect behind a paint film and cause loss blisters or adhesion failure.

While UV, total solar radiation and temperatures on exposure can be easily monitored, it is much more difficult to accurately monitor moisture, especially in a coating. Besides relative humidity and rainfall, the actual time that specimens remain wet (as from night time condensation) is much more important. For example, measurements at Atlas’ South Florida Test Service site near Miami indicated coating samples, on average, have measurable surface moisture, about 4200 hours out of every year (8760 hours), or 48% of the time. While coating specimen temperature can be measured accurately, the moisture content of a coating is much more difficult both in-service as well as under test.

Realize that while these and other environmental stresses (such as atmospheric pollutants) can have independent effects, they cannot only influence one another (e.g., high solar radiation increases specimen temperature which in turn drives out moisture), but they can also act syngergistically. For coatings, the hot and wet subtopical climate of Miami is typically worse than the hot but dry climate of Phoenix, even though Phoenix gets hotter and has higher amounts of annual solar radiation.

While heat, light and moisture are the dominant weathering stresses, others can be significant, especially for some coatings types. Urban and industrial atmospheric pollutants, acid rain, agricultural chemicals and emissions, dirt, ozone, bird droppings, marine and road salt, mold and mildew, etc., can all be important factors but more difficult to test. And service use conditions such as contact with common chemicals such as cleaning agents, personal care products like suntan lotion and insect repellent, gasoline and lubricants, etc., can also be damaging to coatings and are usually not included in common weathering tests.

4. Outdoor Weathering Testing

Testing in Benchmark Climates

One of if not the first documented paint weathering exposure test was started in 1906 in Fargo, North Dakota, US (Figure 3).

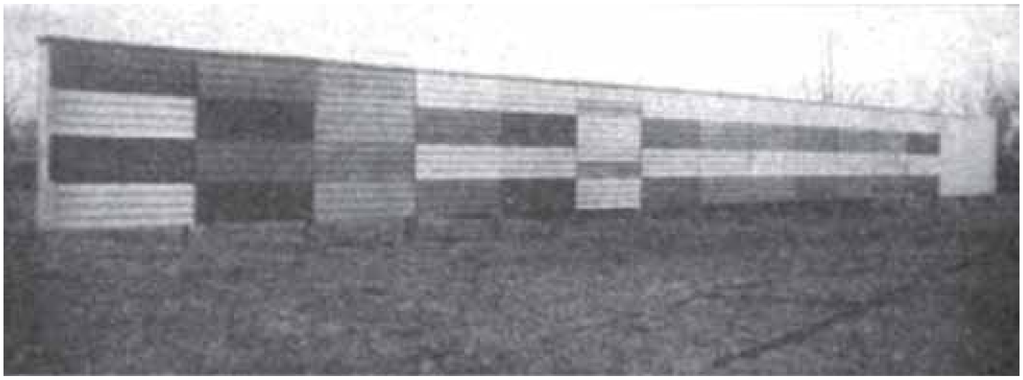


Figure 3 - Controlled irradiance 3-tier rotating rack system (static fixed position irradiance monitor) configuration

Exposures in the moist, subtropical climate of South Florida were first conducted in the 1920's and 1930's as the paint industry became more and more concerned about the weathering resistance of their products, making this area an important historical outdoor testing region. The largest independent test sites are located in areas that are considered an inland location (referred to as DWI, direct weathering inland), and therefore, do not see any adverse corrosive coastal effects from seawater. In the

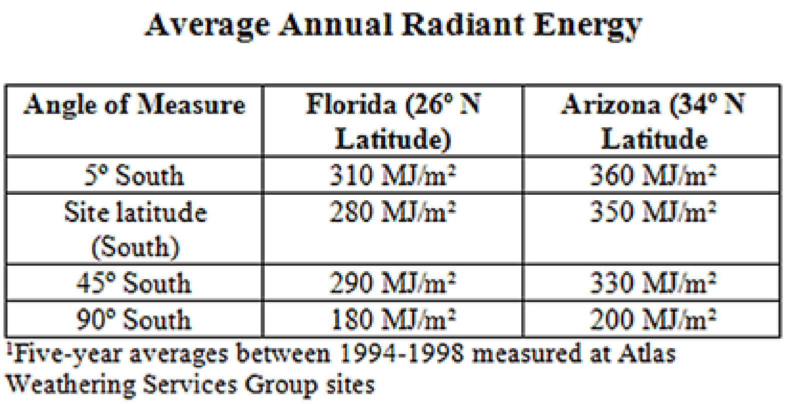
Sonoran desert environment of Arizona, greater extreme temperatures at both ends are seen than in Florida, and are known to cause higher stresses to automotive interior materials than other climates of the world.

Seasonal variability does exist in both subtropical and desert environments. The amount of variation will depend on the test exposure angle and local climate, especially the atmospheric conditions that cause different ratios of direct (beam) and diffuse (scattered) solar radiation. Because of the high percentage of direct beam radiant energy in a dry desert environment such as Arizona, there is a high seasonal variation for 5° inclined (from the horizontal) exposures at that location.

In winter, the sun remains low on the horizon (solar zenith angle). Exposures conducted at 5° in Florida are relatively constant in UV radiation due to the Rayleigh scattering of UV by water vapor; UV reaches the ground from essentially all portions of the sky. Exposures conducted at the at-latitude inclination angles (which are 26° in South Florida and 34° in Arizona) result in minimized seasonal variations as the sun is closer to the perpendicular (DNI, direct normal incidence) of these surfaces over the entire year. A 45° exposure is optimal for Arizona due to the higher UV levels present in the direct solar beam component. Florida has less UV at 45° due to the scattering of short wavelengths by atmospheric moisture (the cause of "blue sky").

Although higher amounts of UV and total solar radiant energy are received by exposures in Arizona, one should not assume that Arizona is therefore always a more severe climate in which to expose materials. In Miami, samples are wet ~15X longer than in Arizona because of the higher moisture received in South Florida. This addition of moisture has shown to be very effective in the degradation of paints and coatings and, in general, far more paints and coatings are tested to this environment than in the desert of Arizona. However, the dry climate of Arizona, in conjunction with the dramatic diurnal temperature cycling, has proven to be very effective in the degradation of interior automotive materials and many other polymers, and may cause increased pigment fade. It is common that many companies will test their materials in both the subtropical and desert climates (and others as well) because the effects of these extremes may result in different types of degradation.

In depth solar radiation and weather data are collected at exposure test sites (Figures 4 & 5). This data, such as the temperature of black (BPT) and white (WPT) coated reference panels or the amount of total ultraviolet radiation (TUVR), is then used to develop accelerated laboratory weathering tests as well as in analyzing the field exposures and establishing test correlations.

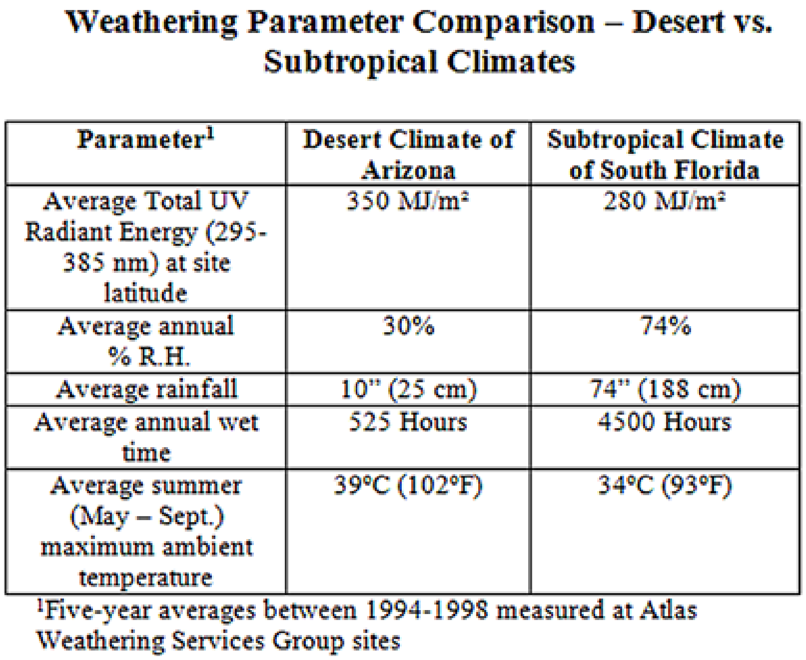


Average Annual Radiant Energy

Angle of Measure	Florida (26° N Latitude)	Arizona (34° N Latitude
5° South	310 MJ/m^2	360 MJ/m^2
Site latitude (South)	280 MJ/m^2	350 MJ/m^2
45° South	290 MJ/m^2	330 MJ/m^2
90° South	180 MJ/m^2	200 MJ/m^2

[1]Five-year averages between 1994-1998 measured at Atlas Weathering Services Group sites

Figure 4 - Average annual Total Ultraviolet (TUVR) received at South Florida and Arizona exposure test sites at major specimen exposure angles



Weathering Parameter Comparison – Desert vs. Subtropical Climates

Parameter[1]	Desert Climate of Arizona	Subtropical Climate of South Florida
Average Total UV Radiant Energy (295-385 nm) at site latitude	350 MJ/m^2	280 MJ/m^2
Average annual % R.H.	30%	74%
Average rainfall	10" (25 cm)	74" (188 cm)
Average annual wet time	525 Hours	4500 Hours
Average summer (May – Sept.) maximum ambient temperature	39°C (102°F)	34°C (93°F)

[1]Five-year averages between 1994-1998 measured at Atlas Weathering Services Group sites

Figure 5 - Comparison of key climate factors for South Florida and Arizona exposure test sites

Direct and Indirect Outdoor Weathering

Figure 6 shows a portion of the direct, static weathering field of South Florida Test Service, located near Miami, Florida. Direct weathering is defined as an exposure to direct sunlight and other elements of weather. This is typically accomplished by mounting the material on an exposure rack. The standard racks shown are made from anodized aluminum and face directly south (in the northern hemisphere) at a fixed angle. The typical sample size is 150 x 305 mm (6” x 12”).

Figure 6 - “Fish-eye” view of static exposure racks in South Florida, a major benchmark location for coatings testing

The most typical angles of exposure are near horizontal (usually 5°), 45°, vertical (90°) and one equal to the station latitude (26° and 34°) in South Florida and Arizona, respectively). Exposures conducted at 90° (either facing directly south or north out of direct sunlight for mildew growth studies) may not provide the most severe conditions, but often match the end-use of the material tested closer than any other angle. Direct weathering tests follow ASTM G7 / G7M – 13 *Recommended Practice for Atmospheric Environmental Exposure Testing on Nonmetallic Materials.* Note this standard requires the use of native groundcover.

Figure 7 shows a typical 45° south facing exposure rack (Arizona). Open, unbacked exposures, are direct weathering tests conducted by either fastening or clamping the specimens at their extremities so that the majority of the material will be exposed to the circulation of ambient air on all sides of the sample. Typical materials for exposure on an open unbacked rack are glass, free-films, plastic and metal sign material, coil coatings, and plastic lenses such as taillight assemblies.

Materials which would commonly be utilized against a substrate material such as plywood sheathing should not be exposed “open back” as the back side cooling of the material from wind and natural convection will not allow the material to achieve the same temperature it will experience in its end-use. The early service life failures of some paints and coatings were due to the continued use of the open rack method for exposure testing when a “backed” exposure should have been used.

Figure 7 - "Open back" exposure testing

Backed exposures are direct weathering tests conducted by mounting the specimens to a substrate (typically ½ or ¾ inch; 12 or 19 mm) untreated bare or kraft paper faced plywood sheathing) to simulate the end-use thermal environment of material. (Figure 8). The backing prevents convective cooling from the rear of the sample and elevated temperatures. Since weathering processes are a synergistic reaction to all factors of weather (solar radiation, moisture, temperature, etc.), the ability to maintain the proper thermal environment of a material in a simulation of end-use conditions is fundamental to good exposure practices.

Figure 8 - Test specimens on a 90° vertical exposure rack

Wood coatings are often applied in various film builds to a single wood board (trade panel) and exposed 90º vertical (Figure 9). Panels are offset to prevent runoff cross-contamination. Panels may also be exposed north-facing (out of direct sunlight) to test for mold and mildew growth.

Figure 9 - "Trade panel" test specimens in vertical exposure are offset to avoid cross-contamination by moisture run-off. Paint samples can also face away from the sun for mold and mildew growth studies

The "Black Box" exposure (Figure 10) simulates the air heat sink characteristics of an automobile body. It consists of a black painted, open bottom metal box approximately 150 x 200 cm box and approximately 25 cm deep. The panels to be tested cover the open top of the box. For many coatings and automotive paints, the black box provides greater rates of degradation than those provided by standard 5º open rack exposures as the black box produces higher panel temperatures during irradiation by the sun later into the day and lower temperatures with longer time of wetness in the morning. The black box panel temperatures are comparable to those encountered on the hoods, roofs, and deck lids of automobiles parked in direct sunlight. ASTM Standard D4141, *Standard Practice for Conducting Accelerated Outdoor Exposure Tests of Coatings*, specifies the use of this black box exposure method.

Figure 10 - "Black Box" exposure for automotive coatings

Indirect, or under glass weathering (Figure 11) is the exposure of materials that are typically are not exposed to outdoor conditions. This method of testing materials is used to determine the colorfastness/durability characteristics of household materials such as drapes, carpeting, upholstery, etc. as well as materials utilized in automotive interiors.

Figure 11 - Exposure behind single strength window glass for testing interior products

The primary test method for indirect weathering is ASTM G24, *Standard Practice for Conducting Exposures to Daylight Filtered Through Glass*. Test specimens are typically placed approximately 3" behind 1/8" thick window glass, which absorbs radiation below 310 nm and transmits 77% of UV radiation and 85% of daylight. Temperatures of exposure are generally increased over direct exposures because less moving air passes over or behind the specimens. Tempered, tinted, or laminated glass may be used based on the end-use application of the material.

Indirect exposures would most commonly be used for interior architectural coatings or coated products intended for interior use such as home or office furnishings.

Corrosion and Special Exposure Tests

Outdoor corrosion testing is a specialized test that is performed on materials in environments that promote rust and other corrosive processes. Corrosion testing is performed at coastal marine locations such as Hoek Van Holland, The Netherlands (Figure 12); Long Key, Florida; Choshi, Japan; and Sochi, Russia. Several other locations around the world have been identified for specialized exposure testing. These include sites for tidal immersion, where specimens are exposed to the sun during low tide and immersed in sea water during high tide (used primarily for marine plastics and coatings), industrial locations, high altitude sites, cold weather climates, and other unique environments, such as Jacksonville, Florida for automotive coatings (acid etch).

Figure 12 - Coatings on exposure at the North Sea corrosion test center in Hoek Van Holland, The Netherlands

Jacksonville, Florida, is known to be one of the largest ports for European and Japanese auto manufacturers. Jacksonville is a unique environment with relatively high annual radiant energy and humidity. There are also several industrial plants that contribute to the pollution in the area. It has been shown that cars waiting to be distributed to US auto dealers were found with an acid etch phenomena on the exterior paint. This obviously created a concern for these auto manufacturers, because the cars were unacceptable to the public before they were even available for sale! Many auto manufacturers now require automotive paint systems to be exposed to this environment before they are approved for use.

5. Outdoor Accelerated Testing

One of the most common questions asked regarding weathering testing is "How long do I need to test my material?" followed quickly by "But I can't wait that long -- can't I do it faster?" Of course, the answer depends on the specific material being tested and where and how long the material is expected to perform in its defined service life.

Exposures for items such as architectural and automotive coatings, roof coatings, etc., may need to be tested for 2, 5, 10, 15 or even 30 years or longer to achieve near complete confidence in the material's durability in that environment. However, customers often cannot afford to wait for materials to sit in these natural conditions without making some assumptions.

The other option is to accelerate the test in some manner. And, as product life expectations become longer, new materials are being evaluated in shorter development cycles. Therefore, accelerated testing is driven by economic as well as competitive concerns.

For all practical purposes, conducting tests in the benchmark locations of South Florida and Arizona and similar climates could be considered "accelerated" tests in relation to many end-use locations because materials degrade faster in these climates than in most others.

If we also consider that many materials are not always directly facing towards the sun, we can consider these tests to be somewhat more accelerated. If the end use of a material is on a vertical exposure (such as the side of a building), conducting the test at 45° may be considered an "accelerated" test as it receives more solar radiation in a given time. Specimens at 45° receive at least 30% more sunlight than vertical, and some studies have shown that the actual rate of degradation may be as much as 2.5 times greater (possibly to the effects of more moisture exposure in Florida).

However, it is possible to use natural sunlight to accelerate exposures even more. Among the most widely recognized and utilized outdoor accelerated weathering test devices are Fresnel solar concentrators, such as the EMMA® and EMMAQUA® devices, (Figure 13). Their names are acronyms:

EMMA – Equatorial Mount with Mirrors for Acceleration
EMMAQUA - Equatorial Mount with Mirrors for Acceleration, with Water (Aqua)

Figure 13 - EMMA/EMMAQUA Fresnel solar concentrator

The altazimuth (2-axis) solar tracking devices were originally developed at Atlas' DSET Laboratories in Phoenix, Arizona during the 1960's and have been in continual development since.

They employ a Fresnel solar concentrator array that utilizes 10 special flat first-surface mirrors to track and concentrate natural (direct beam) sunlight onto specimens mounted on the target board of the device (Figure 14).

Figure 14 - Target board with water sprays during sun tracking for thermal shock

The mirrors uniformly focus sunlight onto the samples at an intensity of approximately eight times the hemispherical (global), normal-incident sunlight, and approximately five times the global normal incident UV radiation. Because the test method exposed samples to the full spectrum of natural concentrated sunlight, it is theoretically one of the most realistic accelerated weathering tests available. The parameters of the test device, spray cycles, etc. are governed by ASTM G90, *Performing Accelerated Outdoor Weathering of Nonmetallic Materials Using Concentrated Natural Sunlight*. Exposures on EMMA/EMMAQUA® are usually timed by an equivalent "year" of average desert (Arizona) or subtropical (South Florida) total ultraviolet radiant energy exposure.

Note that only the direct beam radiant energy is reflected onto exposed samples, the diffuse radiation is rejected. The device is a follow-the-sun tracking rack. Samples are placed in frames and cooled by a 30 km/hr air stream. Specimen temperatures are usually with 5-10°C of those on a static exposure rack. Oscillating or pulsing nozzles are used to spray specimens with deionized water in accordance with established schedules on the EMMAQUA (with water) version. Because a clear dry atmosphere is required, these devices are restricted to desert environments such as Arizona.

Three common test cycles are defined in ASTM G90. Cycle One, commonly used for plastic specimens, utilizes a daytime spray that provides a thermal shock effect several times during a typical exposure. Cycle Two does not include a spray cycle, simulating the dry climate of a desert exposure. Cycle Three, commonly used for coatings, inverts the instrument so that the samples face upward; deionized water sprays periodically wet the specimens during the night to simulate the typical dew formation and wet time of subtropical exposures. Other spray cycles, such as a soak-freeze-thaw, nighttime soak, and day-night sprays can be programmed for special test applications. The system can also go off-track to permit water sprays when the specimens are not "on sun" to avoid thermal shock and quick evaporation. Therefore, Miami conditions can be simulated, even in the desert.

New enhancements to this technique involve customized water spray cycles which have shown to have better correlation than the ASTM standard cycles. In addition, both static and dynamic temperature control has been added. Static control allows a reference sample, such as a Black Panel Thermometer (BPT), to be exposed; the cooling fan adjusts the air flow to maintain the desired set-point temperature. Dynamic temperature control allows for a remote reference temperature probe, such as on a static exposure rack, to control the specimen temperatures in real time during the day, or to utilize electric heating elements behind the test specimens to maintain a higher temperature such as during winter nights.

Weathering laboratories that employ these solar concentrators must have strict quality control measures in place to ensure that exposures are performed to the specifications. For example, the water quality for the sprays must be less than 200 parts per billion (ppb). The mirror reflectance must be monitored at least semi-annual for accurate exposures. The mirrors must be rinsed and/or washed on a prescribed schedule. Finally, the measurement of UV irradiance must be performed according to the ASTM G90 specification.

As the device utilizes natural sunlight, the solar concentration/acceleration factor is seasonally dependent, with the optimal season being May 1 – August 31. Although there are 10 mirrors, only the direct beam solar radiation is used (the diffuse sky radiation is rejected); therefore the actual "acceleration" (based on solar radiation deposited) over static rack exposures is approximately 5-6X (UV) on an annualized basis.

For cases where there is reciprocity failure (a non-linearity of material response versus irradiance), or where specimen temperatures are too high, mirrors can be removed in pairs to lower the irradiance and specimen heating. Due to the cooling airflow requirements, specimen thickness is generally restricted to a maximum thickness of about 1.3 cm (0.5-inch).

Higher irradiance = faster testing

Two new versions of the Fresnel concentrator have been recently introduced, the "Ultra-Accelerated" EMMA/EMMAQUA (UA-EMMA and UA-EMMAQUA), and the "Low Temperature" (LT-EMMA and LT-EMMAQUA). Both devices are predicated on advanced "cool mirror" technology developed in a joint project between Atlas, the U.S. National Renewable Energy Laboratory and the Institute of Laser Optical Technology JSC and implemented in the Ultra-Accelerated Weathering System (UAWS) in 2009 (Figure 15).

Figure 15 - Ultra-Accelerated Weathering System in Arizona

Solar concentration techniques have the disadvantage that unwanted near infrared radiation is concentrated as well, thus greatly increasing the solar-thermal load on the test specimens. At high concentrations, this excess heat cannot be effectively removed by external cooling, so one solution is to remove the solar heat load.

The UAWS is a solar tracking and concentration device like EMMA with the exception that it is uses 29 reflecting facets arranged in a concave surface approximating the curvature of a 10m sphere with the test target at the focal point at approximately 2.5m; this achieves a 100:1 direct normal optical concentration. The facets consist of 96 layers of interference coatings on borosilicate glass. The "cool mirrors" reflect the direct solar beam UV and near-visible (< ca.550nm) wavelengths and transmit (reject) the longer wavelengths. With this technique, approximately 63 years of Miami average total ultraviolet solar radiation can be deposited on the target in one year. However, even with the removal of the longer visible and near IR wavelengths, the high solar flux still provides sufficient energy to require external specimen cooling. The UAWS is principally considered a research tool, but is available for commercial applications.

The UA-EMMA/EMMAQUA (Figure 16) devices replace the standard flat mirrors with ones using this "cool mirror" technology. Twenty reflecting facets are arranged in a parabolic trough configuration focused on a target area slightly smaller than standard EMMA/EMMAQUA, This increases the UV concentration factor from 4-5X for standard EMMA/EMMAQUA to approximately 10-12X as compared to South Florida.

Figure 16 - UA-EMMA/EMMAQUA with “cool mirror” technology

As some materials, such as polyvinyl chloride (PVC) are notoriously thermally labile, a hybrid approach combining standard and Ultra-Accelerated EMMA/EMMAQUA has been developed, Low-Temperature LT-EMMA/EMMAQUA. This technique achieves cooler temperatures by replacing the standard mirrors with “cool mirror” technology, but not increasing the irradiance with additional mirrors. By focusing the cool mirrors on a slightly smaller target area, UV concentration is slightly increased to a factor of 5-6X over south Florida but at black panel temperatures almost identical to static horizontal exposures.

It should be noted that all of the EMMA/EMMAQUA variations and options conform to ASTM G90 - 10 *Standard Practice for Performing Accelerated Outdoor Weathering of Nonmetallic Materials Using Concentrated Natural Sunlight.*

Variability of the Outdoor Environment

Outdoor weathering tests are the most reliable tests in terms of correlation to end-use service life, but variables do exist that do not guarantee repeatable results. Different climates obviously have different amounts of radiant energy, moisture, temperatures, and pollutants. Time dependant variables exist with day-night cycling, seasonal variations, as well as long term variations that may be a result of acts of nature.

Volcanoes can eject ash and pollutants into the air that can lower maximum ambient temperatures and radiant exposure levels. The warming and cooling of the eastern Pacific Ocean, creating the El Niño and La Niña conditions, cause two to three year variations in temperatures, moisture, and wind currents in many affected areas of the world. Hurricanes can cause severe damage to specimens exposed in the subtropical climate of South Florida if weathering laboratories do not take precautions to protect specimens. The variations in the thickness of the ozone layer can cause higher or lower amounts of UVB radiant energy to reach the earth’s surface.

Differences in substrates, shelf aging before exposure, the weather conditions immediately after exposure, and the seasonal and long term variations described above all contribute to variability inherent in natural weathering exposures. However, weathering tests performed by trained, experienced experts should always be included in any R&D or testing program to provide baseline information on the durability of new materials, because there is no artificial accelerated test that can simulate the environment as well as a natural weathering test.

6. Artificial Weathering Devices

Due to the need for more rapid evaluations of the resistance of materials to weathering than can be obtained by outdoor exposure tests, and the need for more controlled conditions, test devices with artificial light sources are generally used to reproduce and accelerate the degradation. These devices include lamps based on carbon arc and filtered long arc xenon, metal halide and special fluorescent lamps. These “laboratory accelerated weathering” device tests are more appropriately referred to as “artificial weathering.”

The acceleration over “real time” weathering occurs for several reasons. Principally, the tests can run continuously at naturally occurring or higher irradiance than solar radiation, uninterrupted by the diurnal cycle, seasonal variations and weather conditions. Temperatures, thermal cycles, humidity and water exposure can also be manipulated to maximum, but not unrealistic, stress levels. Specimens can be exposed to spectral energies at or beyond the limits of their intended service exposures, although extreme caution must be exercised so as not to induce unnatural degradation mechanisms.

In addition to the ability to manipulate and accelerate weathering conditions on demand, a fundamental benefit of a laboratory test is the precision and repeatability over what is essentially an uncontrolled and variable phenomena, the actual weather. Plus, each of the weathering factors can be manipulated independently; thus research can be conducted into the specific response of materials to various weathering factors, experiments which would be difficult or impossible to conduct outdoors.

Artificial weathering devices are often categorized by the type of artificial light source used. The most common types are carbon arc, fluorescent, xenon-arc, and metal halide light sources. Each has its own inherent benefits (and limitations) of which a weathering experimenter must be aware. Since the radiant energy received by an exposed material is considered the most important, we will focus our attention on the quality of the light source, referring to how well each light source resembles natural sunlight in terms of spectral match.

The overarching governing standards for use of these devices, along with practical guidance and cautionary statements, are ISO 4892-1 *Plastics -- Methods of exposure to laboratory light sources -- Part 1: General guidance* and ASTM G151 - 10 *Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use*

Laboratory Light Sources.

Carbon Arc Sources

The carbon arc instrument was first used to evaluate the lightfastness of dyed textiles. The first Atlas Solar Determinator was introduced in 1915, then renamed the Color Fade-Ometer® in 1919, used an enclosed carbon arc (ECA) light source. Its development was a result of a redesign of an earlier Atlas unit, the Solar Determinator. This earlier development itself was an outgrowth of Atlas' Solar-Light carbon-arc stage and photograph studio lighting.

The introduction in the 1930's of the "open flame" carbon arc, in the Atlas Sunshine Carbon Arc Weather-Ometer® with Corex® filters, provides more UV < 300 nm than sunlight but gives a much better match in the 300-340 nm region and deviates less than the enclosed carbon arc at longer wavelengths. When used without filters for faster testing, stability rankings of some materials may be distorted when compared with outdoor testing. The spectral emission in the UV bares little resemblance to daylight, as shown by the spectral power distribution graph in Figure 17.

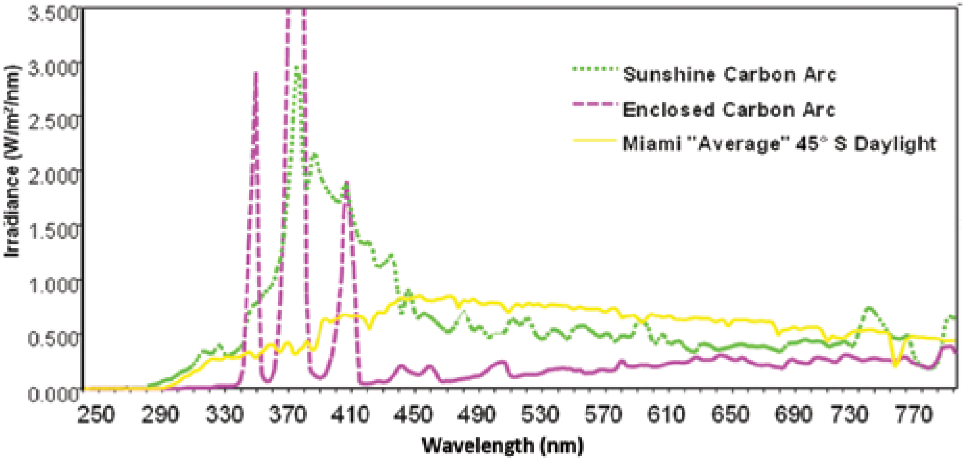


Figure 17 - Spectral Power Distribution of enclosed and Sunshine Carbon Arcs compared to Miami sunlight

Two strong emission bands, peaking at 358 nm and 386 nm are about 4 and 20 times daylight respectively. This type of light source can be expected to have a weaker effect than solar radiation on materials that absorb only short wavelength UV radiation, but a stronger effect on materials that also absorb long wavelength UV and visible light. Therefore, in trying to evaluate the relative light stabilities of materials, some of which absorb only short wavelength UV and others that also absorb long wavelength UV, the enclosed carbon arc could distort the rankings when compared with samples exposed to solar radiation.

There is a large amount of historical data using carbon arcs, and some specifications still require their use. However carbon arc testing has globally been largely discontinued. While reasonable correlation with outdoor exposures has been reported for some few coatings whose weathering mechanisms are appropriate for these limited spectrum sources, this technology is considered obsolete and has been replaced by xenon arc systems. ASTM G152, *Practice for Operating Open Flame Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials* and ISO 4892-4:2013 *Plastics -- Methods of exposure to laboratory light sources -- Part 4: Open-flame carbon-arc lamps*; G153, *Practice for Operating Enclosed Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials* are the primary documents describing performance characteristics of devices that use the carbon arc light source.

Fluorescent UV Sources

Linear fluorescent lamps, similar to those used for residential and commercial lighting, have been developed with specific spectral distributions. These sources are incorporated into fluorescent condensation devices such as Atlas' UVTest (Figure 18). These devices may be used in cycles that may vary light/dark cycles, temperature, condensing humidity and water sprays. Their functional design and use is primarily governed by ASTM G154, *Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials* and ISO 4892-3:2013 *Plastics -- Methods of exposure to laboratory light sources -- Part 3: Fluorescent UV lamps*.

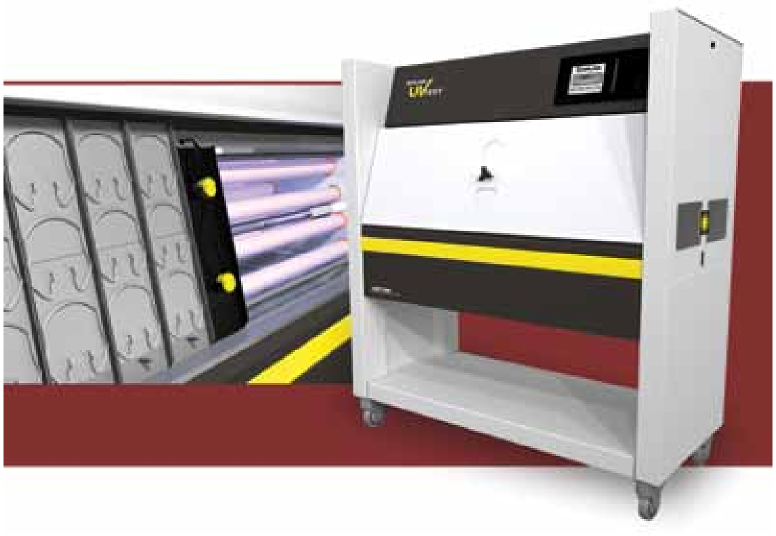


Figure 18 - Atlas UVTest Fluorescent/UV instrument

The fluorescent UVB lamps (FS40 and UVB-313) with a peak around the 313 nm mercury line, has nearly all of its energy concentrated between 280 nm and 360 nm. A large fraction is at wavelengths shorter than those present in terrestrial solar radiation and it has very little energy longer than 360 nm. Reversals in the stability ranking of materials have often been reported between laboratory accelerated and outdoor tests when the accelerated test uses UV-B. This is due to the predominance of short wavelength UV and the deficiency of long wavelength UV and visible radiation; the mechanisms of degradation may be significantly different from those of the "natural" test. The reason for this potential to alter the degradation chemistry is due to the fact that photon energy is inversely related to wavelength according to Planck's Law (Figure 19).

$$\underbrace{E}_{\text{energy}} = \underbrace{h}_{\text{Planck's constant}}\overbrace{\nu}^{\text{frequency}} = \underbrace{h}_{\text{Planck's constant}}\overbrace{c}^{\text{velocity}}/\underbrace{\lambda}_{\text{wavelength}}$$

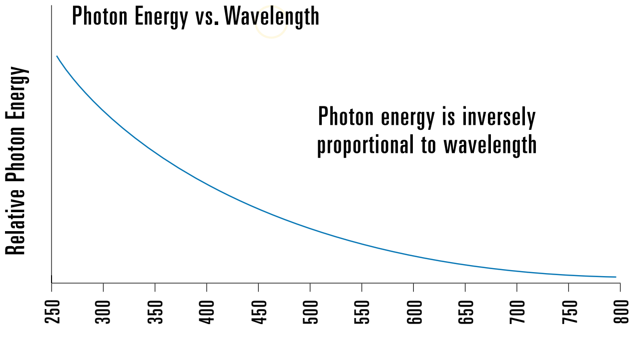
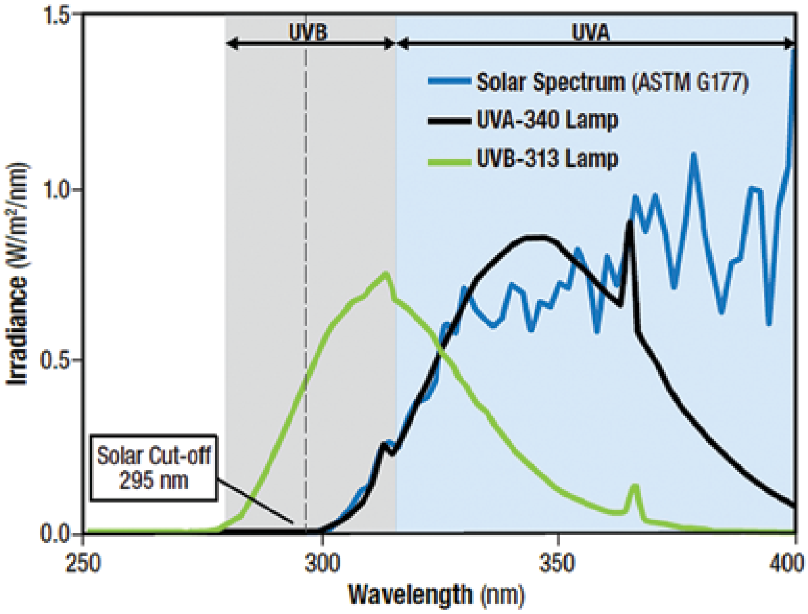


Figure 19 - Planck's Law and photon energy vs. wavelength

If the test light source contains wavelengths below the normal cut-on of terrestrial solar radiation, there is the potential to change not only the degree, but also the type of degradation. While it may be sometimes true that more severe test conditions will merely "speed up" the normal photodegradation processes, this can and should not be assumed. There have been many cases where the chemistry was so altered that the degradation appeared to be less severe or totally different than that outdoors. This "harsher is better" approach to overstress weathering testing was popular up until about the year 2000 when the automotive industry realized that they were spending money to protect materials from UV that would never be seen in service. Unfortunately, this flawed approach is still widely practiced, and often accounts for the reported "lack of correlation" of accelerated weathering tests with outdoor performance.

Both the ISO and ASTM governing standards contain specific notes that their use can initiate ageing processes that never occur in end-use environments, and that they should "only be used upon specific agreement" (ISO) and that "Use of this lamp is not recommended for sunlight simulation" (ASTM). Nevertheless, they are still in use.
Fluorescent black lights, referred to as UVA lamps, are available with peak emissions of 340 nm - 370 nm (e.g., UVA-340 and UVA-351). In the UVA-340 lamp, developed in 1987, the short wavelength irradiance simulates that of direct solar radiation below 325 nm. The UVA-351 spectral distribution at lower wavelengths is similar to that of daylight as filtered through window glass which removes the lower UV wavelengths. Figure 20 shows the natural solar UV spectrum with the UVB-313 and UVA-340 lamps.



UVA-340 lamps match the solar UV spectrum well, especially from 295 to 370 nm.
UVB-313 lamps include significant unnatural radiation below the solar cut-off of 295 nm.

Figure 20 - Comparison of UVA and UVB lamps compared to a standard solar spectrum

Because the UVA lamps do not emit high energy radiation below the cutoff of terrestrial solar radiation, correlation with outdoor weathering is improved but test times are longer than with UVB lamps; however high test "acceleration" that lacks good "correlation" is of no value.

In general, these devices provide irradiance control, water condensation (with optional water sprays) and cycling (using a cooler lights-off period) for dew simulation. The test surface is exposed to a heated, saturated mixture of air and water vapor (relative humidity approaches 100% during the dark cycle) while the reverse side of the panel is exposed to room air which causes the panel temperature to drop below the dew point. This causes water droplets (dew) to form on the exposed surface. The sequence and time intervals for both the ultraviolet cycle and the condensation cycle are programmable and automatic. Likewise, temperatures can be controlled (within limits) during both the UV and condensation cycles.

Fluorescent condensation devices, as they are known, do provide a good simulation of the lower half of the solar UV spectrum (with UVA-340 lamps) but lack the longer UV as well visible wavelengths responsible for some photochemical degradation processes. The lack of near IR wavelengths means that unlike in outdoor exposures, all test specimens will be at the same temperature. This can lead to differences in correlation to outdoors due to the difference in temperature effects on specimen moisture, thermally driven degradation chemistry, etc. In particular, many colorants are sensitive to these missing wavelengths.

Fluorescent condensation devices are mostly best used as screening tools for coating binder UV degradation studies and not as general predictive tools for coating weathering performance. The simulation and natural balance of the three key weathering stresses (heat, sunlight, moisture) as well as their cycles is very limited with this technology. However, they can be very effective research tools when properly used and understood.

Xenon Arc Sources

The first weathering instrument using a xenon arc lamp was developed in 1954 (Xenotest® 150). In use in North America since the 1960's, the xenon long arc lamp, when properly filtered, more closely simulates full spectrum solar radiation than any other artificial light source. Unlike the electrically burning open carbon arcs, the xenon arc is a precision gas discharge lamp in a sealed quartz envelope. The spectral power distribution can be finely tailored through optical filtering to simulate solar radiation ranging from above-the-atmosphere through to sunlight-as-filtered-through-window-glass. As such, it is universally preferred as a light source when the material to be tested will be exposed to natural sunlight.

In the course of six decades of xenon arc development, two instrument systems have emerged: air-cooled and water-cooled xenon lamp devices. The type of cooling has an influence on the overall design and on the optical filtering system. The Atlas Fade-Ometer® and Weather-Ometer® instruments use water-cooled xenon arc exclusively (Figure 21), the smaller Atlas SUNTEST CPS+ and XLS+ II table (Figure 22) top exposure systems as well as the larger SUNTEST XXL and Xenotest (Figure 23) instruments use air-cooled xenon lamp and filters. ASTM G155, *Practice for Operating Xenon Arc Light Apparatus for Exposure of Nonmetallic Materials* and ISO 4892-2:2013 *Plastics -- Methods of exposure to laboratory light sources -- Part 2: Xenon-arc lamps* are the primary standards regarding performance requirements of these instruments.

Figure 21 - Water-cooled xenon arc Weather-Ometers

Figure 22 - Suntest Series air cooled xenon arc instruments

Figure 23 - Xenotest series air cooled xenon arc instruments

Depending on the design of the weathering device, specimens may be exposed in the vertical or in the horizontal position. For large-scale equipment, the vertical style prevails. An example of the test chamber in the water-cooled Weather-Ometers is shown in Figure 24.

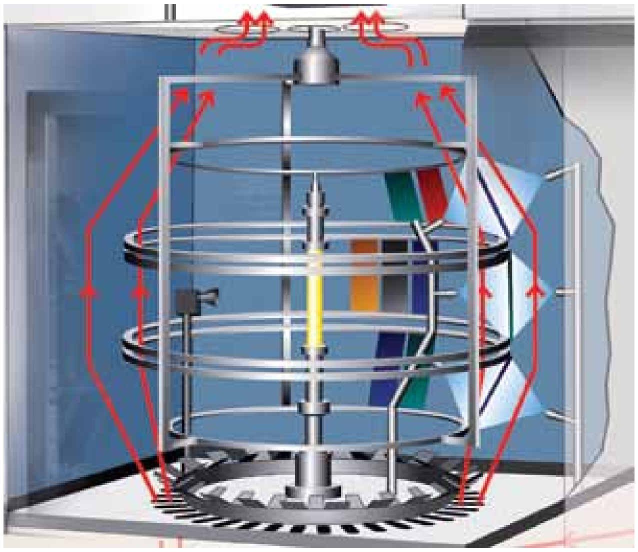


Figure 24 - Representation of Weather-Ometer test chamber

Multi-tier inclined specimen racks contribute to irradiance uniformity; these orient the specimens along the plane of the iso-irradiance lobes of the long arc lamp (Figure 25).

Figure 25 - Tiered specimen rack line of equal irradiance in relation to lamp

For improved uniformity and when other functions are required (e.g., spraying), the entire rack is rotated around the light source by a motor. This provides for water spray options as well as moving specimens through the chamber airstream for more uniform exposure to heat, light and moisture than static sample positioning permits. Studies have shown that there is little difference in moisture uptake between vertical and horizontally oriented specimens (Figure 26). The key factors in moisture uptake by coatings are time and temperature (Figures 27, 28).

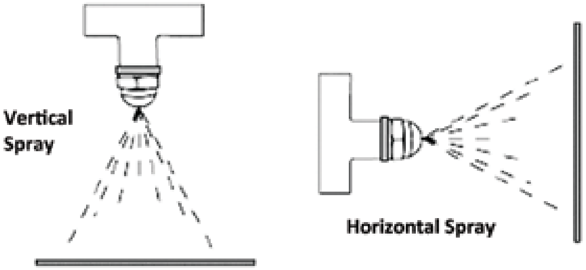


Figure 26 - Orientation of specimens and water sprays

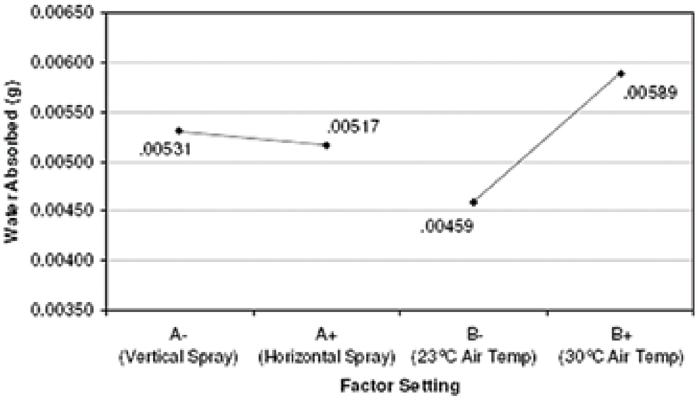


Figure 27 - Effect of water spray orientation and temperature on moisture uptake of coatings

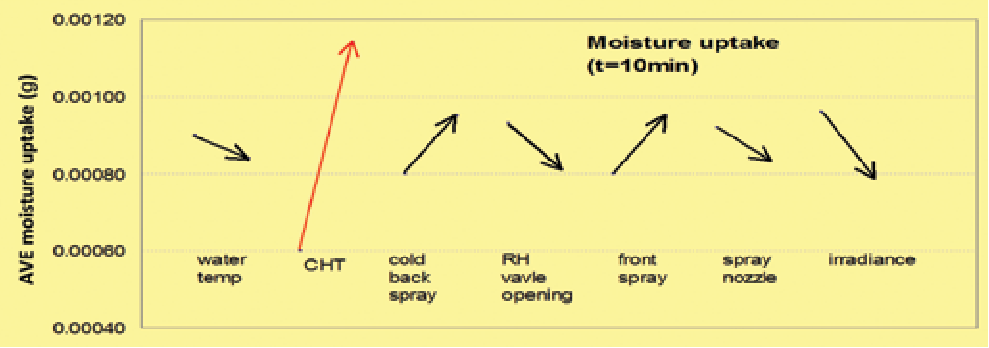


Figure 28 - Factorial analysis of variables influencing moisture uptake; temperature has the greatest influence among the variables

The unfiltered radiation of the xenon arc contains considerable radiation in the short wavelength UV. Thus, the role of the various optical filters is to obtain the desired spectral distribution. An example of some of the historical filter spectra for the water-cooled Weather-Ometers is shown in Figure 29. There are other filters used in the air cooled instrument which provide other spectral distributions. In some cases additional filtering is possible by adding an auxiliary flat glass filter holder to accommodate the wider variety of filters available in flat form, for example to simulate sunlight through specific glazing such as automotive glass.

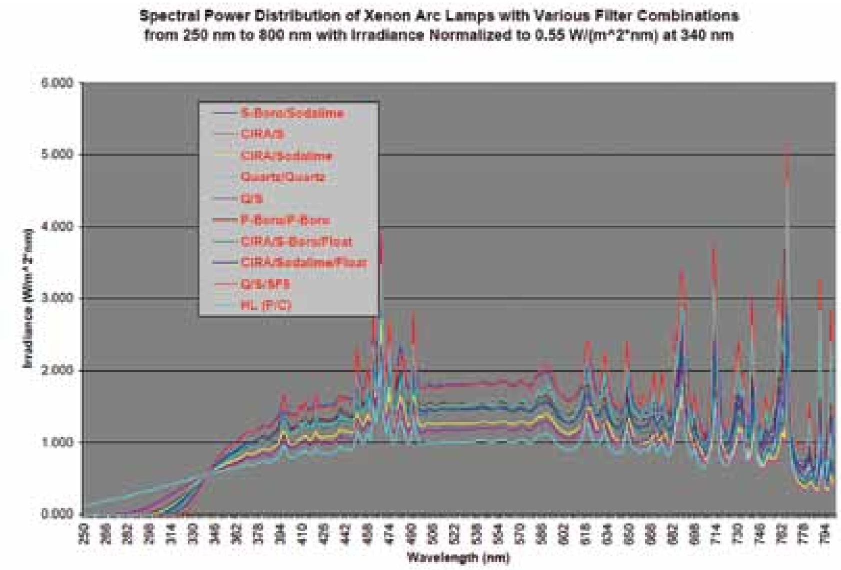


Figure 29 - Examples of spectra available with various lamp filter combinations

Optical filter development to better simulate sunlight is one of the more active areas in advancing accelerated weathering testing. For example, a new filter combination, Right Light™/CIRA (Figure 30) with a more precise UV cut-on wavelength match to sunlight has been used in developing new automotive and aerospace coatings test method. However, be aware that test method standards and specifications often lag the current state of the art by a decade or more.

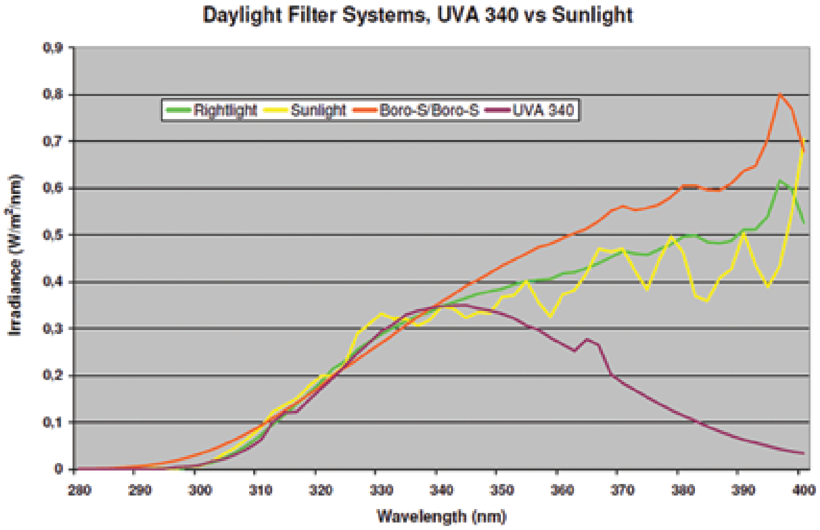


Figure 30 - Right Light/CIRA filter system compared to UVA-340 fluorescent lamps and sunlight in the UV region

Irradiance Control in Xenon Arc Instruments

The irradiance in laboratory weathering instruments, and hence the resulting radiant energy dosage, is continuously measured and controlled. The amount of real or simulated solar radiation can be described in various measurement terms. The most common are radiometric units of irradiance E (W/m^2) and radiant energy H (J/m^2), although other including photometric units are sometimes used. Total Solar Radiation (TSR) in weathering is generally measure over the relevant spectrum of 295-2500 nm. Spectral irradiance is in units of W/m^2 nm and specified at a particular wavelength, such as 340 nm or 420 nm, or over a wavelength range, e.g., 295-285 nm, 300-400 nm, or 300-800 nm.

It is important to understand (and it is a frequent source of misunderstanding) that the unit of measurement does not alter the spectral power distribution that the sample is exposed to as that is determined only by the light source and optical filtering. These measurement units only describe the “light intensity” at some point or portion of that fixed spectrum determined by the light source.

Why have these different units describing narrow-band, wide-band or broad-band solar radiation? A detailed discussion of the reasons is not necessary for this paper but a short explanation is in order. In coatings weathering, the UV wavelengths are generally more important than the longer wavelengths (due to Planck’s Law), but are present at very low levels compared to the longer wavelengths. We could double or triple the UV level at 300 nm, for example, which would have a significant impact on degradation, yet the total

UV/Visible 300-800 nm numerical reading would barely register a change. Therefore, we want to more accurately focus measurement and control on the more significant wavelengths.

There are some specific advantages to the narrow-band single wavelength (e.g., 340 nm) and the wide-band (e.g., 300-400 nm) approaches that are beyond the scope of this paper. Largely, the use of one or the other is practically related to the prevailing convention of the organization that created a particular test method or standard; there is usually little practical implication in terms of material response in a test. Most modern weathering instruments can be configured to use any of the measuring methods.

Weathering Instrument Geometry

Xenon weathering instruments are available in two geometrical configurations: vertical sample orientation using a rotating rack that surrounds the light source, and static horizontal "flat-bed" with the source overhead. Higher end performing instruments use the first approach as this provides the highest (and automatic) irradiance uniformity over the exposure area as well more uniform exposure to airflow, humidity and water sprays. Even though most instrument designs technically meet standards does not mean that there are no performance and test result differences; the standards generally are designed so as not to exclude even the lowest performing equipment. Therefore, some test specifications either require specific makes and models or particular hardware configurations to assure the quality and utility of the test results.

One advantage to flat-bed instruments is that they can generally accommodate test specimens with greater depth (3-dimensionalty) than rotating rack instruments where specimens are more typically flat panels.

Advances Beyond Standards

For the weathering researched, modern enhancements to Atlas' Weather-Ometer® line of xenon arc instruments include Full Spectrum Monitoring (FSM) which uses a portable on-rack precision spectroradiometer to precisely characterize the spectral irradiance that is delivered to the test specimen plane. Another, Specimen Specific Surface Temperature (S^3T)monitoring technology permits real-time non-contact in situ test specimen temperature measurements. And XenoLogic™ used in Xenotest® xenon instruments provides for high irradiance and longer lamp lifetimes.

Metal Halide Light Sources

The automotive manufacturers and their suppliers continue to experiment with new technology and testing approaches. This is exemplified by efforts to expose larger components such as instrument panels, door assemblies and bumper fascia systems to gauge the effects on stressed and formed multi-component systems. Metal Halide Global® (MHG) arc lamps with special power supplies provide spectral power distributions that closely match direct solar plus sky radiation. Because of their high efficiency, these sources are ideally suited for use in large scale multiple lamp arrays and are effective for thermal loading studies. They are used in some European test methods (such as DIN 75 220, *Aging of Automotive Components in Solar Simulation Units*) and comply with certain military testing requirements (MIL-STD 810G).

Laboratory Corrosion Testing

Corrosion testing of coatings and substrates is often considered a topic separate from "weathering," however coatings weather from the effects of the environment, and substrate corrosion is really just a manifestation of that.

By far, the most widely used corrosion test methods are ISO 9227:2012 *Corrosion tests in artificial atmospheres -- Salt spray tests* and ASTM B117 - 11 *Standard Practice for Operating Salt Spray (Fog) Apparatus*, often referred to as the Neutral Salt Spray (NSS) or "salt fog" test. This consists of exposure of test panels to a 5% sodium chloride (salt) saturated fog at elevated temperature. It can be an aggressive test, however there is substantial disagreement over the relevance and correlation of the test with any real world results, as well as relating the test time to outdoors. One factor may be that the steady state conditions used in the test never occur outdoors.

Several improved basic wet-dry test cycles have been introduced over the years which have offered improved correlation for some coatings. These Cyclic Corrosion Tests (CCT) have now expanded to a variety of fairly complete cycles involving alternate electrolytes, complex temperature and wet/dry cycles (some even involving refrigeration), solution sprays, ramps and holds, etc. Most of these have been pioneered by the global automotive industry.

Unfortunately, it is not currently possible to combine classical weathering testing involving solar radiation with corrosion test exposure to dilute salt atmosphere at the same time. However, ASTM D5894 - *10 Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet*) does alternate between the exposures; some coatings tests use the concept to alternate between a salt spray (fog) and xenon arc weathering.

Advances in Artificial Weathering Test Methods

It is important to note that no artificial test can ever precisely duplicate outdoor exposure conditions. Since outdoor exposure conditions can and do vary greatly on both short term, seasonal and long term cycles, the use of laboratory artificial weathering devices such as the xenon arc Weather-Ometer®, Xenotest® and Suntest, are primarily for the controllable, repeatable and reproducible conditions that the technique provides. Any acceleration over real-time weathering should be considered a bonus rather than the primary reason for implementation, although we recognize that this is not usually the case.

While many test methods have shown good correlation to outdoor weathering

(South Florida or Arizona test sites) for many materials, they do not purport to be equivalent or apply to all materials and products. Their main value is in providing short term interim data and material comparisons until the real time weathering tests are validated.

It must be recognized that standardized test methods have limitations. First, most test methods are universal one-size-fits-all methods which do not factor in specific materials. Also they typically do not represent and may not predict performance in any specific climate. Just as an automobile user manual details the operation of the vehicle but contains no driving instructions, standards may specify conditions, but not how long to run a test or how to interpret the results. This requires much skill and experience as well as specific correlation and acceleration data.

Most standard weathering test methods have remained unchanged for decades, despite advances both in equipment technology and advances in our knowledge of weathering testing, especially for coatings. A recent new xenon arc test method, ASTM D7869-13 *Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings* is the result of over 20 years of research and 10 years of coordinated effort by a consortium of companies*.

Base-coat/clear-coat (BC/CC) paint systems have become a mainstay of the automotive industry, yet failures of these complex and varied systems have cost the industry and continue to be experienced. Often, the accelerated weathering methods used to predict 5 to 10 year performance have resulted in many false positives (failed coatings known to have good performance) false negatives (passed a coating which prematurely failed outdoors), failed to differentiate between coatings with different field performance, or generally failed to reproduce specific failure modes seen in benchmark South Florida outdoor exposure testing or in-service use.

The findings of the multi-year effort centered on three key attributes:

1. The spectra (SPD) used in existing tests did not adequately match sunlight, particular in the critical UV cut-on wavelength
2. Moisture delivery in existing tests was not adequate in terms of method or amount
3. Temperature effects of the natural diurnal cycle were not reproduced in the current testing protocols

One key aspect is that the research showed that the photodegradation chemistry changes in the coatings, as measured by sophisticated analytical techniques, was different in characteristics and/or magnitude between the accelerated laboratory and natural outdoor weathering tests.

***** *The author would like to recognize the entire team that worked together for as many as 10 years on the testing and adoption of this standard. The team includes Lynn Pattison, Don Campbell and Don Barber from BASF; Jacob Zhang and Matt McGreer from Atlas; Karen Henderson and Don Smith from Bayer; Jill Seebergh and Doug Berry from Boeing; Jeff Quill from Q-Lab; Todd Fitz and Nicole Verweys from Honda; and Tony Misovski, Cindy Peters and Mark Nichols from Ford.*

Using clues from EMMAQUA® testing and moisture uptake studies, it was determined that major changes in testing methodology were required. These changes resulted in the new standard. In summary, the new method incorporates:

1. A new xenon lamp optical filter to precisely match the UV cut-on wavelength of terrestrial solar radiation
2. A multi-step irradiance, temperature and humidity profile to better match the natural diurnal cycle conditions of South Florida exposures
3. A repeating 24-hour sequence of long term dark-soak and short daytime cycles to provide adequate coating moisture uptake and greater test acceleration

In short, the new test method was able to achieve vastly improved test correlation, validated with approximately 25 different mono-coat and BC/CC automotive and aerospace paint systems, and achieve a 40% greater test acceleration over the previously used standard method.

Although the new methodology has yet to be extensively evaluated for other paint and coating technologies, the science-based methodology, which is more realistic in terms of weathering stress delivery, is likely to be adopted more broadly in the accelerated laboratory weathering testing of paints and coatings.

6. Conclusion

A variety of weathering testing techniques is available to the coatings formulator, resin and additives development researcher, and end-user. Real time exposures in end-use and/or benchmark locations is still necessary, however the use of accelerated weathering techniques is a practical necessity.

The pace of development of new and improved accelerated techniques has quickened, and the industry is benefitting from better and faster tests. However, it must be recognized that standards development and specification modernization are historically slow processes and the best available techniques may not be included for a decade or more.

Although it may have taken 100 years (Atlas introduced the technique of laboratory accelerated fade and weather testing in 1915), we now have greater confidence in our approach to the accelerated weathering testing of coatings, and this will continue into the future.

For further information contact your local Atlas representative or contact us at:
www.atlas-mts.com.

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