According to **Figure 8-2**, the first step of JNF requires a relatively small amount of radiant exposure. However, as exposure increases, subsequent steps of JNF require much larger amounts of radiant exposure. This means that a light-sensitive material is at greatest risk of damage when it is new or has not received enough light exposure to noticeably fade. As the color starts to fade, it requires progressively more energy to cause an equal increment of damage. **Figure 8-3** depicts a more realistic picture regarding the differences in the incremental rate of fading for two different materials.

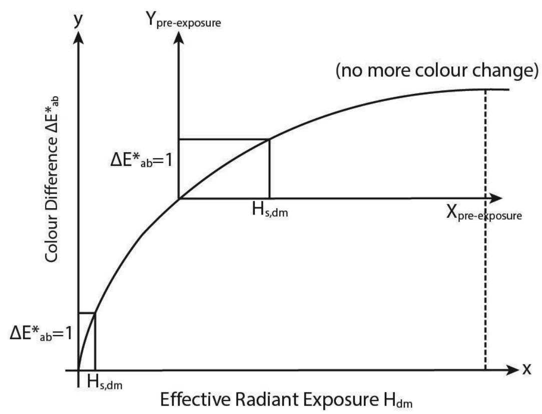

Figure 8-2. The amount of damage (effective radiant exposure, H_{dm}) and the consequential effect (color change, ΔE^{*}_{ab}). The threshold of effective radiant exposure, $H_{s,dm}$, is the amount of exposure that causes one unit of ΔE^{*}_{ab} for the material concerned, and this threshold value increases as damage progresses. (Graphic redrawn from original in CIE 157:2004[15]; reproduced with permission)

8.1.3 Relative Rate of Damage over Time, Based on the Light Sensitivity of an Object. It is inevitable that light-sensitive objects will be damaged under normal display conditions when exposed to visible light. The goal is to understand, manage, and minimize such damage. To do so, it is helpful to understand the relative risk of exposure. **Annex C** provides a chart that associates the rate of fading with materials commonly found in museums. It quantifies the relative risk to light exposure over time for different classes of light-sensitive materials and uses the concept of *useful exhibit life* to emphasize the extent of damage.

How much change in appearance can be sustained before an object is considered to have no further useful exhibition life? This is a subjective question whose answer will vary widely because change in appearance

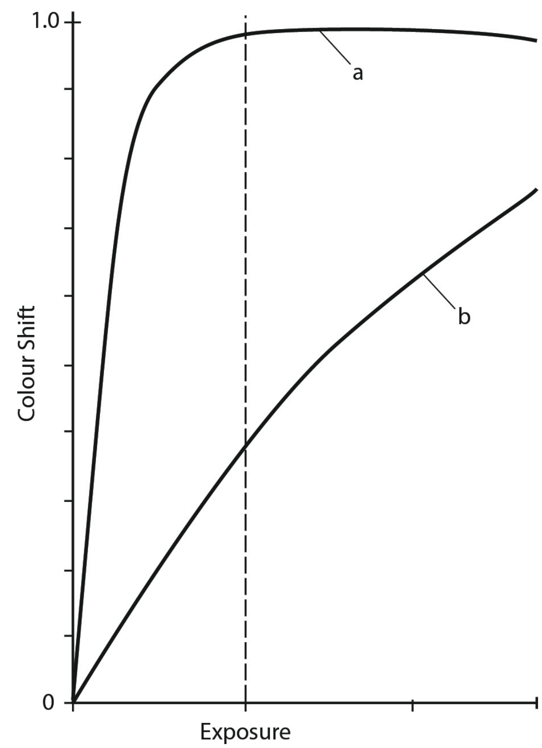

Figure 8-3. This graph shows the color shift versus exposure for two hypothetical materials, *a* and *b*. It illustrates that different types of materials exhibit different incremental rates of fading. (Graphic redrawn from original in CIE 157:2004[15]; reproduced with permission)

is relative. Thus, useful exhibition life will be between one unit of JNF and total fade, based on a myriad of factors including the personal opinion of the viewer and the type of visual damage incurred. The important point is that the long-term risk of exposure over time should be taken into consideration.

8.2 Damage Factor 2: The Concentration of Irradiance on the Surface of a Material

The relevance of Damage Factor 2 can be summarized as follows:

- Light in excess of the minimum amount necessary to appreciate an object is considered to cause *unjustifiable damage*.
- There is no point causing a little damage (with insufficient light) for no purpose (the artifact cannot be adequately seen).

8.2.1 Illuminance. Since visible light causes photochemical damage to a broad range of museum artifacts, it is essential to control the illumination received by an object. Museum light level recommendations are based on *using the smallest amount of light necessary for a viewer to appreciate an object on display*. It is important to note that while museums use visible light to determine appropriate illuminance levels, damage is caused by the total amount of irradiance.

Within the international museum community, an illuminance level of 50 to 100 lux (approximately 5 to 10 fc) is recommended for highly sensitive to moderately sensitive materials (i.e., most paper and textile based objects with colorants ISO 1 through ISO 6). An illuminance of 200 to 400 lux (approximately 20 to 40 fc) is recommended for materials with a low sensitivity to photochemical damage (i.e., most oil paintings with colorants ISO 7 and ISO 8). For most light-sensitive objects, illumination above these levels is not necessary to satisfactorily view an object and is avoided because it causes unjustifiable damage. IES recommended illuminance values conform to this international norm (see Illuminance table in **Annex A**).

Museum conservators often specify illuminance values as a range; the smallest quantity necessary should be used. Expressing illuminance levels as a range has the added benefit of allowing lighting designers to balance artworks of different reflectances. For example, dark-colored (low-reflectance) objects might be illuminated at a higher level than lighter-colored artworks, to maintain a balanced luminance value among the objects. To achieve this, a useful technique is for the lighting designer to light the darkest object in a gallery to an acceptable level and then use lower levels to balance the rest of the exhibit accordingly. While it takes more illuminance to see low-reflectance materials clearly, the increased light level will cause increased damage. In addition, while the action spectrum of a particular material determines how quickly a particular object will fade, the quantity of light required

Sidebar: Guidelines for Illuminating Light-Sensitive Materials

The following techniques may help to increase the apparent brightness of light-sensitive materials under low illuminance levels:

- Design the visitor's pathway so there is sufficient time to visually adapt to lower luminance levels.
- Control ambient light levels so objects appear brighter than surrounding area.
- Choose wall and casework colors that help artwork appear bright in contrast to the background.
- Select surfaces carefully to reduce reflectance and the potential for specular reflections. Reflectance values of the wall and floor have a tremendous impact on how brightly objects are perceived; objects often appear brighter when placed in an environment with lower reflectance (darker) surfaces (see **Figure 8-4**).
- Select wall colors carefully. White or light-colored walls sometimes cause veiling reflections on glazing and make it difficult to focus on dark objects.
- Use tightly focused beams of light to illuminate less-sensitive materials while missing adjacent highly sensitive materials. Care should be taken that the focus is maintained so that light-sensitive objects are not over-exposed when luminaires are re-lamped.
- Light the background behind the display without illuminating the actual light-sensitive object. This is a valuable technique when the shape (silhouette) of an object is significant, or to increase the apparent depth of the display.
- Avoid direct glare from luminaires (see **Section 3.5.6** for more information on reducing direct glare).
- Reduce veiling reflections from objects, paintings, and exhibit cases (see **Section 3.5.7** for information on reducing veiling reflections).

Figure 8-4. Artworks illuminated at 50 lux (approx. 5 fc) that appear significantly brighter because of high contrast between artwork and wall. (Photo courtesy of Smithsonian American Art Museum)

to appreciate an object is based on such variables as reflectance, contrast, size of details, and age of the viewer.

As people age, visual acuity deteriorates. To compensate, a higher level of illumination is necessary for an older individual to view an object satisfactorily. If more than 50 percent of the visitors to a museum are expected to be over 65, there may be justification for increasing illumination to a higher level within the range of 50 to 100 lux (approximately 5 to 10 fc) for high-sensitivity and medium-sensitivity materials, and to a range of 200 to 400 lux (approximately 20 to 40 fc) for low-sensitivity materials. This change can be accomplished using dimmers to raise levels temporarily for special tours of seniors. This is a particularly good application for LED lighting because LEDs do not change CCT when dimmed.

It is important to note that while illuminance recommendations suggest the same illuminance level for medium-sensitivity and high-sensitivity materials, the highly light-sensitive materials will fade a minimum of 8 times[25] more quickly than the medium-sensitivity material will. Minimizing light exposure is the only way to minimize light damage. Typically, museums will exhibit very highly light-sensitive material for three months and then return them to dark storage for at least several years.

8.3 Damage Factor 3: Duration of Exposure and the Principle of Reciprocity

The amount of damage to an object is related equally to the concentration of illumination and to the duration of exposure. To minimize damage, it is necessary to control not only the concentration of illumination at any moment in time, but also the total amount of illumination accumulated over a specific period. According to the principle of reciprocity, an object exposed at 50 lux (approximately 5 fc) for 10 hours will have the same amount of damage as if it were exposed at 500 lux (approximately 50 fc) for one hour, since both periods of exposure total 500 lux-hours (approximately 50 fc-hours). Museum light level recommendations are based on both the intensity and the duration of illumination. Thus, it is important to *use the smallest amount of light necessary to appreciate an exhibited object, and for the shortest amount of time*. Ideally, a light-sensitive object should not be illuminated at all when it is not being viewed.

One important application of this principle is to reduce the amount of light when light-sensitive materials are not being viewed. Occupancy sensors, both wireless and hard-wired, coupled with dimmers and programmable sequences of operation can be used to reduce the amount of illumination during periods of non-occupancy. Other methods, such as frequent rotation of objects and setting limits of frequency for exhibiting an object, are commonly used to reduce total time of exposure for individual light-sensitive objects. Daylight is particularly difficult to incorporate as a source of illumination because in periods of non-occupancy it cannot easily be turned off. One solution may be to place a removable opaque covering over the object during periods of non-occupancy.

While lighting designers can specify controls to reduce the duration of exposure, the principle of reciprocity is most useful for museums and collectors in determining how long light-sensitive materials should be placed on view. It is the entire design team's responsibility to employ methods such that relatively small quantities of light allow visitors to fully see and appreciate light-sensitive materials. It is the museum's or owner's responsibility to determine the light sensitivity of each object on display and determine the appropriate duration of exposure. It is very important to remember that placing objects in the dark will not restore damage caused by light. *Removing the light only stops further damage until the next time of exposure*.

Several museum publications recommend that light levels in galleries be limited on an annual basis to a maximum number of lux-hours (fc-hours) per year. Determining a "light budget" for light-sensitive objects is an extremely useful method for managing the amount of damage and developing an exhibition plan to parse out the useful life of an object. It is important to note that light budgets are only a management tool, not a tool to determine illuminance. Illuminance is determined by how much light is necessary to view an object; light budgets consider how long an object might last at a given illuminance. Light budgets should not be used to justify excessive lighting of a collection on some days (sunny days, for example) simply because the collection will be under-lit on other days (cloudy days). Since all light is damaging to light-sensitive materials, excessive lighting causes damage with no justification, and under-lighting causes damage with no benefit. Illuminating light-sensitive objects when they are not being viewed

Sidebar: Guidelines for Reducing Exposure Times

The following are examples of lighting techniques for reducing damage due to duration of exposure:

- Turn lights on only when displays are being viewed.
- Use occupancy sensors to automatically turn off lights when displays are not being viewed.
- Limit light exposure on displays with timers, switches, or removable opaque cloth when the installation of occupancy sensors is not practical.
- Rotate highly sensitive objects off view.
- Develop an exhibition plan for medium-sensitivity and high-sensitivity museum objects to take them off display for extended periods and extend their life.
- Close blinds or shades to eliminate daylight before and after museum hours.
- Design exhibitions and buildings to provide appropriate visual arrangements so that recommended low light levels can be achieved while providing satisfactory viewing.

causes unnecessary damage, and museums should employ methods to eliminate this wasted exposure.

8.4 Damage Factor 4: The Spectral Power Distribution of Light Sources (UV, IR, and Visible)

Since all three of these types of radiant energy cause damage, each needs to be controlled to preserve light-sensitive objects. UV and IR rarely have a perceptual effect on the visual appearance of an object; therefore, the goal when lighting light-sensitive objects is to minimize these forms of radiation as much as possible. Since light (visible energy) is necessary to view an object, the lighting designer's goal is to illuminate light-sensitive objects with the minimum quantity of light necessary to provide a satisfying viewing experience.

Table C-3 in **Annex C** provides estimates of the relative sensitivity to UV of various materials and the types of damage caused. This information can assist in decisions about risk and the need for various levels of UV filtration.

8.4.1 Ultraviolet (UV) Radiation. UV radiation (10 nm to 400 nm) is extremely harmful to objects sensitive to optical radiation because of its high energy as compared with visible or IR radiation. UV damage increases logarithmically as wavelength decreases; therefore, for example, UV in the range of 320 to 380 nm is significantly more damaging than UV of 380 to 400 nm. UV has sufficient energy to result in the deterioration and discoloration of many types of organic materials, which is why it is essential to minimize, if not eliminate, UV radiation. In order to determine when it is necessary to filter a light source for UV radiation, it is necessary to use the appropriate metric for its measurement.

Typically, the absolute level of UV radiation is measured in watts (W) or microwatts (µW) of radiant energy over a specific surface area specified in metric units such as square meters or square centimeters (W/m^2 or $\mu W/cm^2$). (By comparison, illuminance is measured in lumens (lm) over a specific surface area when measuring visible light for purposes of illumination.) For museums, the principal concern is the relative proportion of UV to visible radiation emitted by a light source. This is determined by measuring the ratio of UV to light radiation. Knowing this ratio allows museums to determine whether UV filtration of the light source is required. Since the levels of visible and UV radiation both decrease geometrically in the same proportion as the distance from the source increases, museums have adopted the ratio of UV to visible radiation as the preferred metric for measuring the level of UV energy from a light source. However, it is preferable that the illuminance reading be taken close to the light source to be sure that the reading is based on the output of a specific lamp and is not impacted by other light sources or from light reflected from surrounding surfaces.

The ratio of UV to visible radiation is given in units of microwatts of UV per lumen (µW/lm). The µW/lm metric assumes that museums will tightly regulate the quantity of visible light and choose sources with minimal relative quantities of UV radiation. Ideally, all UV radiation should be filtered, but complete elimination may not be practical in certain circumstances. When the museum UV standard was developed in the mid-1970s, a level of 75µW/lm was recommended as a reasonable and fairly object-safe compromise; this value is the approximate UV output of an incandescent lamp, a reference source that is still widely considered acceptable without UV filtration due to its relatively low UV output. In addition, UV radiation should be based on all wavelengths below 400 nm because wavelengths between 380 nm and 400 nm greatly increase material damage but have little effect on the appearance of objects and the human visual response.

Subsequently, some publications suggested a lower value of 20 µW/lm, due to the availability of very effective glass UV filters, which were not readily available when the original standard was developed. While most museum collections do not require filters on incandescent light that is less than 75µW/lm, museum conservators may recommend additional filtration for particularly UV-sensitive materials. (Refer to **Annex C** for information about how UV will damage museum materials, and to **Annex D** for assistance with risk management decisions.)

Light sources that usually require special UV filtration include metal halide, fluorescent, and daylight sources (see **Table 8-2**). Museum-grade UV filters shall block a minimum of 99 percent of the light below 400 nm. Specifiers should be aware that the manufacturers of many so-called "UV filtering" lamps and filters available use 380 nm as the basis for the cutoff when calculating UV filtration efficiency. It is essential to test these light sources with a UV meter that reads in µW/lm based on a UV cutoff value of 400 nm, or with a spectrometer.

While many institutions and collectors have recognized the need to reduce UV radiation, they neglect the fact that visible light causes damage as well. Reducing UV to minimal levels is important but is only one in a series of steps essential for protecting objects from "light"-induced damage.

Table 8-2. UV Content of Typical Light Sources (Source: CIE 157:2004[15]; reproduced with permission)

Light Source	UV Content (µW/lm)
Daylight	400 – 1,500
LED	<5
Incandescent	70 – 80
Tungsten-halogen	40 – 170
Fluorescent	30 – 100
Metal halide	160 – 700

8.4.1.1 Measuring UV. If museums know that the UV characteristics of their light sources are within an acceptable range, then measuring UV is not essential. For example, incandescent lamps and the current generation of LEDs that use a blue excitation source of around 450 nm are well characterized and are considered safe without supplementary UV filtration. In the case of daylight, which has a very high UV content, field verification to confirm filter effectiveness is important. While high quality UV filters used for daylight have a very long life, many institutions prefer to confirm effectiveness after years of use due to the high UV risk posed by daylight.

The most common meter used by museums is an instrument that contains two sensors, one for illuminance and one for UV. This type of meter is the de facto standard for UV measurements in museums. The UV sensitivity of this meter is weighted toward the range of 370 to 390 nm, rather than the more typical peak sensitivity of 365 nm for a standard long-wave UV meter. Although these meters cannot read radiation below 350 nm, generally this is not a problem since most UV filters that are efficient at eliminating UV radiation above 370 nm are also efficient at removing shorter-wave UV. This type of UV meter is useful for the assessment of risk to museum collections but will not provide a precise characterization of UV radiation.

Alternatively, a standard long-wave UV meter can be used in conjunction with a light meter. This is the least precise method for estimating UV radiation, in part because the typical peak sensitivity for this type of meter is 365nm, with a fall-off in sensitivity at 380nm. This meter may provide useful information as long as the limits of this type of reading are understood.

Ultimately, the most precise method for calculating the risk of UV is with a spectrometer. It should be noted that the museum convention of using the µW/lm specification does not distinguish between sources that emit UV in the more energetic (and significantly more damaging) shorter-wavelength range within the UV spectrum. For this reason, it would be useful to know both the µW/lm value and the spectral power distribution (SPD) of the filtered light source from 300 to 400 nm.

The reader is referred to **Section 10.5** for more information about daylight-specific metrics to evaluate UV.

Sidebar: Techniques for Limiting UV Exposure in Sensitive Materials

- Choose a light source that produces minimal UV (with the range of 20 to 75 μW/lm or smaller).
- Filter all sources that generate UV in excess of 75 μW/lm, including every window, skylight and discharge lamp (fluorescent and HID).
  - Daylight UV filter options include architectural window film, the PVB interlayer of laminated glass, UV-filtering acrylic, and UV-filtering polycarbonate sheets (Lexan®).
  - For high heat applications (such as HID), use glass UV filters.
  - Theatrical polyester films can be used temporarily to filter UV from fluorescents and some low-wattage HID lamps.
  - Filters may need to be tested after installation and then periodically thereafter to make sure they are maintaining their UV-absorbing (or UV-reflecting) properties.
- Control the amount of visible light (which will automatically reduce the amount of UV).

8.4.2 Infrared (IR) Radiation and Thermal Management. IR radiation has a low energy level and does not induce the same type of photochemical damage caused by UV and visible radiation. However, IR energy will result in the radiant heating of an object's surface. A significant increase in surface temperature results in accelerated chemical activity, as well as physical changes due to the impact on relative humidity, moisture content, and dimensional properties of the exposed material.

Direct unfiltered sunlight has a high IR content and therefore should be avoided, even if the period of exposure is brief. Incandescent (including halogen) sources also have a high IR-to-lumen ratio. In general, if the lamp is placed at a sufficient distance from the object (to avoid convective heating of the surrounding air), the risk of IR related damage is minimal. For example, ceiling mounted luminaires are typically far enough away that the heating effects do not directly affect objects. Special care to manage IR energy is required when specifying any light source installed close to exhibit objects such as traditional picture mounted "frame lights." Care should also be taken when illuminating objects in vitrines, as sources with high IR output may cause a "greenhouse" effect, due to heating of the air contained within the vitrine. Similarly, care should be taken when locating luminaires within a showcase (see **Section 9.3 Exhibit Cases** for information regarding monitoring and design).

Currently, there is no standard for an acceptable museum-based IR irradiance level. In order to determine whether a light source is increasing the surface temperature of an object, a non-contact IR thermometer may be used to measure heat gain. The surface of the object should be read before it is illuminated, and again after a sufficient period of illumination to allow the object to heat up to a constant temperature. For objects with light and dark surfaces, a reading should be done on a dark surface, where more IR radiation is absorbed. If a non-contact thermometer is not available, an approximation of heat level can be determined by placing the back of one's hand in the path of illumination, near the object, to detect any sensation of heat from the source; there should be none.

8.4.3 Spectrum of Visible Radiation. Energy in the visible region (380 to 770 nm) is a significant cause

Sidebar: Techniques for Limiting IR Exposure in Sensitive Materials

- Reduce the illuminance to the recommended IES levels for light-sensitive materials (see **Table 8-1** in **Section 8.1**). The use of LED sources will greatly reduce the IR component while maintaining acceptable illumination. Other light sources, such as tungsten-halogen, will require a reduction in illumination to reduce the IR component of the light.
- Design displays so that transformers, luminaires, and associated electronics do not heat up the environment inside sealed casework. Carefully evaluate the results, and change as needed.
- Place thermometers inside sealed cases to check whether luminaires are heating the internal case environment.
- Place light sources far enough away to avoid producing heat in the display.
- Use a non-contact thermometer to measure luminaires' effects on paintings or objects.
- Keep sensitive materials out of direct daylight. Apply low-emissivity coatings to windows and skylights.

of fading of organic dyes and pigments. The issue of assessing how different CCTs and discontinuous spectra affect museum materials was first raised in the 1950s, and later in the 1960s.[24] In 1985, a Berlin research group led by Jürgen Krochmann developed a method for calculating the Spectral Damage Function (SDF) of light sources based on how different wavelengths of light (using a xenon source and filters) affected 54 samples of typical museum materials.[26] In 2004, an international committee incorporated the use of SDF into its recommendations with the publication of the CIE Report *Control of Damage to Museum Objects by Optical Radiation* (CIE 157:2004[15]).

The shortcoming of SDF is not the principle but rather the impossibility of defining a responsivity function representative of all museum objects. Therefore, when working with Spectral Damage Function calculations, there are a few important things to remember:

- The sole utility SDF has is to assist with the selection of light sources based on generalizations about susceptibility to light-induced damage from a broad range of representative materials. SDF provides no utility for calculating the rate of damage for individual museum objects.
- By design, SDF is a blunt instrument because the primary cause of fading of pigments and dyes is the absorption of the action spectra for that material. It is useful to note that small differences in SDF values can be disregarded. SDF is most useful for comparing the relative damage potentials of two or more light sources.
- The maximum SDF calculation for a UV-filtered light source of 6000 K is approximately double the damage induced by a UV-filtered light source of 3000 K, based on the Krochmann data.[26] **Figure 8-5** shows the relative material-damage potential of different light sources at various CCTs, with the damage potential of any source type increasing with higher CCT. However, the range in damage potential variance throughout the CCT range is different depending on the type of source; for example, LEDs have significantly less variation compared with blackbody radiation.

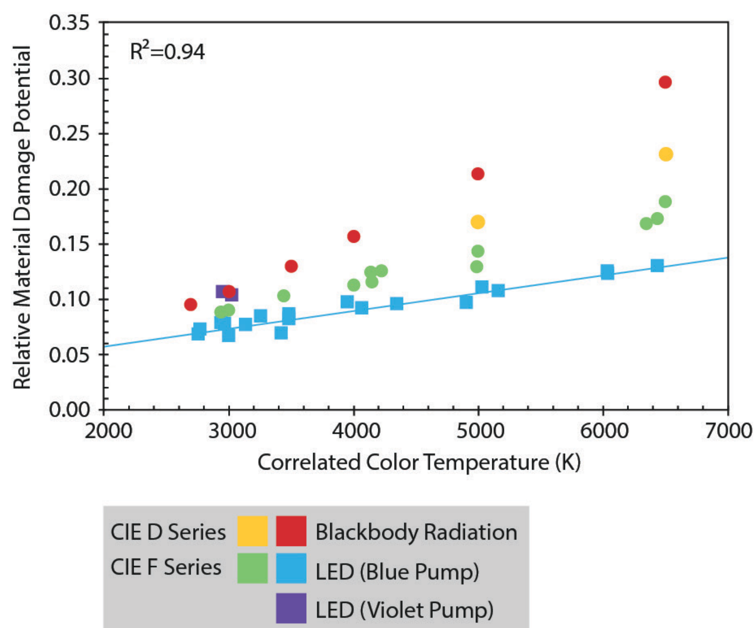

Figure 8-5. The CIE spectral damage potential (S_{df}) versus CCT for various sources. While the linear correlation between damage potential and CCT is high for all source types, the standard blue-pump LEDs have the lowest damage potential at any given CCT. For this analysis, the S_{df} coefficient was set at 0.12. (Graphic redrawn from original.
Source: http://www1.eere.energy.gov/buildings/ssl/pdfs/true-colors.pdf)

CIE 157:2004 provides a useful table showing the SDFs for full-spectrum sources ranging from 2500 K to 7500 K in increments of 500 K.[15] To simplify comparison, all values were normalized based on assignment of a value of 1 for Source A (2850 K).

The benefit of SDF is that it assists lighting designers with the selection of light sources. However, the primary cause of fading is the spectrum of light that is absorbed by the colorant. In other words, the action spectrum for most materials is the inverse of the colorant's reflectance spectrum. For example, if a red painting is illuminated, the red component of the incident light is reflected and all other energies are absorbed—it is those absorbed energies (in this case, orange, yellow, green, blue, indigo, and violet) that are the primary cause of color fading (see **Section 8.4.4**).

There is controversy within the scientific community about how to best apply SDF. At the time of this writing, the consensus is that SDF is most relevant to the preservation of very light-sensitive and moderately light-sensitive objects where daylight should also be excluded. The evidence is ambiguous regarding risk to low-sensitivity objects. Assuming that there is an aesthetic justification, the relative risk should not preclude the use of relatively "cool" (high-CCT) daylight or electric light sources, between 3500 K and 6000 K. For artworks of low light sensitivity, the primary considerations are total exposure to visible light and UV.

Sidebar: Guidance for Choosing an Appropriate Spectrum for Sensitive Materials

- Do not use daylight to illuminate highly light-sensitive materials.
- SDF calculations are useful for the selection of light sources but are not in common use. Standard museum practice is limited to controlling illuminance, reducing the length of exposure, and eliminating UV.
- While higher-kelvin sources are more damaging, the selection of a light source (and its associated spectrum) is only one of several competing factors to be considered by decision makers in lighting objects while balancing aesthetics and preservation.
- Choose light sources with a low damage potential for objects of high and medium light sensitivity. In most cases, "cooler" sources (higher CCT) will be more damaging than "warm" sources (lower CCT).

8.4.4 Specific Susceptibility to Damage Based on Light Source Spectrum. In **Figure 8-6**, the absorptance curves illustrate the difference between the generalized response of light-sensitive materials tested by Krochmann and his colleagues based on a composite response of 54 different materials (dotted line) and specific individual dyes (see **Section 8.4.3**).[26] Although the general absorptance curve describes estimated average risk, each material has its own unique response to individual wavelengths of light due to the specific nature of the dye or pigment and its unique reflectance properties. For example, blue colors will reflect shorter wavelengths, which will reduce the amount absorbed in that region of the spectrum.

In addition, materials may be especially susceptible to specific wavelength-related damage due to the *action spectrum* of the particular material. The action spectrum is a wavelength region that can cause more damage than other regions because of the unique absorption characteristics of the specific material. Saunders and Kirby found that while an SRD does not exactly correspond with the inverse of a responsivity curve, they support the concept that spectral responsivity is related to spectral absorptance. It is difficult to determine the precise chemical composition of a single museum object to determine its unique light sensitivity, and practically impossible to determine the unique wavelength susceptibility for every object within a collection. The practical solution is for museum conservators to assess an object's light damage risk based on general categories as described by the general damage curve. When unique wavelength-specific properties for specific groups of light-sensitive materials are known, a conservator may recommend a lighting spectrum tailored to that material.

8.5 Preservation of Light-Sensitive Materials: Summary

Lighting and exhibition design policies have a direct impact on the factors that determine the rate of damage to an object:

- The light sensitivity of an object; as part of the team, the museum conservator communicates this information to the lighting designer

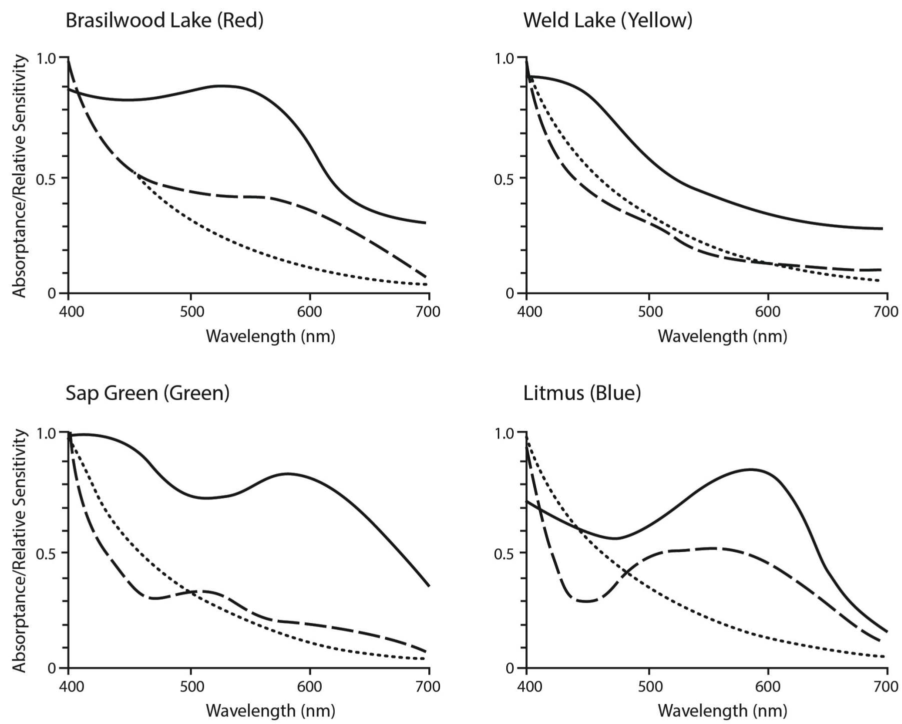

Figure 8-6. Spectral absorptance (solid line) and relative spectral sensitivity (broken line) for four artist's pigments. The dotted lines show relative spectral sensitivities normalized at 400 nm based on the Krochman relative spectral sensitivity function. (Graphs redrawn from original by Cuttle and Ne'eman 1999, after Saunders and Kirby 1994; page 14 of CIE 157:2004[15])

- The light level (illuminance)
- The length of exposure; this determines damage over time
- The spectral power distribution (SPD) of the light source and its effect on the object's specific susceptibility

9.0 Typical Lighting Solutions for Museum Exhibitions

"Museums provide places of relaxation and inspiration. And most importantly, they are a place of authenticity. We live in a world of reproductions – the objects in museums are real. It's a way to get away from the overload of digital technology."
– Thomas P. Campbell

Most museum exhibits can be categorized into one of the following four groups:

- Flat objects or accompanying flat material on vertical surfaces
- Three-dimensional objects
- Objects in exhibit cases
- Dioramas

The lighting design should work in harmony with the entire exhibit design. While the solutions below provide individual design considerations for each of the four groups, the lighting designer should take a holistic approach in the final design, considering the unique characteristics of each object, the individual exhibition method, and the surrounding conditions, including all architectural surfaces (walls, floor, ceiling, windows) and shiny or luminous surfaces.

9.1 Flat Objects on Vertical Surfaces

Uniformly illuminating a large vertical display is one of the more difficult lighting problems in museums. **Figure 9-1** shows the typical dimensions involved. Paintings, prints, documents, and explanatory labels comprise this important category. The illumination becomes even more difficult when a transparent material, either acrylic or glass, is used to protect the artifact. The combination of the specular surface and improperly placed luminaires can make it difficult, if not impossible, to see the artifact due to reflected glare. Preferences for placement of luminaires and lighting distributions have been studied by Loe et al.[27] Generally, the lighting should provide uniform intensity over the entire surface. Luminaires positioned so that the beam's center axis is 30 degrees from the vertical will produce minimal shadows and glare-free viewing while allowing the visitor to approach the artifact closely without casting his or her own shadow on the artifact (see **Figures 9-2** and **9-3**).

The following formula should be used as a guide; the wall-to-luminaire distance should be increased or decreased as required to avoid shadows from oversize frames on paintings, and the angles of incidence and reflection should be computed to avoid glare to the viewer.

Optimal luminaire distance from wall = (ceiling height – eye level) x 0.577

Lighting flat displays with lumnaires aimed at 30 degrees from vertical reduces the amount of glare, but round-distribution lamps may create an elongated scallop of light at this angle. Light striking the canvas from 45° has the benefit of fitting into the canvas with less of a "halo" of extra light around the frame. The increased beam control, unfortunately, comes at the expense of more glare at the eye level of children and people in wheelchairs.

9.1.1 Wall Wash. A good method for achieving uniform illuminance over a large vertical surface is to employ "wall wash" luminaires. These units are designed to use many types of lamps while evenly diffusing light. A luminaire and lamp combination should be chosen that provides the required color, intensity, and uniform distribution with long lamp life. The lighting designer should understand the manufacturer's recommendations for mounting

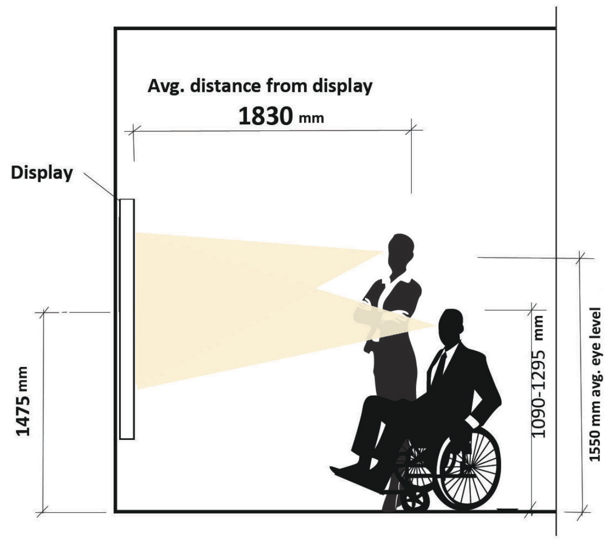

Figure 9-1. Average viewing heights and distances from displays. (© Illuminating Engineering Society)

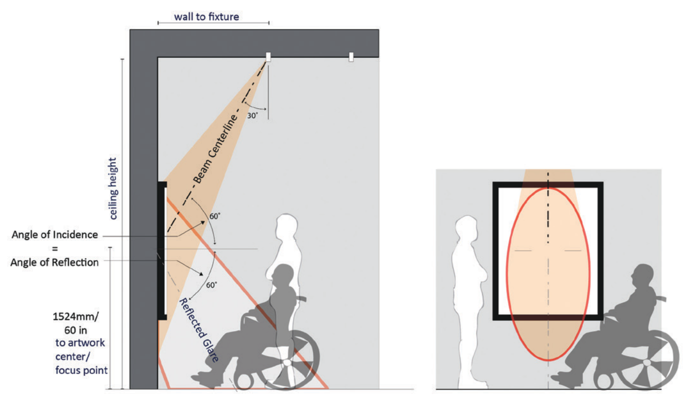

Figure 9-2. Depicting a 10° spot light aimed at 30° off the vertical. The section view allows assessment of glare and potential head and frame shadows cast onto artwork. (Images courtesy of Kaitlin Page/ Rachel Edmunds)

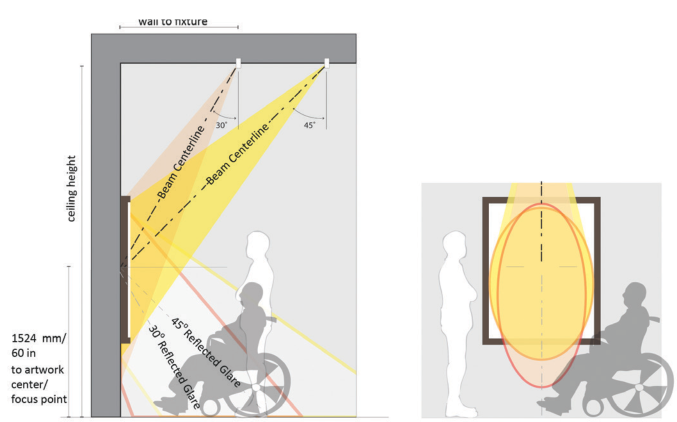

Figure 9-3. Comparison of a 10° spot aimed at 30° and 45° off the vertical. (Images courtesy of Kaitlin Page/ Rachel Edmunds)

and spacing distances, but should let the desired result guide the final design. When lighting paintings in period frames with deep moldings, it may be necessary to place luminaires further from the wall to avoid distracting shadows at the top of the painting. Most luminaire and lamp manufacturers can provide charts that show the illuminance at each point on the wall based on luminaire location and aiming. The designer should request this information!

For flat displays on vertical surfaces, wall washing may be used as the primary technique to provide illumination for displays, or as the first layer in a multilayer system that may include precision spotlighting of individual objects.

If the surface has an irregular texture that should not be noticeable or is offensive and intrusive, wall wash units mounted farther from the surface will mute the texture. Conversely, wall wash units mounted close to the vertical surface will accentuate texture. Wall washers are usually the luminaire of choice for murals, particularly tall murals where spotlights or floodlights would cause unpleasant reflections and/or unwanted highlights.

9.1.2 Spotlights. For small- and medium-size pictures or label panels mounted on a wall, spotlights are usually selected. The mounting position, and the resulting angle of incidence, can be determined by following the diagram in **Figure 9-11**.

It is also possible to use optical projectors, which can "frame" the object, but this can cause an artificial appearance. If projectors or narrow-spot lamps are used, it may become necessary to provide additional soft lighting in the display space to prevent a painting from looking like a transparency. It is also practical to allow some spill light onto the surrounding area for a softening effect. If a picture label is separate, it should be located in the spill-light area, away from the frame shadow. Some exhibits may require individual spotlights to provide sufficient illuminance for labels and wall texts.

9.2 Large-Scale Three-Dimensional Objects

Irrespective of size, three-dimensional objects should be illuminated to reveal the object's shape, texture, color and details, allowing the visitor to experience the object as intended by the curatorial and design team. Three-dimensional objects allow lighting designers to employ their entire palette of controllable qualities of light for the task. (See **Section 3.5 Angle** for more information about how to use light to reveal form.)

Lighting large monumental objects poses special challenges. These objects are often the central focus of the museum and require the designer to devote extra time to detailing special lighting equipment that is carefully integrated into the architecture. Light from multiple directions will model the sculpture, expressing depth by highlighting some areas while allowing others to fall into shadow. Uplighting is often a valuable technique, both for practical reasons when it is impossible to service ceiling mounted equipment, and for aesthetic reasons to see the underside of objects that are placed over viewers' heads. Shadows can either be an asset that helps reveal the form, size and intricacy of a sculpture, or a deficit that obscures detail and creates visual noise by casting odd shadows on the wall, floor and ceiling.

9.2.1 Minimizing Glare. Direct glare from luminaires can be minimized by selecting luminaires with 45-degree cutoff. Glare can be further minimized for objects at or below eye level by locating luminaires so that when aimed at the object, the center-beam axis of the luminaire is 30 degrees or less from the vertical (see **Figure 9-11**, **Section 9.1**). Veiling reflections are typically a smaller problem than direct glare on three-dimensional objects, though veiling reflections may obscure the color [see **Figure 3-19(4)** in **Section 3.5.2.1**, sidelight image of eagle] or cause extreme nuisance glare when lighting shiny materials such as glass and polished metal.

There are few problems for the viewer when the object is at eye level (or lower) and is lighted from all sides. For relatively low and small objects, the luminaires may be steeply angled, limiting the risk of glare for the observer on the opposite side. When an object is tall, some light may go past the display and cause direct glare for the viewers on the far side looking upward at the artifact.