Table 11. Ranges of Exterior Horizontal Illuminance in North America under a Clear Sky.

Time	Winter	Summer
Morning (8 AM)	600 – 27,000 lux (60 – 27,00 fc)	18,000 – 50,000 lux (1,800 – 5,000 fc)
Noon (12 PM)	8,000 – 94,000 lux (800 – 9,400 fc)	71,000 – 107,000 lux (7,100 – 10,700 fc)
Afternoon (4 PM)	7,000 – 65,000 lux (700 – 6,500)	36,000 – 74,000 lux (3,600 – 7,400 fc)

8.1.2.2 Overcast Sky An *overcast sky* has an 80% to 100% cloud cover. Its luminance varies with solar altitude and has a zenith-to-horizon luminance ratio of about 3:1. **Table 12** provides example ranges of ground-level illuminance under overcast skies.

Table 12. Ranges of Exterior Horizontal Illuminance in North America under an Overcast Sky.

Time	Winter	Summer
Morning (8 AM)	100 – 25,000 lux (10 – 2,500 fc)	4,000 – 45,000 lux (400 – 4,500 fc)
Noon (12 PM)	7,000 – 78,000 lux (700 – 7,800 fc)	14,000 – 100,000 lux (1,400 – 10,000 fc)
Afternoon (4 PM)	2,000 – 50,000 lux (200 – 5,000 fc)	11,000 – 70,000 lux (1,100 – 7,000 fc)

8.1.2.3 Partly Cloudy Sky The *partly cloudy sky* is defined as having a 40% to 70% cloud cover that makes it a highly variable daylight source. Under a partly cloudy sky, the sun can be alternately obscured, partly obscured, or unobscured, with all of this occurring within a relatively short span of time. For example, in a partly cloudy sky, bright white cumulus clouds that are three times brighter than the blue sky at zenith can appear at any location on the sky dome. These conditions cause rapid and wide changes in luminance distribution and chromaticity that can affect a building on any of its orientations.

8.1.3 Reflected Light from Sun or Sky Reflected light is the third component of daylight. Its source can be composed of sunlight or skylight reflected from objects (e.g., trees, buildings, walls) and ground surfaces (grass, snow, concrete) in the surround. Reflected sunlight or sky light can be a large component of the total daylight in a gallery space, beyond what is considered the "primary" daylight zone.

The overall properties of the reflected light result from the combined effect of light source and reflecting surface, particularly surface colors and finish. For example, sunlight that undergoes multiple reflections within the surrounding environment can diminish in intensity but take on the color of the surround. This filtering of daylight's spectral content is sometimes referred to as "local color" and can make daylight unique to a place.

8.1.3.1 Nuisance Reflected Light Reflected sunlight can be an extreme nuisance, especially in a gallery or museum. Exterior and interior specular (shiny) surfaces can cause unanticipated conditions of glare, heating, light trespass, and false triggering of photo-sensing control systems. Non-planar surfaces can compound this problem; e.g., sunlight reflected from curved glass or metal building facades, or from the windshields of passing vehicle.

8.2 Energy and Damage

Museums and galleries are damage-sensitive environments. Risk of damage to the display object occurs through two primary mechanisms: photochemical reactions on a molecular level triggered by exposure to visible radiation and UV; and heat-induced damage, such as surface cracking, due to radiant heating effects of visible and non-visible radiation.

8.2.1 Light and Ultraviolet (UV) Energy Light is primarily responsible for the fading of organic pigments, so illuminance shall always be controlled to IES recommended levels (refer to **Annex B**). UV is extremely damaging to materials because it attacks the object itself by inducing cracking, crazing, and yellowing, and by otherwise destroying materials while providing no benefit to the viewer. Daylight is the biggest source of UV in the museum environment, so special care shall be taken to filter UV energy.

The UV spectrum extends from 10 nm to 400 nm. Although the sun radiates less energy in the UV region than in the visible spectrum, these shorter wavelengths present an exponentially higher damage potential, particularly to organic materials (e.g., paper, cloth, pigments). UV radiation can be up to 200 times more damaging than the visible blue-green band centered at 500 nm. Short wavelength radiation can cause structural damage by the breakdown of molecular bonds. This molecular damage is cumulative and irreversible, and can occur, or can continue to occur, after exposure. Short wavelength UV-C (100 to 280 nm) has the highest energy and can cause the most damage, but due to filtering by the earth's ozone layer the amount that reaches ground level is very low. The ground-level amount of UV-B (280 to 315 nm) is higher, but soda-lime glass is effectively opaque to wavelengths shorter than 315 nm. The content of UV-A (315 to 400 nm) at ground level is higher yet. It is interesting to note that in the ISO/CIE definitions, the visible and UV spectra overlap 20 nm, in the band of 380 to 400 nm, to capture the damage caused in this band when considering each spectral range. Although UV is a primary contributor to damage, in order to assess the damage potential of daylight, visible and non-visible spectra should be considered together along with the spectral range in which damage occurs (see **Section 8.5.4**).

Some typical methods of managing UV radiation from daylight are through the use of spectrally selective glazing coatings, UV absorbing paints and finishes, and plastics in the form of UV-blocking polyvinyl butyral (PVB) film, either as an interlayer or as an applied film (see **Section 8.8.1.4**).

8.2.2 Non-Visible Spectrum (IR) About 50 percent of the energy from solar radiation lies in the IR part of the spectrum (wavelengths longer than 800 nm). Longer wavelength IR energy raises an object's surface temperature, which tends to dry out objects and cause their surfaces to crack. Shading devices, spectrally selective glazing, films, and filters can be used to reduce long wave radiation from radiating through the building envelope. This in turn reduces solar heat gain and resultant increases to cooling load.

8.2.2.1 Exposure and Minimizing Risk of Damage *Irradiance* is the density of radiation on a surface, usually expressed in watts per square meter (W/m^2). The exposure of an object to UV, IR and visible light over time (hours, h), can therefore be expressed as:

Exposure (watt-hours per square meter, Wh/m^2) = Irradiance (W/m^2) x Hours of exposure (h)

This equation makes clear that exposure is a product of time and irradiance. However, to account for the response of the various materials that make up the display object, damage should be assessed on a wavelength-by-wavelength basis.

Daylight control strategies such as automatic daylight control via time switch or occupancy sensing may be used to minimize exposure. For example, space programming based on "safe zones" determined by plotting the movement of sun patches through a space over the course of a year can assist with selecting the best locations for light-sensitive artworks. (Refer to **Section 4 Preservation of Light-Sensitive Materials** for conservation discussion and limits.)

8.3 Daylighting Design in Museums

Daylight fenestration in a museum or gallery space usually fulfills one or more of three basic functions: the illumination of the display object, the illumination of the architecture, or the provision of a view.

8.3.1 Daylight as Object Illuminant Daylight can be used to illuminate display objects, either exclusively or in combination with an electric light source. In an effort to balance preservation with viewing requirements, collections establish well-defined illumination criteria for use when planning for light levels in exhibits. These criteria are based on the light sensitivity of each individual display. Typically, the sensitivity is specified as high, medium, or low and results in a recommended illuminance level (see **Section 4**). When daylight is used in combination with electric light, there is usually a recommended ratio of daylight to electric light to account for the total illuminance (see **Section 8.5**). Lighting designers should consult with a museum's conservator, curator, and lighting personnel to understand target illumination criteria established for a collection as whole, and to identify individual display objects with special requirements.

8.3.2 Daylight as Architectural Illuminant In this situation, daylight can illuminate interior architectural surfaces, or non-exhibition areas, but not the display objects. Used this way, daylight can create luminous room surfaces that provide ambient lighting for wayfinding or make a room feel like it is daylighted, but it does not contribute significantly to the irradiance of the display objects (see **Figure 73**). An extension of this concept is the use of daylighting devices to provide a causal relationship for the presence of light in the room, but with the daylight contribution actually providing minimal illuminance of artwork and architectural surfaces. The theatrical design term for this lighting technique is "motivated light." It is found in common use in art galleries where skylights are covered with large amounts of light-blocking material (scrims, fully closed louvers, white wash, and neutral density films) so that the skylight still glows like a light box, but very little light reaches the artworks (see **Figure 74**).

Figure 73. There are a large number of windows in the Lincoln Gallery at the Smithsonian American Art Museum, providing a view to the street and interior courtyard and yet allowing very little light to enter the gallery. (Lighting design by Scott Rosenfeld; image courtesy of The Smithsonian American Art Museum.)

Figure 74. Ponce Museum of Art, Ponce, Puerto Rico; completed 1965. Photo shows skylight renovation completed 2006. (Architects: Edward Durrel Stone; LG Architecture. Daylighting consultant: Tanteri + Associates.)

8.3.3 View Provision Fenestration can offer visual connection between indoor and outdoor spaces. Views to the outdoors, such as to a sculpture garden or an atrium, provide museum visitors visual relief and can extend their visit time. Fenestration that is solely for view function typically utilizes a reduced visual transmittance (VT or Tvis) to balance the ratio of exterior and interior luminances.

Although fenestration systems can provide multiple daylight functions, systems that are designed with a clearly defined function tend to have more-effective controls. In addition to functionality, other important factors to consider include visual comfort and energy savings.

8.3.4 Visual Comfort Museum lighting designers should provide luminous environments that are comfortable to view. With the introduction of daylight, the control of room surface and object brightness is critical in the prevention of glare. Bright daylight-transmitting glazing surfaces, seen directly or by reflection, should be eliminated from an observer's field of view. Reductions in brightness contrast can be achieved through a variety of means, such as through the selection of interior materials, finishes and coatings; by splaying or chamfering the daylight aperture; or through careful placement of adjacent room surfaces. Together, these techniques aim to reduce visual discomfort but also provide added benefits such as reduced interior illuminance requirements and associated electric lighting energy cost savings.

8.3.5 Energy Savings There are many reasons to value daylight in the museum environment, but the overall energy savings from daylight harvesting is not a compelling argument. Using daylight as the primary illuminant will reduce energy consumption spent on electric lighting, but it is necessary to calculate the additional heat load created by daylight, and how dissipating this heat will affect the total net energy reduction.

Typically, reducing the connected load used for electric lighting will significantly reduce HVAC usage. However, museums are less likely to see this savings because even during the cooling period museums expend energy to maintain a steady climate necessary for artifact conservation. Museums typically accomplish this careful balance of temperature and humidity (and energy inefficiency) by cooling return air and then reheating it before it is returned as supply air. While daylight can provide a small benefit to the mechanical (HVAC) systems, these savings are difficult to calculate.

Another distinguishing factor between daylight harvesting in museums as compared to other building types is that daylight illuminance should be reduced to a relatively low target illuminance level of 200 to 400 lux (20 to 40 fc). As a point of comparison, daylight harvesting in office applications has a higher target level of illuminance as well as a much higher acceptable upper range of illuminance. The greatest energy savings from daylight harvesting is possible in spaces dedicated to exhibiting materials that aren't light-sensitive.

It is important to note that while allowing large quantities of light into the museum environment is often a welcome break from galleries with lower illuminance levels, the decision to designate a space to only house materials like marble, glass and ceramic should not be taken lightly. Exhibition arrangements often change over time, and it is often difficult and expensive to eliminate daylight after construction is complete.

8.4 Daylighting Techniques and Typologies

Museums employ a wide range of traditional and non-traditional daylight delivery systems. These delivery systems can use either one or a combination of two basic daylighting techniques: sidelighting and toplighting.

8.4.1 Sidelighting Sidelighting is a technique for lighting the perimeter of a building where daylight enters a room from the side through glazed vertical apertures, typically called *windows*. Sidelighting can be from one side (unilateral) or two sides (bilateral). In contemporary buildings, *unilateral sidelighting* lends itself to continuous fenestration and curtain wall construction. Large ranges in daylight illuminance along a horizontal plane (greater than 25:1) should be avoided. For windows with clear glazing, the distance from the window wall to the inner wall should be limited to twice the window head height. Placement of the window head close to the ceiling increases daylight penetration, but the simultaneous increase to view of sun and sky and the potential for glare should be considered.

Equatorial facing windows (south facing in the Northern Hemisphere) may be shaded using horizontal devices, while windows oriented 45 degrees or more away from the equator, including polar facing windows, may be better served by vertical shading devices. Polar facing windows can provide the benefit of admitting higher-efficacy skylight into the building envelope with minimal direct-solar shading requirements. However, polar facing windows may require more extensive glare control measures due to their view toward high-luminance equatorial facing surfaces on other structures. Equatorial facing windows may allow higher levels of daylight due to their prolonged exposure to direct sunlight (in predominantly non-overcast climates). However, they may require more extensive control measures to address glare and thermal effects.

Bilateral sidelighting uses supplemental lighting from apertures located on a wall opposite the primary window wall to increase the overall amount of daylighted floor area and improve uniformity. The second set of windows often occupies only the upper part of the wall. Sloped ceilings can be employed with this design, the higher window head height resulting in increased daylight penetration (see **Figures 75** and **79**). In bilateral sidelighting, at least one set of windows is exposed to the sun, necessitating glare control.

Figure 75. Temple of Dendur Gallery, Metropolitan Museum of Art, New York. (Image courtesy of Scott Rosenfeld.)

8.4.2 Toplighting Toplighting is a technique for lighting the core of a building or space by introducing daylight from above. Sunlight and or sky light is collected from a building's roof through horizontal, vertical or sloped glazed apertures, transmitted, and then redistributed to a space located below from an emitting aperture located at or near the ceiling plane. Top-lighting glazing can be tilted to increase daylight transmission, but with this configuration additional heat gain and dirt accumulation should be considered. Operable glazing in a toplighting device can provide ventilation and cooling. Toplighting devices require special attention to prevent moisture penetration and dripping due to condensation.

Traditional toplighting devices include skylights, clerestories, monitors, and atria. A newer method involves the use of core devices. Each of these methods is discussed below.

8.4.2.1 Skylights Museums and galleries employ an extensive array of toplighting For example, skylights can have highly variable well geometries and above-roof glazing forms (e.g., domes, pyramids, or polygons). These can employ a range of devices such as louvers, diffusion panels, and translucent glazing to deliver uniform, glare-free daylight distribution (see **Figures 76** and **79**).

Figure 76. Daylight-diffusing luminous ceiling at the Art Institute of Chicago. (Image courtesy of Scott Rosenfeld.)

8.4.2.2 Monitors and Clerestories Roof monitors are a popular toplighting solution for large display spaces. The basic form of a roof monitor is a high bay flanked by two lower bays with vertical glazing connecting the two roof levels. By extending the roofline of the upper bay and adding a high reflectance roof surface to the lower bay, direct sun is shaded and interior light levels are significantly increased due to reflected light. Clerestories are a single-bay version of a roof monitor.

8.4.2.3 Saw-Tooth Roofs Saw-tooth roofs have repetitive clerestory or roof monitor elements (see **Figure 77**). Saw-tooth roofs can be polar facing or equatorial facing. If equatorial facing, they should incorporate a glare and heat control strategy due to their high degree of solar exposure. Polar facing skylights can provide general illumination of large open floor areas and are often found in museums built from repurposed industrial spaces.

Figure 77. Crocker Art Museum, Sacramento, CA. (Architect Gwathmey Siegal and Associates Architects. Photo by Bruce Damon/Crockerart/CC3.0)

8.4.2.4 Atria Similar to skylights, atria take on a variety of enclosure geometries and glazed roof forms (e.g., ridge, shed, pyramid and dome). (See, for example, **Figure 78** and **79**.) In atria, because the ratio of glazing area to floor area is so high, lower-transmittance glazing and translucent glazing are often used to control direct sunlight through attenuation and diffusion.

Figure 78. Guggenheim Museum, New York. (Architect: Frank Lloyd Wright; photo by Evan-Amos)

8.4.2.5 Core Devices *Core toplighting* strategies are used to transmit sunlight from the collection area to the distribution point over distances that can exceed traditional sidelighting and toplighting techniques. Core solar lighting systems are designed to steer or redirect direct solar flux; in doing so they provide relatively minor contributions from diffuse skylight.

A core lighting system typically consists of sunlight collection and redirecting devices—devices that utilize mirrored louvers or prismatic elements integrated into conventional fenestration elements—or it can be a stand-alone device.

Tubular daylighting devices (TDDs) are simple open-air piping systems designed to collect sunlight or skylight at roof level, transport it through a high-reflectance light duct, and emit it at room level in a controlled distribution pattern. TDDs come in standard and custom fabrications.

Hybrid solar lighting (HSL) devices combine a sunlight collection system with various transport systems such as fiber optics or hollow waveguides. Some HSLs incorporate an electric light source somewhere in the system, which powers on when sunlight is absent. HSL luminaires are typically ceiling mounted to provide some form of top light. HSL systems can collect sunlight from a roof or a wall. A façade-mounted HSL system can transport sunlight laterally to a depth that exceeds the daylight penetration depth of conventional windows.

Heliostats also support deep-core lighting. Heliostats are single or dual-axis sun-tracking mirror systems that redirect sunlight either directly into a room or outdoor space, or into a light distribution system.

Figure 79. An example of a top-lighting and skylight system, and of top-lighting and side-lighting in glass-enclosed atria. National Gallery of Canada, Ottawa, Canada. (Architect: Moshe Safdie; image by Wladyslaw/CC3.0)

Traditional toplighting and deep-core strategies can provide a solution for the multi-story museums located in dense urban environments. These buildings are characterized as being obstructed at varying levels and orientations, but maintain daylight access at their rooftop. It can also provide a solution for museums with underground gallery spaces that have daylight access above from a roof, facade, or ground area (see **Figures 80a**, **80b**, **80c**).

With deep-core devices, special consideration should be given to suitability of the spectral quality of daylight delivered to an interior environment. The same can be said for sidelighting and toplighting;

Figures 80 a, b, c. Examples of skylights providing core lighting for lower floors. (Daylighting consultant: Tanteri + Associates; photos By Matthew Tanteri)

however, in a deep-core lighting device there is a greater distance between occupant and light source, and less of a chance for a view to connect the qualities of emitted daylight with its natural source.

8.4.3 Combinative Strategies Many well-known museums utilize hybrid daylighting techniques to successfully integrate daylighting. The staggered building section is probably the best representation of this combinative approach. A staggered building section overcomes the limited depth of daylight penetration from unilateral sidelighting by coupling sidelighting with some form of toplighting, such as a skylight, monitor or clerestory. For example, a window combined with a clerestory (single-bay version of a roof monitor) overcomes the limited daylight penetration of unilateral sidelighting. The deep penetration of daylight that this allows provides greater flexibility in the layout of spaces (see **Figure 81**).

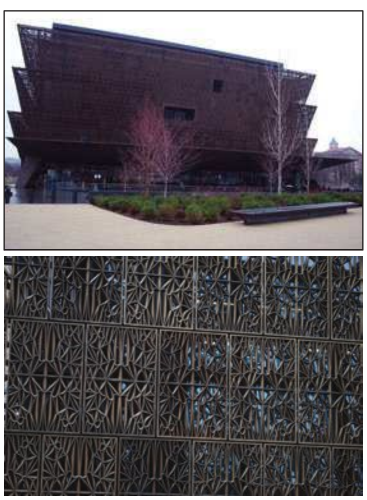

Figure 81. An example of staggered building sections (top) and brise soleil (bottom) used at the National Museum of African American History and Culture. (Architect Freelon Adjaye, Bond/Smith Group. Photographs by Scott Rosenfeld and Jonas Kaplin)

8.4.4 Shading Devices As a rule, direct sunlight should be avoided in display spaces. Shading devices can block direct sun but allow the admission of diffuse light from the sky and reflected light from the surround.

Effective daylighting systems employ a variety of interior and/or exterior shading devices that include overhangs, fins, hybrid forms, screens, brise-soleil, and diffusers (see **Figures 83** and **84**).

Figure 84. Example of a brise-soleil (on the building behind the sculptures) at the Yorkshire Sculpture Park Underground Gallery. (Image by Carol Rose, CC2)

8.5 Performance Metrics

There are several types of performance metrics for evaluating the amount of and quality of light in the museum environment. They fall into two general sections—those describing the amount of light illuminating an object and those describing the color of the light illuminating an object. This section describes the different metrics available and how they can be used in planning for daylighting in museum spaces.

8.5.1 Object Illuminance and Luminance In most daylighted environments, the illuminance at a point will vary over time, depending on the time of day, season, and weather conditions. As daylight and electric light levels are additive, the total illuminance value from daylight and electric light shall be considered when planning for light levels in exhibits. Illuminance is typically measured in the plane of the surface of the object. For example, the illuminance level taken for a painting on a wall is vertical illuminance.

Depending on what type of daylighting strategy is employed in an exhibit space, it may be appropriate to target a fixed illuminance level (more appropriate for active daylight systems), or an average or maximum illuminance level (more appropriate for passive daylight systems, which allow daylight levels to vary depending on exterior weather conditions).

8.5.2 Values Used to Assess Damage or Risk: Maximum Instantaneous Value The measurement of light falling onto an object at any given time is termed the instantaneous illuminance value. Given the variability of daylight in an interior environment over time (intensity and direction) and space (direction and distribution), it is often not possible to specify a target illuminance value for a particular object. If this is the case, a maximum instantaneous value may be specified based on conservation requirements. (Refer to **Section 4** for illuminance recommendations based on an object's sensitivity to light.)

8.5.3 Values Used to Assess Damage or Risk: Cumulative Value Due to the variability of daylight, it is typically not possible to design a space to provide a constant level of daylight to illuminate objects; therefore, a cumulative value is commonly used to express the total exposure to light of an object over time.

The "reciprocity rule" of photochemical action states that the light damage to an object is directly proportional to the level of object illuminance and the duration of exposure. The total exposure of an object over a specified period can be described in terms of lux-hours or footcandle-hours. This single value can be used to assess the relative exposure of an object. (Refer to **Section 4.3** for additional information.)

8.5.4 Values Used to Assess Damage or Risk: SDF Curves Laurence Berkeley National Laboratory (LBNL)'s *Window 5.2* software, widely used by the architectural industry, provides the following three metrics to assess a light source's spectral damage function (SDF):

- **Tdw-ISO.** This weighted metric describes the damage potential of all wavelengths of radiation up to 700 nm. The wavelengths are weighted using the spectral damage function (SDF) curves found in CIE 89/3. The advantage of these calculations is that energies are weighted, so short-wavelength UV is treated as more damaging than longer wavelengths. For example, UV energy at 350 nm is considerably more damaging than UV at 380 nm, and blue light at 450 nm is considered more damaging than longer-wavelength yellow light at 580nm. The National Fenestration Research Council (NFRC) has adopted this standard, and it is used to report on a wide range of window glazing products.
- **Tdw-K.** This is similar to Tdw-ISO but only includes the spectrum up to 500 nm. Tdw-K was replaced by Tdw-ISO in 2005.
- **Tuv.** This is the unweighted total amount of UV from 300 to 380 nm. This is the least precise of the three metrics. The metric of microwatts per lumen suffers from the same problems as Tuv because short-wavelength UV is treated as equally damaging as long-wavelength UV.

In addition to these three metrics, the Harrison Damage Function, based on early research on the influence of spectrum in causing damage to low-grade paper, provides a weighted value of mostly UV energy. **Figure 85** provides examples of the SDF curves.

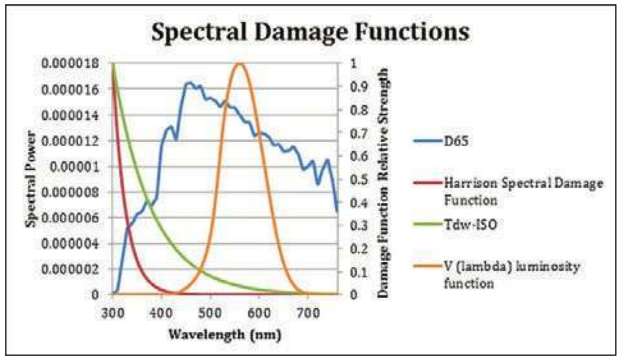

Figure 85. Examples of spectral damage function curves and the SPD function for daylight of 6500 K (D65). (Graph courtesy of Scott Rosenfeld and Masahiro Toiya)

A complete set of performance criteria should be established for parallel evaluation between products. Tdw-ISO is only one of several competing criteria; museums are cautioned that simply choosing the glazing product with the lowest Tdw-ISO can result in yellow glazing with a CCT that is lower than necessary for conservation purposes. At the time of this writing, utilizing spectral damage functions such as Tdw-ISO is somewhat controversial within the conservation science community; what is well established is that the primary mechanism of damage is excess exposure to illuminance and the presence of UV. Tuning the visible portion of the spectrum is not currently standard practice in museums, so there may be no reason to reduce CCTs for low-sensitivity artworks. The same is not true for highly light-sensitive artworks, where spectral differences make a bigger difference and where using daylight as a primary light source is ill advised.

8.5.5 Recommended Ratios and Maximum Value Although not true for all art, it is generally preferred that the viewing surfaces of art have some degree of uniformity of illuminance over the length and width of the object. An illuminance maximum-to-minimum uniformity of 2:1 is recommended for the primary viewing portion.

8.5.6 Glare There is potential for glare in daylighted spaces because of excessive brightness or contrast due to direct solar penetration, reflected sunlight penetration, and direct or reflected views of daylight fenestration. These should be avoided both to preserve artwork and to enhance the viewing experience. Various techniques may be employed to control glare, such as through the specification of appropriate glazing and visible transmittance, the application of shading devices, and the physical layout of display objects within the room.

8.5.7 Damage Concerns Uniformity can also have an effect on potential damage to objects. If the illuminance varies significantly over the area of an object, there is a potential for increased damage where light levels are higher. Therefore, when assessing daylight levels, it is recommended that measurements be taken over the entire object surface.

8.6 Color Metrics

8.6.1 SPD, Chromaticity, and Correlated Color Temperature (CCT) The chromaticity of daylight entering a building is a product of multiple factors: solar position, sky type, atmospheric content, and the color of the surround. It is a dynamic property that changes with location, season, and time of day.

Each light source has a specific spectral power distribution (SPD) that will affect objects in different ways. An understanding of the composition of a light source's spectrum helps determine the amount of potential damage to artwork that it may have, as well as how color will appear under that source.

The SPD of daylight varies as a function of season, sky condition, time of day, and geographic location. Unless these variations are known, the standard illuminant D65 is typically used to represent daylight in colorimetric calculations. D65 was put forth by the International Commission on Illumination (CIE) to represent "average daylight." It simulates noon conditions and is based on a CCT approximation of 6500 K for the midday sun in Western and Northern Europe.

Sunlight above the atmosphere, called *extraterrestrial radiation*, has a relatively constant CCT of about 5900 K. Once it passes through the earth's atmosphere, it becomes *terrestrial radiation* and changes color over the course of the day. Rayleigh scattering of sunlight by small particles tends to scatter shorter wavelengths more, which gives the sky its blue color. This subtractive effect makes the portion of direct sunlight that passes through the atmosphere appear red, orange, yellow or white. The actual color depends on the make-up of atmospheric particles and the length of the path that sunlight travels through the atmosphere. The latter depends on the angle of the sun in the sky, which corresponds directly to sun position. **Table 13** provides examples of CCTs for some common light sources. (Refer to **Section 3.3.2** for more information on SPD, CCT and chromaticity.)

Table 13. CCTs of Various Light Sources.

CCT	Source
1850 K	Candle flame, sunset, sunrise
4100 – 4150 K	Moonlight
5000 K	Horizon daylight
5500 – 6000 K	Zenith daylight
6500 K	Overcast sky

Note: These CCTs are approximate; considerable variation can be present.

8.6.2 Color Rendering Index (CRI) Daylight from the sun and/or the sky is defined as having a CRI of 100 (except near sunrise and sunset). However, once daylight is reflected or transmitted through colored materials, such as those of exterior surfaces and glazing systems, its CRI is lowered in proportion to the extent of coloration. Materials that transmit or reflect equally across the visible part of the spectrum are best to maintain high CRI values (refer to **Section 8.7.1.2**). Accurately quantifying the color rendition characteristics of a light source is a complex problem, considering not only color rendition, but also color fidelity, discrimination, and preference. (For additional information, refer to **Section 3.3.3** in this document, and to IES DG-1-16, *Color and Illumination*, and IES TM-30-15, *Method for Evaluating Light Sources Color Renditio*n.)

8.7 Documentation and Testing

Proper documentation of design concepts is the key to creating successful museum environments, and is particularly important when museum spaces introduce daylight. Proper documentation and testing of the design of a space ensure that the concept can be realized with as little uncertainty as possible.

8.7.1 Daylighting Specifications The materials used throughout a space will determine how daylight is introduced and how it will interact with room surfaces and finishes. The specification process ensures that the qualities and technical aspects of the materials and building elements meet the design intent. Proper specifications will allow the design team and owner to confirm that the materials used in a museum building perform as expected. When considering a design that introduces daylight into a museum, the specifications for the following components should be reviewed at each stage of the design process:

- Glazing
- Surface finishes, such as paints and metal finishes
- Active daylight control elements, such as roller shades and blinds
- Passive daylight control elements, such as sun shading devices
- Lighting controls
- Luminaires
- Façade systems

The specification allows the designer to describe the design intent of the daylighting system's components and how those components interact with each other. The inclusion of a lighting control narrative in the lighting controls specification helps to describe the functionality required of any daylight-responsive lighting controls.

The design team shall specify performance requirements for the glazing for any apertures that allow daylight to enter the museum environment. The architect, owner, façade consultant, MEP engineers, and lighting consultant can all have input into the performance requirements of the glazing systems. From a daylighting perspective, the following information is critical for inclusion and review in the glazing specification:

- Visible transmittance (VT)
- CRI of transmitted light
- UV performance

8.7.1.1 Visible Transmittance (VT) *Visible transmittance* is the percentage of visible light that passes through the glazing; the higher the VT, the more light that passes through the glass. VT in conjunction with glazing area regulates the total amount of luminous flux that passes through a glazing system.

8.7.1.2 Color Rendering Index and VT The color quality of light transmitted through glazing can be significantly influenced by the glazing elements that the light passes through. Color rendering index, CRI or R_a, is a useful metric to ensure that the fidelity of the transmitted daylight is similar to that of the non-filtered daylight (pre-glazing). Both the glass and the coatings applied to the glass affect the CRI of the transmitted light, and these elements should be carefully researched and specified to ensure the highest CRI possible that meets the overall requirements of the daylighting system.

The ability of a particular type of glazing to render color is determined by the spectral composition of the transmitted daylight. CRI is an industry standard test for color fidelity that is done using a reference illuminant, not in situ. Architectural glazing manufacturers typically use a metric called R_a (D65) to report color performance of glazing. R_a (D65) characterizes the ability of a glazing system to portray an average of eight color samples under a CIE standard illuminant with a CCT of 6500 K, compared to the same samples seen under the same source without the glazing. Glazing selections can also be compared with CRI (R_a) values based on other standard illuminants from the CIE's canonical daylight series: D50, D55, D65 and D75. For example, a south-facing window might use D50 to simulate warmer-toned horizon light, while a north-facing skylight that receives light from an unobstructed blue sky might use D75.

Clear float glass is the most common glazing substrate. It contains iron oxides that give it a slightly greenish tint, which increases with substrate thickness and reduces R_a (D65) slightly but overall is still considered very good. **Table 14** shows several examples of glazing with their transmittance and R_a (D65) ratings.

Table 14. Examples of Transmittance and Color Rendering Ability of Typical Window Glazing.

Substrate	Visible Light Transmittance (%)	Color Rendering Index, R_a (D65)
2 mm Clear	91	100
5 mm Clear	90	99
10 mm Clear	87	97
19 mm Clear	84	95

Note: General color rendering indexes, R_a values, above 90 are considered "very good."
(Source: http://www.me.en.sunguardglass.com/cs/groups/sunguardme/documents/native/gi_005564.pdf)

Low-iron glass substrates are often specified for museum daylighting elements because they provide the highest light transmittance with the least amount of spectral distortion the R_a (D65) rating is typically greater than 98. These substrates are often called "water white" due to their reduced green tint when compared to clear float glass. Trade names for low-iron glass include Starphire,® Optiwhite,™ and UltraWhite.™

Tinted substrates absorb light differently across the visible spectrum, which can lead to a "warm" or "cool" tonality. Some tinted substrates that have nearly even absorption at all visible wavelengths are called "neutral" gray. However, all tinted substrates, including some "neutral" grays, should be used with caution, as they can significantly alter daylight's spectral composition so that R_a (D65) falls below 85.

Low-emissivity (low-e) and solar coatings can also significantly reduce CRI, so it is important to ensure that properties of glazing meant to improve performance in other aspects of the building, such as thermal factors, do not affect the color quality of the transmitted light. Most low-e coatings applied to the surface of high performance glazing reduce R_a (D65) to below 90. However, some low-e coatings on low-iron glass can maintain R_a (D65) above 96.

8.7.1.3 UV Performance The UV performance of glass can be specified in several ways. The design team may specify a total quantity of UV, in microwatts per lumen, allowable from transmitted daylight, or they may specify a specific UV transmittance at particular wavelengths. Spectral data for light transmitted through the glazing are key to evaluating the performance of different glazing makeups, and it is recommended that this information be reviewed during the design, specification, and construction process.

8.7.1.4 Films In addition to the glazing makeup itself, there are many types of films available to modify the quantity and quality of light transmitted. A clear neutral-density film can be used to reduce the quantity of light passing through glazing, and a diffusing film can be used to mitigate direct light exposure from directional sources, including sunlight. These may be applied to the surface of glazing, or it may be laminated between glass sheets.

8.7.1.5 Applied Films Tinted or low-e coated films may also be applied to glazing. Tinted films degrade CRI worse than tinted glazing and can have a short life.

8.7.1.6 Laminated Glass Laminated glass is a "sandwich" with some type of interlayer placed between two or more pieces of glass. Many museums rely on interlayers of polyvinyl butyl (PVB) for its UV-filtering properties. PVB blocks almost 99 percent of the UV radiation present in sunlight, but does not significantly reduce visible light (see **Figure 86**). When laminated between two panes of glass it can provide safety and security by maintaining the geometric integrity of the pane in case of breakage. It is also an excellent noise barrier.

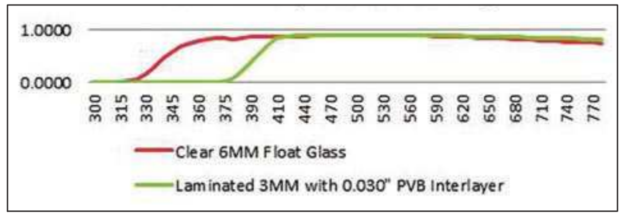

Figure 86. Spectral power transmittance functions for clear glass and laminated glass, from 300 nm to 780m. (Shown in 5-nm increments from 300 to 400 nm; in 10-nm increments from 400 to 780 nm.) (Source: Matt Franks, Arup)[6]

Ethylene vinyl acetate (EVA) is another popular plastic film used to make laminated glass. It shares many similar properties with PVB, such as having very high UV blockage (at least 99 percent) and very high visible light transmittance (at least 92 percent).

When addressing the use of films either in existing spaces or as part of a new design, the performance of these elements should be evaluated and specified to meet the needs of the project. Other than their short life span, applied films typically work well for retrofit applications. However, they should not be thought of as a "one size fits all" solution; for example, they should not be used on historic glass.

8.7.1.7 Fabric Shades Perforated or woven fabrics are a popular choice for reducing illuminance and for providing view. They are specified by openness factor. Fabrics with an openness factor greater than 1 percent allow a view out; with a dark color facing inward, they improve visibility to the outside. Fabric roller shades are often used as a post-construction solution to reduce illuminance, especially from windows. Fireproofed theatrical "shark's tooth" scrim or fireproof greenhouse cloth can be used to reduce illuminance in skylight applications.

8.7.1.8 Interior Finishes Selection Interior finishes will contribute to the performance of daylighting systems. Materials that transmit or reflect equally across the visible part of the spectrum are best to maintain high CRI values. Specification of interior finishes should match any assumptions that have been made in calculating performance of daylight systems. A change in color of a material used to reflect light can directly affect the quantity of light that passes through the daylighting system. Since lighter-colored materials (high surface reflectance) are more efficient at reflecting daylight, they are commonly used in daylight delivery systems. The design team should discuss the impact of interior finish colors and weigh this along with aesthetic design decisions.

An often-overlooked quality of interior finishes is the specularity, or mirror-like reflection, of the material.

Even a finish that is not typically seen as specular can introduce issues with direct reflection of light sources if its surface has too much of a specular reflection component; an example is semi-gloss paint. Materials that are more diffuse (such as matte paint), are less likely to show bright spots from specular reflections of light sources.

8.7.1.9 Testing While the specification process documents the design to ensure compliance of the components of a daylighting system with the design intent, it is important that designs and components be tested during both the design and construction process.

8.7.1.10 Models One of the easiest and most accurate ways to predict and understand the quality, quantity, and distribution of daylight in a space is with a scale model. Since the quantity and distribution of daylight in a space remain constant as long as the geometric relationships among elements are kept constant, a scale model built out of materials with the same qualities as the proposed design can allow the space designer to see and measure the quality of daylight in a proposed design in an accurate way. Photographs from within a scale model are a particularly useful tool in the understanding and presentation of design concepts. A scale model can also be used to benchmark and verify the output of computer models of daylighting performance.

8.7.1.11 Mockups If the project budget allows, full-scale mockups of gallery spaces are the best way of understanding the daylighting performance of a proposed design for new construction projects. These mockups, which usually occur late in the design or just before construction, are an excellent way to understand the quality of daylight in a space. They can help confirm material selections, such as glazing transmittance and roller shade transmittance. A full-scale mockup may be used as a testing bed for daylighting elements and as a means to introduce the owner to how the space will appear and function.

Manufacturers should be made aware that the mock-up elements should be the same as the final product. Some manufacturers will provide a mockup sample simply for color and not include all interlayers, such as the UV-reducing PVB. The end user should “trust but verify” at each step of the design process.

8.7.1.12 Materials Testing Throughout the design and construction process, materials that are critical to the daylighting system performance should be evaluated based on testing from an independent source using recognized testing procedures. Evaluation of spectral data for glazing systems and transmittance data for roller shades and blinds allows the design team to be confident that their performance will be acceptable. In addition, all interior materials and finishes should be reviewed by the conservator to avoid the potential for off-gassing of volatile components that can cause damage to museum objects.

8.7.1.13 Construction Submittals The construction submittal process allows the design team to review each aspect of a daylighting system as proposed by a contractor to ensure that the relevant aspects of the system meet all design requirements. For budgetary or other reasons, many building designs are relayed as performance specifications that relate the desired performance qualities of materials rather than naming specific materials or manufacturers. In this case, the construction submittal for each element of the system should be evaluated to ensure that the performance does indeed meet the design requirements. If it does not, the contractor should be instructed to make changes in order to correct deficiencies. Again, the conservator should review the specific materials and finishes.

Construction submittal data pertaining to daylighting systems in museums should include (but is not limited to) all of the items listed in **Section 8.7.1**.

8.7.1.14 Passive vs. Active Daylighting Systems Daylighting systems can be characterized by whether they operate in an active or passive state. A passive daylight system is fixed, or static, allowing daylight levels to vary with exterior daylight conditions. Passive systems, while they do not have moving parts that require programming or adjustment, do benefit from commissioning processes (see **Section 8.7.3**). Verification of the distribution and quantity of daylight can be part of the commissioning process, and ideally should be measured at different times of day and weather conditions to get as complete a picture as possible of whether a daylight delivery system is meeting design intent or not.

An active daylighting system contains elements that vary automatically in response to exterior daylight conditions in order to maintain a range of target interior daylight illuminances. Active daylighting systems include a moving element that responds to some aspect of daylight. This could be roller shades or blinds, external louver systems, or any other element that actively adjusts, either continuously or at fixed intervals. Since these systems are typically intended to adjust dynamically to maintain a particular range of light levels within a space, a common commissioning tool for these types of systems is a data-logging light meter. This type of meter can be installed in a space for a specific period to record light levels at pre-defined intervals. These data can then be compared to expected design performance,