Weathering and Light Stability Testing of Printed Materials

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Abstract

This paper explores four technologies used for testing weathering and light stability of printed materials, giving special attention to those most commonly used today: xenon arc test chambers (ASTM G155, ISO 4892-2) , fluorescent UV weathering testers (ASTM G154, ISO 4892-3), and a variant of the fluorescent tester for simulating indoor lighting. The inherent strengths and weaknesses of each tester will be discussed and general guidelines will be given for which tester appropriate for a particular material or application. Spectral sensitivity of materials and the importance of proper units of measure for light intensity will be discussed, leading to conclusions on the difficulties and opportunities that arise from accelerated testing.

In this paper, the brand name QUV® will sometimes be used to indicate a fluorescent tester. The brand name Q-SUN® will sometimes be used to indicate a xenon tester. Both brand names are trademarks of Q-Lab Corporation.

I. Accelerated Weathering: A Historical Perspective

While it is clear that weatherability and light stability are important for many products, the best way to test is sometimes controversial. Various methods have been used over the years. Most researchers now use natural exposure testing, xenon arc chambers, or fluorescent UV testers, best known by the trade name QUV Weathering Tester.

The two testers are based on completely different approaches. Xenon arc test chambers reproduce the entire spectrum of sunlight, including ultraviolet (UV), visible light, and infrared (IR). The xenon arc is essentially an attempt to reproduce sunlight itself, from 295 nm - 800 nm (see Figure 1).

The QUV, on the other hand, does not attempt to reproduce sunlight, just the damaging effects of sunlight that occur from 300 nm - 400 nm. It is based on the concept that, for durable materials exposed outdoors, short-wave UV causes the most weathering damage.

A version of the QUV was developed specifically for materials and systems which will be exposed to interior lighting conditions. This tester, designated the QUV/cw, uses standard cool white fluorescent lamps in place of the ultraviolet lamps used in common accelerated weathering tests.

Obsolete Technologies

Two other technologies have been referenced in test standards used for printed materials: carbon arc, discussed below, and a device known as the HPUV (manufactured by Atlas Material Testing Technology, LLC based on a design from Hewlett Packard), which used a mixture of high power cool white lamps and fluorescent UV lamps. The UV lamps were used with a borosilicate glass optical filter to eliminate short wave ultraviolet light from the spectrum. This combination made the device useful for materials subject to interior lighting and sunlight through windows. This device was manufactured in the 1980's and into the 1990's and has been unavailable for a number of years.

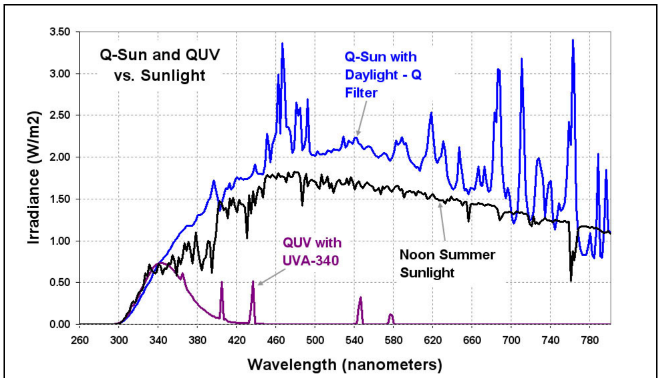

***Figure 1**. Sunlight compared to the Q-Sun and the QUV. The QUV provides the best available simulation of sunlight in the short-wave UV region from 365 nm down to the solar cutoff. However, it is deficient in longer wavelengths. The Q-Sun reproduces sunlight's full spectrum, which is critical for testing many products that are sensitive to long-wave UV, visible light, and infrared.*

Currently written into ASTM D3424 and ASTM F-1946/1946M, the unavailability and relative obscurity of the device have resulted in adoption of xenon arc and fluorescent UV tests in the standard. The other major standard referencing the HPUV is ASTM D4674, Standard Practice for Accelerated Testing for Color Stability of Plastics Exposed to Indoor Office Environments. This document also references use of fluorescent UV testers using cool white lamps or UVA-351 lamps. Both methods are discussed below.

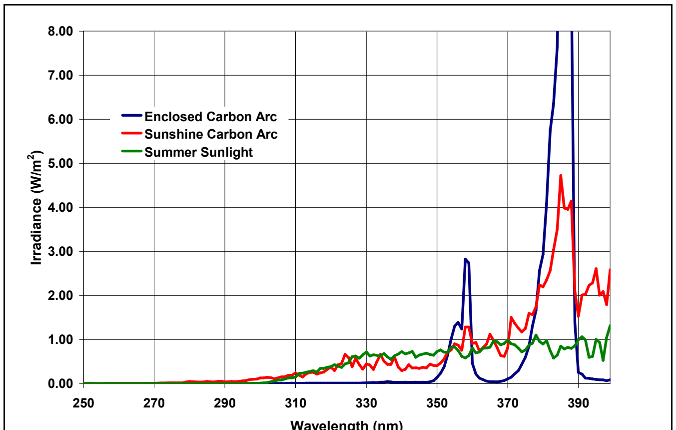

***Figure 2**. Sunlight compared to the Enclosed Carbon Arc and Sunshine Carbon Arc in the UV region. The Enclosed Carbon Arc consisted of two large energy spikes in the long wave UV spectrum, while the Sunshine Carbon Arc traded these spikes for more short wave UV energy. Although used for weathering and light stability testing for decades, today neither is considered an accurate representation of sunlight in the visible or UV parts of the spectrum.*

Carbon arc testers were the first weathering and light stability testers developed nearly a century ago. Currently this technology is only manufactured in Asia and has been replaced in the market mainly by xenon arc testers but for some applications fluorescent UV testers. Carbon arc machines produce full spectrum light, meaning that the spectra includes ultraviolet, visible, and infrared energy. However, neither version of the carbon arc discussed below accurately reproduces sunlight.

The enclosed carbon arc emits very large energy spikes in the long wave UV part of the spectrum but virtually none in the short wave band (figure 2). The sunshine carbon arc dampens the huge energy spike in the long wave UV part of the spectrum, although it is still quite large. However, the spectral shift results in unrealistic short wave UV energy, well below the solar cut-on of 295 nm. Either spectrum can result in unrealistic degradation. In addition to the spectral deficiencies of carbon arc, the technology is expensive and very labor intensive to operate. The light source was composed of carbon rods that had to be changed every day. Despite these deficiencies, the technology was quite useful for light stability testing for decades

Because of their obsolescence, the remainder of this paper will ignore carbon arc and the HPUV. Of the two current technologies, QUV and xenon arc, which is the better way to test? Depending on your application, either approach can be quite effective. Your choice of tester should depend on the product or material you are testing, the end-use application, the degradation mode with which you are concerned, and your budgetary restrictions. Section V will give some specific guidelines

II. QUV Weathering Tester, aka Fluorescent UV Weathering Tester

QUV Sunlight Simulation

The QUV is designed to reproduce the damaging effects of sunlight on durable materials by utilizing fluorescent UV lamps. Introduced in 1970, by the early 1980's it was the most widely used type of weathering tester in the world, which holds true to this day.

The UV lamps are electrically similar to the common cool white lamps used in general lighting, but the spectrum they produce is quite different than common fluorescent lamps. The coatings in the glass of the tubes are carefully designed to produce mainly UV rather than visible light or infrared energy.

There are different types of lamps with different spectra for various exposure applications. UVA-340 lamps provide the best available simulation of sunlight in the critical short-wave UV region. The spectral power distribution (SPD) of the UVA-340 matches sunlight very closely from the solar cut-on at 295 nm to about 360 nm (Figure 3). UVA-351 lamps (Figure 4) simulate sunlight through a window and are sometimes used to test light stability of plastics for interior use (see ASTM G-4674 Method IV). Not shown are UV-B lamps, which are commonly used in the QUV for very durable materials. They typically cause faster degradation than UV-A lamps, but their short-wavelength output below the solar cut-on can cause unrealistic results for many materials.

QUV Indoor Lighting Simulation.

In recent years, an option to test with cool white lamps in the QUV was developed to address the needs of producers of materials for interior use that are subject to photodegradation. Polymers for interior use and digital inks for photographic prints are two commonly tested materials in the QUV/cw. Use of this technology is specified in ASTM F1945, Practice for Determining the Lightfastness of Ink Jet Prints Exposed to Indoor Fluorescent Lighting. This tester includes control of irradiance (discussed below), which increases test repeatability over standard light boxes.

The QUV/cw is capable of producing exposing specimens to more than 20 times the amount of energy materials see in typical indoor lighting conditions (see Figure 5). This is due to the close proximity of specimens to the lamps in the QUV and to the ability of the QUV to send higher amounts of power to the lamps.

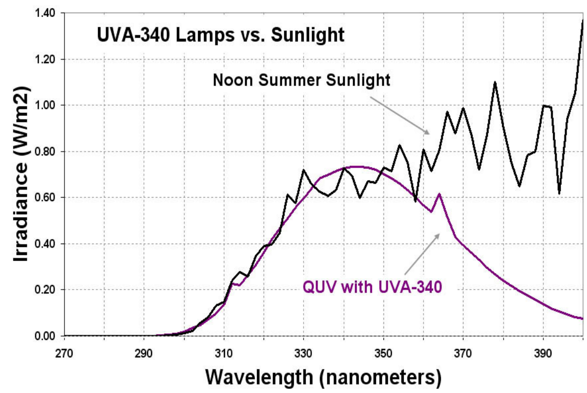

***Figure 3**. UVA-340 lamps provide the best available simulation of sunlight in the critical short-wave UV region.*

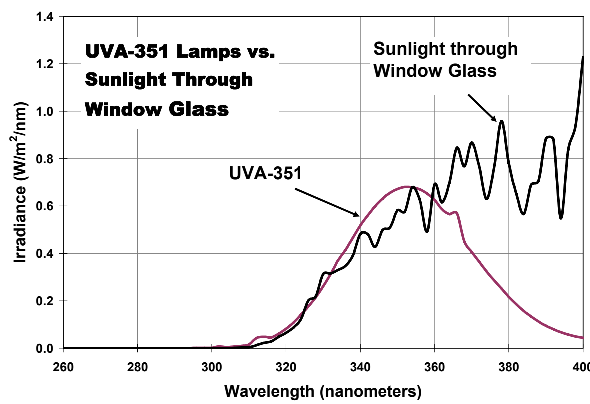

***Figure 4.** UVA-351 lamps are designed to simulate sunlight through window glass in the UV portion of the spectrum.*

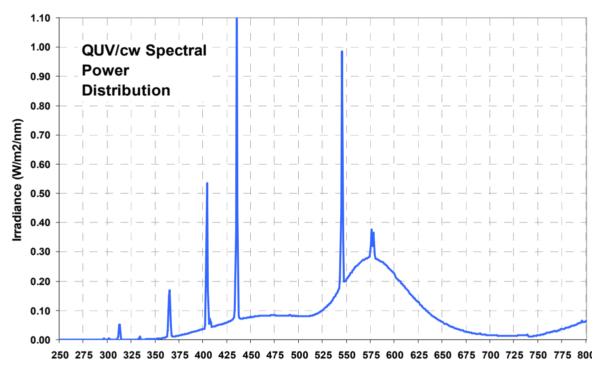

***Figure 5.** Spectrum of a typical cool white lamp commonly used in interior lighting in operation in an irradiance controlled QUV Accelerated Weathering Tester.*

QUV Control of Irradiance.

Control of irradiance (light intensity) is necessary to achieve accurate and reproducible test results. Q-Lab Corporation introduced this technology, trade-named Solar Eye Irradiance Control, in 1992. This precision light control system allows the user to choose the intensity level of the lamps, and the closed feedback-loop system monitors and controls the irradiance. For many materials, the ability to program high irradiance results in faster degradation and therefore shorter test times. (1)

With irradiance control, lamps routinely last more than 5000 hours, compared to 1600 hours for older technology. The Solar Eye Control system largely eliminates variations in UV intensity and therefore greatly reduces variations in test results.

In the QUV, control of irradiance is simplified by the inherent spectral stability of its fluorescent UV lamps. All light sources decline in output as they age. However, unlike most other lamp types, fluorescent lamps experience no shift in spectral power distribution over time. This enhances the reproducibility of test results and is a major advantage of testing with this technology, particularly for very sensitive materials like many printing inks.

Figure 6 shows the spectra of new and aged QUV lamps. Note that there is no significant shift in the spectrum.

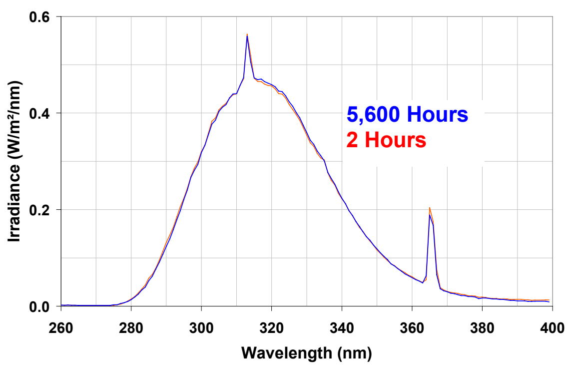

Figure 6. *While all light sources decline in output as they age, the QUV's Solar Eye control system keeps the irradiance at a consistent level by varying the power to the lamps.*

QUV Moisture Simulation

A major benefit of using the QUV is that it allows the most realistic simulation of outdoor moisture attack. Outdoors, materials are frequently wet up to 12 hours a day. Because most of this moisture is the result of dew, the QUV uses a unique condensation mechanism to reproduce outdoor moisture (see Figure 7).

Because materials experience such long wet times outdoors, the typical QUV condensation cycle is at least four hours. Furthermore, the condensation is conducted at an elevated temperature (typically 50˚C), which greatly accelerates the moisture attack. The QUV's long, hot condensation cycle reproduces the outdoor moisture phenomenon far better than other methods such as water spray, immersion, or high humidity.

In addition to the standard condensation mechanism, the QUV can also be fitted with a water spray system to simulate other damaging end-use conditions, such as thermal shock or mechanical erosion. The user can program the UV to produce cycles of wetness alternating with UV, a situation that is identical to natural weathering.

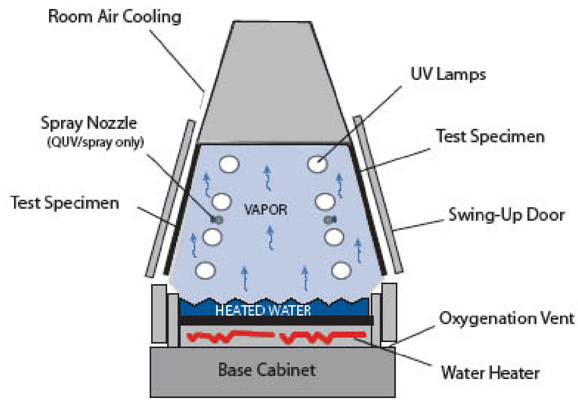

Figure 7*. The QUV simulates outdoor moisture attack through a realistic condensation system. Heated water evaporates, creating100% RH inside the chamber. Specimens are slightly cooler than the hot, moist chamber air, leading to liquid water continuously condensing on the specimes.*

III. Xenon Test Chamber

Xenon Sunlight Simulation

Xenon arc testers are considered the best simulation of full-spectrum sunlight because they are capable of reproducing a very accurate simulation of sunlight in the UV, visible, and infrared regions. To simulate natural sunlight the xenon arc spectrum must be filtered. The filters reduce unwanted radiation and/or heat. Several types of glass filters are available to achieve various spectra. The filters used depend on the material tested and the end-use application. Different filter types allow for varying amounts of short-wave UV, which can significantly affect the speed and type of degradation. There are three commonly used types of filters: Daylight, Window Glass, and Extended UV. Figures 13-15 show the spectra that these filters produce. Also included is a close-up look at these spectra in the critical short-wave UV region from about 295 to 400 nm.

Xenon Control of Irradiance

Control of irradiance is especially important in a xenon tester, because xenon lamps are inherently less spectrally stable than

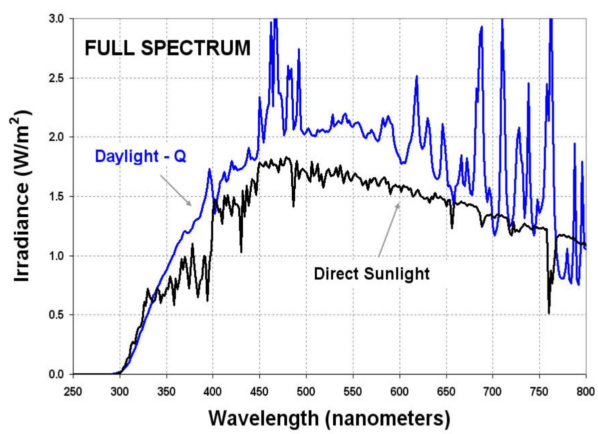

Figure 8a. *Sunlight compared to the Q-Sun with Daylight Filters. Daylight Filters are commonly used for simulations of outdoor exposure. They are an excellent reproduction of the full spectrum of natural sunlight, and are recommended for studies that value correlation to natural weathering.*

fluorescent UV lamps. Xenon arc testers are typically equipped with an irradiance control system that monitors and controls the irradiance in a particular portion of the spectrum.

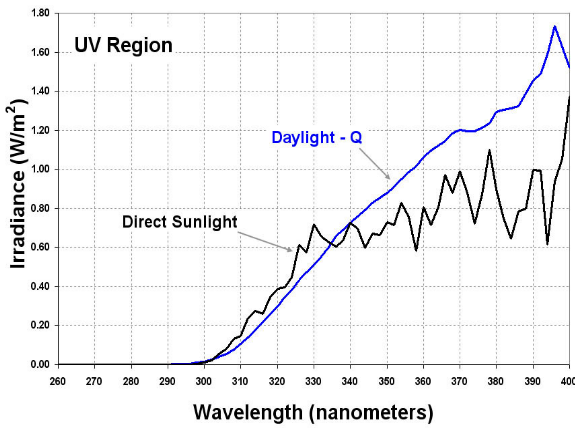

Figure 8b. *Sunlight compared to the Q-Sun with Daylight Filters, UV region*

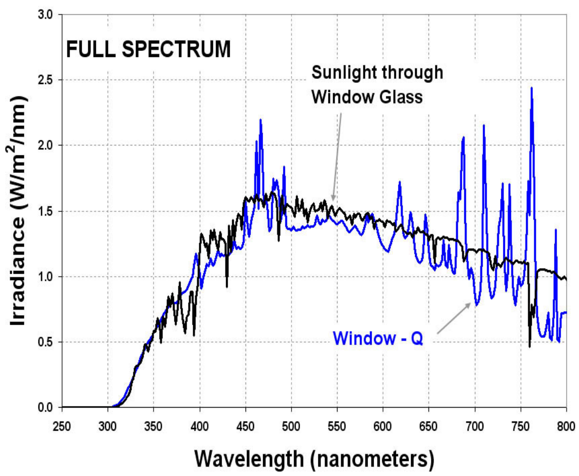

Figure 9a. *Sunlight through glass compared to the Q-Sun with a Window Glass Filter. Designed for indoor light stability testing, this filter provides a spectrum that is essentially identical to sunlight through window glass. The spectrum is also useful for simulating general lighting conditions because it encompasses the same damaging wavelengths.*

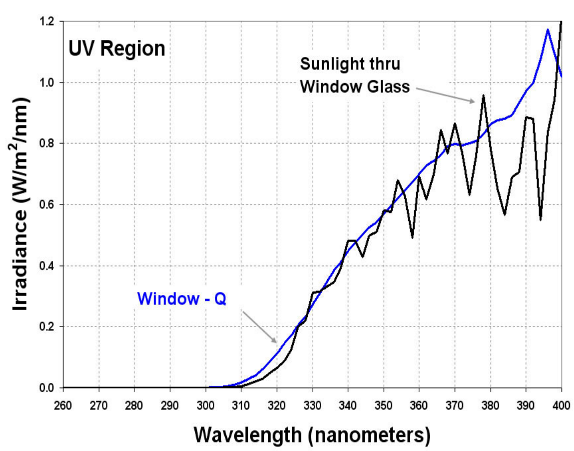

Figure 9b. *Sunlight through glass compared to the Q-Sun with a Window Glass Filter, UV region only.*

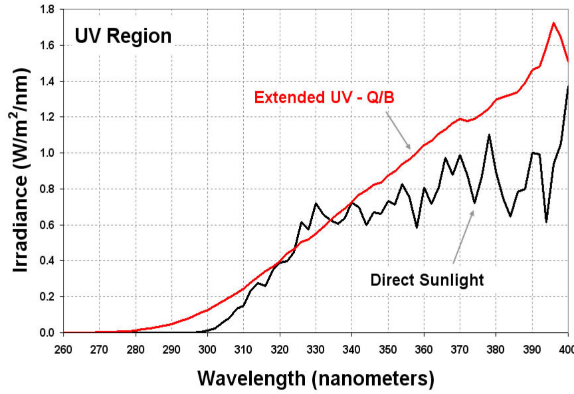

Figure 10. *Sunlight compared to the Q-Sun with Extended UV Filters UV portion only. Certain automotive test methods require a spectrum that includes short-wave UV below the sunlight cutoff of 295 nanometers. Q/B Filters produce that spectrum. Although they allow an unrealistic amount of short-wave UV, these filters often provide faster results.*

An inherent characteristic of xenon arc lamps is that the spectrum changes as the lamp ages, reducing its useful life. Figure 11 illustrates the difference in spectrum between a new lamp and a lamp that has been operated for 1000 hours. It's clear that, over time, the spectrum changes significantly in the longer wavelengths. However, when this same data is graphed as a percentage of change over time (Figure 12), it also becomes apparent that there is a similar shift in the short-wave UV portion of the spectrum.

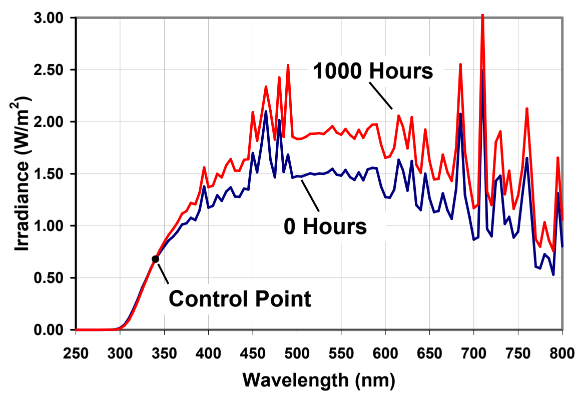

Figure 11. *After 1000 hours of use, xenon lamps change in spectral output, but the controller maintains the spectrum at the control point.*

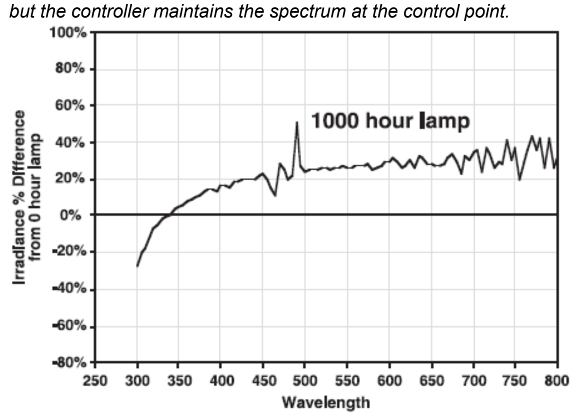

Figure 12. *As xenon lamps age, the spectral output shifts in both the short and long wavelengths of light.*

There are ways to compensate for spectral shift. For instance, lamps can be replaced on a more frequent basis to minimize the effects of lamp aging. Also, by using sensors that control irradiance at either 340 or 420 nm, the amount of spectral change in a particular area is minimized. Despite the spectral shift from lamp aging, the xenon arc has proven to be a reliable and realistic light source for weatherability and light stability testing.

Xenon Moisture Simulation.

Most xenon arc testers simulate the effects of moisture through water spray and/or humidity control systems. The limitation of water spray is that when relatively cold water is sprayed onto a relatively hot test specimen, the specimen cools down. This may slow down the degradation. However; water spray is very useful for simulating thermal shock and erosion. In a xenon arc, highly purified water is necessary to prevent water spotting. Because humidity can affect the degradation type and rate of certain indoor products, such as many textiles and inks, control of relative humidity is recommended in many test specifications. Modern xenon test chambers are available with relative humidity control.

IV. Weathering and Light Stability of Printed Materials

Printed materials are categorized by their intended use. Outdoor materials are exposed to all the elements of the weather, sunlight, high temperatures, dew, and rain. Therefore, the methods of test used for these printed materials should not be qualitatively different than those used for other outdoor materials, such as coatings and plastics. Differences will occur in the quantity, or duration of weathering exposures. Tests of materials intended to be used for weeks or months outdoors will be timed in terms of dozens or perhaps hundreds of hours, while more durable products will be tested for hundreds or even many thousands of hours in an accelerated test chamber. Discussion on relating test chamber exposures to outdoor durability is at the end of this paper.

For indoor materials, we generally assume that products in use are not routinely subject to wetness. However, changes in relative humidity can create problems as materials absorb and release atmospheric moisture to achieve equilibrium with the indoor environment. In addition, the nature of indoor light is worth examining as we seek ways to create laboratory, accelerated test methods for materials such as inks for digital photographic prints.

Figure 13 below shows the spectra of common indoor lighting sources. The spectrum of each has been normalized at 500 lux, approximately equivalent to typical office or factory lighting. (2)

The cool white version of the QUV is capable of delivering 20,000 lux exposures using a standard cool white lamp, shown in both graphs. All of these light sources emit some energy in the long-wave UV spectrum, 360-400 nm. This is important, since UV energy causes more rapid fading of inks than visible light. Within the visible light spectrum, shorter wavelengths also contribute to color degradation of inks. Of the types represented here, only the metal halide provides more relative energy in the short-wave visible part of the spectrum than cool white fluorescent lamps.

While this data may well represent commercial lighting environments lacking substantial sunlight through windows, it only represents one part of the market for printed materials. Consumers commonly display digitally printed photos and artwork in their homes. Therefore, it is important to characterize this lighting environment as well. To this end, Kodak conducted a study on long-term light levels and spectral energy distributions in 32 homes in 4 cities. The study concluded, "From the shape of the spectra, it is evident that indoor display lighting…is dominated by indirect window-filtered daylight. Only 8% of the total irradiance is in the UV region (300-400 nm), with 24% in the blue (400-500 nm), 31% in the green (500-600 nm), and 35% in the red (600-700 nm)." (3)

Further work has been done to characterize the average home spectrum from this study and compare it with the spectra of xenon arc and cool white fluorescent testers. Figure 14 represents a histogram comparing the three spectra. (4)

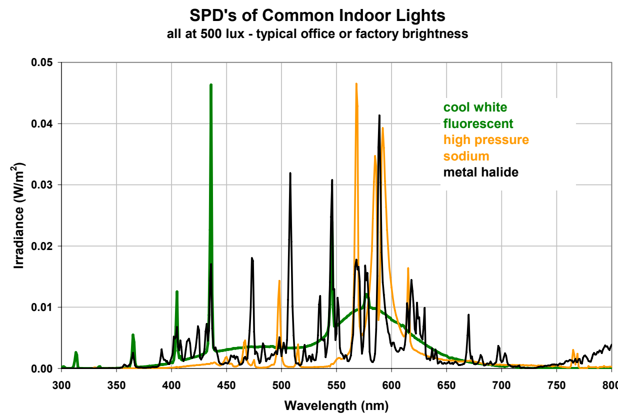

Figure 13. Spectra of three common indoor lighting types: cool white fluorescent, high pressure sodium, and metal halide. Cool white lamps are used to test inkjet photo inks as well as other types of indoor materials.

As shown, neither artificial lighting source is completely accurate, but both approximate reasonably well the critical UV and blue regions of the spectrum. The importance of these regions is discussed below.

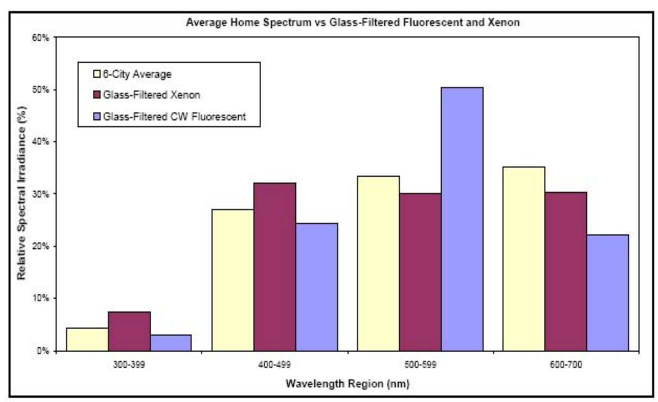

Figure 14. This histogram compares the spectra of the city average from the Kodak study to window glass filtered xenon and cool white fluorescent lamps of the type used in the QUV/cw.

Spectral Sensitivity and the Use of Lux Measurements

An unfortunate custom has appeared in some methods for testing inks intended for digital photography printing. ASTM F1945 and many internal methods use lux as a unit of measure of light intensity. Calculating lux requires knowledge of the sensitivity of the human eye, which is quantified by the human photopic response curve. To calculate lux, the irradiance at each wavelength is multiplied by a weighting factor from the photopic curve, which peaks at 555 nm. The curve drops to zero below 380 nm and above 780 nm, where human vision ends.

The problem with this approach is that the weighting factors do not correlate with material sensitivities to light. Quantum theory teaches us that shorter wavelengths are more energetic and therefore are more likely to break chemical bonds.

Photodegradation begins when a photon breaks a bond, starting a chain reaction that changes material properties. Past research has verified this for various ink formulations. Wavelengths in the UV region (300-400 nm) cause most fading and color change, followed by those in the short wave visible light part of the spectrum (400-500 nm). (5)

Figure 15 shows the photopic response and photonic energy curves juxtaposed to demonstrate the incompatibility of these concepts.

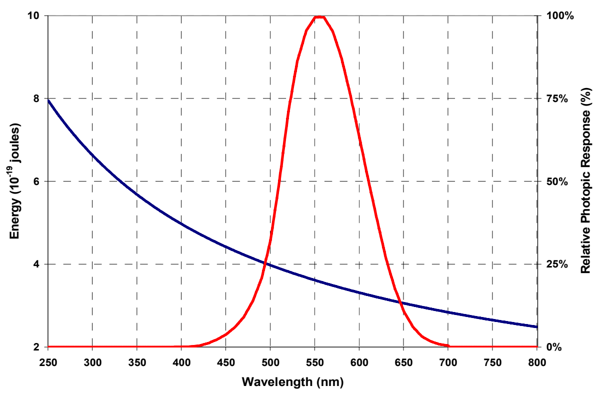

***Figure 15**. The photopic response curve peaks at 555, representing the peak efficiency of the human eye. Photonic energy at this wavelength is generally too weak to break chemical bonds and cause changes in physical properties.*

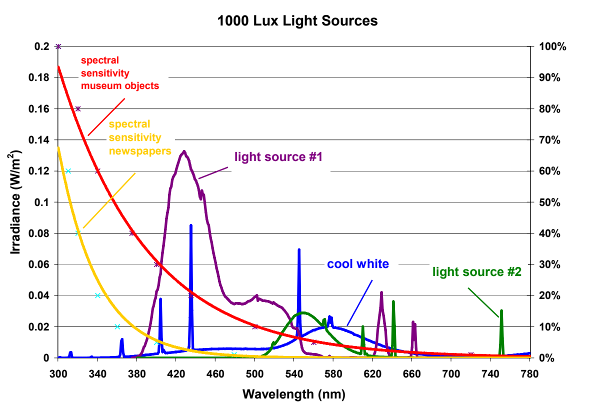

***Figure 16**. Three light sources, one real and two hypothetical, are shown at the same lux intensity. Also shown are relative spectral sensitivities of newspapers and more delicate museum objects. Where the areas under the curve intersect, photodegradation will occur.*

Figure 16 depicts spectral sensitivities of typical newspapers and museum objects, combined with a cool white spectrum and two hypothetical spectra. All light sources depict a 1000 lux exposure, yet have very different spectra. Light source #2 is unlikely to cause any significant photodegradation of newspaper print, but cool white lamps and light source #1 both contain short wavelengths that overlap with the sensitivity of this printed material. Photodegradation occurs where areas under the sensitivity and spectral curves of the light sources intersect. Clearly, Light source #1 would cause much more severe fading than the other two, even though all three light sources would measure the same on a lux meter. This demonstrates that use of lux to measure lightstability tests is inappropriate and misleading.

Service life predictions are often developed on the concept of reciprocity. This concept assumes that a limited exposure to high-intensity light will have the same effect as a long exposure to low-intensity light. Such calculations are often made using lux, even though so-called “warm” light sources are less likely to cause photodegradation than “cool” sources at the same lux level, as demonstrated above. Reciprocity only works on some materials, and then only if the spectrum, temperature, and humidity levels are constant.

V. Technical Summary: The Right Testing Program for the Right Job

Deciding on the right weathering test program can be confusing, especially if you’re new to this type of testing. What is best accelerated tester for you? Below are some general guidelines. As with any generalization, there may be exceptions to the rule.

The QUV with cool white lamps may be best for simulating commercial indoor lighting conditions where there is minimal ultraviolet energy from sunlight. For simulating home lighting conditions, which are typically dominated by sunlight through windows, a xenon arc equipped with window glass filters may be a better choice. For humidity sensitive printing inks, a xenon arc tester with relative humidity control may be preferred.

If you are testing printing materials for outdoor use, a xenon tester with daylight filters is generally the best choice because, in addition to providing short-wave UV energy, it accurately reproduces long-wave UV and short wave visible light, which are known to cause fading of inks. While a standard QUV can most accurately reproduce short-wave UV energy, it cannot simultaneously provide longer wavelengths. Outdoor durability testing must be substantially more robust, because materials exposed outdoors typically receive up to 200 times the amount of light energy compared to indoors.

VI. Conclusion and Discussion

In this paper, we examined laboratory weathering and light stability technologies currently used to test printed materials. Two obsolete technologies continue to be referenced in a few remaining test standards, but xenon arc and UV fluorescent testers dominate the market today because of their wide availability and use in multiple industries. Test standards for both technologies exist for printed materials.

UV fluorescent technologies have been modified to provide a very good simulation of typical commercial lighting environments. Xenon arc with window glass filters are the best way to simulate environments that combine artificial lighting with sunlight through windows, and this environment is typical for residential applications. Materials intended for outdoor use should be tested in a xenon arc tester with a daylight filter to accurately reproduce outdoor degradation of printed matter. Test times should be substantially longer to match the outdoor environment.

An issue that is somewhat unique to the testing of inkjet materials for artistic and photographic prints is the use of lux as a measurement of light intensity during laboratory tests. The inappropriateness of this unit of measure was discussed. Service life predictions are often based on the assumption of the Law of Reciprocity, but in reality this law is of limited use. Certainly, use of lux as a unit of measure can provide very misleading results when combined with the concept of reciprocity. At a minimum for reciprocity to hold, the spectrum of light and all other relevant factors must be held constant. This leads to concluding remarks about the usefulness of accelerated testing and the difficulties relating laboratory tests to the service life of the products manufacturers wish to market.

While there is no singular acceleration factor between hours in a laboratory test chamber and outdoor durability in months or years, it is safe to assume it will take several hundred to a few thousand hours in a laboratory test chamber to achieve similar degradation of a material exposed on an outdoor test rack for multiple years. It is beyond the scope of this paper to discuss in detail the dynamics of acceleration or the difficulties encountered by researchers attempting to correlate their laboratory and outdoor test protocols. Suffice it to say, while it is often possible to calculate a laboratory to outdoor acceleration factor for a given material or system of materials, this factor applies only to that material or system. Any change in formulation or system components can result in significantly different acceleration factors.

Besides this fact, correlating laboratory results to a product's service environment is made very difficult simply due to the fact that the results of weathering differ, sometimes dramatically so, based on geography or differences resulting from angle of exposure, radiated heat from surrounding surfaces, or the amount of insulation provided by the substrate of the printed material on exposure.

Therefore, the best way to look at accelerated weathering is to think of it as a very useful tool for decision making. Questions that can be answered by an accelerated test include the following:

- Which formulation will have the best relative lightstability?
- Will a particular change in formulation result in an increase, decrease, or no change in weatherability?
- How does my product compare with my competitors' in terms of weatherability?
- Will my customers find that their inkjet photographic prints last as long as traditional prints?
- Due to rising costs, I have to find lower cost additives or chemical feedstocks. Can I formulate a product that as similar durability to what I currently offer using these lower cost alternatives?

Users of accelerated weathering testers are often disappointed to learn that there isn't a simple formula, or even a complex one, that they can use to predict service life of their products. Yet, despite this inconvenient fact of life, many companies reap significant benefits by seeking answers to questions like those posed above.

For example, imagine you are trying to enter a new market, and you believe you have developed a low cost alternative to a product or system marketed by a competitor. You begin testing in an accelerated weathering chamber and learn that, in fact, the competitor's product retained acceptable color and appearance after 500 hours in a test chamber, while yours had failed at 300 hours. You might breathe a sigh of relief that you tested before going to market in this case. Now, your R&D department has a tool for testing, reformulating, and retesting to achieve similar performance levels in a relatively short period of time.

This example highlights the use of a reference material in your weathering tests. In this case, the reference material is from the market leader you wish to compete with. If you are that market leader, the reference material is your tried and true product. This is your own internal benchmark against which you can develop lower cost materials to compete in an increasingly global market. Perhaps you have a "super" material that's too costly to market, but you hope to lower its costs over time through a program of continuous testing as new raw materials become available. A second kind of reference might be a material that doesn't perform so well in actual use. If you run the "good" and "bad" materials as references in your accelerated laboratory tests, you can rate candidate materials against both and develop a valuable internal rating system, a continuum of weatherability, for a variety of materials and formulations.

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Author Biography

Sean Fowler received his BS in Management from Malone College in Canton, Ohio and his Masters in Business Administration from Kent State University in Kent, Ohio. Currently he is Technical Marketing Specialist at Q-Lab Corporation. He works with a variety of industries to help them develop practical weathering testing protocols. Sean has developed technical training programs and held seminars around the world, in addition to providing direct technical support to customers. He is a member of the Society of Plastics Engineers (SPE) and the American Coatings Association (ACA).