ATLAS
MATERIAL TESTING SOLUTIONS
ACCELERATING YOUR EXPERTISE

WHITE PAPER

HIGH IRRADIANCE WEATHERING TESTING

JULY 17, 2013

AUTHOR: ALLEN F. ZIELNIK
SENIOR CONSULTANT – WEATHERING SCIENCE

HIGH
HIGH
IRRADIANCE
THE TRACK TO FASTER RESULTS

AMETEK
MEASUREMENT & CALIBRATION TECHNOLOGIES

ATLAS®
MATERIAL TESTING SOLUTIONS

AMETEK®
MEASUREMENT & CALIBRATION TECHNOLOGIES

Disclaimer

Atlas Material Testing Technology LLC
4114 N. Ravenswood Avenue
Chicago, IL 60613 USA
Phone +1 773.327.4520
Fax +1 773.327.5787
www.atlas-mts.com

Table of Contents

Executive Summary

The need to determine the weathering performance and service lifetimes of materials and products exists in many industries for both new and existing products. However, the increasing durability of many products and shortened product development cycles has made the time required for outdoor testing problematic. Although industry has relied on various outdoor and laboratory accelerated weathering techniques for many decades, the test accelerations achieved have improved little.

Although many factors may influence weathering, the three principal environmental stresses that affect most products are heat, moisture and sunlight. Of these, the first two offer a somewhat limited opportunity for increasing test acceleration without negatively altering the normal weathering degradation chemistry, and therefore the test results. Increasing the irradiance levels of the natural or artificial solar radiation, however, affords a greater opportunity for increasing test acceleration than most other factors.

High irradiance testing methods have demonstrated the ability of increasing current test acceleration routinely by up to three to sixfold for many materials without degrading the correlation to real time results. Additionally, experimental methods have demonstrated viability at much higher irradiances, up to a factor of about sixty-fold. Many industry standard test methods already exist which utilize or allow high irradiance.

Some weathering degradation chemistry can be driven by factors unrelated to the irradiance. In these cases, increasing the irradiance will not result in increased test acceleration. Therefore, high irradiance testing does require a simple process to validate suitable correlation with both outdoor and laboratory results at traditional solar irradiance levels.

This white paper will describe high irradiance benefits, techniques, and a simple but necessary validation process. High irradiance testing may offer one viable way to achieve the "need for speed" in your weathering testing.

The degree of weathering acceleration attainable with traditional tests has not kept pace with the business "need for speed."

Introduction

When the weatherability of materials is an essential performance characteristic of a product, knowing the degradation characteristics to be expected over time is a critical element that must be determined as early and accurately as possible. To accomplish this, the key weather stresses of heat, light and moisture are applied in ways designed to accelerate this natural process.

Traditional weathering tests, and their governing standards, usually involve irradiance levels up to approximately the high noontime level of sunlight in a sunny location such as South Florida or Arizona. When going beyond this "one sun" level to achieve greater test acceleration it becomes increasingly important to validate the testing. This paper briefly describes the use and advantages of high irradiance in accelerated weathering testing, the necessary validation steps, and the testing options available.

Why perform accelerated testing?

Weathering testing of materials and products is necessary in many industries to determine failure modes, product performance, or service lifetimes. As many products are expected to perform without significant degradation for years, or even decades, real time product testing can be a technical and economic challenge. Therefore, many industries must rely on accelerated weathering techniques to either substantially reduce test times or achieve a longer real world equivalent for a given test duration.

The need for speed

Accelerated weathering testing can speed time to market and reduce the indirect costs associated with long term outdoor exposures, e.g. long product development cycles and lost business opportunities. However, many of these routine tests are based on standards and methods that were developed decades ago and have not kept pace with advances in weathering technology and scientific knowledge. Many of the tests most commonly performed may only provide accelerations over real time outdoor testing on the order of four to six-fold (actual values are material specific, however).

For today's greatly shortened product development cycles, common in the automotive industry, or for durable very long lived goods, as with renewable energy or building products, even this test acceleration rate is often insufficient and costly. Therefore, much of weathering research has focused on two key objectives:

- Improving correlation of accelerated tests with real world performance
- Increasing test acceleration rates

The correlation effort has mainly focused on two separate fronts. On the hardware side, there have been major advances in optical and control technologies. These include, among others, an improved spectral match to sunlight, monitoring of the spectral characteristics of the laboratory light source, better specimen temperature

"One-sun" level testing has often been the norm, but higher irradiance offers an opportunity for more test acceleration.

measurement and control, improved test parameter uniformity, better accuracy, reproducibility and repeatability.

On the applications side, the development of new test method cycles, some of which provide a substantive break from decades old approaches and take full advantage of the new hardware developments, have demonstrated both improved test correlation and acceleration[i]. Advances on both of these fronts have moved out of the research and engineering laboratories and have led to new technologies. Some of these have already been commercialized as new products or services.

High irradiance is one tool which may further increase test acceleration and aid in meeting the "need for speed." It provides an opportunity for "accelerating the accelerated test." The two key advantages are:

- Shortening test times over natural and traditional accelerated weather testing
- Providing a longer equivalent service life exposure in the same time frame as conventional accelerated weathering

Companies with high value durable products, or those seeking quicker test results, can especially benefit from high irradiance testing. As high irradiance testing may offer secondary business advantages such as the potential to reduce testing costs or increase testing throughput, many laboratories may benefit from this test option.

Methods for accelerating weathering in tests?

Natural weathering may involve multiple degradation and failure modes. These may result from the action of one or more environmental stressors leading to undesirable changes to important product properties. The primary weather factors for most organic materials are heat, light and moisture, and their cycles. Individually or in combination, they may produce different effects. For example, the ultraviolet (UV) component of natural solar radiation may cause a coating to yellow and lose gloss, while moisture may simultaneously result in cracking and loss of adhesion to the substrate.

Current weathering testing is based on three fundamental approaches:

I. Natural weathering is based on field exposures in a local climate. As locations will vary in the three main weathering stress levels of heat, solar radiation and moisture, some will be more severe than others for particular materials. Several locations, such as hot/moist South Florida (USA) or Chennai (India) and hot/dry Arizona (USA) or Kalahari (South Africa) serve as weather testing benchmarks. Exposures in these locations are typically more severe than in most other locations, and often already provide some degree of test acceleration over more temperate climates.
II. When degradation and failure primarily result from cyclic stresses, test acceleration may be achieved through faster cycling, i.e., "time compression," of the natural daily and seasonal rhythms.

ATLAS MATERIAL TESTING SOLUTIONS

Benefits:

- ***Shorter tests***
- ***Longer outdoor equivalents***

III. In other cases, an intensification of stress, such as exposure at higher temperature or irradiance, may be used. The resulting degradation at the overstress level(s) can be used to predict that at normal levels.

In practice, a combination of these approaches is usually used in weathering testing. As would be expected, however, there are many underlying fundamental limits and precautions that must be observed when applying these concepts to ensure meaningful results.

Primary weather factors

The main external environmental stresses of heat, light and moisture are not independent factors in weathering. The level of solar radiation, along with ambient air temperature, will affect the specimen temperature. This, in turn, will affect the moisture levels in an exposed specimen. These combined factors may result in stress synergy whereby the resulting degradation is greater, or different, than that resulting from either individual stress alone. For example, some plastics will micro-crack when exposed to a combination of UV and moisture, but not to either stress alone[ii]. Examples of key weather stress factors are shown in Figure 1.

The message is that the more an accelerated test alters the natural balance of heat, light and moisture from that outdoors, the more likely the results will differ. Failure to adequately account for this natural balance in test design is often the basis for accelerated tests resulting in poor correlation with outdoor exposures.

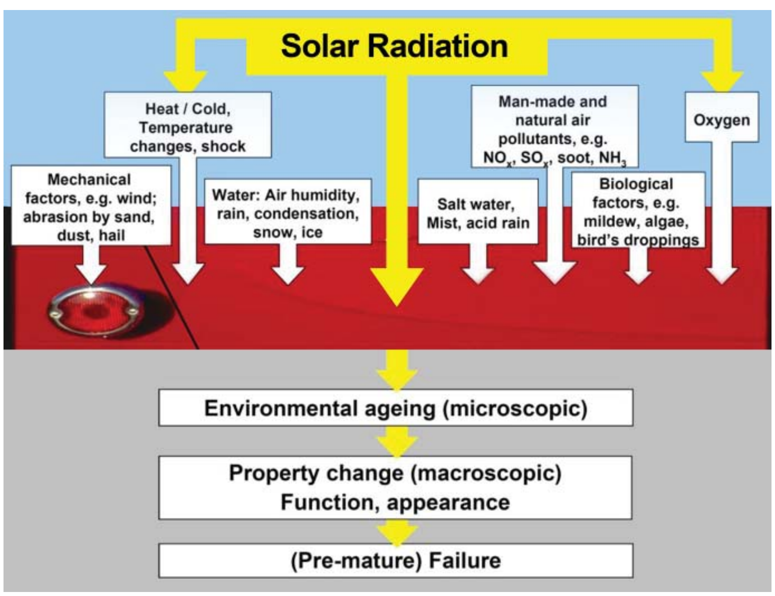

Figure 1 - Factors which can influence product weathering

Of these three main weathering stresses, temperature may be the easiest to manipulate in testing. However, the practical range available for test acceleration is usually quite limited. Sample material-specific factors such as chemical activation energies (E_a), glass transition temperatures (T_g), softening and melting points, and other inherent material properties all limit the range available for applying stress. A too high temperature, for example, can result in scorched samples as is sometimes

ATLAS
MATERIAL TESTING SOLUTIONS

Primary weather factors:

- ***Heat***
- ***Moisture***
- ***Solar radiation***

seen with PVC or automotive fabric testing.

Similarly, moisture levels in accelerated testing are limited to the range of relative humidity levels achievable at a given test temperature in a chamber. Water spray or condensation times can also be adjusted, but may effectively be increased only to the point of specimen saturation. Nylon-6 is a polyamide polymer where moisture alters the $\mathbf{T}_g$. As the photochemical degradation rate is frequently higher above the $\mathbf{T}_g$ (Figure 2), the apparent weathering rate may change with the relative humidity of the test.

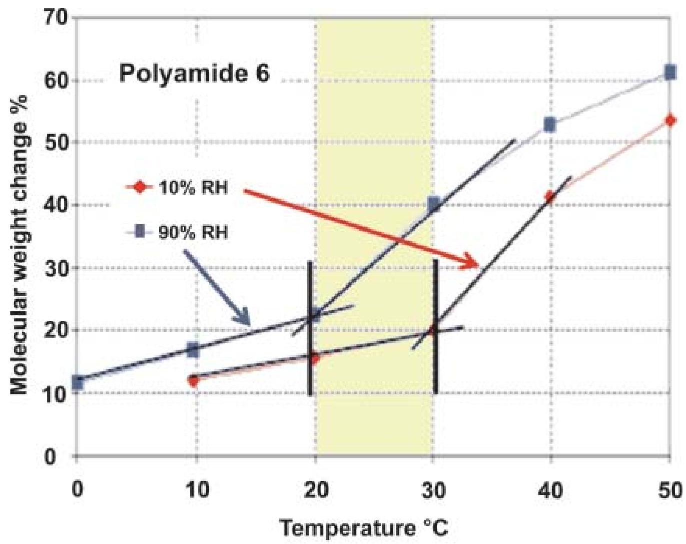

Figure 2 - The $\mathbf{T}_g$ of Nylon 6 decreases with increasing moisture. As weathering rates often increase above the $\mathbf{T}_g$, different test results may be obtained depending on the test relative humidity and temperature parameters[iii].

High irradiance testing includes established outdoor and laboratory techniques.

Solar irradiance

The sun's terrestrial irradiance[1] is the radiant power per unit of area reaching the earth's surface. It varies throughout the daylight hours in a natural diurnal rhythm, and at any point in time is affected by many factors. In accelerated testing we typically have greater flexibility to increase the irradiance level than we have to raise most other stresses, such as heat or moisture. High irradiance is one viable approach for achieving increased test acceleration for many products.

Locations such as Arizona's Sonoran Desert, the site of Atlas' DSET Laboratories exposure test facility, inherently provide higher solar irradiance than most other locations[iv]. Solar concentration techniques such as Atlas' EMMA® and EMMAQUA® can further increase the irradiance by a factor of four to eight. Artificial light source laboratory devices such as Atlas' xenon arc Weather-Ometer® and Xenotest® instruments can continuously vary irradiance over a wide range without changing the spectral power distribution. Usually the limiting factors are the natural balance of the stresses, or test specimen parameters such as temperature limits. Nevertheless, higher test irradiance often provides the greatest opportunity for controlled test

1. ***E*** is Irradiance in Wm^{-2}; $\boldsymbol{E_\lambda}$ is the spectral Irradiance in $Wm^{-2}\ nm^{-1}$

acceleration than do the other weather stress factors.

What is high irradiance testing?

The term "high irradiance" refers to any irradiance higher than that of natural sunlight. Therefore, a sunlight reference is required. CIE Publications No. 20[v] and 85[vi] have traditionally served as an internationally accepted "definition" of standard reference sunlight. For testing purposes, CIE No. 20 specifies spectral irradiance values of:

- 60 W/m^2 between 300 and 400nm
- 1000 W/m^2 between 300 and 3000 nm

Later, international standards added a similar irradiance level for daylight behind 3mm window glass:

- 50 W/m^2 between 300 and 400nm

Figure 3 shows the comparative differences between the two spectra in the UV region.

For comparison, using "daylight" filters in a xenon arc weathering instrument, this

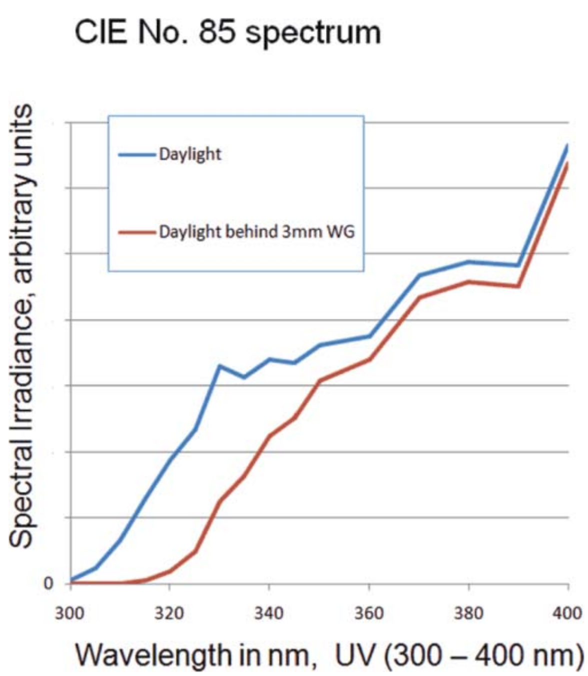

Figure 3 - Comparison of UV spectra for daylight and behind window glass testing in CIE references

is approximately equivalent to a spectral irradiance of 0.51 W/m^2 nm at 340nm, historically quoted as the level attained on a south-facing inclined test rack in South Florida (average noon). It is also effectively the default in ISO 4892-2[vii] and other widely used standards.

As there are no global solar radiation monitoring networks in place, and the accuracy and precision of individual measurements are subject to many variables, a comparison of the above values with modeled data can serve as a check.

MATERIAL TESTING SOLUTIONS

Defining a standard reference for natural solar radiation.

Atlas has used its proprietary CESORA[2] software, based on the global SMARTS[3] database, to compare the calculated spectral ranges at several locations at summer solstice noon, and found reasonable agreement (±10% of the CIE values) for Arizona and Florida weathering benchmarks (Figure 4)[viii]. This supports 60 W/m² between 300 and 400nm as a reasonable 1-sun reference value (Figure 5).

wavelength range	Arizona	Florida	Frankfurt	Milano	CIE No. 85 (table 4)
nm	E (W/m²)	E (W/m²)	E (W/m²)	E (W/m²)	E (W/m²)
280-300	0.016	0.017	0.008	0.016	0.01
300-400	60	62	48	59	66
400-800	566	584	469	532	617
800-4000	420	387	350	347	434
280-4000	1046	1033	867	938	1117

Figure 4 - Comparison of modeled outdoor and CIE irradiance values

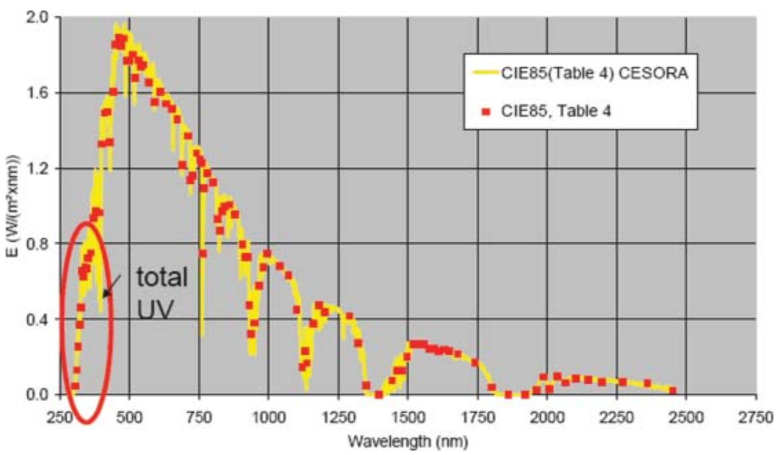

Figure 5 - Modeled outdoor versus CIE reference values

A matter of definition

Atlas uses the CIE values to establish a "1 sun" baseline, with 1.5-sun, 3-sun, etc., being simple arithmetic multiples of that value. Note however, that "sun" is not a standardized term and others may use different reference values. For example, 0.35 W/m² at 340nm has been a historical setting for some standards, e.g. ASTM G155[ix], Cycle 1. Although largely based on equipment limitation of earlier testing devices, some may consider this to be their "1 sun" level. This would make the approximate 0.7 W/m²nm at 340nm used in some fluorescent condensation (e.g., UVTest) and xenon standards, to be at a 2-sun level while Atlas would consider it circa 1.4-sun. Many standards (e.g., ISO 4892-2, ISO 11341, JASO, VDA) currently allow testing up to 3-sun (180 W/m² and 162 w/m² for behind window glass in the UV region) levels.

For consistency, Atlas will reserve the term "high irradiance" to refer to ≥ 2-sun as based on the CIE and ISO references. The important point however, is to recognize that the term "sun" is arbitrary and useful only to convey a relative magnitude of sunlight intensity and is not a test acceleration factor.

2. Calculation of Effective Solar Radiation (CESORA)
3. SMARTS model developed by Dr. C. Gueymard

Achieving high irradiance

There are three common ways to achieve higher irradiance:

I. Concentrating optics such as mirrors or lenses
II. Higher output or multiple light sources
III. Decreased distance between the light source and specimen

Devices such as the Atlas' EMMA® and EMMAQUA® Fresnel solar concentrator[x] implement the first principle. These employ ten special first surface mirrors to focus direct beam solar radiation onto the test target). Instruments such as the Atlas' Xenotest® Alpha+ or the SEC 3 SUN solar environmental chamber primarily use the second approach. The third relies on the inverse square law, whereby the specimens are positioned closer to the light source, as in the Atlas Ci5000 HE Weather-Ometer® and the SEC 10 SUN chambers. These last two techniques are usually used in combination for the greatest effect.

Spectral power distribution

It is recognized that even small deviations in the spectral power distribution of a light source from that of outdoor sunlight can impact weathering results. This has resulted in a continual effort to "get the light right" in testing to improve correlation; this is true for both outdoor and laboratory accelerated techniques. A good example is the development of the Right Light™ filter technology[xi] for the Ci-Series Weather-Ometers, which is the closest solar spectral match yet achieved (Figure 6). To avoid inaccuracy when referring to multiple "sun" levels, the light should be as close a spectral match as possible to full spectrum sunlight, as even small deviations may become more pronounced in their effect on specific test materials at high irradiance.

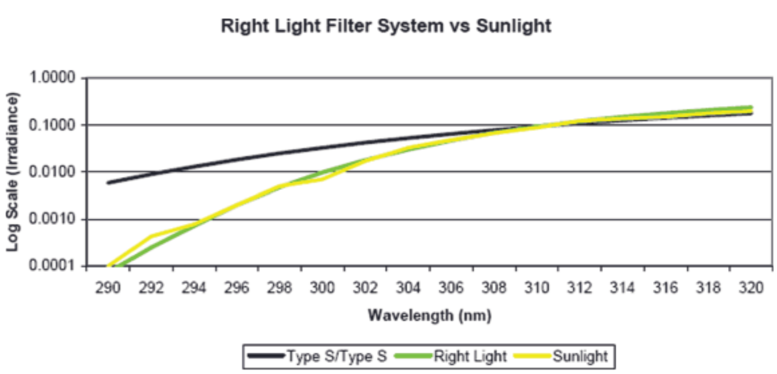

Figure 6 - Small deviations in spectral match can be significant in weathering chemistry; Right Light optical technology is the closest spectral match to sunlight in the critical UV region. Log scale used to highlight the differences.

Increasing the irradiance full spectrum is not without consequence, however, as undesired thermal energy from the infrared region can be difficult to mitigate. Atlas' UA-EMMA doubles the UV irradiance over conventional EMMA while eliminating most of the visible and IR wavelengths.

ATLAS
MATERIAL TESTING SOLUTIONS

"One-sun" level defines the relative irradiance, but the spectra must match sunlight too.

Atlas' very high irradiance Ultra Accelerated Weathering System[xii] (UAWS) also concentrates only UV and very low wavelength visible sunlight onto the specimen, and offers an opportunity for achieving high levels of acceleration for UV degradation. As these devices do not provide full spectrum solar radiation, the term "suns" is best avoided when describing their light intensification factors.

Thermal and moisture effects in weathering

As noted previously, light, heat and moisture stresses are linked in weathering and it is important to properly regulate the temperature and moisture stresses as irradiance is increased. Temperatures, in particular, become more difficult to manage at high irradiances. Therefore, Atlas' high irradiance offerings are optimized for superior temperature management (Figure 7). The Atlas Xenotest® Alpha+, for example, allows for a wide range of irradiance while keeping the temperatures (both black panel/black standard and chamber air temperature) constant.

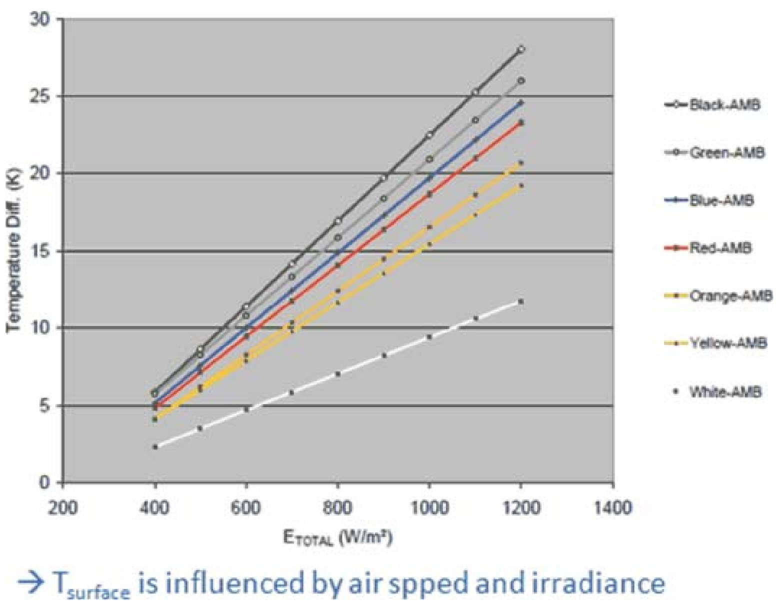

Figure 7 - Excellent linearity of color coated panel surface temperature control achieved with increasing irradiance in Alpha+[xiii]

Temperature management and control becomes more critical with high irradiance testing.

Weathering test acceleration & correlation

An acceleration factor (AF) is commonly used to describe the relative degree of acceleration of a test. The AF is a simple equation that indicates how much faster the accelerated test produces the equivalent amount of property change as compared to a natural outdoor exposure, whether at a test site or in-use service condition.

$$AF_{(light,\ heat,\ moisture,\ etc.)} = \frac{t_{outdoor}}{t_{accelerated}}$$

Although AF is a simple concept, there are several important points to note:

- Valid only for a specific combination of a natural exposure and an accelerated test
- Correlation must be maintained; i.e., the degradation chemistry and resulting changes must be faithfully reproduced
- Applies to the times (or time-dependent variable such as radiant exposure) to reach a specific and equal amount of a property change, e.g., be it chemical, appearance, physical, etc., and not to the increased level of any stress
- May not be constant or linear with exposure time

Often, theoretical or pseudo-AF's are calculated by relating two exposures. An example would be the test hours in ISO 4892-2 Method A required to reach the same radiant exposure of one exposed outdoors, such as at Atlas' Sanary sur Mer (France) Mediterranean test site. Note that this involves no property measurement; it does not even involve a test specimen. However, this is not a valid use of the AF concept, which must be based on the times (or a time-dependent parameter such as radiant exposure) required to produce an equivalent property change. Note that as products weather age they may become increasingly more susceptible to the effects of an applied stress. This is characteristic, for example, of UV-stabilized polymers (Figure 8).

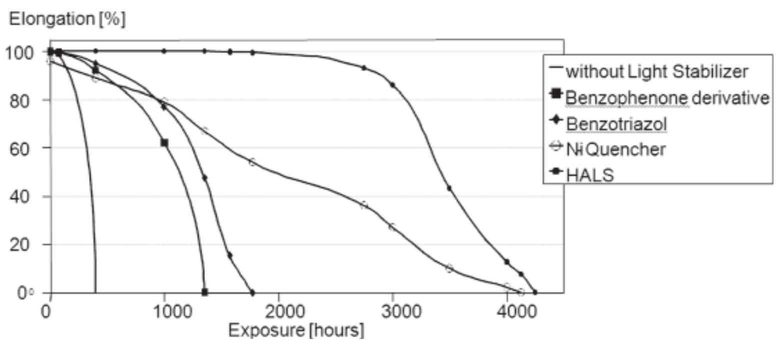

Figure 8 - Polypropylene with various additive stabilizers; note the change in tensile elongation is not linear with exposure time (accelerated weathering)[xiv]

If the rate of degradation changes during the natural or accelerated exposures, the acceleration factors will also change. Therefore, be aware that AF's are usually not constants, and several data points may be necessary to establish correlation. The important take away is that acceleration factors and any increase in applied stress, such as higher irradiance, are not interchangeable. A 3-sun level test may not produce either three times the property change or an equal amount in one third of the time.

To illustrate, the 3M Company, in the long term testing of their plastics, coatings, paints and polymers, has reported true AF's ranging from 1.8 to 50 when comparing their particular xenon arc weathering tests to South Florida benchmark exposures[xv].

MATERIAL TESTING SOLUTIONS

Weathering test "acceleration" must be defined as a function of a specific property change in your individual product.

The principle of reciprocity

In film photography, reciprocity is the inverse relationship between the intensity and exposure time that determines the reaction of a light-sensitive material. The basic principle is that if reciprocity is observed, equivalent radiant exposures (radiant exposure = irradiance x time) will produce the same amount of photochemical change, no matter what combination of time and light intensity. These two exposure variables were the camera's aperture (f-stop) and shutter speed.

If reciprocity holds true, a short exposure at higher irradiance would be exactly equivalent to that of a longer test at low irradiance, provided they delivered the same radiant exposure and produced identical results[xvi].

This can be visualized for weathering exposures in Figure 9; ***H*** is the radiant exposure, ***E*** is the irradiance and ***t*** is time.

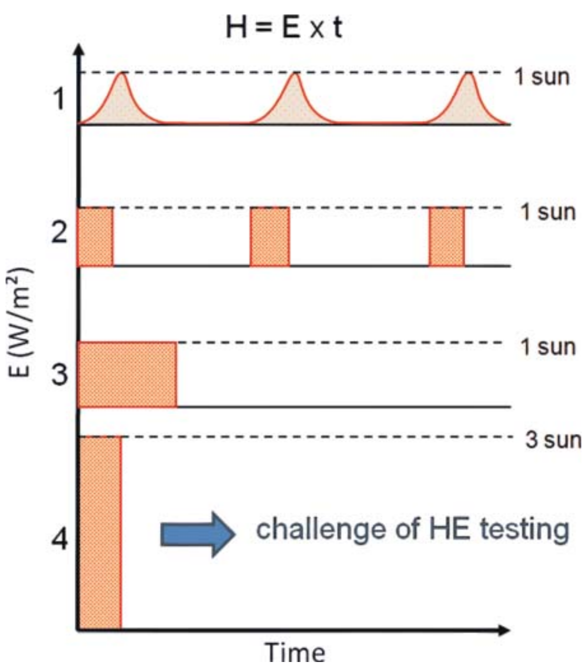

Figure 9 - Illustration of natural and laboratory equivalent radiant exposures ***(H)***

Line 1 illustrates diurnal irradiance over 3 days showing the natural diurnal cycle. Line 2 is the effective steady-state irradiance to equal Line 1. Line 3 shows the reduced time to achieve the equivalent 3 day radiant exposure by eliminating night dark times and using continuous light. Line 4 shows the equivalent radiant exposure by tripling the irradiance but decreasing the test time to one-third. For reciprocity to be obeyed, the type and amount of property change must be equivalent in all four cases.

For photographic film, it was found that for very short or very long exposures, or both, reciprocity "fails." However, the effect was repeatable and could be accounted for and exposures corrected. This concept was used to modernize and expand the current concept of reciprocity beyond the original linear photography model.

Actual test "acceleration factors" are highly variable and specific to your product and the test conditions.

This "Schwartzschild effect[xvii]" can be described by a modern power law equation:

$$k=AI^p$$

Where ***k*** is the rate of reaction, ***A*** is a proportionality constant, ***I*** is intensity, and ***p*** is the experimentally derived Schwartzschild coefficient (slope of line of log(***k***) v. log(***I***) plot). This equation can be rewritten as:

$$\Delta P=E^p$$

Where Δ***P*** is the change in some material property, ***E*** is the irradiance level, and ***p*** is the above Schwartzschild coefficient[xviii], sometimes referred to as a reciprocity factor.

When ***p*** = 1, reciprocity is linear, i.e., strictly observed. For ***p*** < 1, the rate of property change increases less than expected from the increased light intensity. However, even if reciprocity is not linear the effect may be repeatable for a given material. In such cases, high irradiance testing may still be used for materials with high ***p*** values, provided an equation can be fit to the data. As ***p*** values decreases, the correlation goes down and the test acceleration factor decreases, limiting its usefulness.

In addition to acceleration factors, the 3M researchers experimentally determined exponent ***p*** for over 50 different materials with values ranging from 0.2 to 1.12 and a mean of 0.64. Jorgensen[xix] examined polyvinyl chloride (PVC) and UV-stabilized polycarbonate (PC) polymers at irradiances up to 50-sun using a solar concentrator. Values for ***p*** were 0.67 for the PVC and 1.1 for the PC over a very wide irradiance range. National Institute for Standards and Technology (USA) researchers have experimented and extensively reported on weathering photo-reciprocity[xx].

Non-reciprocity and an inability to fit an equation to the data would result if non-photon processes are the dominant rate limiting factors[xxi]. Non-photon degradation mechanisms (Figure 10) are a likely source of reciprocity failure. For example, moisture hydrolysis, oxygen diffusion and thermally influenced free radical and oxidative reactions are frequently involved in the weathering of polymeric materials.

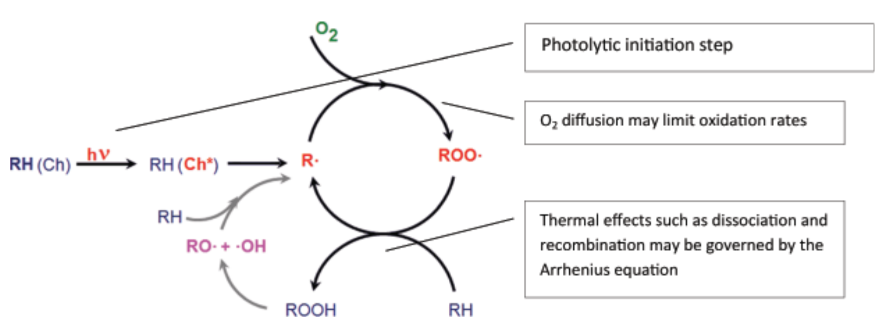

Figure 10 - Photolysis is an initiating step in polymer auto-oxidative degradation, but subsequent reactions may be influenced by secondary factors independent of irradiance. Lastly, other co-stresses (Figure 11) may be involved in natural material weathering that can affect reciprocity and correlation.

Reciprocity equates total radiant exposure to identical property change, regardless of the time it takes.

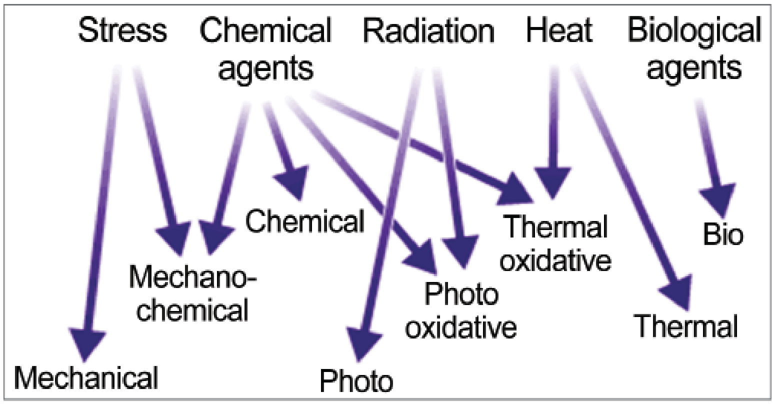

Figure 11 - Weathering factors and possible resulting degradation mechanisms

In such cases a mathematical relationship of property change to radiant exposure at higher irradiances cannot be established. This means that if accelerated test data is to be used to estimate a property change under normal exposure, reciprocity must be determined by correlating the results at the higher test irradiance(s).

The consequence of ignoring reciprocity effects (particularly for low values of p) is to generally underestimate material degradation and to overestimate service life based on the accelerated test. Where a mathematical relationship cannot be established, high irradiance testing will not be predictive. Therefore, validating reciprocity through correlation studies should be considered a necessary step in high irradiance testing.

This does not imply that high irradiance testing is more complicated, but rather serves to reinforce the fundamental message that all accelerated testing results, including weathering, must be properly validated through correlation studies. This applies equally to conventional accelerated weathering testing at ≤ 1-sun irradiance.

Testing for reciprocity

A simplified method to test for reciprocity is currently being developed as a new ISO Technical Report[xxii] to validate reciprocity in weathering tests. In summary, exposures are conducted at the standard and any increased irradiance(s). To help isolate irradiance effects from any complicating effects from heat and moisture, these are held constant as the irradiance is increased. The measured property changes are then plotted as a function of radiant exposure (the time-dependent parameter). A curve is then fitted to the graph to determine the degree of deviation (shown in Figure 12 as R^2 in a linear regression analysis; R^2 is the square of the Pearson's correlation coefficient, r).

ATLAS
MATERIAL TESTING SOLUTIONS

The modern concept of reciprocity allows for some degree of non-linear response, provided it is reproducible.

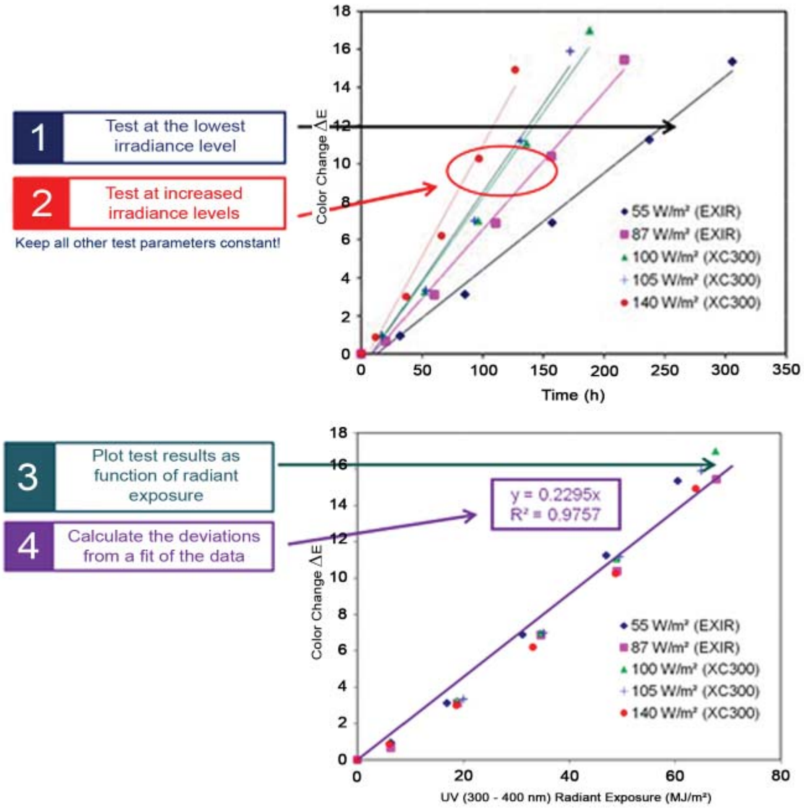

Figure 12 - Simplified reciprocity validation method using ORWET[xxiii] orange lacquer coating standard reference material; ISO 4892-2 xenon test method (no water spray). Note that the property change (ΔE) is very linear with radiant exposure for this material.[xxiv]

The Pearson correlation coefficients[xxv] can also be calculated. A good correlation, for example, would be a Pearson correlation coefficient >0.9 as per the draft ISO standard.

Note that a non-linear change to a property with radiant exposure, which is common, is not the same as a reciprocity failure. For example, Figures 13 and 14 illustrate xenon testing of two polyurethane automotive seating materials (backed by foam or fabric), and show a non-linear ΔE color change with exposure time at three irradiance levels[xxvi].

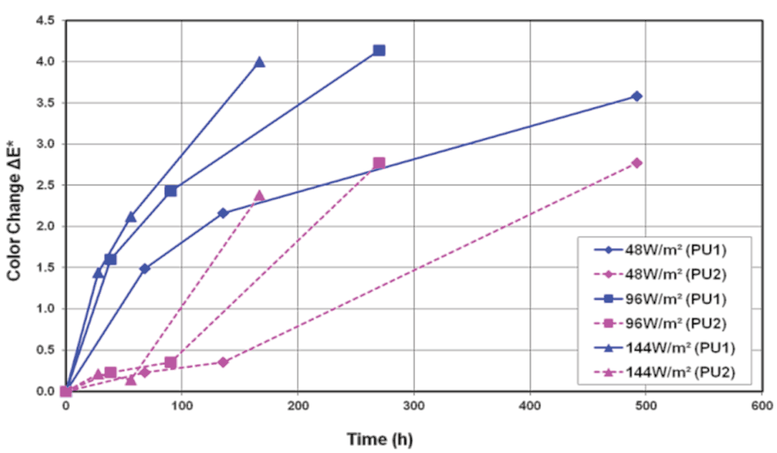

Figure 13 - When the ΔE is plotted as a function of radiant energy it is easier to visualize that the correlation at the three irradiance levels for each specimen type.

ATLAS
MATERIAL TESTING SOLUTIONS

Materials strongly influenced by factors other than light will not likely be good candidates for high irradiance testing.

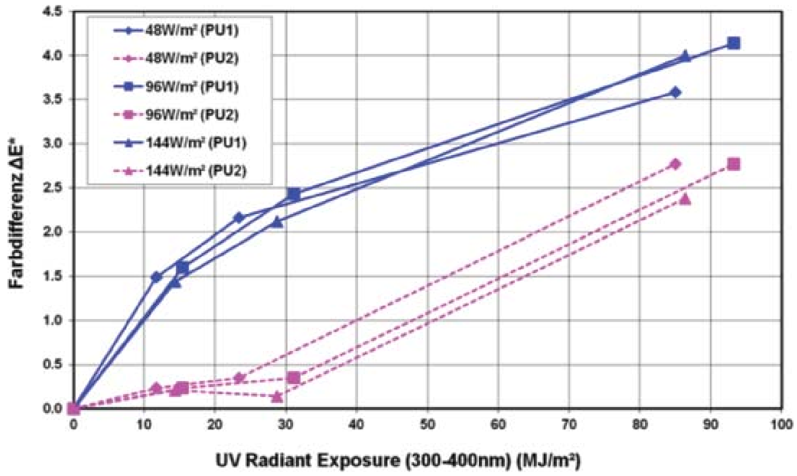

Figure 14 - Although the property change is not linear with radiant exposure, the amount of the change at equal radiant exposures, but different irradiances, was similar; this is an indication that reciprocity was obeyed. A curve fit showed excellent R^2 values (R^2 is the square of the Pearson correlation coefficient, r).

A curve fit of the data (Figure 15) at the three irradiances for each polyurethane (ΔE versus radiant exposure) shows excellent R^2 values (Pearson correlation coefficients r >0.9) showing a high (though not linear) degree of reciprocity; these are examples of materials validated for high irradiance testing.

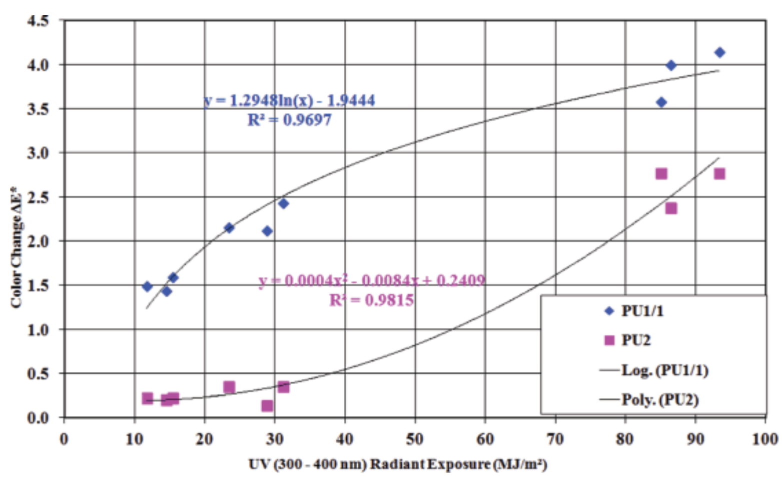

Figure 15 - A fit of the data at three irradiances for two polyurethanes, ΔE versus radiant exposure shows good reciprocity.

The important point to note is that the material property change does not need to be linear with radiant exposure for the sample to obey reciprocity. These are separate concepts.

When reciprocity is not observed, extrapolating meaningful data from high irradiance testing becomes substantially more complex. This is often beyond the capability of many laboratories. However, when reciprocity is validated (e.g., r >0.9), increasing irradiance up to 3-sun levels (as currently used in many high irradiance standards), will further increase the acceleration factor attained at conventional 1-sun testing. This can result in an additional threefold reduction, for example, in accelerated testing time (over 1-sun testing) to reproduce an equivalent outdoor radiant exposure.

ATLAS
MATERIAL TESTING SOLUTIONS

Many materials have a high degree of reciprocity, but reciprocity cannot be assumed.

Acceptance of high irradiance techniques

Testing at irradiances >1-sun has been common for decades. For example, there is 20 years of experience with the Xenotest® Alpha HE and 50 years with EMMAQUA® weathering. There are many applications (Figure 16) where the effectiveness of high irradiance testing has been successfully demonstrated.

APPLICATION	IRRADIANCE (UV)	INSTRUMENT / TECHNOLOGY	REFERENCE
Textiles	up to 3-sun	Xenotest® Alpha	1), 2)
Automotive Interior Materials	up to 3-sun	Xenotest® Alpha	1), 3)
Automotive Coatings	up to 3-sun acceleration factor to South Florida up to 63	Xenotest® Alpha Ultra Accelerated Weathering System (UAWS)	1) 4)
Polymers	up to 2-sun up to 4-sun	Ci35, Ci4000, Ci5000 Weather-Ometer® EMMAQUA®	5) 6) 7)
Solar Materials/ CPV Encapsulants	up to 32-sun	Modified Ci4000 Weather-Ometer®	8)

References:

1) Artur Schönlein et al. GUS-Jahrestagung, Stutensee (2013).
2) Jochen-Wilfried Stuck, DEK Fachtagung „Echtheitsprüfungen in der Textilindustrie", Gelnhausen (1996).
3) Jörg Boxhammer, Polymer Testing 20 (2001), 719 ff.
4) Henry K. Hardcastle et al. SunSpots Volume 40, Issue 88 (2010).
5) James Pickett et al. Polym. Degrad. Stab. 93 (2008), 1597 ff.
6) Kurt Scott et al. Service Life Prediction of Polymeric Materials (2009), 83 ff.
7) Henry K. Hardcastle et al. 2nd European Weathering Symposium, Gothenburg (2005).
8) Michael Kempe et al. SunSpots Volume 39, Issue 85 (2009).

Figure 16 - Published examples using high irradiance

As weathering technology has evolved, test standards have been migrating to higher irradiance levels. There are industry and OEM proprietary tests in the automotive industry specifying up to 3-sun levels, and many standards either specify or permit high irradiance (Figures 17 and 18).

XENON WEATHERING STANDARD	SCOPE	ALLOWED IRRADIANCE LEVELS UP TO 3 SUN (i.e. 180 W/m2 (UV) for daylight filters)	COUNTRY
ISO 4892-2	Plastics	Daylight and window glass	International
ISO 11341	Coatings	Daylight and window glass	International
ISO 105-B06	Automotive interior	Window glass, set of exp. cond. no. 6	International
ISO 105-B10	Textiles	Daylight	International
ASTM G155	Non-metallic materials	Daylight (cycle 9); window glass (cycle 10)	USA
ASTM D6695	Coatings	Daylight (cycle 1)	USA
VDA 75202	Automotive interior	Window glass, option A	Germany
JASO M346	Automotive interior	Window glass	Japan
JASO M351	Automotive exterior	Daylight	Japan

Figure 17 - Some representative high irradiance xenon arc weathering standards

EMMAQUA® STANDARD	SCOPE	COUNTRY
ISO 877-3	Plastics	International
ASTM D3841	Glass-fiber reinforced polyester	USA
ASTM D4141	Coatings	USA
ASTM D4364	Plastics	USA
ASTM D5722	Coated hardboard	USA
ASTM E1596	PV modules	USA
ASTM G90	Non-metallic materials	USA
SAE J576	Optical automotive plastics	USA
SAE J1961	Automotive exterior	USA
SAE-AMS-T-22085	Preservation sealing tape	USA
JIS Z2381	General	Japan

Figure 18 - Representative Fresnel solar concentrator weathering standards

Is high irradiance right for you?

Many industries rely on accelerated weathering testing to provide data faster than is possible with real time outdoor exposures. However, the speed of accelerated weathering at a near-normal solar irradiance level, as is used in many common standards, may still be insufficient when testing long lived durable products, or where product development cycles are very short. For these, high irradiance testing offers an opportunity to significantly decrease testing time, or increase the outdoor equivalent age. High irradiance may also substantially reduce testing time for routine repetitive quality assurance (QA) of known materials in instances where correlation has been demonstrated.

High irradiance testing can be implemented through various techniques, including outdoor and laboratory accelerated options. These can also serve, when advantageous, to complement conventional weathering testing methods. Secondary benefits include the potential to reduce testing costs as well as time, and those resulting from the ability to make critical product decisions earlier in the development cycle.

All accelerated weathering results should be validated with outdoor exposures as any accelerated methodology has the potential to introduce bias. High irradiance testing does require verifying reciprocity in order to have confidence in the results, and some materials will prove unsuitable for the technique. This can be confirmed through a simple procedure. Atlas, the pioneer in weathering testing and high irradiance

Property change does not need to be linear with radiance exposure, provided there is a high degree of reciprocity.

techniques, offers a range of standard and custom high irradiance product and testing service solutions and the technical expertise to guide you through your implementation.

For more information about high irradiance testing or to discuss if high irradiance testing may be appropriate for your needs, please contact an Atlas Weathering Consultant.

Contact Details

Phone: +1-773-327-4520 • Fax: +1-773-327-5787 • E-mail: atlas.info@ametek.com

ATLAS MATERIAL TESTING SOLUTIONS

Reciprocity equates total radiant exposure to identical property change, regardless of the time it takes.

References/Citations

[i] ASTM D7869 - 13 Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings

[ii] Blaga, A; Yamasaki, R J;Mater. Sci., 1976, 11, 1513

[iii] Trubiroha and Patuska

[iv] Atlas Network of Weathering Products and Services, Pub. No. 2066, 2011, p.43

[v] CIE Publication No. 20-1972 "Recommendations for the integrated spectral irradiance and the spectral distribution of simulated solar radiation for testing purposes"

[vi] CIE Publication No. 85-1989 "Technical report – Solar spectral irradiance":, ISBN 3 900 734 22 4

[vii] ISO 4892-2:2013 "Plastics -- Methods of exposure to laboratory light sources -- Part 2: Xenon-arc lamps"

[viii] Schönlein, A; Haillant,O; Senff, S; "Surface Temperatures of Color Painted Specimens in Natural
and Artificial Weathering with Different Laboratory Light Sources for Optimized Testing and Investigations", 4th European Weathering, 2009

[ix] ASTM G155 - 05a "Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials"

[x] ASTM G90 - 10 "Standard Practice for Performing Accelerated Outdoor Weathering of Nonmetallic Materials Using Concentrated Natural Sunlight"

[xi] McGreer, M; Chesler, J; "Improvements in Simulating Natural Sunlight Within Artificial Weathering Devices", NPCA/FSCT Coatings Tech Conference Vol.1, ISBN 978-1-61567-602-6, April, 2009

[xii] Hardcastle, K; Jorgensen, G; Bingham, C; "Ultra-Accelerated Weathering System I: Design and Functional Considerations"; 4th European Weathering Symposium, 2009

[xiii] Schonlein, A; Gesellschaft fuer. Umweltsimulation. (GUS)

[xiv] Dr. Zah, Cariant GmbH

[xv] Ketola, W; "How Long Do I Have to Run My Accelerated Test", 6th International Automotive Weathering Technology Symposium, 2007

[xvi] Bunsen, R.W. and Roscoe, H.E., Ann. Phys., 108, 193,1859

[xvii] Rudolph Seck and Dennis H. Laney (1983). Leica Darkroom Practice. MBI Publishing Company. p183. ISBN 978-0-906447-24-6

[xviii] Graham Saxby; The Science of Imaging. CRC Press. p141. ISBN 978-0-7503-0734-5, 2002

[xix] Jorgensen, G; et al., "Use of Uniformly Distributed Concentrated Sunlight for Highly Accelerated Testing of Coatings," in Service Life Prediction, Methodology and Metrologies, J.W. Martin and D.R. Bauer, eds., ACS Symposium Series 802, American Chemical Society, Washington, D.C. p.11, 2002

[xx] Martin, J; Chin, J; Nguyen, T; National Institute of Standards and Technology, "Reciprocity law experiments in polymeric photodegradation: a critical review", Prog. In Org. Coating 47, p292-311, 2003

[xxii] ISO/TC 61/SC 6 N 1339 Plastics – Deterministic acceleration of laboratory weathering (draft,2013)

[xxiii] Schulz, U.; "Accelerated Testing: Nature and Artificial Weathering in the Coatings Industry, p.91, ISBN 3-86630-908-2, 2009

[xxiv] Schönlein, S.; et al; GUS-Jahrestagung, Stutensee, 2013

[xxv] Schulz, U.; "Accelerated Testing: Nature and Artificial Weathering in the Coatings Industry, p.162, ISBN 3-86630-908-2, 2009

[xxvi] Jörg Boxhammer, Polymer Testing 20 (2001) 719 ff.

ACCELERATING YOUR EXPERTISE

4114 North Ravenswood Avenue
Chicago, Illinois 60613, USA
Phone: +1-773-327-4520
E-mail: atlas.info@ametek.com

www.atlas-mts.com

MEASUREMENT & CALIBRATION TECHNOLOGIES