Quantifying the Indoor Light Environment: Testing for Light Stability in Retail and Residential Environments

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Abstract

Indoor products may be subjected to a wide range of interior lighting environments. These environments include residential incandescent, commercial fluorescent, and industrial metal halide illuminants. Products may also be exposed to sunlight coming through a window or an automobile windshield. Each of these light sources has its own unique spectrum. In a like manner, each material has its own unique spectral sensitivity. This paper surveys a wide variety of the most commonly used indoor light sources, including direct and indirect window-filtered sunlight. The results indicate that direct window-filtered sunlight is the most severe interior lighting condition that your product will probably see. Because a xenon arc test chamber can provide an excellent simulation of sunlight through window glass, it is the best method of simulating this worst-case indoor lighting environment for testing the light stability of your product.

Introduction

Light can be a significant cause of damage to inks, dyes, textiles, coatings, cosmetics, pharmaceuticals, papers, plastics, and other indoor materials. This damage may affect both a product's aesthetic and physical properties. Aesthetic damage is usually in the form of fading, color change and gloss loss.

Currently, a single standard (or benchmark) has not been established as the universal method for testing the light stability of interior products. This is because there are dozens of potential retail and residential lighting environments.

Spectrum

The electromagnetic spectrum is normally divided into ultraviolet light (UV), visible light, and infrared energy (IR). Infrared energy consists of wavelengths, which are longer than the visible red wavelengths and starts above about 760 nanometers (nm). Visible light is defined as the wavelengths between 400 and 760 nm. Ultraviolet light consists of radiation with a wavelength shorter than 400 nm.

To understand the significance of spectrum on photodegradation, we must look at the Quantum Theory, which states that, unlike other forms of energy, light comes in discrete particles called photons or quanta. Photons behave much like tiny projectiles traveling at the speed of light (they are even subject to gravity). The "size" of a photon is inversely proportional to wavelength - the shorter the wavelength, the bigger the photon. Photochemical reactions are caused by a single photon colliding with a single electron. If the photon is "big" enough (i.e., contains more energy than the organic. Physical property damage may include cracking, crazing, strength loss, or embrittlement.

If the photon is not big enough, the energy imparted by the collision is harmlessly dissipated and no reaction occurs. For each type of chemical bond, there is a critical threshold size of photon (and hence a critical threshold wavelength) with enough energy to cause a reaction. Light of any wavelength shorter than the threshold wavelength can break the bond, but light of wavelengths longer than the threshold can never break the bond - regardless of the intensity (brightness) of the light.

An analogy to the Quantum Theory is throwing objects at a window. If you threw 20 kilograms of sand at a window, one grain of sand at a time, the glass would remain intact. But if you threw one 5 kilogram rock, the glass would shatter.

Because of the Quantum effect, the shortest wavelengths of sunlight found on the earth's surface, the UV, are almost exclusively responsible for the photochemical damage done to modern exterior-grade materials. Furthermore, even within the UV, the shorter wavelengths are vastly more destructive than the longer UV wavelengths. For interior-grade materials like inks and dyes, longer wave UV and short wave visible often have a significant effect.

Once the bond is broken in the primary photochemical reaction, any number of degradation sequences can occur. The molecule may become weaker and its molecular weight may decrease. There may be a rearrangement of atoms within the molecule, resulting in a change in physical properties. There is frequently a chain reaction of damaging chemical changes.

IR radiation typically causes heat buildup in radiated specimens which can result in thermal degradation in some materials. IR does not cause photodegradation; however, the increased temperatures it creates will typically lead to an increase in the rate of photo-initiated degradation.

Spectral Sensitivity of Materials

The spectral sensitivity of a material is a measure of how the amount of damage, caused by a unit of light energy, varies according to the wavelength of light. Spectral sensitivity may vary greatly from material to material. Similar materials, formulated for the same application, may have significantly different spectral sensitivities. Figures 2 and 3 depict the spectral sensitivity of several common plastics. Notice how the sensitivity is usually inversely proportional to wavelength (i.e., shorter wavelengths are more damaging). This has profound consequences for material science.

Quantifying the Damaging Potential of a Light Source

The photodegradation potential of a light source can be understood by reviewing its Spectral Power Distribution (SPD). SPD is defined as the "Intensity of a light source as a function of the individual wavelength."

To determine a material's photodegradation risk factor, one can compare its unique spectral sensitivity to the SPD of the light source(s) that it could encounter during its expected service life. For example, Figure 4 shows a graph of the SPD of sunlight superimposed on a graph of the spectral sensitivity of polypropylene and polyethylene. The region underneath where the two graphs overlap is the region of risk. The larger the area of risk, the greater the expected degradation.

Lux

Indoor lighting is normally measured in lux. Lux is based on the Photopic Response Curve. This is a standardized measure of the human eye's response to light, defined as a unit of illuminance equal to one lumen per square meter (equivalent to .093 footcandles).

Because lux is based on the human eye's response to light, it is very useful for comparing relative light levels and relative efficiency of various light sources. Lux is useful only for purposes of human vision, not for photodegradation.

Researchers use lux to quantify, monitor and control indoor lighting. This works well for illumination comparisons. Unfortunately, some researchers inappropriately use lux to try to quantify the quality of light when studying material durability. This misuse is due to a misunderstanding of the nature of lux itself.

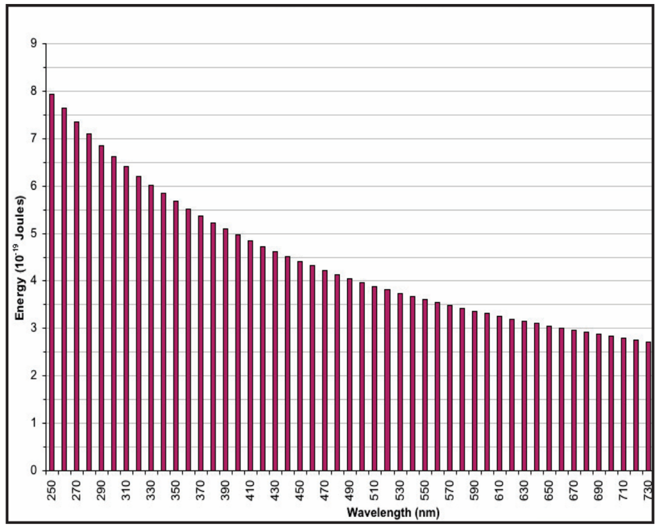

Figure 1, Energy Per Photon. The "size" of a photon is inversely proportional to wavelength.

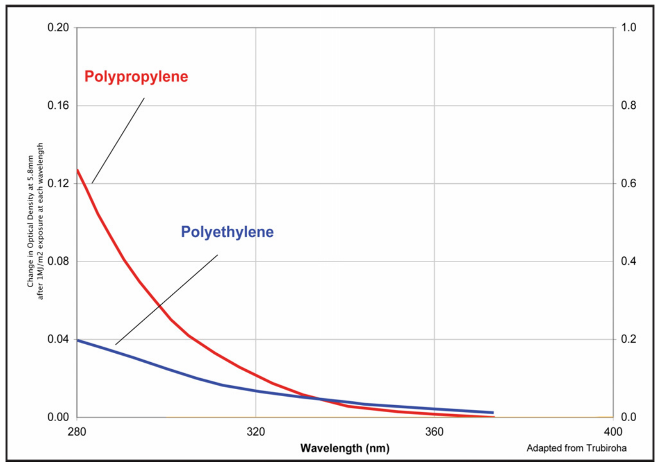

Figure 2, Spectral Sensitivity of Polyolefins. Different materials have different spectral sensitivities.

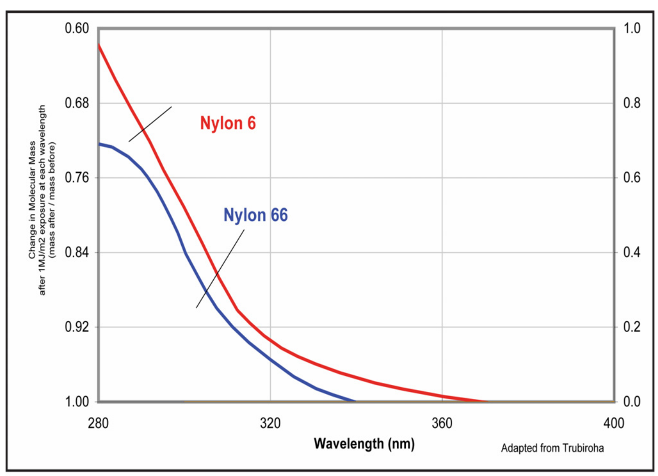

Figure 3, Spectral Sensitivity of Polyamides. Similar materials can have significantly different durabilities.

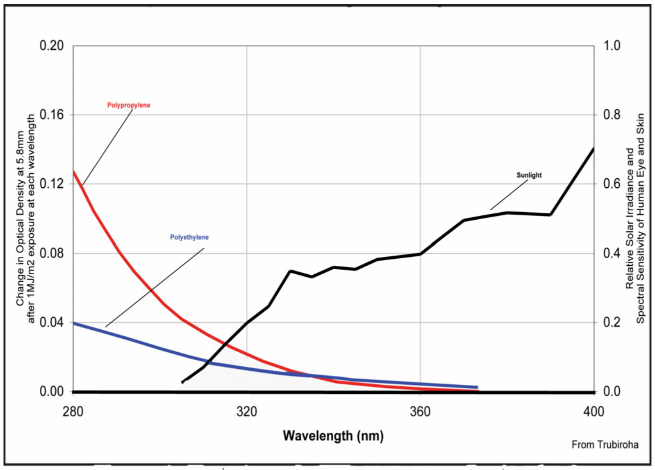

Figure 4, Photodegradation Risk Factor for PP & PE. The greater the area of risk, the greater the expected degradation.

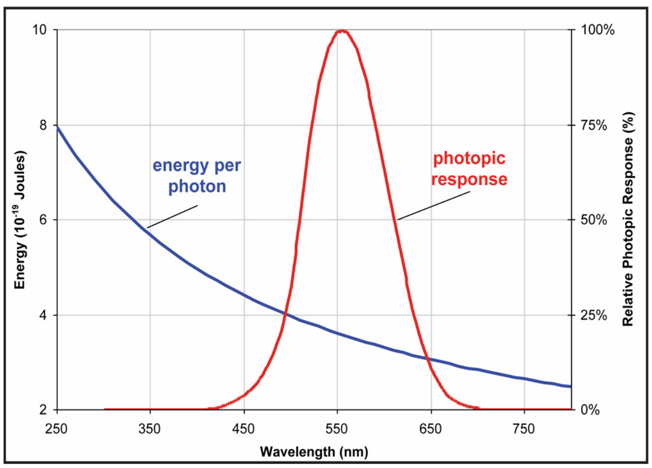

Figure 5, Photopic Response Curve vs. Photon Energy. The human eye's response to light is centered at 555 nm.

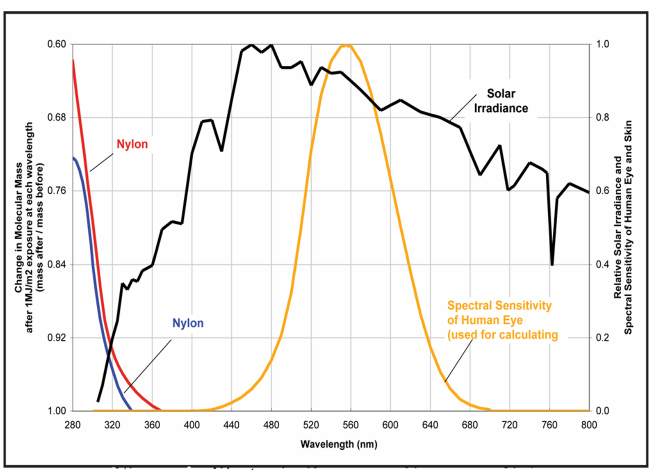

Figure 6, Photopic Response Curve vs. Nylons. There is little relationship between the spectral sensitivity of most material and the eye's response to light. This is particularly true for more durable materials, like plastics.

The Photopic Response Curve, upon which lux is based, is a bell-shaped curve that is centered at 555 nm and extends from approximately 400 nm to 700 nm. While a useful measure of the light efficiency for illumination, it is worse than useless for material science. "Worse than useless" because it is misleading. In other words, there is no relationship between the spectral sensitivity of any material and the eye's response to light. In fact, in the long wave UV, exactly the region where the eye's response is dropping to zero, we find the spectral response of most materials climbing rapidly. While using a luxmeter to determine illumination levels for taking photographs, reading or viewing artwork is extremely useful, it should not be used for quantifying the photodegradation risk factor of a lighting environment. It should not be used to generate "reciprocity formulas."

Unfortunately, several photography test standards specify the use of lux as a means to time radiant dosage. A more appropriate measurement would be to use radiant energy measured in an appropriate spectral region, typically in watts per square meter (W/m^2).

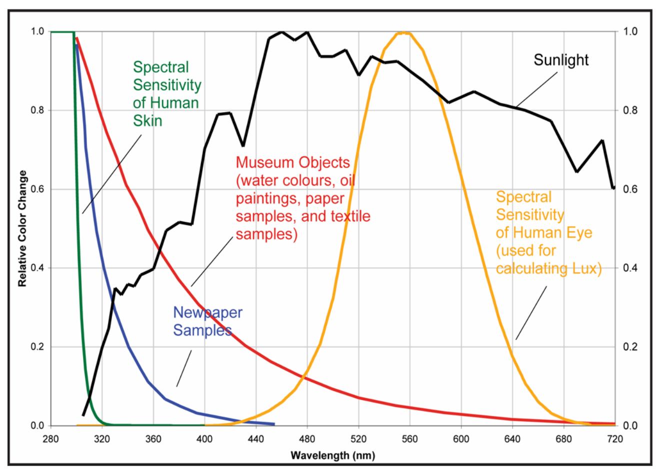

Figure 7, Photopic Curve vs. Skin/Museum/Newspaper. In the region where the eye's response is dropping to zero, we find the spectral response of most materials climbing rapidly. Lux are not useful measure of the potential for photodegradation.

Survey of Manufactured Light Sources Used Indoors

Indoor lighting comes in a large number of options. Market pressure for cost savings and conservation has resulted in a constant stream of new refinements: brighter, longer lived, more efficient, smaller, etc. This section will examine a number of the most common types of lighting that a material would be expected to encounter indoors.

For the purposes of this paper, the term artificial light sources (i.e., lamps) refers to the process of how light is created. Artificial light can be categorized as either incandescent filament or electric discharge.

According to a recent Kodak study (Bugner et al), residential home lighting intensities are 120 lux per 12 hour day. Typical commercial intensities would be much higher. Henry Wilhelm has published a benchmark of 420 lux per 12 hour day for commercial lighting. Measurements in our own offices indicate that 500 lux might be a more realistic benchmark. Therefore, for purposes of comparison, all of the following graphs show the manufactured light source at 500 lux.

Incandescent Filament Lamps consist of a glass bulb containing a wire filament (usually tungsten) that radiates light when heated. Filaments of standard incandescent lamps are enclosed in a vacuum or in a gas-filled bulb. Much of the energy is lost as heat; therefore, standard incandescent lamps are very energy inefficient. Incandescent lamps are the typical "light bulbs" (such as soft whites) used for residential home lighting and tungsten halogen lamps. Following is a Spectral Power Distribution (SPD) graph of three incandescent lamp types.

Halogen Lamps are a type of incandescent lamp with an outer jacket made of borosilicate glass and a tungsten halogen capsule that is made from quartz and contains a filament, lead wires and a halogen gas mixture. The halogen gases allow the filaments to operate at higher temperatures and higher efficiencies than other incandescent lamps. Halogens provide brighter, whiter light with better color characteristics, longer life and improved energy efficiency.

Electric Discharge Lamps create light from an electric discharge between two electrodes in a glass tube, like a lightning bolt. However the arc is continuous. As the current is passed through a low pressure gas, the electrons collide with the gas atoms, releasing photons of radiation. Electric discharge lamps include: mercury vapor lamps, metal halide lamps and high pressure sodium lamps. These are all known as High Intensity Discharge or HID lamps. Another type of electric discharge lamp is the fluorescent lamp.

Mercury Vapor Lamps contain two operating electrodes and a starting electrode. The light produced is in the characteristic mercury emission lines (404 nm, 435 nm, 546 nm and 577 nm) plus a small amount of UV energy. A clear mercury vapor lamp produces a blue-green colored visible light. Mercury vapor lamps are used for retail store lighting, street lighting, industrial high-bay, and parking lot lighting.

Metal Halide Lamps are a type of electric discharge lamp that provide long life and good color rendering properties. They are the most common lamp type for factory lighting, industrial warehouses and retail stores. The lamp type is called "metal halide" because a compound of a metal and iodine is called a "metal halide" salt.

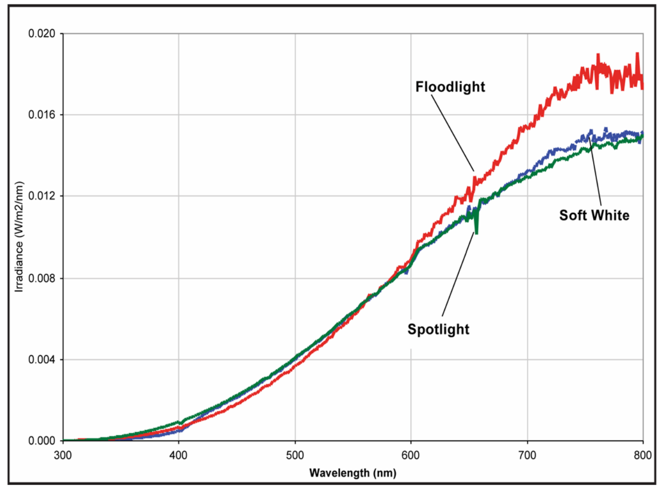

Figure 8, Incandescent Lamps at 500 lux. Incandescent Lamps are widely used in residential lighting applications.

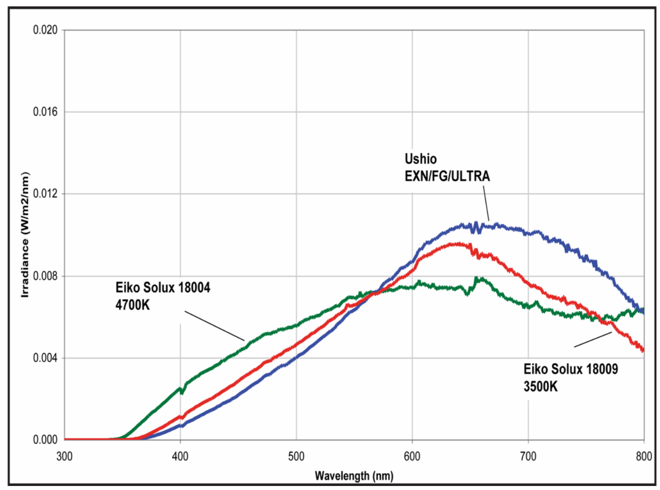

Figure 9, Halogen Lamps at 500 Lux. Halogen Lamps are frequently used to provide longer life and energy efficiency.

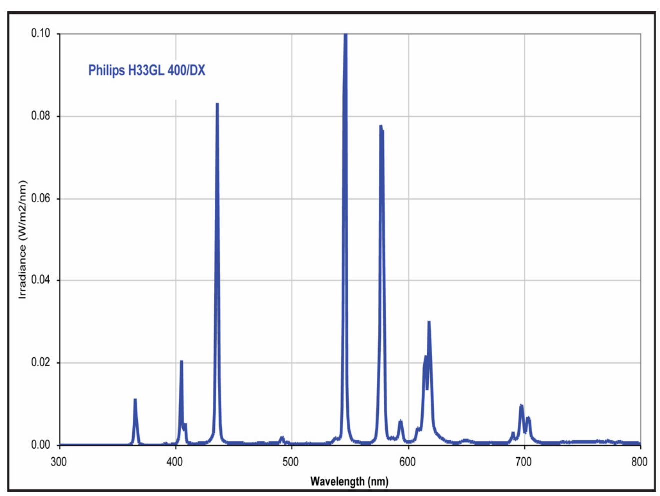

Figure 10, Mercury Vapor Lamps. Mercury Vapor Lamps produce light in characteristic emission lines rather than in a continuous spectrum.

Sodium Lamps are electric discharge lamps. Sodium and mercury vaporize within the lamp, producing visible light. Sodium lamps are strongest in the yellow and orange range of the spectrum and weakest in blue-green wavelengths. Mercury is sometimes added to strengthen blues and greens. Sodium Lamps have the highest efficacy of all lamps currently available.

Low Pressure Sodium Lamps emit a single frequency of light, a monochromatic yellow at 589 nm. They are best suited for outside areas such as parking lots or street lighting, because the monochromatic light is conductive to viewing in detail.

High Pressure Sodium Lamps provide warmer yellow-orange color and are used for both street lighting and industry interiors like factory lighting and warehouses. They are the most efficient HID lamps available today.

Fluorescent Lamps are a type of mercury vapor lamp used for commercial retail lighting and office environments. They are more efficient than incandescent lamps and radiate less heat. Fluorescent lamps typically consist of a long, narrow glass tube whose inside surface is painted with a fluorescent phosphor. The tube also contains an inert gas and a small amount of mercury. When electricity is passed through the lamp, the mercury vapor is excited and emits UV radiation. The UV is absorbed by a phosphor coating on the inside of the glass tube. The phosphor then re-emits visible light. The many types of fluorescent lamps are usually categorized by the light output of their phosphors.

Cool White Fluorescent Lamps are the most widely used fluorescent lamp and are popular for their economy. They are used in areas where color rendering is not critical.

Warm White Fluorescent Lamps improves color in offices, stores by emitting a “warmer” light than cool white.

Daylight Fluorescent Lamps are designed to simulate the color of daylight and are used in locations where color rendering is important (e.g., jewelry stores, color matching booths, museums, hospitals, etc.).

Compact Fluorescent Lamps are designed to replace screw-in incandescent bulbs combining the efficiency of fluorescent lighting with the convenience of standard incandescent bulbs. They are primarily used for residential home lighting, hotel and restaurant lighting. Like traditional fluorescents, compact lamps come with a variety of phosphors to function in a range of applications.

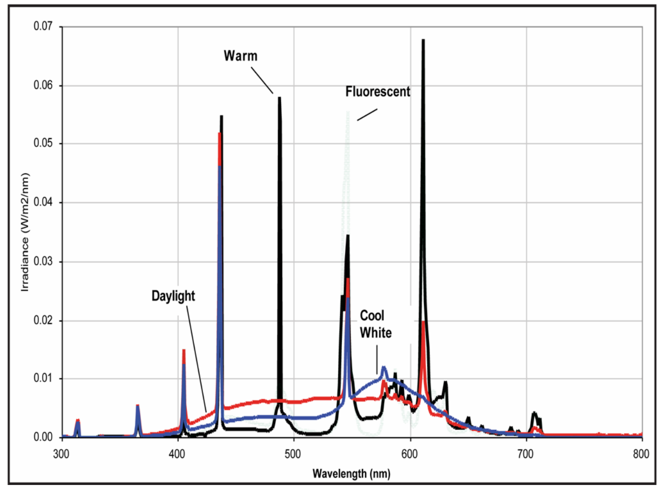

Figure 11, Metal Halide Lamps at 500 Lux. Metal Halide Lamps are usually used for industrial and retail applications.

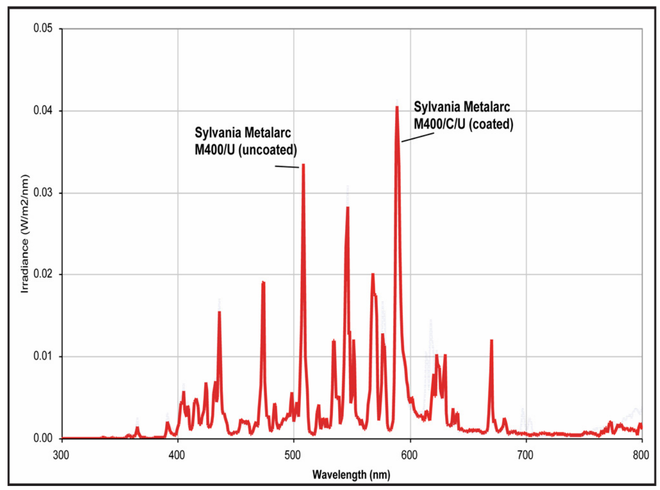

Figure 12, Sodium Lamps at 500 Lux. Sodium Lamps have very high efficiency.

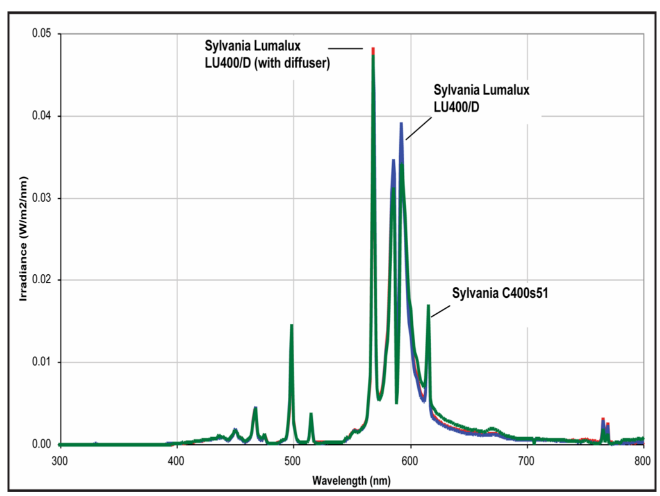

Figure 13, Fluorescent Lamps at 500 Lux. The many types of fluorescent Lamps are usually categorized by the spectral output of their phosphors.

Natural Light Sources

Natural light sources include direct sunlight and indirect (diffuse) sunlight. The CIE (International Commission on Illumination) defines direct sunlight in publication 85, table 4 (1989). This is equivalent to noon, summer sunlight in the Northern Hemisphere. This is also known as Air Mass 1. Numerous ISO and ASTM committees have incorporated this sunlight benchmark in their test methods and specifications.

The spectrum and intensity of sunlight vary throughout the day. When the sun is lower in the sky, there is more filtering from the earth's atmosphere. An extreme example of this occurs at sunset, when most wavelengths except for the long wave visible are filtered, and the sunlight appears red. Figure 14 shows the spectral power distribution of direct sunlight measured at various times throughout the day.

"North Sky" sunlight (diffuse sunlight) is of course much less intense overall than direct sunlight. But counter-intuitively, the proportions of UV wavelengths in diffuse north sky sunlight are virtually identical to the proportions in direct sunlight. They have the same "relative SPD" because of UV scattering. Figure 15 shows the spectral power distribution of benchmark CIE Sunlight compared to North Sky Sunlight. Figure 16 illustrates that the relative proportions of North Sky and Direct Sunlight are virtual identical due to UV scattering (normalized at 420 nm).

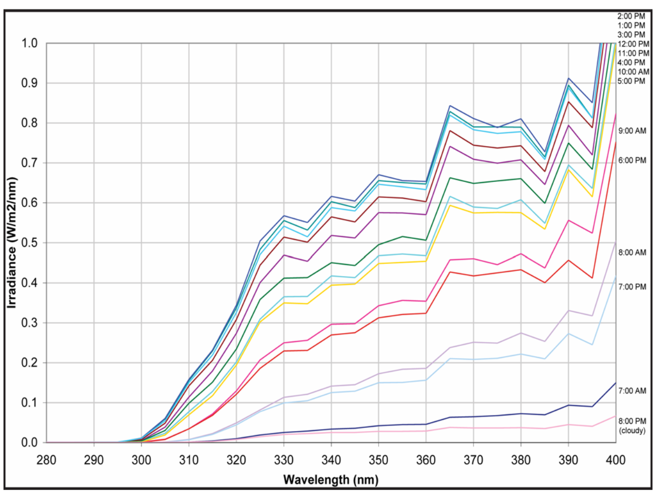

Figure 14, Sunlight Throughout the Day. Because of the filtering effect of the earth's atmosphere, the spectrum of sunlight changes throughout the day.

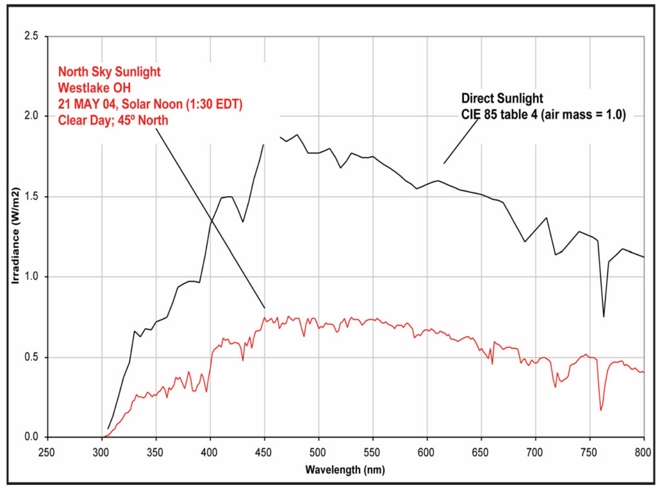

Figure 15, Air Mass 1 Compared to "North Sky" Sunlight. North sky sunlight is much less intense than direct sunlight.

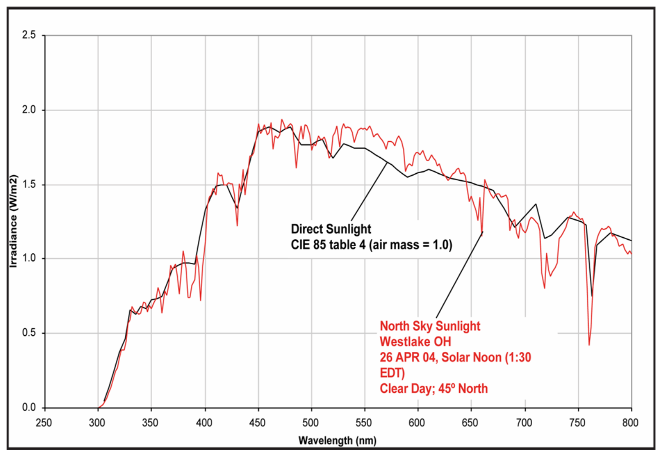

Figure 16, Air Mass 1 Compared to "North Sky" Sunlight – Normalized Data. The relative proportions of north sky and direct sunlight are virtually identical due to UV scattering.

Window-Filtered Sunlight

The shortest of the UV wavelengths are filtered out by window glass and the solar cut off shifts from approximately 295 nm to about 310 nm. Glass that is dirty, thicker, tinted, laminated, or double-pane would have even less UV transmission. The figure below compares direct sunlight (Air Mass 1), and sunlight filtered through window glass.

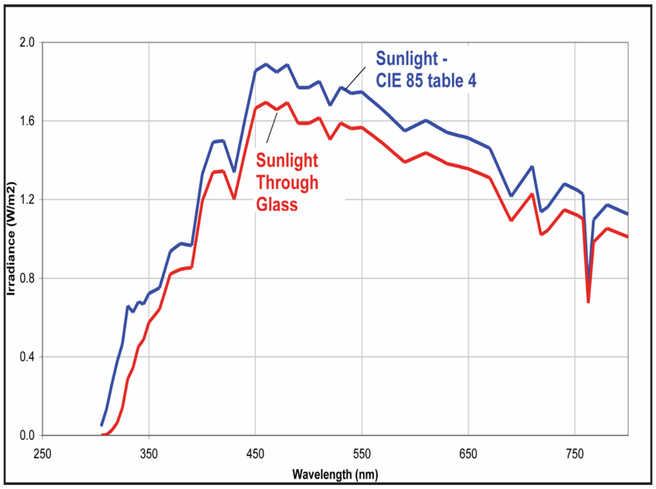

Figure 17, Sunlight and Sunlight Through Window Glass. The shortest of the UV wavelengths are filtered out by window glass.

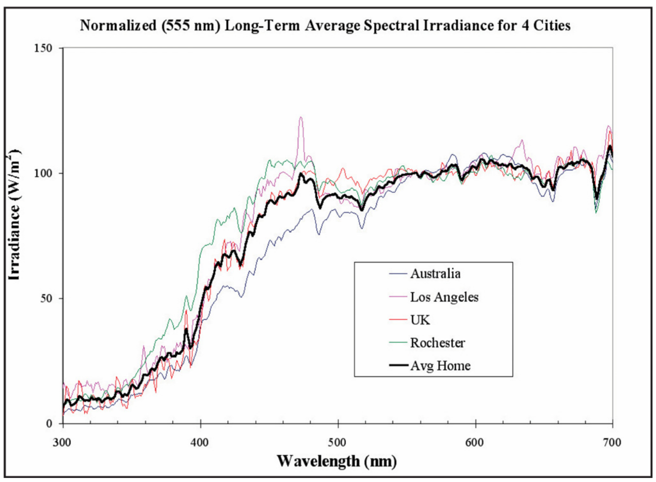

Figure 18, Long-term Average Indoor SPDs for Homes in the Kodak Study. The spectrum of residential interior lighting is dominated by sunlight coming through the window. (Bugner, et al).

In a recent study conducted by Kodak (Bugner et al), long-term light levels and spectral energy distributions were measured in 32 homes in 4 cities (Rochester, London, Los Angeles & Melbourne). Figure 18 plots the average in-home SPDs in these cities.

The Kodak 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 26% in the blue (400-500 nm), 31% in the green (500-600 nm), and 35% in the red (600-700 nm). Note the relatively low energy levels in the UV region. This is likely due to the combination of glass filtration and partial absorption of light reflected off interior surfaces."

Sunlight and Man-Made Light Sources Compared

A comparison of the spectrum of window-filtered sunlight and the various man-made indoor light sources illustrates that sunlight through glass encompasses the spectral emissions of all the common manufactured indoor light sources (Figure 19). In other words, window-filtered sunlight typically produces more of the highly damaging, short wave UV than man-made light sources. Therefore, it is the most severe spectrum that an indoor product is likely to encounter.

A comparison of light intensity shows that direct sunlight which comes through the window is approximately 200x brighter than the normal lighting level for a well lit room. Indirect (or North Sky) sunlight has only about 70% of the intensity of direct sunlight, and a very similar spectrum. This is still about 150x more intense than a typical well lit room. Figure 20 shows the relative intensities of natural sunlight through glass compared to the man made light sources at 500 lux. This is the same data as shown in Figure 19, except with a change in scale to show the normal full intensity of sunlight. As illustrated, the manufactured light source intensity is trivial by comparison.

Therefore, on the basis of both spectrum and wavelength, it can be said that window-filtered sunlight is the most severe lighting condition that most products can be expected to encounter during their service life indoors.

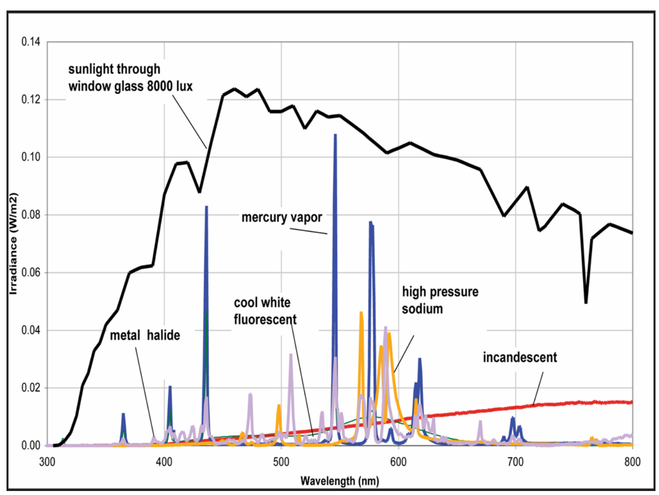

Figure 19, Sunlight Through Glass & Manufactured Lamps – Spectral Comparison Window-filtered sunlight contains more of the damaging wavelengths than man-made light sources.

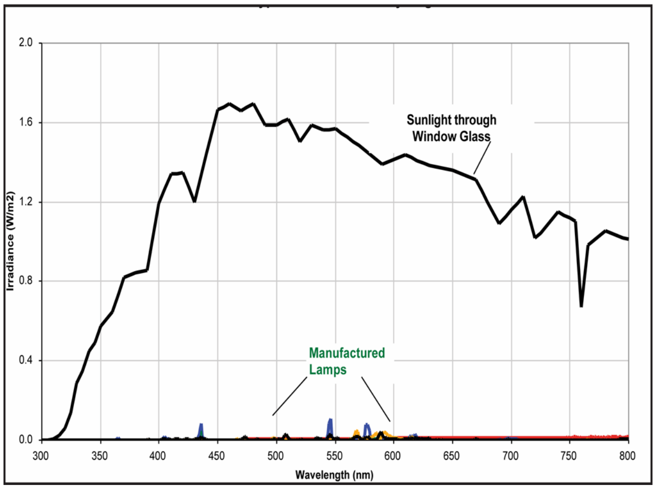

Figure 20, Sunlight Through Glass & Manufactured Lamps – Intensity Comparison Sunlight through glass is 200x more intense than a typical well-lit office.

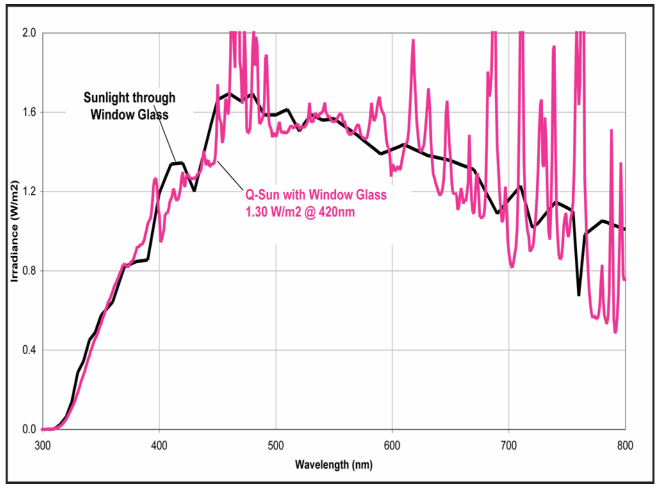

Figure 21, Xenon Arc & Sunlight Through Window Glass Xenon Arc provides an excellent simulation of sunlight through glass.

Laboratory Simulations

Laboratory test chambers with xenon arc lamps are frequently used for testing the light stability of materials. A xenon arc lamp consists of a glass tube filled with xenon gas, in which an electric discharge is created between two electrodes. Because the xenon lamp produces an excess of very short wavelength UV, it is necessary to use special optical glass filters to modify the UV and produce the desired spectrum. There are many types of filters for xenon lamps and it is important to use the proper filter.

A xenon arc, when properly filtered, provides a surprisingly good simulation of window filtered sunlight. As shown in Figure 21, the xenon arc reproduces all of the damaging wavelengths, including UV, visible light and infrared light.

Consequently, several industries have standardized on the xenon arc to test products for indoor light stability. A partial list is provided in table A.

Table A. Industries Standardized on Xenon Arc (partial list)

ISO 11341, Paints and Varnishes
ASTM D6695, Paints and Related Coatings
ISO 4892, Plastics
ASTM D4459, Plastics for Indoor Applications
ISO 104 B02, Lightfastness of Textiles
AATCC, TM 16 Lightfastness of Textiles
ISO 12040, Graphic Technology - Prints and Printing Inks
ISO 18909, Imaging Materials - Processed Photographic Films and Paper Prints
ASTM D3424, Lightfastness of Printed Matter
ASTM D4303, Lightfastness of Artists' Pigments

Conclusion/Recommendations

1. In residential, retail, and manufacturing environments products may be exposed indoors to a myriad of natural and artificial light sources.
2. There is not a single representative indoor light spectrum that addresses all of these environments. However, because the most severe indoor lighting environment is sunlight filtered through window glass, it is reasonable that the best laboratory simulation would mimic this spectrum and intensity.
3. A xenon arc with a Window Glass Filter produces an excellent simulation of direct sunlight through glass.
4. Filtered xenon is the preferred method for testing indoor light stability.

Appendix on Reciprocity

The Law of Reciprocity is often used to predict service life of materials exposed to light. For example, museum conservators commonly use it to estimate the amount of light that they can use in their displays while minimizing photodegradation. Reciprocity assumes that a limited exposure to high-intensity light will have the same effect as a long exposure to low-intensity light. This is sometimes true, as far as it goes. Unfortunately, it really doesn't go very far. There are several reasons for this.

1. Every material has its own unique spectral sensitivity.
2. Temperature will accelerate the rate of a chemical reaction. While most photochemical reactions are not temperature sensitive, the typical subsequent secondary reactions are driven by temperature.
3. Many photo-initiated reactions will continue in the absence of light.
4. Humidity can cause a number of reactions (e.g., dye migration).
5. Ozone and other gases can cause fading of inks and dyes.
6. Some degradation reactions are non-linear. A classic example of this is when a UV absorber protects a material, but eventually is "used up" resulting in a sudden degradation "crash."
7. Historically, most of the measurements of light used for reciprocity calculations have been taken using a luxmeter and consequently measure a portion of the spectrum which is relatively harmless to most photosensitive materials. Further, these measurements are often used to compare light sources with significantly different spectra. Discrepancies between sources with a high UV content versus a low UV content are not apparent from luxmeter measurements. However the relative photodegradation risk factor would be significantly different.

Consequently, reciprocity will only work on some materials and then only if there are no variations in spectrum, temperature, and humidity.

Acknowledgments

SPD curves of sunlight and manufactured light sources were measured by Gregory Fedor and William Solarz at Q-Panel's central research lab.

References & Suggested Reading:

ISO 11341, Paints and varnishes - Artificial weathering and exposure to artificial radiation - Exposure to filtered xenon-arc radiation

ASTM D6695, Standard Practice for Xenon-Arc Exposures of Paints and Related Coatings

ISO 4892-2, Plastics - Methods of exposure to laboratory light sources, Part 2: Xenon-arc sources

ASTM D4459, Standard Practice for Xenon-Arc Exposure of Plastics Intended for Indoor Applications

ISO 105 B02, Textiles - Tests for Colourfastness - Part B02: Colourfastness to artificial light: Xenon arc fading lamp test

AATCC TM 16, Colorfastness to Light

ISO 12040, Graphic Technology - Prints and printing inks - Assessment of lightfastness using filtered xenon arc light

ISO 18909, Imaging Materials - Stability of color photographic images -Methods for measuring

ASTM D3424, Standard Test Methods for Evaluating the Relative Lightfastness and Weathering of Printed Matter

ASTM D4303, Standard Test Methods for Lightfastness of Colorants Used in Artists' Materials

International Commission on Illumination Technical Report on Solar Spectral Irradiance Publication No. CIE 85 1st ed. 1989

Bugner, D. et al. Survey of Environmental Conditions Relative to Display of Photographs in Consumer Homes, 13th International Symposium on Photofinishing Technology Proceedings, pp. 31-36 2004.

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Trubiroha, P. The Spectral Sensitivity of Polymers in the Spectral Range of Solar Radiation, International Conference on Advances in Stabilization and Controlled Degradation of Polymers, A.V. Patsis, ed. Technomic Publishing Company, 1989

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Douglas Bugner, Joseph LaBarca, David Kopperl, Jonathan Phillips, David Skye, Irene Baker, Caryn Cunningham, Paige Miller, and Thomas Kaltenbach, Research and Development Laboratories, Eastman Kodak Company. Survey of Environmental Conditions Relative to Display of Photographs in Consumer Homes, 13th International Symposium on Photofinishing Technology Proceedings, pp. 31-36. 2004.

Standards Organizations

American Association of Textile Chemists and Colorists (AATCC) One Davis Drive, Research Triangle Park, North Carolina 27709, USA.

American Society of Testing and Materials (ASTM) 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428-2959, USA.

Commission Internationale De L'Eclairage CIE Central Bureau Kegelgasse 27, A-1030 Vienna, Austria.

International Organization for Standardization (ISO) 1, rue de Varembé, Case postale 56CH-1211 Geneva 20, Switzerland.