REFLECTED ENERGY MATCHING
AS A CONSERVATION TOOL

Fading of Fugitive Colors and the Evaluation of Museum Light Sources

by Ruth Ellen Miller and Jack V. Miller

1.0 ABSTRACT

Fading is a form of photochemical damage. It is caused by light energy being absorbed into and altering the molecular structure of light-sensitive surfaces. But light reflected by the surface is not absorbed. Therefore, reflected light energy will not and cannot cause fading. If the color of the light matches the color of the object, substantially all of the energy will be reflected at the illuminated surface instead of being absorbed into the surface. The degree of color matching (or how much of the incident illumination is reflected by the surface, instead of being absorbed) establishes the "**REM Factor**" (Reflected Energy Matching Factor) of the light source. The exhibit life of an object is proportional to the REM Factor of the light source, which is measurable and predictable for any lighting system.

A series of 36 fading tests with 9 different light sources were conducted using ISO (International Standards Organization) blue wool test samples #1 through #4 for 250,000 cumulative footcandle hours. This represents 100 footcandle years, or 10 years' typical museum illumination at 10 footcandles.

Sunlight was found to cause the most fading during accelerated tests. Solar fading was then established as the basis for comparison with the observed fading produced by the other 8 light sources.

Typical museum lighting, including UV-filtered fluorescent lamps, full-voltage incandescent, IR-filtered incandescent and even dimmed incandescent lamps were tested and found to produce substantial fading of the test samples.

The least fading of the ISO samples was found with acrylic fiber optic illumination. This illumination system transmits absolutely no UV or IR energy and has no dominant peaks in the visible spectrum of the emitted light. Acrylic fiber optic lighting that was color-filtered to precisely match the blue color of the fading test samples further reduced the fading. Fiber optic lighting that intentionally mismatched the color of the fading test samples produced fading that was nearly identical to lighting with no color filtering at all. This confirmed

that the REM Factor (Reflected Energy Matching Factor) of the full lighting spectrum, both visible and invisible, to the reflected color of an exhibit artifact is a primary determiner of the fading characteristics of any light source.[1]

These initial tests were limited to ISO blue wool fading samples. Although ISO blue wool samples are widely used by museums to monitor cumulative light, they do not represent the absorption spectra of other colors. While these test result can be applied to other colors and other materials, it was felt necessary to repeat these tests with additional colors. Additional tests would prove conclusively that Reflected Energy Matching was valid for all colors and materials. They would further prove that the elimination of non-visible energy from illumination was beneficial for all collections and all conservation lighting applications.

As a second series of tests, fading tests of 5 different colored samples were conducted for the same 250,000 FcHr (Footcandle Hours) or 100 FcYr (Footcandle Years). An ISO #2 blue wool fading sample was used to evaluate blue color fading. The remaining 4 color test samples were selected to have the same fading characteristics as the ISO #2 blue wool fading samples. These samples are considered fugitive enough to be displayable only for short periods of time at low light levels. Organic water colors in viridian green, chrome yellow, carthane rose (orange) and lake crimson were selected to evaluate fading of other colors.[2]

The REM Factors (Reflected Energy Matching Factors) were calculated for each light source as a proportion of the measured test fading compared to that of sunlight. Direct sunlight is the standard with a REM Factor of 1.00 100%/ 100%). The REM Factor then becomes an expression of the expected average exhibit life of that set of sample colors under a particular light source compared to its life in direct sunlight of the same intensity. As an example, the REM Factor of 6.3 (non-color filtered acrylic fiber optic illumination with no UV or IR) from the ISO #2 Blue Wool testing indicates an average exhibit life of 6.3 times that of the exhibit under the same intensity of direct sunlight.

Other common museum light sources were tested. Cool-white fluorescent lamps had calculated REM factors of 1.03 and 1.1 in the two tests, almost

---

[1] Jack V Miller, “Evaluating Fading Characteristics of Light Sources”, (Seaford, DE : NoUVIR Research, 1993).

[2] Ruth Ellen Miller and Jack V. Miller, “Fading of Fugitive Colors By Museum Light Sources” (Seaford, DE: NoUVIR Research, 1993).

identical to that of direct sunlight. Incandescent parlamps had REM factors of 1.1 and 1.0 and dimmed incandescents a REM Factor of 1.3. UV filtering fluorescent lamps and IR filtering halogen lamps doubled expected exhibit life with REM Factors of 1.9 and 2.1 respectively. Non-color-filtered acrylic fiber optic illumination removing all UV and IR energy but leaving the full spectrum of visible light, showed significant increases in exhibit life with REM Factors of 6.3 and 3.3 in the two tests. This indicates that such lighting will extend exhibit life by better than 3 to 6 times.

Using Reflected Energy Matching Theory and matching the color of light to the color of the object led to very large increases in expected exhibit life. The closer the color match, the more impressive was the reduction in fading observed. Acrylic fiber optic illumination tinted with a light pastel color of the same hue as each color sample gave a REM Factor of 11.8. This represents an increase in safe exhibit life of over ten times. Finally, fitting acrylic fiber optic lighting with REM filters (Reflected Energy Matching Filters) exactly matching the hue and saturation of each color sample resulted in a REM Factor of 71.4. Correctly matching illumination to object color practically eliminated fading in fugitive colors during the test life of 250,000 footcandle hours, the equivalent of ten years full time display at moderate museum lighting levels (10 footcandles).

Interestingly, deliberately mismatching colors by using red tinted acrylic fiber optic illumination on a blue sample resulted in a REM of 7.1. This value is only slightly higher than the value for full visible spectrum fiber optic illumination. This demonstrates again that fading is the result of absorbed energy. It also demonstrates that all of the visible spectrum energy outside that matching the color of the test sample was absorbed and technically wasted as far as illumination. Only the reflected energy was available for vision and only the reflected energy did not cause damage to these fugitive samples.

The tests indicate that filtering non-visible light can double exhibit life and that eliminating all UV and IR in illumination can extend exhibit life by a factor of 6. Additional matching of the light illumination color to the color of an object can extend that object's life up to 70 times. Because only the light reflected from an object aids vision, and all mismatched light energy is absorbed by an object, such color matching resulting in these huge increases in exhibit life do not change the visual appearance of the object illuminated.

1.1 BACKGROUND

While the initial results of this testing were published by NoUVIR Research in 1993 a good deal has happened since that date to both substantiate the test results and the test conclusions. NoUVIR Research has continued to conduct evaluations of the output of hundreds of individual lamps from HID sources to "new" fluorescent lamps to the LED sources just no coming onto the market. Additionally NoUVIR has conducted fading tests on numerous materials from textiles to historic stamps.

In the past ten years NoUVIR Research has provided safe, conservation lighting for some of the rarest and most valuable collections in the world. These range from Thomas Jefferson's handwritten draft of the Declaration of Independence to the charter documents of the United States to the baseball uniforms of Babe Ruth, Bob Feller and Ted Williams. We have been consulted on safe lighting for artifacts as varied as objects from the Titanic (displayed underwater), dinosaur skeletons, historic paintings, the collected Inverted Jenny stamps and the Tiffany diamond collection.

In 2000, the Illuminating Engineering Society of North America published museum guidelines in line with NoUVIR's Research and the particular tests covered here. These new guidelines state, "Visible light contributes to both vision and damage; infrared (IR) and ultraviolet (UV) energy, which are not visible, contribute only to damage. Unless all artifacts in a display area are totally insensitive to exposure, UV and IR should be controlled."[3] The IES recognizes the fact that both UV and IR are significant causes of photochemical damage and should be eliminated.

Both the lighting and the museum communities are becoming more and more interested in the practical aspects of the interaction of light and matter. In 2002, Jack Miller was one of a limited number of experts invited to the Getty Institute for a symposium of preserving paper artifacts specifically focused on the issues of light, lighting, fading and photochemical damage. Reflected Energy Matching Theory was one of the conservation techniques discussed at this symposium. The National Archives, recognizing the validity of the principles of Reflected Energy Matching Theory has set an absolute cut off of 550 nanometers for illumination of the United States Charter Documents. They recognize that

[3] *The IESNA Lighting Handbook: Reference and Application*, ed. Rea, Mark S. (New York: The Illuminating Engineering Society of North America, 2000), p 14-4.

blue light does not add to the vision of yellow paper. It only results in fading damage.

The continuing study done at NoUVIR Research coupled with ten additional years of experience in museum conservation lighting added a great deal of confirmation and practical information to the data published earlier. Printing technology has increased, allowing for the easy addition of illustrations and photographs. Rather than reprint earlier papers, a new edition, combining the two earlier papers and more recent test results, newer calculations and improved illustrations was needed. This research paper (book) is the result.

2.0 PURPOSE

The initial purpose of this investigation was to measure and provide a numerical factor to quantify the fading characteristics of the various types of lighting systems used in museum and other display lighting applications. These numerical factors for various light sources would allow anyone to accurately predict the fading characteristics of a particular lighting system for a specific displayed item and to select the optimum light source to minimize fading. For the first time it would be possible to quantify the artifact safety of proposed lighting systems by type.

A secondary purpose was to demonstrate that this numerical evaluation of damage potential applied both to ISO #2 blue wool fading samples, and to fugitive watercolor samples in non-blue colors having fading rates comparable to those of the ISO #2 samples. These numerical factors for various light sources would then allow anyone to accurately predict three factors: 1) the fading characteristics of a particular lighting system for a specific displayed item; 2) the optimum light source to minimize fading; and 3) the relative fading rates of typical fugitive organic pigments.

The last and most important purpose of this research is to describe and quantify the safest illumination possible for any given artifact. The principles of lighting described here can extend the life of fugitive art and artifacts by up to seventy times. This can mean the difference between the display of a significant piece of art to the public and continual storage in the dark. More importantly it can mean the difference between an artifact's continuing existence and its destruction by uncontrolled or improper light energy. This is incredibly important!

3.0 THE CAUSE OF FADING DAMAGE

There are only two components in the illumination of any object:

1) light reflected from the object and seen by a viewer; and

2) light absorbed by the object which is invisible to a viewer.

None of the reflected light is absorbed. None of the absorbed light is reflected and visible to the viewer. It is only the reflected light that creates data forming the visual image. It is only the absorbed light that causes fading damage.

This is certainly not a new concept. A theory proposed by Grotthus in 1817 stated that only light actually absorbed by a molecule can produce a chemical change. At a later date it was recognized that Grotthus' principle means that the wavelengths of light must overlap[4] an absorption band of a compound before it can produce a chemical reaction.

Photons are photons. They are spinning particles, moving through space at 186,000 miles per second... until they hit something. The only difference between the photons of different colors of light is the photon wavelength (spin frequency). Most radiometric spectral charts use frequency in Hertz (rotation in cycles per second) instead of nanometers (the distance the photon travels to make one rotation cycle). Both, however, are accurate description of the same phenomena.

If the wavelength of a colliding photon matches the wavelength (resonant spin frequency) of an atom of dye molecule it will be reflected. If the wavelength of a colliding photon is sufficiently longer or shorter than the wavelength of a dye molecule (dissonant frequency), an atom of the dye molecule absorbs the photon and is chemically changed into a new compound having different chemical, physical and optical properties. This change can range from short-term existence in an excited state to a permanent physical change from which it can never recover.

This principal applies to all photons, visible or invisible. It makes no difference whether a photon is an ultraviolet ray, visible ray or infrared ray. The difference between any of them is only wavelength or spin frequency. When the wavelength is shorter, the frequency is higher... and the spin diameter is smaller. Therefore smaller (ultraviolet) photons in light sources penetrate materials more

---

[4] Thomas B. Brill, *LIGHT Its Interaction with Art and Antiquities*, (Plenum Press, 1980), p. 175

deeply before probability dictates a collision. The larger (infrared) photons have a higher probability of interaction with molecules nearer the surface.

Science terms are not very useful unless they can be visualized so the principles can be applied. The photon can be visualized as a structure like an Argentine Gaucho's bolo, with the fading material represented by randomly-spaced tree branches. Short UV wavelength photons penetrate surfaces deeply, like bolos with short strings miss some tree branches before hitting one. Conversely, long IR wavelength photons tend to impact closer to the surface, like bolos with long strings hit the first outer branches of a tree.

3.1 RELATIVE SPECTRAL DISTRIBUTION OF LIGHT

A spectral distribution curve is a plot of the intensity of light at each wavelength of the electromagnetic spectrum. Light source manufacturers normally provide technical data for a lamp which includes the brightness of light output at each wavelength, including the invisible ultraviolet bands, through the visible spectrum, and then into the infrared bands.

Spectral distribution curves also may be provided for colored dyes and pigments. These curves indicate the efficiency of absorption or reflection at each wavelength provided by a standard light source. Therefore, a spectral curve may apply to a painted surface to identify its hue (color) and chroma (purity) or it may apply to a color filter to identify the color of light passing through the filter.

A spectral distribution curve may also be used to indicate the efficiency with which light is converted to a meter reading in a light-sensing device, such as a light meter. If the meter is equally sensitive to light at all wavelengths, it is called a radiometer. If the sensitivity matches the sensitivity of the human eye, the meter is called a photometer or light meter. Like the human eye, the light meter reads only visible light. It is blind to the invisible radiation in ultraviolet and substantially blind to infrared portions of the electromagnetic spectrum.

A spectral distribution curve similar to those shown in most lighting handbooks is shown as Figure 1. Note that there are two nearly identical curves plotted. The vertical axis of the chart indicates relative sensitivity to light in the visible spectrum from zero to 100%. The horizontal axis represents the wavelength of visible light in nanometers (10^{-9} meters).

The dashed line curve is the CIE (Commission Internationale de l'Eclairage) luminous efficiency curve that represents the relative efficiency with which the average observer can see various colors (wavelengths) of the visible spectrum. The CIE curve is at 100% efficiency at a light wavelength of 560 nanometers, indicating that the human eye sees yellow-green light much better than any other color. Conversely, the eye sees the extreme ends of the light spectrum far less efficiently. If red light in a band from 620 to 770 nm wavelength enters the eye, only 6% of that red light is sensed. At the other end of the spectrum, if violet light in a band from 450 to 380 nm enters the eye, only 3% of the violet light is sensed.

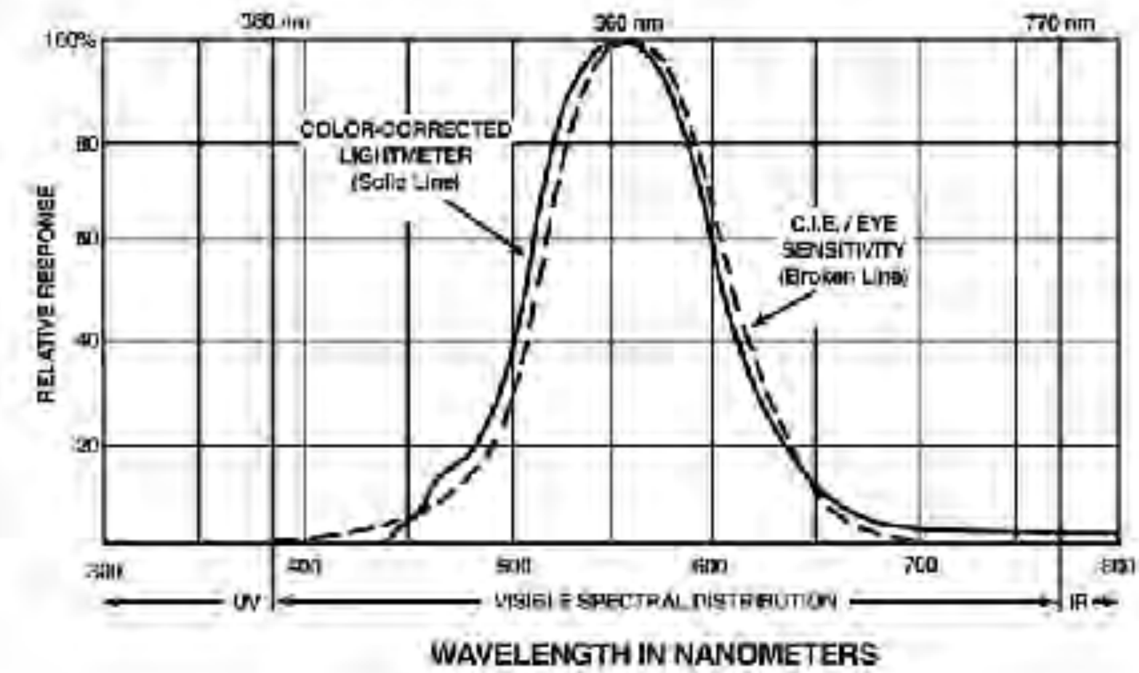


Figure 1. Relative Spectral Sensitivity

The solid line on the chart indicates the relative spectral sensitivity of a light meter that is "CIE color-corrected" to match the human eye as closely as practical. Note that people cannot see light that has a wavelength longer than 770 nm, but most light meters do see some infrared past 800 nm. Also, people (particularly young people) can see violet light down to a wavelength as short as 380 nm, where the ultraviolet band begins, but the light meter is blind to violet light shorter than 450 nm.

The definition of the "light" seen by a light meter is that it closely matches the relative sensitivity (as well as the relative *insensitivity*) of the human eye. It is pretty well known that damaging UV and IR rays are invisible to both the eye and the light meter. It is not so well understood that "visible" light at the ends of the light spectrum is *mostly invisible* as well. This means that extremely high levels of light near either end of the visible spectrum could be present in illumination of photosensitive artifacts... and the light meter would not warn about the hazard. It is entirely possible (and often an actual fact) that at a conservator-comforting recommended light meter reading of only 5 fc, the radiant energy equivalent of hundreds of footcandles is irradiating an exhibit. This phenomenon will be later described in discussions of the spectral curves of individual light sources.

3.2 COLOR MISMATCHED LIGHT

The only portion of the electromagnetic spectrum that provides useful visual information in an exhibit or display is in the visible reflected portion of the spectrum, from 380 nm to 770 nm wavelength. Nearly all UV wavelengths shorter than 380 nm and the IR wavelengths longer than 770 nm will be absorbed by the object those rays impinge. As recognized by the new IES Guidelines, light energy outside that spectrum (UV and IR) does not aid vision

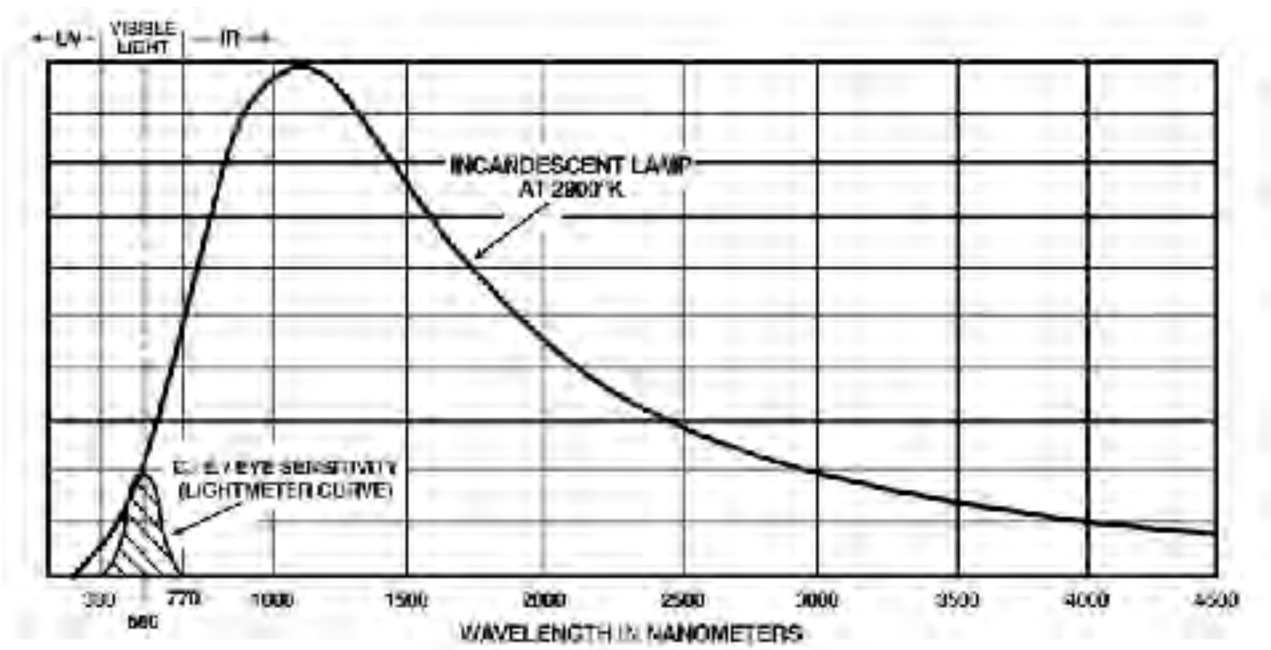


Figure 2 - Spectral output of a quartz-halogen lamp at 3200°K

and does result in damage. Unfortunately the vast majority of the energy of typical museum light sources is outside this visible spectrum. As a result, most of the energy of conventional sources only causes photochemical damage.[5]

Typical incandescent or halogen lamps, emit four times as much red as blue light and have over 90% of their energy output in the infrared portion of the spectrum; invisible to both the eye and a light meter. This is shown in the spectral output in Figure 2. An antique blue silk dress, dyed with natural indigo, looks gray under such red-dominant lights. This is because the light contains very little energy in the blue and green portions of the visible electromagnetic spectrum. Without this light energy, the color perceived by a viewer is dull and lifeless.

The object is suffering from more than just perceived color distortion. The over-abundant red light, and the large invisible infrared component, are absorbed by the blue dye molecules impregnated into the silk fibers. The color-mismatched red and infrared rays attack the blue dye molecules, breaking them down. As this damage occurs, and the apparent color fades, the dress looses the ability to reflect even blue light. This accelerates fading process even more.

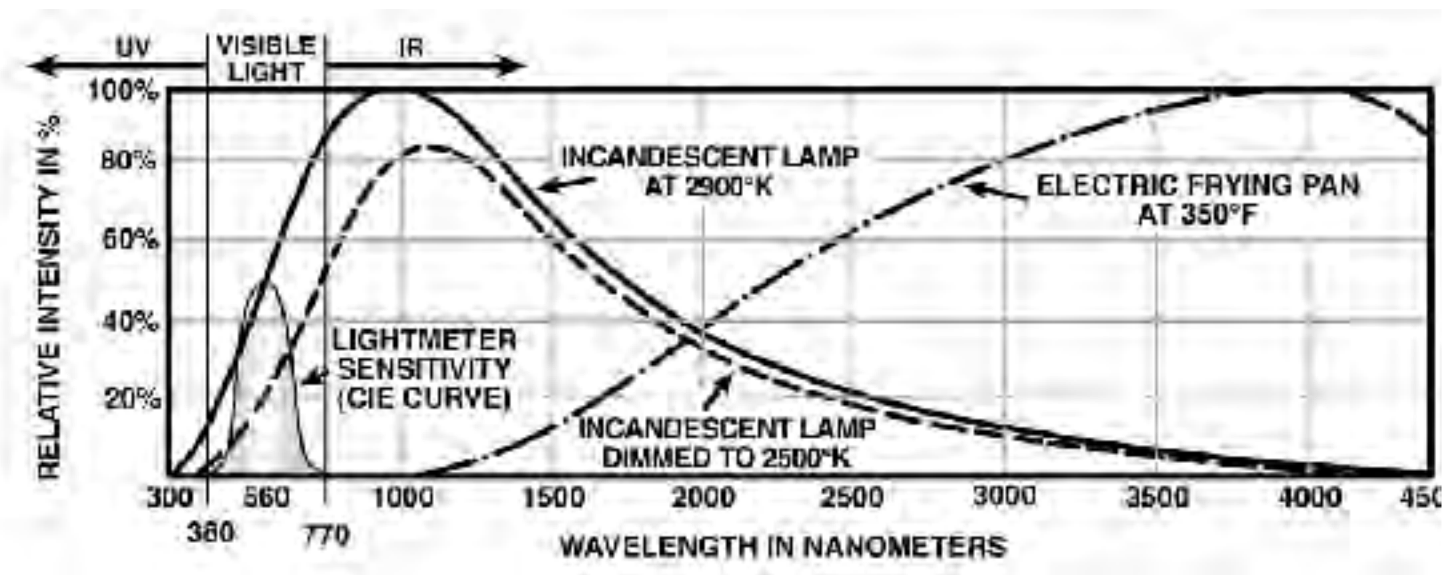


Figure 3. Spectral output of full-voltage vs dimmed incandescent lamps

---

[5] The IR in conventional lighting is also a major factor in photomechanical damage, created by the stresses of temperature and temperature driven humidity cycles. While outside the scope of this paper, a complete examination of these processes along with simple solutions for micro-climate control of case environments is available in a 150-page textbook from NoUVIR Research titled *Protecting Museum Exhibits From Their Environments*.

A sad fact is that the common technique of dimming incandescent lighting to achieve "conservation levels" simple moves the spectral output more toward the red and infrared. A careful examination of the spectral outputs of full-voltage and dimmed incandescent lamps shows that lowering the visible light by 50% only lowers the total energy impacting an artifact by about 10%. Figure 3 shows these spectral outputs superimposed. As this 10% reduction in total energy is accomplished by increasing the color mismatch between the light and the artifact, the net result is often an increase in damage to the collection.

Fluorescent lighting, while more energy efficient, is still over 70% IR. All fluorescent lighting has a significant UV component (up to 7%) which increases as the phosphors in the lamp age. Between IR, UV and mismatched visible light, the fading damage shown in figure 4 occurred in less than 30 days in a retail environment.

Figure 4. An example of fading due to UV, IR and color mismatched visible light.

Visible reflectance at any wavelength in the visible spectrum can occur only if there is illumination at that specific wavelength representing a color hue. In simple terms, one can only see those colors in an object that are also present in the light. If a green surface, colored with a green pigment reflecting light at 550 nanometers is to be seen, the illumination must have some green light in it that contains that 550 nm color. Further, if the green color is to be fully visible, the source must contain a substantial amount of green light.

Tri-stimulus light sources, fluorescent, HID and LED create the illusion of white light by blending red, blue and green light. An RGB computer monitor creates "white" in exactly the same the same manner. In somewhat the same way printers "make" colors by blending cyan, magenta, yellow and black. As anyone familiar with either monitors or printing processes will know, it is impossible to truly represent every color with these metamers.

The spectral output of a tri-stimulus fluorescent source is shown in Figure 5. It is clear that a few colors are vastly over represented and that others are missing completely. This color mismatch results in very poor presentation in showing art and colored artifacts and a very high ratio of absorbed light energy with its associated risks of fading.

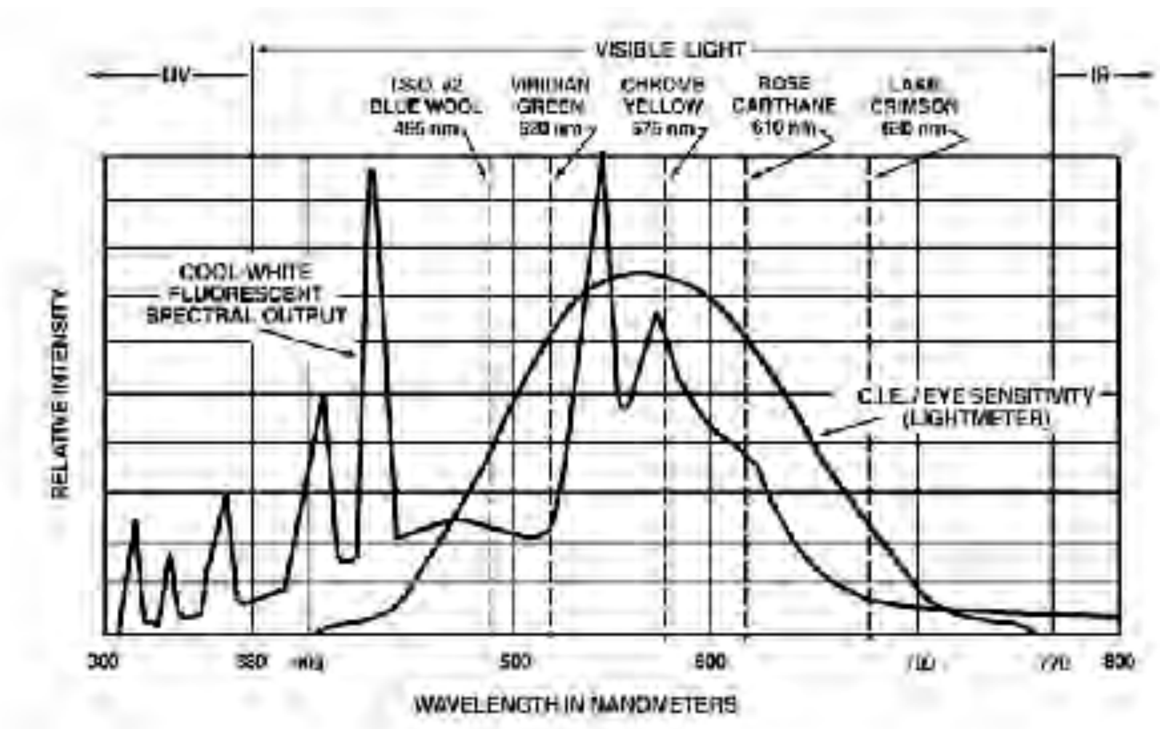


Figure 5. Spectral Output of a Tri-Stimulus Source.

3.3 COLOR MATCHED LIGHT

Conversely, for good presentation, the incident light color falling on an object must accurately match the color of the object. If most of the light matches it will be reflected from the dye or pigment molecules and will not enter the surface. In the example of the antique blue silk dress, primarily blue light will be reflected from the dye molecules in the silk fibers. If the color of the light is carefully matched to the blue of the silk, the color of the dress will appear natural and vivid. And, since the light rays are almost entirely reflected (instead of absorbed); fading will occur very slowly.

4.0 ISO BLUE WOOL FADING SAMPLE TESTS

ISO (International Standards Organization) blue wool fading samples are available in graduated fading resistance[6]. A material that fades as easily as an ISO #1 fading test sample is considered too light-sensitive for exhibition, even for short durations. A material comparable to ISO #2 is twice as light stable as ISO #1; but is still considered too fugitive to display without perceptible fading, except for brief times at very low light levels. An ISO #3 sample is twice as light stable as #2 (four times more light stable than #1). Materials having the fading rate of ISO #3 are considered displayable, but only under low levels of carefully controlled light. Each successively higher ISO fading sample number is twice as light stable to the point of perceptible fading as the preceding one, in successive steps to ISO #8 which is considered color-fast enough to display for extended periods of time at moderately high light levels.

4.1 ISO BLUE WOOL FADING TEST APPARATUS

ISO test samples #1 through #4 were used in a series of 36 fading tests with 9 different light sources. The sources were direct sunlight plus 8 electric light sources; including 2 different fluorescent light sources, 3 different incandescent light sources and 3 different fiber optics sources. There was no detectable fading shown by any light source on the #4 sample, so it is not included in the data.

Test samples .375" wide by .500" long (9.5mm x 11.7mm) were mounted on small test sample holders, masked to permit a .250" (6.4mm) diameter circle of light to expose only the center area of each sample to light, as shown in

[6] ISO fading samples are available from TALAS, a division of Technical Library Service, NY, NY.

Figure 6. Therefore, the fading of the exposed circle in the center could be visually compared to the original color of the surrounding unexposed area of each sample in each of the 9 tests A though I. A tenth sample J of the same dye lot is also shown, which was stored in a black polyethylene envelope at room temperature during testing. This was a control sample to be sure that other environmental factors did not fade the backgrounds of any of the samples during testing. The samples were stored in a light-proof folder after testing, and were exposed to light only for short periods of time for visual examination by several individuals who evaluated the respective fading levels.

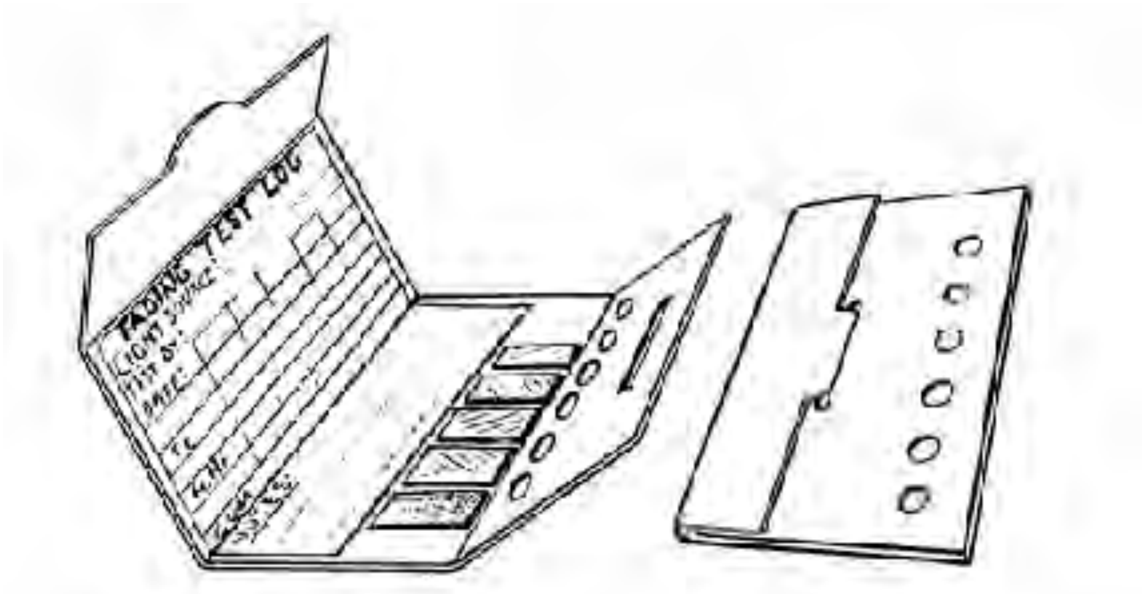


FIGURE 6. Test Sample Folder

4.2 LIGHT SOURCES USED IN FADING TESTS

The test light sources included a broad range of lights that are in use for both museum and other forms of display lighting. The sources are described for tests A through I, below:

A. SUNLIGHT The fading samples were illuminated with direct summer sunlight. The test samples were mounted on a sidereal tracker operating on clear days between 10:00 a.m. and 2:00 p.m. at 40° N. Latitude. Solar illumination at 10,000 fc provided the most severe fading of the exposed areas on all the test samples. This should be expected. Sunlight has very high levels of UV and IR, as well as a great amount of visible illumination outside the spectral band reflected by the blue wool samples.

B. COOL WHITE FLUORESCENT LAMP For test B the samples were mounted near the lamp surface of a bare, cool-white 40-watt fluorescent lamp operating at 4700 K°, using a high-frequency electronic ballast. Since the preferred 10,000 fc levels of other sources could not be obtained with fluorescent lamps, the spacing of the test samples was adjusted to provide 2,000 fc. Exposure time was increased proportionally to reach the 250,000 FcHr cumulative test total.

C. 50% DIMMED PAR 38 INCANDESCENT Test C used a l00-watt incandescent parlamp (integral parabolic reflector lamp) with a lightly-frosted integral lens. The lamp was dimmed to approximately 50% of lumen output as measured on a CIE color-corrected meter. The resulting light dimmed to a visibly yellow-red hue at a color temperature of 2200 K°. The lamp and dimming level were selected because they appear and have been measured in museums where dimming rheostats are commonly used to lower footcandle levels on artifacts to recommended exhibit limits[7].

D. FLUORESCENT LAMP WITH UV FILTER A portion of the same fluorescent lamp of test B was used for test D, with the addition of a .125" (3mm)-thick acrylic UV filter between the lamp and the test samples. Test B and D were run concurrently and near the center of the fluorescent tube where lamp outputs were common to both tests.[8]

E. MR-16 HALOGEN, DICHROIC REFLECTOR A bare, MR-16 12-volt quartz-halogen spotlight, operating at 3100 K° and having a ellipsoidal dichroic reflector, was used for test E. The desired 10,000 fc test illumination was easily achieved by placing the test samples on the optical axis near the lamp.

F. MR-16 HAIOGEN WITH FRONT IR FILTER The same type of lamp used in test E was used for test F, but with a high-quality dichroic "hot mirror" IR filter placed in the beam between the lamp and the test samples. The filter losses were offset by moving the test samples nearer the lamp to re-establish the 10,000 fc level.

G. ACRYLIC FIBER OPTICS A NoUVIR® COLD-NOSE® fiber optic projector[3] with acrylic fiber light guides was used for test G. The projector used an ellipsoidal-reflector halogen lamp to illuminate the samples through 6' (1.9 meter) long by .120" (3mm) diameter acrylic optical fibers. The fiber ends

---

[7] *The IESNA Lighting Handbook: Reference and Application*, p. 14-11

[8] Note that UV outputs can be significantly higher at the ends of fluorescent lamps.

terminated in tiny, highly-polished parabolic reflectors to concentrate the light at 10,000 fc onto the test samples. This test provided the full visible light spectrum sharply cut off at 380 nm at the violet end and 760 nm at the red end of the visible spectrum. The light had no UV or IR content.

H. FIBER OPTICS WITH RED FILTER The lamp and fiber optics apparatus as in test G, with no UV or IR, was used for test H. The blue wool samples were illuminated for test H through a red filter that transmitted a minuscule amount of blue light and substantially all of the red light above 630 nm in the spectrum. This test was designed to intentionally mismatch the illumination color with respect to the sample color. The blue samples appeared nearly black under the red light.

I. FIBER OPTICS, BLUE REM FILTER™ Another set of fiber optics apparatus, similar to that of tests G and H, was used for test I. However, for test I the blue wool samples were illuminated through a blue filter that transmitted only blue wavelengths shorter than 500 nm. The blue REM filter™ (Reflected Energy Matching Filter)[4] was selected so the blue wool samples looked exactly the same color, in a side-by-side comparison, as the samples which were illuminated with unfiltered "white" fiber optics light of test G. There was no visual distortion for a viewer.

J. REFERENCE STANDARD A set of the four ISO fading samples from the same dye lot were retained in dark storage in a black envelope for post-test comparisons.

4.3 ISO BLUE WOOL FADING TEST PROCEDURES

The fading tests were conducted for an accumulated 250,000 FcHr (footcandle hours). The cumulative level of 250,000 FcHr was selected as an illumination level that is known to fade photosensitive materials.

50 exhibit hours per week, 50 weeks per year, gives us an expected 2,500 exhibit hours per year for a typical museum. 250,000 FcHr represents 100 footcandle years. This is equivalent to 10 years display at the moderate museum illumination level of 10 fc. It is also equivalent to 2 fc for 50 years, 5 fc for 20 years, or 20 fc for 5 years. The point is that this is the range for most museum lighting. It is a well accepted practice to perform accelerated tests as fading is a process and it is the total cumulative illumination, not the instantaneous measured illumination level in footcandles or lux that causes photochemical damage and fading.

5.0 ISO FADING TEST RESULTS

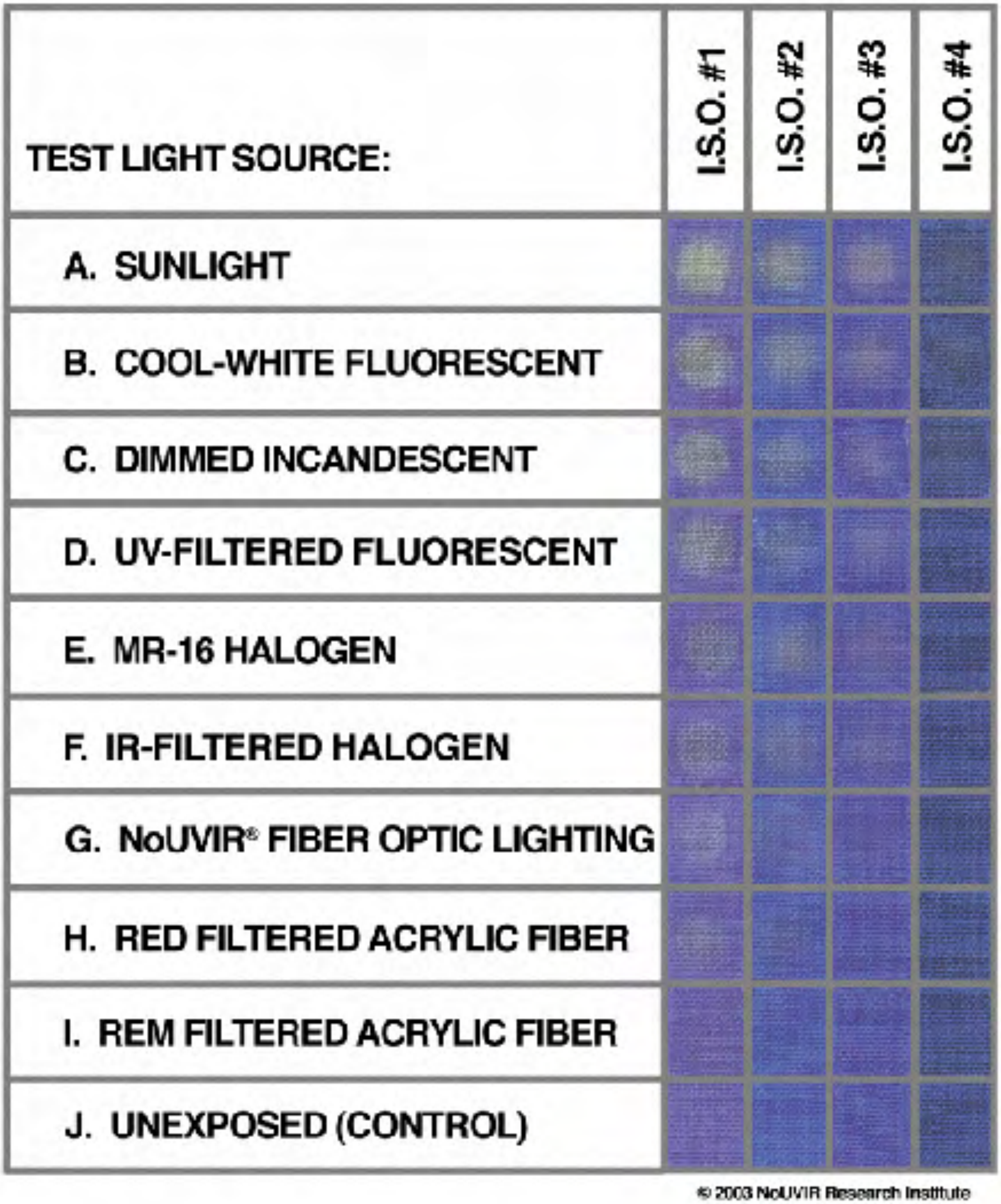


Figure 7. ISO Blue Wool Fading Tests

The actual results of the ISO blue wool fading tests are shown in Figure 7. They show that light sources with the greatest amount of absorbed spectral energy (including UV and IR) produce the most fading. Although the ISO fading test standards were developed to provide doubled fading resistance with each successively-higher ISO number; the ISO numbers are not usable in calculating the exhibit life for an object. The actual observed fading data must be converted to usable numbers that progressively increase with the cumulative illumination. They must also be weighted for doubled fading resistance to obtain an accurate assessment of the fading severity of the light source used.

The fading levels for each light source on the ISO blue wool samples in are shown in a conversion chart in Figure 8, which is used to determine the REM Factor (Reflected Energy Matching Factor) for each light source. Figure 8 is a black-and-white copy of the Figure 7, with the fading evaluations and tabular data included.

LIGHT SOURCE:	I.S.O. #1 1X	I.S.O. #2 2X	I.S.O. #3 4X	I.S.O. #4 8X	CUMULATIVE WEIGHTED FADING VALUE	% OF SOLAR FADING	REM FACTOR
A. SUNLIGHT	100	80	30	0	380	100%	1.0
B. COOL-WHITE FLUORESCENT	100	60	[illegible]	0	340	89%	1.1
C. DIMMED INCANDESCENT	100	80	10	0	300	79%	1.3
D. UV FILTERED FLUORESCENT	90	50	5	0	210	55%	1.8
E. MR-16 HALOGEN	90	50	5	0	200	53%	1.9
F. IR FILTERED HALOGEN	80	40	5	0	180	47%	2.1
G. NoUVIR® FIBER OPTIC LIGHTING	50	5	0	0	60	16%	6.3
H. RED FILTERED ACRYLIC FIBER	45	5	0	0	55	14%	7.1
I. REM FILTERED ACRYLIC FIBER	5	0	0	0	5	1%	100
J. UNEXPOSED (CONTROL)	0	0	0	0	0	0	∞

Figure 8. Conversion of ISO Fading Levels to REM Factor

5.1 FADING PERCENT OBSERVATIONS

As indicated in Figure 8, the fading of each ISO test standard sample shown in Figure 4-1 was evaluated over the full fading range from 5% (first detectable fading) to 100% (no visible remaining blue dye). The test samples were examined with a binocular magnifier. Careful examinations were made several times by three different observers under various light sources, including sunlight. The per-cent-of-fading estimates of all observations were fairly consistent and were averaged. Although the degrees of observed fading are somewhat subjective, this subjectivity would apply equally to all the samples and all the light sources. Since the intent is to compare the fading of the various light sources rather than establish absolute values any minor error in observed fading, applied to all sources, would still provide a valid comparison between those sources. The use of several observers and three ISO samples of differing sensitivities gives us an accurate evaluation of the fading characteristics of the various light sources. The observed fading level for each individual sample is shown superimposed on the respective sample image shown in Figure 8.

5.2 CUMULATIVE WEIGHTED FADING NUMBERS

The fading of all three test samples, ISO #1, #2 and #3 were made cumulative. There are several reasons for this: 1) The range of any one ISO sample was not broad enough to cover the extremes of fading characteristics of the light sources being tested. 2) As seen in Figure 6, the ISO samples of differing sensitivities are not entirely uniform in color. ISO #1 has a reflected wavelength at approximately 460 nm (nanometers), which in pigment color would be called ultramarine blue. ISO #2 at 480 nm has more green content and is close to manganese blue in color. ISO #3 at 440 nm has slightly more red content and is cobalt blue in color. The various light sources, having different color spectra, fade each sample at a different and non-linear rate. 3) The fading rate for each sample is asymptotic, following a curve that flattens out in time as the exposed dye molecules are depleted and progressively more light is required to fade the underlying layers of color.

The cumulative fading per-cent for each ISO# sample must be weighted by its fade resistance. ISO #1 thus has a weighting of 1. ISO #2 has a weighting of 2 (because it is twice as fade-resistant as #1). ISO #3 has a weighting of 4 (four times more fade resistant than #1). The cumulative weighted fading number for each source is then the sum of the weighted observed fading per-cent of each successive sample illuminated by each light source.

5.3 PERCENT OF SOLAR FADING STANDARD

The solar fading standard was established at 100%. To convert the cumulative weighted fading number for each source to a percentage of solar fading, the cumulative percentage fading for each source was divided by 380, the cumulative weighted fading number for sunlight.

5.4 REFLECTED ENERGY MATCHING (REM) FACTOR

The REM Factor for each light source is obtained by dividing the per-cent of the solar fading of sunlight (100%) by the per-cent of the solar fading of each respective light source. The REM Factor then is a number which is directly proportional to the exhibit life of a display object under each specific selected light source, using sunlight as a standard of 1.0.

A. SUNLIGHT (REM Factor = 1.0) By definition sunlight is established as 100% of the solar standard. 100%/100% gives a REM Factor of 1.0 for solar illumination. Obviously there is a need for additional test data to compare direct solar radiation with reflected sunlight, diffused sunlight and sunlight through various window materials for evaluating those options. While we plan to do evaluations of these variants of solar illumination in future tests, it should be obvious that sunlight is not a safe illumination for even mildly fugitive museum artifacts.

B. COOL WHITE FLUORESCENT LAMP (REM Factor = 1.1) The cool-white bare fluorescent lamp produced 89% of solar fading. ("Cool white" is a marketing term that has nothing to do with thermal output. All fluorescent lamps radiate between 70 to 75% of their energy as IR. And none are particularly white as the spectral output distribution in Figure 5 demonstrates. Be wary of descriptive terms used without quantitative data in their support.) Dividing 100% solar fading by this value (100%/89%) results in a REM Factor 1.1 for the fluorescent lamp. Fluorescent light is known to produce high fading levels because of the significant amount of UV energy in the spectrum, which cannot be seen by either the human eye or a light meter.[9] There are also a number of

[9] As a matter of fact it takes at least two UV meters, one long wave (350 nm) and one short wave (250nm) measuring absolute, values µw per sq. centimeter and not µw per lumen, to come close to accurately measuring UV. There are no UV meters currently available to measure the mercury emissions of fluorescent and HID sources in the 150 nm range.

dominant wavelength peaks in the visible spectrum of fluorescent lamps, to which the light meter is either totally or partially blind. As a result, the light meter may indicate a safe light level when there is actually an excessive light level that the meter cannot see. It was not surprising that the fluorescent lamp would be the most damaging of the electric light sources tested.

C. 50% DIMMED INCANDESCENT (REM Factor = 1.3) The incandescent lamp dimmed to 2200 K° still had measurable UV and very high IR. It produced 79% of the solar fading. 100%/79% produces a REM Factor of 1.3 for the dimmed incandescent lamp. While we recognize IR as a significant danger to artifacts, it was not expected that the dimmed incandescent sources would produce fading as severe as 79% of solar fading (and only 10% less fading than bare fluorescent lamps).

As mentioned above, for many years museum conservators have been dimming incandescent lamps with rheostats to reduce illumination in an attempt to preserve the artifacts. This is ineffective and may even be destructive. A CIE "color-corrected" light meter has a green filter over the photocell that substantially excludes the red end of the spectrum. Although the meter reading goes down as the lamp voltage is reduced, most of the energy is still there, lurking outside the meter's range, peaking around 1,000 nm. As shown in Figure 3, this energy cannot be read on a light meter, but it can instantly be felt as infrared energy on human skin and by the blue wool test samples... and by the surfaces of rare objects and artifacts.

D. FLUORESCENT LAMP WITH UV FILTER (REM Factor = 1.8) The fluorescent lamp of test D, with a .125" (3mm)-thick acrylic UV filter only reduced the fading to 55% of solar fading. 100%/55% equals a REM Factor 1.8. It should be noted that the UV filter produced only a 34% improvement in fading over the bare, unfiltered fluorescent lamp. This indicates that the UV filter was not very effective for museum use.

The problem is with the definition of UV. UV filters are almost exclusively tested and rated for long wave UV (300 to 380 nm). Most commercially available UV meters measure only this component of UV radiation. They do not measure and are not evaluated for the short wave UV in the 200 to 300 nm range. And there are no meters readily available to measure very short wave UV in the 100 to 200 nm range. Fluorescent lamps generate light by stimulating phosphors with UV mercury emissions. Mercury has strong emission lines at 150 nm, 250 nm and 350 nm. UV filters catch some (and the best ones most) of the 350 nm emissions. The rest impact the art and artifacts.

It should also be noted that most commercially-made UV filters that claim significant fading reductions are made of *amber-tinted* acrylic. The amber-colored tint also removes visible light from the violet end of the spectrum. The reduced violet light then improves the reflected energy matching for any artifact except those that are purple or violet in color. The reduced fading is partly a result of color filtering for reflected energy matching.

E. MR-16 HALOGEN LAMP (REM Factor = 1.9) The bare MR-16 halogen spotlight lamp of test E (at 3100 K°) produced 53% of solar fading. 100%/53% provides a REM Factor 1.9. This is only slightly above that of an filtered fluorescent and shows the damage caused by the huge IR content of this source. Although the dichroic reflector allowed some IR energy to pass through its glass reflector, there is still a great amount of IR in the beam. A lens placed in the beam will focus enough remaining IR to ignite a piece of paper.

This energy should be considered when MR-16 lamps are dimmed, as they often are, to meet recommended light levels in museums. Just as described for the test C (incandescent parlamps), dimming the filament of a halogen bulb shifts its energy peak further into the infrared area of the spectrum where it is invisible to a light meter. At a similarly dimmed color temperature, the only real difference in light output between a parlamp and a halogen lamp is that the quartz bulb envelope of the halogen lamp transmits more of the UV rays emitted by the filament.

F. MR-16 HALOGEN WITH FRONT IR FILTER (REM Factor = 2.1) The same lamp of test E, with a dichroic "hot mirror" IR filter in the beam, produced 47% of solar fading with a REM Factor of 2.1. There was slightly less fading with the IR filter in place, but it was hard to detect by those who examined the test samples. This indicates that the addition of the IR filter simply didn't help enough to see any significant difference in fading. Several manufacturers offer halogen lamps with integral IR filter lenses. One should not assume that such lamps would significantly reduce fading without actually testing them. Even the highest-quality "hot mirror" available did not remove all of the IR from the beam. Paper ignition by a focussed beam took only a few seconds longer than it does with the bare MR-16 lamp without the IR filter.

G. ACRYLIC FIBER OPTICS (REM Factor = 6.3) For the NoUVIR® fiber optics system, the full visible light spectrum is transmitted through the fiber, but the UV and IR content of the light is completely removed. The fiber optics produced 16% of solar fading. 100%/16% gives a REM Factor of 6.3. No heat was perceptible in the beam. It was not possible to focus the light to heat paper at all, so there was no possibility of ignition.

H. ACRYLIC FIBER OPTICS WITH RED FILTER (REM Factor = 7.1) Instead of the bare fiber optics of test G, the blue wool samples were illuminated for test H through a red filter that transmitted virtually no blue light; but did transmit all of the red light in the beam. As in G, above, the red-filter fiber optics produced 14% of solar fading, with a REM Factor of 7.1; almost the same fading as seen in the unfiltered fiber optics. In summary, the extreme color mismatch of the red light severely faded the blue samples.

I. ACRYLIC FIBER OPTICS WITH BLUE FILTER (REM Factor = 100) Instead of the bare fiber optics of test G (or the red-filter fiber optics of test H), the blue wool samples were illuminated for test I through a blue filter that transmitted blue light that precisely matched the color of the reflected energy. The blue-filtered fiber optics produced only 1% of solar fading. 100%/1% = REM Factor 100. It must be noted that the REM Factor of 100 for the blue-filtered fiber optics light is only applicable to an artifact having the same blue color. As long as the color of the incident light matches the reflected energy color of the object, the fading is virtually eliminated. Simply put, blue light does not fade a blue object.

6.0 COLOR FADING SAMPLE TEST SAMPLES

The above testing fully demonstrated the effectiveness of Reflected Energy Matching as a conservation practice for ISO blue wool samples. It further gave a very effective evaluation of the photochemical safety of the various light sources commonly found in museum environments. The next question to address was if these results would change significantly with colors other than blue. It was necessary to demonstrate empirically that the very significant fading reductions gained through Reflected Energy Matching applied to all colors.

The ISO #2 blue wool fading sample was used for blue dye fading. Other colors used were known to be comparably fugitive. The reflectance of each color is spread over a wavelength band. However, each color has a dominant spectral peak that makes that specific color identifiable by the observer. Each color was compared to a spectral chart to visually determine the wavelength of the reflectance peak. The dominant visual color and its peak wavelength on the spectral chart were estimated by several observers in sunlight. For instance, the ISO #2 blue wool sample appeared to have the hue corresponding to 495 nm on the spectral chart. The colors selected for fading samples were:

ISO #2 blue wool: reflectance spectral peak **495 nm** wavelength;

Viridian Green: reflectance spectral peak **520 nm** wavelength;

Chrome Yellow: reflectance spectral peak **575 nm** wavelength;

Carthane Rose (orange): reflectance spectral peak **610 nm** wavelength;

and

Lake Crimson: reflectance spectral peak **680 nm** wavelength.

6.1 COLOR FADING TEST PROCEDURES

The color fading tests were conducted for 250,000 FcHr (footcandle hours). The cumulative level of 250,000 FcHr was selected as illumination that is known to significantly fade I.S.O #2 photosensitive materials. It is also the value used in the earlier testing of the blue wool samples.

Testing was done on the five color samples listed above using the test apparatus and procedures described in section 4.1. For continuity it was important to follow as closely as possible the testing procedures of the earlier testing. To save time, and because the color fading testing was not designed to address photochemical damage by radiation outside the visible spectrum, UV filtered fluorescent lighting, dimmed incandescent lighting, and IR filtered incandescent lighting were not evaluated. Quartz Halogen lighting is in fact incandescent lighting and did not vary from incandescent test results significantly. It was not evaluated separately in this round of testing.

Experience with both the first set of tests and the color testing done here led to some refinement in the criteria used to judge photochemical damage. As discussed later under Observation of Percent Color Loss Due To Fading, the colored samples were evaluated on the basis of the visible remaining color of the *original* hue. The word "original" is italicized to emphasize the fact that many fugitive dyes do not merely fade out to white. Instead they tend to fade out a component in the original color and change to another hue. It is of critical importance to both the exhibit designer and the conservator to know that watercolors, textiles or any artifacts colored with fugitive dyes will not only fade in brilliance, but will actually change the colors in the composition.

6.2 LIGHT SOURCES FOR COLOR FADING TESTS

While the number of light sources was reduced for this test, the sources still cover the range of sources common to museum environments. New sources specific to this test included lightly color filtered and exactly color matched acrylic fiber optic lighting. Acrylic fiber optic lighting was used for the color filter testing as it is the only UV and IR free illumination source available. Each source is briefly described below:

SUNLIGHT Sunlight used in this series of tests exactly matched that used and described as Source A in the earlier ISO blue wool testing. Each of the colors of the chosen test samples are well represented in the full spectrum of sunlight as shown in Figure 9.

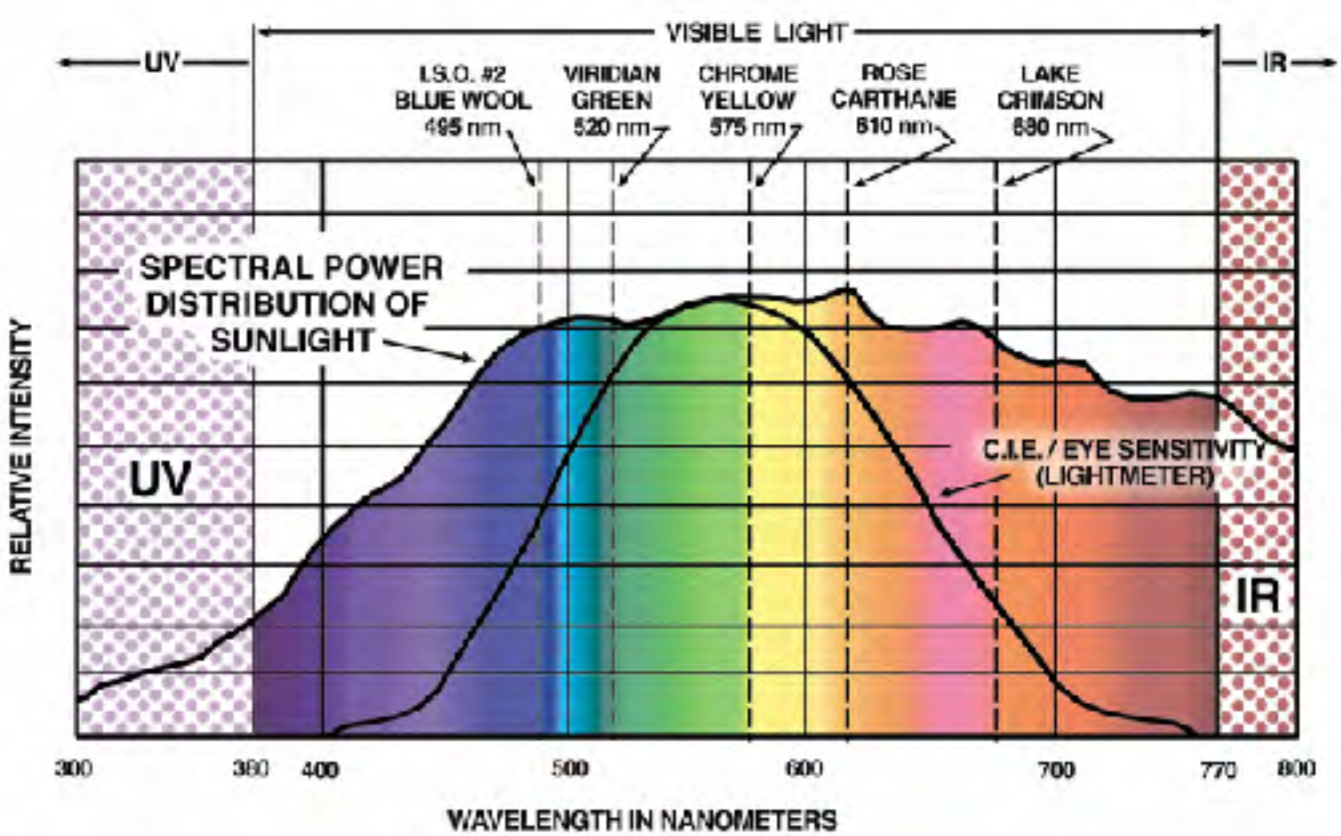


Figure 9. Visible spectrum of sunlight

COOL-WHITE FLUORESCENT Identical to the lighting and procedures used as Source B in the earlier testing. Note that the as in the earlier testing the unfocused and unfocusable nature of a fluorescent source necessitated longer exposures at lower intensities to accumulate the required 250,000 footcandle hours. Some of the test colors are significantly underrepresented in fluorescent light as they would be in HID and LED sources. This is shown earlier in Figure 5.

INCANDESCENT A l00-watt incandescent par-lamp (integral parabolic reflector lamp) with a lightly-frosted integral lens was used. The lamp was operated at full voltage to produce light at a color temperature of 2900 K°. The incandescent lighting used in this test roughly approximated the unfiltered MR-16 halogen lamp used as Source E in the earlier testing. All test colors are represented as was shown in Figure 2 earlier.

NoUVIR ACRYLIC FIBER OPTICS Used as Source G in the earlier testing, the NoUVIR acrylic fiber optic illumination provides a full visible spectrum almost exactly matching sunlight, with the exception that it contains zero UV or IR radiation. The NoUVIR spectral output is shown in Figure 11.

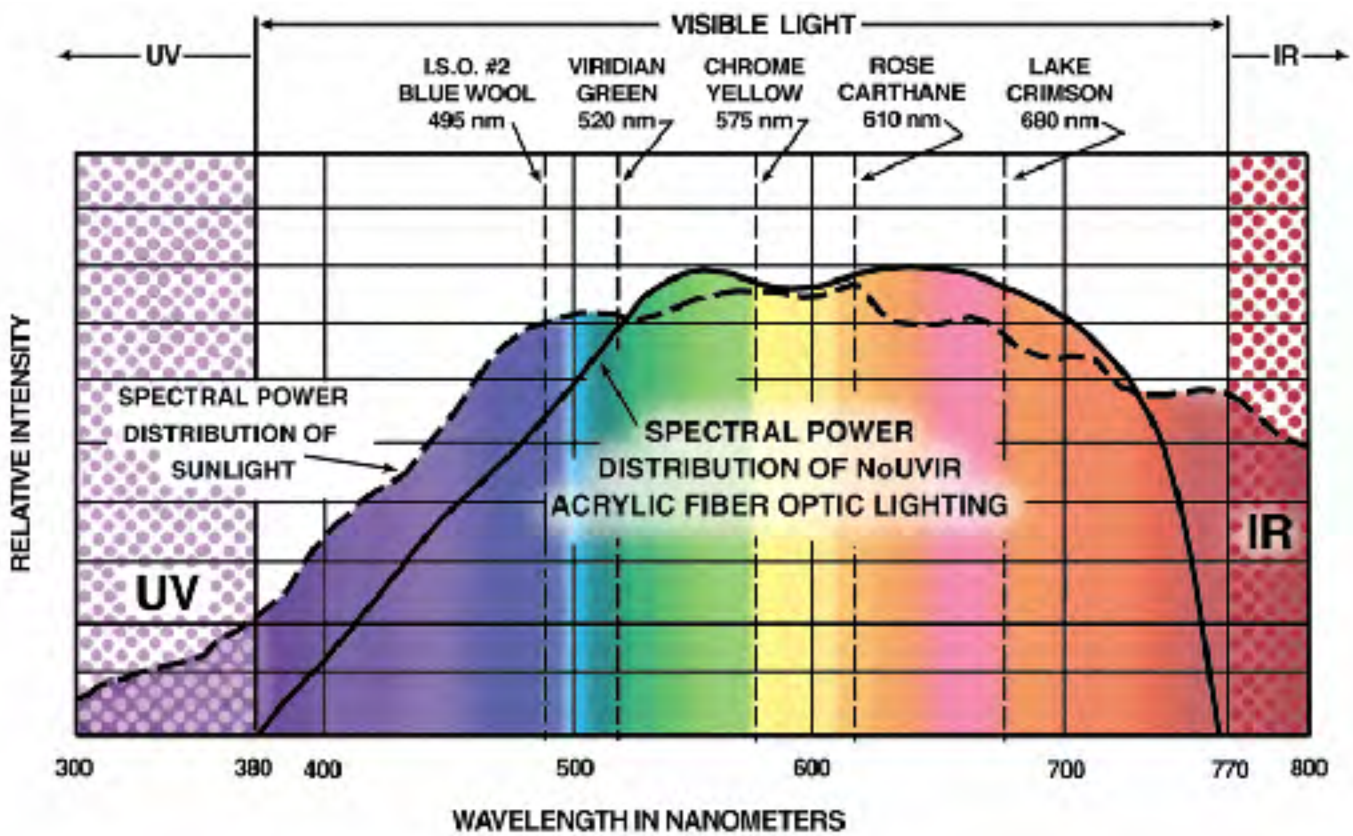


Figure 10. Spectral Output of NoUVIR Fiber Optic Illumination

LIGHT TINT OPTICAL FIBER The same lamp and fiber optic apparatus used in the bare optical fiber test, was used for the light-tint tests. Filters cut from high-quality photographic gel filter material[10] were placed between the emitting end of each miniature parabolic reflector and the respective test sample. Filters for this test were chosen to roughly match the hue of each test sample to evaluate the effects of partial Reflected Energy Matching. The transmissivity curves for the light-tint filters are shown in Figure 11, along with the reflectance spectral peak for each color sample.

The light-tint filters attenuated the 10,000 fc bare fiber illumination an average of 30%. Therefore, the tinted illuminance on the samples was approximately 7,000 fc. However, the observed brightness of the color-filtered samples, compared to samples illuminated side-by-side with 10,000 fc by bare fiber optics, appeared identical. The difference in measured energy was all in that energy absorbed by the sample. The hue, value and chroma of each of the samples appeared unchanged by tinting the illumination.

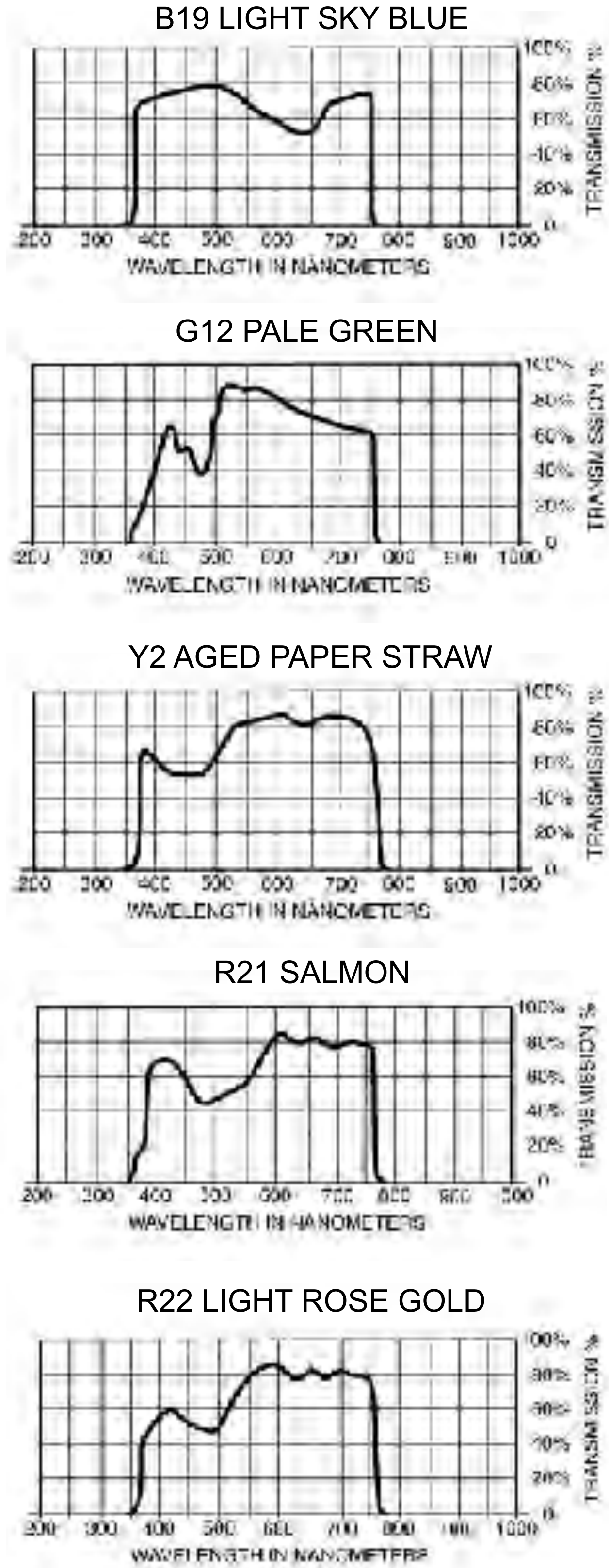


Figure 11. Transmission Curves of The Light Color Tint Filters

[10] REM Filter kits, in two sizes and 40 different colors are available from NoUVIR, (302) 628-9933.

REM FILTER OPTICAL FIBER A similar set of fiber optic apparatus was used for REM filter (Reflected Energy Matching Filter) tests. The filter colors were selected, so the samples looked exactly the same color, side-by-side, as samples illuminated with unfiltered light of the bare optical fiber tests.

The REM Filters attenuated the 10,000 fc bare fiber illumination with an average filter transmissivity of 25%. Therefore, the 10,000 fc level of bare fiber optic illumination produced a measured 2,500 fc. But the hue, value, chroma *and intensity* of the samples appeared unchanged by fully REM-filtering the illumination. In effect, *visibility and full apparent color and brightness were maintained at 1/4th the measured illumination levels*. This is because the filters did not remove any illumination intensity from the colors being reflected. The filters only removed intensity from colors which were not present in the color samples. Because this light energy was only being absorbed, its removal had no effect on the appearance of the sample. It did, however, have a tremendous effect on the life of the sample.

Note that when filters are properly selected (sometimes several color filters in a stack) there is no visual color distortion. The viewer is unaware that the light is colored at all. This technique has been used in several museums with the approval of the conservators (who are most concerned with preservation of the artifacts) and also with the approval of the curators (who are most concerned with the presentation of the true colors of the artifacts). The transmissivity curves for the REM filters are shown in Figure 12 along with the visually-apparent peak and the relative reflectance spectral band for each color sample.

Visibility or the process of seeing is always a three-art system between a light source, an object and the viewer. The eye can only see the colors that are reflected by the object . Absorbed frequencies are irrelevant to vision. They only add to damage. Removing this energy does not change the reflected light of the object's appearance. When comparing objects side-by-side; viewers cannot pick out an object that is correctly filtered from an object with no filtering.

One of the first artifacts to use this technique was the cancelled U.S. check that purchased Alaska. Because the lighting filtered all UV and all IR, and then used stacked filters to match the sepia inks and aged paper; the conservators allowed the check to be displayed three times longer than at any other previous venue.

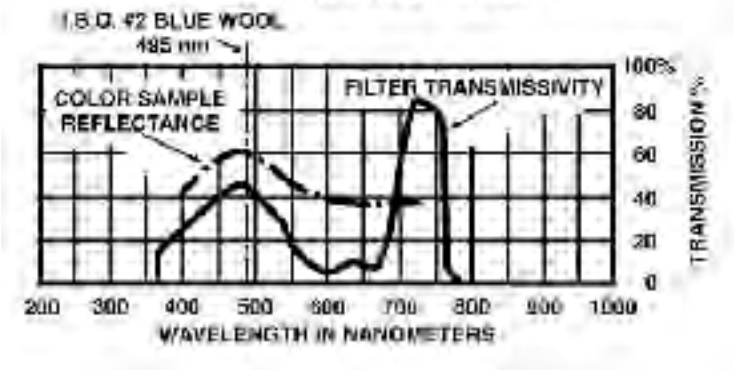
Figure 12. Historic Check that Bought Alaska Lit with REM Filters.

For the first time a museum was allowed to display this rare check for the whole period of the exhibit. The curator stated that not only did the check "look the same" in color, but that it was more easily readable by visitors (even at a minimal set limit of 2.7 footcandles). Documents are still the most popular artifacts for REM filtering. But everything from stamps to furniture are being lit this way without distortion.

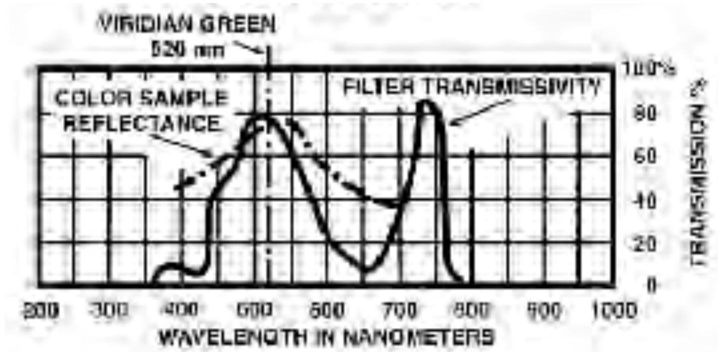
Figure 13. Historic Costumes. *These Adrian creations for the movie, Marie Antoinette (1938), were made with gold lace, antique gilt braid, embroidery, velvets and buttons from the time period. Each costume was REM filtered to protect the fragile textiles. The red "queen's dress" has the hemline left in shadow as the bottom edge of the dress was badly damaged in storage at MGM. Visitors could not detect the REM filters on the fabrics. The plumes, cravats, hose, wigs and gemstones were lit with unfiltered "Pure-white" fiber optic lighting.*

The transmissivity curves for the REM filters in the last set of tests a 1% are shown in Figure 14, along with the visually-apparent peak and the relative reflectance spectral band for each color sample. Filters B10 and G10 both have a peak at 750 nm. This does not affect the visible chroma or hue of these filters, because the eye sees only about 2% of the light at that wavelength at almost 770 nm where IR begins as shown in Figure 9. The same is true of the 350 nm peak of filters Y10 and YR1 as 380 nm is the threshold for UV. Eyes do not see 350 nm light. Remember too, that although the filters may transmit these wavelengths, the UV and IR free acrylic fiber optic illumination has no radiation above 770 nm or below 380 nm and closely matches he color/CIE spectral power distribution.

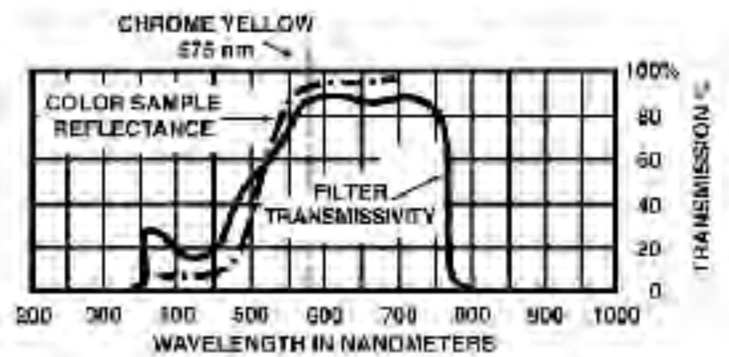
B10 UNIFORM NAVY BLUE



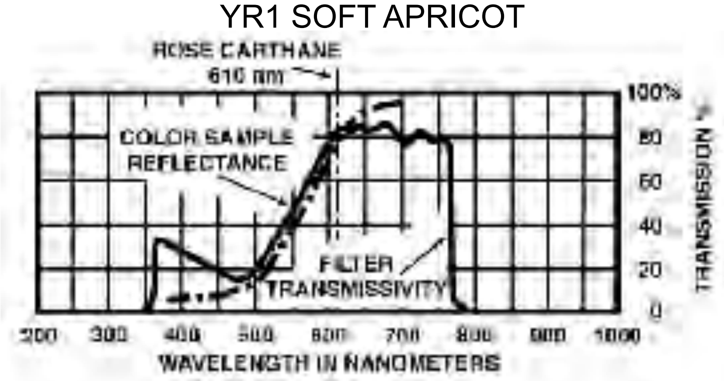
G10 FERN GREEN



Y10 MODERN YELLOW



YR1 SOFT APRICOT



R11 NO ORANGE RED

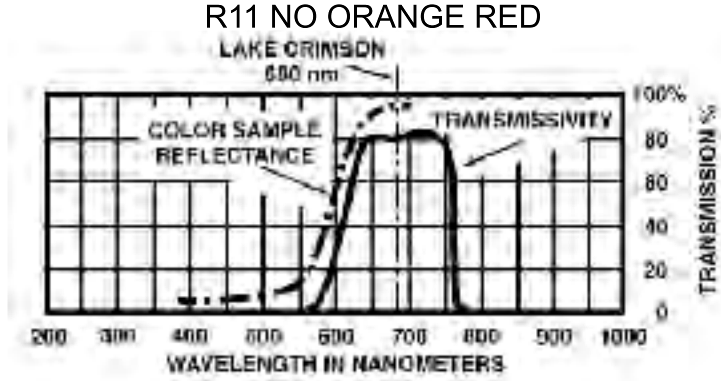


Figure 14. Transmission Curves of The REM Filters

6.3 COLOR FADING TEST RESULTS

The results of previous ISO blue wool fading tests indicated that light sources with the greatest amount of absorbed spectral energy (including UV and IR) produce the most fading on the color samples. This was again demonstrated in the color fading tests. Just as with the earlier test results, the actual observed fading data must be converted to usable numbers. They must be averaged over the full visible spectrum of colors to obtain an assessment of the fading severity of the light source used, and the numbers must then be converted to a factor that is proportional to expected exhibit life. The actual test results are shown in Figure 13.

LIGHT SOURCE	I.S.O. #2 BLUE WOOL	VIRIDIAN GREEN	CHROME YELLOW	ROSE CARTHANE	LAKE CRIMSON	AVERAGE COLOR FADING	% OF SOLAR FADING	REM FACTOR
DIRECT SUNLIGHT % FADING (COLOR LOSS)	100	100	50	50	50	70%	100%	1.0
COOL-WHITE FLUORESCENT % FADING (COLOR LOSS)	90	80	30	60	80	68%	97%	1.0
2900°K INCANDESCENT % FADING (COLOR LOSS)	100	90	20	50	60	64%	91%	1.1
UNFILTERED ACRYLIC FIBER OPTIC LIGHTING % FADING (COLOR LOSS)	25	20	0	20	40	21%	30%	3.3
LIGHT TINT ACRYLIC FIBER OPTIC LIGHTING % FADING (COLOR LOSS)	0	10	0	0	20	6%	8.6%	11.8
REM FILTERED ACRYLIC FIBER OPTIC LIGHTING % FADING (COLOR LOSS)	0	0	0	0	5	1%	1.4%	71.4

Figure 15. Light Source Fading of Fugitive Colors

6.4 OBSERVATION OF PERCENT COLOR LOSS DUE TO FADING

As indicated in Figure 15, the percentage fading in each color sample shown was evaluated over the full fading range from 5% (first detectable fading) to 100% (no visible remaining color of the *original* hue). As described above, many fugitive dyes do not merely fade out to white. Instead they tend to fade out a component in the original color *and change to another hue.* It is of critical importance to both the exhibit designer and the conservator to know that watercolors, textiles or any artifacts colored with fugitive dyes will not only fade in brilliance, but will actually change the colors in the composition. Many of the soft pastel colors, browns and rusts in objects and artwork in prestigious galleries today are only the photochemical remains of lively, bombastic, brilliant colors.

Due to the tendency of some dyes to change hue, rather than merely fade in value, it was necessary to visually evaluate the fading of the samples. A reflectometer would not accurately indicate the changes in appearance. For example, the lake crimson darkened to red. This particular viridian green changed to blue and then began to fade. A second intent of the testing was to demonstrate what happens to the appearance of the color samples, and to simulate actual fading that occurs to real objects in real museum environments viewed by real people.

> *Look at American Colonial period portraits as an example of fading and color change impacting how art is viewed is. Individuals often look grim and lifeless. The vivid reds of rosy checks and lips have faded to light rust and partially disappeared leaving checks pale and hollow, lips thin to erase subtle smiles. The important violet and lime green needed to create a "living" flesh tone turn brown creating a pasty skin. What were portraits showing vivacious founders of a new nation are perceived as formally stiff and unhappy people.*

The test samples were examined without optical aids and also with a binocular magnifier. Careful examinations were made several times by different observers under various light sources, including sunlight. The percent-of-color-loss estimates of all observations were fairly consistent and were averaged. As all samples had equivalent fugitivity, there was no need to weight individual data items for this test. The average color fading of the five color samples was then compared to solar fading and a REM Factor was calculated from the data.

As with the earlier ISO blue wool testing, the degrees of observed fading are somewhat subjective. This subjectivity is balanced and is uniform over all the samples tested. The percent of fading expressed as a factor of solar fading is accurate and applies equally to all light sources. Since the intent is to compare the fading of the various light sources; any minor error in observed fading, applied to all sources, would still provide a reasonably valid comparison between those sources. The percent of observed fading for each sample is shown beneath each respective color sample of Figure 15.

6.5 FADING OF INDIVIDUAL COLOR SAMPLES

BLUE SAMPLE FADING Because the criteria for evaluating fading in this study was more exacting than that of the earlier tests, fading values for the ISO #2 Blue Wool samples varied slightly from the original tests. The ISO #2 samples fade damaged 100% of the observable blue dye under sunlight, 90% under fluorescent light and 100% with incandescent light. The actual samples showed a slight yellow tint on the faded circles. This is typical of some museum exhibit experience that has been reported, in which the blue dye is entirely destroyed. Then the wool fibers become oxidized to yellow in the presence of light and oxygen.

It is not surprising that sunlight is the most damaging form of illumination. It was interesting that the incandescent tests faded the blue wool samples more than the fluorescent light tests. The reason for this apparent anomaly is explained by examination of the spectral charts for those light sources. In the spectrum of the incandescent lamp shown in Figure 2, it may be seen that there is a great deal of energy in the red end of the spectrum between 600 nm to 770 nm. Additionally there is a huge infrared component outside the visible spectrum. All the red and infrared radiation is a gross mismatch from the 495 nm reflectance peak of the blue wool sample. All of this energy is absorbed and causes fading.

Conversely, examination of the fluorescent light spectrum in Figure 5 shows that there is far less red and infrared radiation. The blue and green spikes in the fluorescent output while not close enough in color for good presentation, are close enough that a major portion of this energy is reflected. This resulted in less fading of the blue sample than with the incandescent source.

The fiber optic sources produced far less fading in the blue wool samples. Bare fiber resulted in 25% of solar fading. Light-tint filtered fibers gave an average of 0% fading. REM filter fiber optic illumination showed barely perceptible fading for lake crimson and absolutely 0% fading (undetectable at this exposure level) for all of the other samples. There was no change in the ISO #2 blue wool, viridian green, chrome yellow or rose carthane with the accumulative exposure of 250,000 FcHr.

The reason for the dramatic reduction in fading achieved by the B10 REM Filter is shown by comparing the transmission curve of the B-10 filter to the spectral distribution of the ISO #2 Blue Wool Sample in Figure 14. The solid line is the spectral distribution of the illumination, and represents the output spectrum of the bare fiber times the transmission of the B10 REM filter. The dash-dot line is the reflectance spectral distribution of the test color sample. The vertical dashed line is the visual peak of the reflected color. The dye spectral reflectance distribution is typical of a number of dyes in this general color. The reflectance curve shown is generic for approximately the hue of the blue wool #2 sample, and is extracted from data published by Feller.[11]

Since the spectral distribution curve of the color-filtered illumination closely matches the reflectance distribution of the dye in the blue sample (as seen in Figure 14) the fading due to wavelength mismatching is dramatically reduced. In the test exposure of 100 FcYr, fading cannot be detected on the sample. The portion of the reflectance spectrum between 700 and 770 nm is not shown in the Feller data. But the visual color match and the lack of fading suggest its presence.

VIRIDIAN GREEN SAMPLE FADING Most artists will say that green is a combination of the primary colors of blue and yellow. The viridian green sample clearly exhibits this characteristic by changing its hue from green to blue. This is typical of many green dyes in old scenic textiles that now have blue foliage. Yellow molecules have been destroyed first, turning the originally-green leaves to blue.

Green samples faded in a manner generally similar to the blue wool samples. The greatest fading occurred at 100% under sunlight. The fading dropped to 80% under fluorescent light, and then up to 90% under incandescent

[11] Robert L. Feller, Ed. Artist's Pigments, A Handbook of Their History and Characteristics (Cambridge: Cambridge University Press, 1986), p. 145, Fig. 1, curve a.

light. Once again, the incandescent lamp is more damaging than a fluorescent lamp to the green dye.

As described above for the ISO #2 blue wool sample, the viridian green dye spectral reflectance distribution is also typical of dyes in this general color. The reflectance curve shown is again extracted from data by Feller.[12]

Consistent with the wavelength-related blue sample tests, the fiber optic sources produced far less fading in the viridian green samples: 30% for bare fibers, 10% for light-tint filtered fibers and 0% (undetectable in this exposure) fading for G10 REM filter fiber optic illumination.

CHROME YELLOW SAMPLE FADING The chrome yellow sample did not change color. It is a primary color and simply faded towards white. The test samples lost approximately 50% of their yellow intensity in sunlight, 30% in fluorescent light and 20% in incandescent light. Since most chrome yellows darken instead of fade in light, it is suspected that the brand of chrome yellow used in our tests may have actually been made with arylide or diarylide yellow pigment. However, the hue and chroma appeared to accurately match other chrome yellows. Feller's data[13] for chrome yellow was available and is shown as the dash-dot curve in Figure 14. No fading could be seen in any of the fiber optic tests, including those using the Y10 REM filter.

CARTHANE ROSE (ORANGE) SAMPLE FADING Just as green is often made up of blue and yellow, orange is usually made of red and yellow. Therefore, just as green loses yellow and turns blue, the more fugitive yellow dye molecules in orange hues are destroyed first. This leaves a pale red color as the result of fading. A dramatic example of fugitive yellow loss is seen in many ancient tapestries. Obviously gold items have lost all their original yellow color to become dull brown objects in the scenes.

One very surprising test result was that *the fluorescent lamp faded this sample even* ***more than sunlight*****.** This is probably caused by a dominant color spike of blue-violet light at 440 nm in the cool-white fluorescent spectral distribution of Figure 5, and absent in the sunlight spectrum of Figure 9. The carthane rose sample proved to be very fugitive, and some fading was observed for both bare and light-tint fiber optic illumination. However, no fading could be detected for the test sample illuminated through the YR1 REM filter.

[12] Feller, Robert L., p145, Fig , curve c.

[13] Feller, Robert L., page 190, Fig. 1, curve a.

The dye spectral reflectance distribution is also typical of dyes in this general color. While the fugitivity of particular dyes may vary, this data is valid for all orange colors. The reflectance curve shown on the chart is extracted from data published by Feller.[14]

LAKE CRIMSON SAMPLE FADING It became apparent during tests that lake crimson is extremely fugitive, probably closer to ISO #1 (undisplayable at any light level). Lake crimson samples have some yellow content, but the red dye molecules are even more fragile than the yellow ones. The faded areas of the circles have therefore turned slightly orange. Similar to the carthane rose fading described above, we again find the fluorescent lamp at 80% to be more damaging than sunlight, which faded only by 50%. Since sunlight contains more ultraviolet, the fluorescent light's violet/blue spikes at 410 nm and 430 nm, plus the green/yellow spike at 490 nm create a spectral mismatch. This accounts for the fluorescent lamp fading the 680 nm lake crimson color more severely than sunlight.

The fiber optic sources exhibited less fading than the fluorescent or incandescent sources. But some damage was evident. Even though the R11 REM filter transmission closely matches the pigment reflectance curve, extreme fugitivity produced a slight (5%) fading. Feller data[15] for lake crimson pigment is shown as the dash-dot curve in Figure 14.

The extreme fugitivity of the lake crimson samples tended to skew the test data slightly when averaged with the other color samples. For this reason there are slight differences in the calculated REM numbers between the two sets of tests. While the individual values may vary slightly, the overall results of both tests agree and support Reflected Energy Matching Theory as a conservation tool. Both tests also strongly support the elimination of non-visible radiant energy wherever possible in a museum environment.

6.6 AVERAGE COLOR FADING

As described above, the percentage fading of all five hues of test samples in Figure 15 were added and then averaged by dividing by 5 (the number of test samples). The fading rates of the various hues were fairly uniform and although the lake crimson sample was more fugitive than the others, there was no need to

[14] Feller, Robert L., page 190, Fig. 2, curve d.

[15] Feller, Robert L., page 264, Fig. 7, curve g.

weight data as with the ISO Blue Wool testing. Averaging the data from all five of the test samples tends to mitigate the slight variations in fading between the different colors. In all, because of the range of colors and materials tested and the more exacting definition of fading used in this test, the results of the color fading testing should be considered the more accurate of the two tests.

6.7 PER-CENT OF SOLAR FADING STANDARD

As with the earlier testing, the solar fading standard was established at 100%. Then to convert the average color fading number for each light source to a percentage of solar fading; the average color fading for each source was divided by 70, the average color fading number for sunlight.

6.8 REFLECTED ENERGY MATCHING FACTORS

The REM Factor for each light source was again obtained by dividing the per-cent of the solar fading of sunlight (100%) by the per-cent of the solar fading of each respective light source. The REM Factor then is a number which is directly proportional to the exhibit life of a display object under each specific selected light source, using sunlight as a standard of 1.0. A REM factor of 3.3 (non-color-filtered acrylic fiber optic illumination)in this test indicates a three fold increase in exhibit life.

SUNLIGHT (REM Factor = 1.0) By definition sunlight is established as 100% of the solar standard. 100%/100% equals a REM Factor of 1.0 for solar illumination. For these tests direct solar illumination provided a standard for comparison to the other light sources. It would be rare for a museum to use direct sunlight as a light source, but it is quite common to use filtered and/or indirect sunlight. Therefore, there is a need to test sunlight as "daylighting". Tests are planned to compare direct sunlight (as a standard) to reflected sunlight, diffused sunlight and sunlight through various window materials.

COOL WHITE FLUORESCENT LAMP (REM Factor = 1.0) The cool-white bare fluorescent lamp produced 97% of solar fading. When divided into 100% solar fading the slight reduction was not mathematically significant (0.03). We are left with a REM Factor of 1.0 for the fluorescent lamp. Fluorescent light is known to produce high fading levels because of the significant amount of UV (up to 7%) in the spectrum. These damaging rays cannot be seen by a light meter. There are also a number of dominant peaks in the spectrum of fluorescent lamps to which the light meter is partially blind. As a result, the light meter may indicate a safe light level when there is actually a number of excessive light levels at wavelengths that the meter sees dimly or cannot see at all. Therefore, it is not surprising that the fluorescent lamp would be the most damaging of the electric light sources tested.

The spectral spikes in the fluorescent spectrum can fool the human eye, in a metameric process, into actually "seeing" colors that aren't there. As a matter of fact, different spectral peaks at various wavelengths can cause the eye to perceive the same color. That is the reason many different gas-discharge lamps claim to produce "white" light, when they actually produce spaced-apart, narrow-band spikes of colored light at specific wavelengths. But the test samples (and museum artifacts) are not as easily fooled as the human eye. So those spike patterns are usually absorbed, just as Grotthus stated in 1817, to cause photochemical damage. Since the intensity of the narrow spikes is very high in comparison to the CIE curve, as seen in Figure 5, they can cause severe damage to mismatched colors in a very short time.

INCANDESCENT LAMP (REM Factor = 1.1) The incandescent lamp at 2900 K° still had measurable UV and very high IR. It produced 91% of the solar fading. 100%/91% results in a REM Factor of 1.1 for this source.

As described earlier, dimming incandescent lamps will not necessarily reduce fading. While dimming incandescent lamps with rheostats to reduce the illumination to preserve artifacts is common practice, this shifts the spectral peak further into the red and infrared portions of the spectrum. Conservators have found significant fading of blue and green textiles after only a few years, within acrylic cases, dimmed to only 5 fc. These results indicate why.

The reason for this fading is seen in the visible incandescent spectrum of Figure 2. The CIE "color-corrected" light meter has a green filter over the photocell that substantially excludes the red end of the spectrum. Although the meter reading goes down as the lamp voltage is reduced, most of the energy is still lurking outside the meter's range, peaking around 1,000 nm. Energy at 1000 nm cannot be read on a light meter, but it can instantly be felt as infrared energy on human skin and by the test samples. Because the red and infrared severely mismatches blue or green surfaces, rapid fading of sensitive materials can be expected.

BARE ACRYLIC OPTICAL FIBER (REM Factor = 3.3) The bare fiber optic illumination has no measurable UV and zero infrared radiation. This eliminates the more than 90% of the radiant energy of the quartz halogen source that is outside the visible spectrum and cannot aid vision. This reduction provided an exhibit life for artifacts that is 3.3 times longer than sunlight, 3.3 times longer than fluorescent light and 3.0 times longer than incandescent light for the same cumulative exposure in footcandle hours.

The REM value of the ISO blue wool sample in Figure 15 is lower than the value sown in the earlier testing in Figure 8. This is because the later evaluations used much stricter guidelines for fading. In the color fading tests of Figure 15, fading was evaluated as *any* color sift of the sample during the 250,000 FcHr test duration. Color shift is more visible, but slightly more subjective, then the criterion of fading to a lighter shade used for the earlier testing of the ISO blue wool samples in Figure 8.

LIGHT-TINT FILTERED OPTICAL FIBER (REM Factor = 11.8) The light-tint filtered fiber optic illumination also has no measurable UV and has zero infrared radiation, plus some color matching. Therefore it provided an exhibit life for artifacts that is 11.8 times longer than sunlight, 11.8 times longer than fluorescent light, 10.7 times longer than incandescent light and 3.5 times longer than bare acrylic fiber illumination for the same cumulative exposure in FcHr.

REM FILTER OPTICAL FIBER (REM Factor = 71.4) The REM filtered fiber optic illumination also had no measurable UV (long or short wave), zero infrared radiation, and very close color matching. It therefore demonstrated an exhibit life for artifacts that is 71.4 times longer than sunlight, 71.4 times longer than fluorescent light, 64.9 times longer than incandescent light and 21.6 times longer than bare optical fiber illumination.

7.0 PRACTICAL APPLICATIONS

The fading tests show that various color samples fade differently under various light sources having identical cumulative footcandle levels. This is because the various light sources have very different spectral outputs which result in varying color mismatches with different artifacts. The most practical application of this research is the ability to easily compare spectral outputs of various light sources and evaluate their expected relative effects on collections.

Overall these tests establish that plain fluorescent and incandescent sources are no safer in museum use than direct sunlight of the same intensity. This information is vital to the exhibit life of display objects, from watercolors to costumes. Partial UV and IR filtering can reduce fading damage by half.

Complete elimination of UV and IR (which is practical only with acrylic fiber optic illumination) will extend exhibit life by 3 to 6 times. Elimination of UV and IR coupled with color matching of light can extend exhibit life by 70 times. *With proper lighting conservators can increase exhibit life dramatically and increase exhibit visibility and presentation at the same time.*

If the exhibit has known fading characteristics in terms of a relative ISO number, lighting can be selected to minimize fading and extend the exhibit life of the artifacts. If the exhibit has unknown fading characteristics, a tiny sample as small as 3/8 by 1/2 inch, can be removed from a covered or inconspicuous place, or taken from a similar contemporaneous artifact of poor condition and less value. Using the procedures described in this paper, the fading susceptibility of the unknown material may be tested with samples of known fading rate to determine the fading characteristics of the unknown material.

The fading rate and exhibit life for an unknown material can then be predicted for any light source at any footcandle level. Small test kit folders shown in Figure 6 may be used to hold samples of unknown material in the folder with an ISO fading sample and watercolor samples approximating the color of the unknown material.

7.1 LIGHTING SINGLE-HUE ARTIFACTS

For a typical application of Reflected Energy Matching to single-hue artifacts, assume that the exhibit object was not a watercolor fading sample, but George Washington's blue wool coat having the fading characteristics of the ISO #2 samples. The typical ISO #2 fading characteristic of the coat indicate that the blue dye is too fugitive to exhibit, except for short periods of time at very low light levels. From Figure 13 it can be seen that in 100 FcYr 90% fading would occur with fluorescent light and 100% of the blue color would be faded out by typical museum incandescent lighting.

Therefore, even at 5 fc, 100% fading would occur in 20 years with conventional lighting. The coat would be virtually destroyed as a historic costume. However, if the color of the light was partially matched with fiber optics and light-tint filters, it could be exhibited for the same 20 years and fading would be only 5%. Further, if full REM filter light was used, the fading at the end of 20 years would still be undetectable, and the coat could probably be exhibited with its original hue clearly visible for centuries.

Figure 16. Marilyn Monroe Costume. *Reflected Energy Matching is not limited to museums. This case is in a casino. Customers enjoyed seeing this famous dress from “the Red Dress Sitting” by photographer Milton H. Green for* Life Magazine*, January 1957. The dress has aged over the decades from red to a more tomato color. Using fiber optic lighting, REM filters matched the current hue of the dress exactly. The dress was exhibited in one of the model poses that supported the fragile material using the case’s acrylic floor. The case also was sealed using a passive micro-climate control system. Glare and pollution were outside. Exacting lighting matching the artifact’s needs and pure, treated air were inside. When the costume was returned to archives, careful examination showed no change though exhibited in a hostile environment.*

7.2 LIGHTING MULTIPLE, SINGLE-HUE ARTIFACTS

In the George Washington blue wool coat example, there is only one exhibit artifact of a single color. However, if the blue coat is displayed on a conservation mannequin form with a red hat; the coat can still be REM filter illuminated with matching blue light and the hat can also be REM filter illuminated with matching red light. The optical control of fiber optic light fixtures[16] can permit exact control over aim, focus and intensity of each individual luminaire. Each light beam can be color tinted and adjusted to preclude spillover of one color light

[16] The control described is possible and practical in the over fifty different fiber optic luminaires available from NoUVIR Research at (302) 628-9933.

onto the other color of an object or exhibit. If the red hat had the extreme fugitivity of the lake crimson test sample, at the end of 20 years, the hat would only show 5% fading. And all the time, the colors would be clearer and brighter, without distortion

Tight optical control is obtainable. An extreme test of optical control is shown below. Figure 17 shows the beam of a close-up pinspot luminaire on a 1-mm acrylic fiber next to a penny on a green moire cloth.

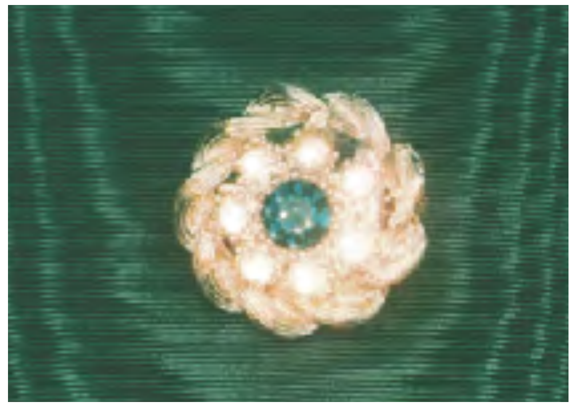


Figure 17. Control. Left - Beam of single “close-up” fiber optic luminaire shows control. Right - broach with emerald lit at 300 fc, beams lighting diamonds to 100 fc and textile lit a 3 fc (REM filtered for green). Tight beam control can allow jewelry to be exhibited with costumes instead of in separate cases**.**

The second photograph in Figure 16 shows a broach lit with three close-up pinspot luminaires while the fabric behind it is lit with a wide focus luminaire. The three tight beams overlap the center stone, lighting it to an intensity of 300 fc. The surrounding stones are outside the overlap and lit to 100 fc. No light from the broach impinges on the surrounding fabric. (For truly rare artifacts, a small piece of matching cloth could be mounted under the broach to block the tiny holes through the jewelry.) The fabric itself is lit with REM filtered light to only 3 fc. Because all of this 3 fc is reflected light, the background does not appear dark, even directly adjacent to the brightly lit broach. The experiment shows extreme control.

Each individual light beam can be color tinted. Each individual light beam can be adjusted to preclude spillover of one color light onto another color in an exhibit. In the case mentioned above, fiber optic illumination makes it relatively easy to illuminate both the George Washington coat and the hat with different filtered light matched to the color of the artifact at different footcandle levels. Each could be lit to exacting conservation specifications. And all the time, the colors would be cleared and brighter without distortion.

Application is to light objects that are historically connected like a personal journal and a presidential desk set together at different footcandle levels and with different REM filtering if it applies. Another application is to point out a specific artifact that is exhibited in a set.

Figure 18. Application. Left - Rare Judi Garland “test dress”, 1 of 1, from the *Wizard of Oz* is lit at 16 fc from chest to hem. White blouse is embrittled and lit at 3 fc. Slippers at case’s floor are lit at 18 fc. Right - Ruby Red Slippers brilliantly sparkle.

Figure 19. Application. Example of control pointing out a rare Jewish rebellion coin in a group of Biblical coins.

7.3 LIGHTING MULTI-COLORED ARTIFACTS

So far we have addressed exhibit artifacts of single colors. However, multi-colored artifacts are common exhibits. Obviously, removal of all UV and IR from the lighting is a big step towards reflected energy matching to improve the REM Factor and increase the exhibit life by 2.63 times, using bare acrylic optical fibers. That preserves the value of the collection, and saves costs in both labor and the duplication of exhibits for rotation.

However, fiber optics lighting may also be adapted to multicolored object illumination with REM filters by restricting each light color to a respective object color area. Instead of one or two conventional reflector lamps flooding an exhibit with uncontrolled light, the use of fiber optics permits as many as 32 individual fiber optic luminaires to be driven from a single lamp.

Light emitted from each individual fiber optic luminaire may be focussed to a beam an inch or two in diameter, or it may be zoomed to several feet in diameter. Any beam may be color-filtered to match different colored areas on artifacts and dimmed to the desired level in the exhibit, much like tiny versions of stage lights. Thus, very accurate reflected energy matching of different adjacent colors may be achieved to extend exhibit life many times that of conventional lighting systems. All colors may be vividly illuminated with reflected energy matching light that permits the exhibit to be displayed for centuries instead of years.

An example of this type of color-matching might be the illumination of a fragile United States Union Civil War battle flag with a tinted REM filter for the red and white field and a tinted blue for the star field. Or the simple “silkscreen” like artwork of a travel poster having a blue sky over a blue-green lake set in an emerald green meadow. Each colored area can be framed with color-matched light so there are virtually no absorbed wavelengths. The colors would be as brilliant and the exhibit life would be dramatically extended.

An experiment to test exacting control with REM filters was done on a stamp. The small scale would make the control extremely difficult. A 29¢ United States first class stamp was lit using a close-up pinspot for the blue field of the flag, a close-up spot for the red of the flag and two lightly tinted blue close-up spots for the light blue White House image filling the bottom half of the stamp.

The beams were trimmed to square the image. Figure 20 shows the beams untrimmed so the photograph obviously shows the REM filters.

Figure 20. Application. Photograph intentionally shows bleed, so REM filters can be detected on 29¢ United States first class stamp.

The lighting of a rare edition of *Sara Crewe* by Frances Hodgson Burnett with one page REM filtered for an illustration and the opposite page of text not filtered. Those viewing the original of the more famously known, *A Little Princess*, could not tell which side was lit with bare fiber optics and which side was further filtered.

7.4 LIGHTING AT MINIMUM RADIANT ENERGY LEVELS

It has been observed in both demonstrations and in actual museum installations, that conversion of typical incandescent track lighting to bare acrylic fiber optic illumination provides improved visibility at the same measured footcandle levels, or provides comparable visibility at **lower** footcandle levels. Most exhibits are made of colored artifacts. Color rendition, and hence visibility of colored artifacts, is dependent on uniformly illuminating the entire visible spectrum.

Poor color presentation is simply the result of not having light that matches the colors of an artifact. As demonstrated earlier, if you illuminate a blue or green object with red light, you see a chroma change towards gray. The problem can be colors missing in the illumination, colors greatly overrepresented in the illumination or both.

The reason fiber optic illumination can provide improved color visibility is shown in Figure 21. This illustration superimposes the visible spectral output of bare acrylic fiber optic illumination, incandescent light and the spectral reflectance curve of ISO #2 blue wool. The spectral output curves are adjusted for the same measured intensity in footcandles.

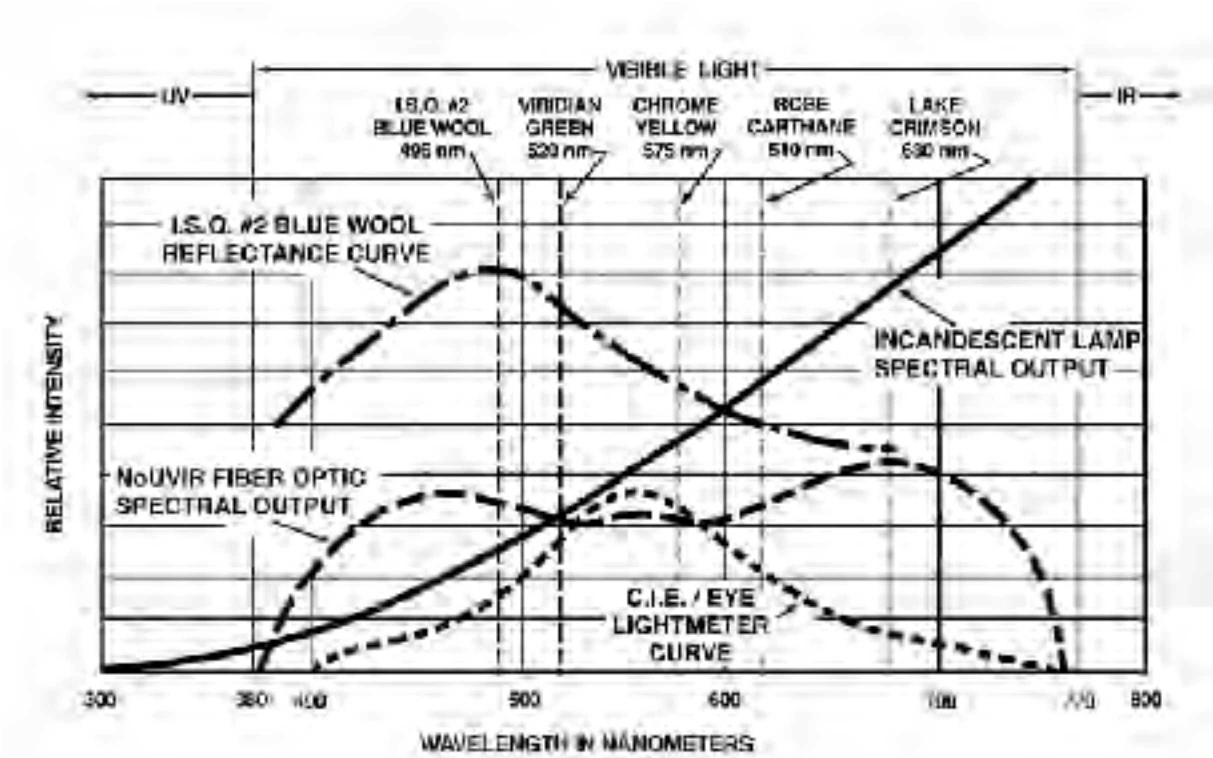


Figure 21. Spectral Output of Incandescents and Acrylic Fiber Optic Illumination compared to the Spectral Reflectivity of Blue Wool.

By comparing the relative energy at each particular frequency you can clearly see that the acrylic fiber illumination has significantly more energy in the areas matching the reflectance of the blue wool and significantly less energy in the areas absorbed by the blue wool. The lower energy in the absorbed portions of the spectrum results in longer life. The greater energy in the reflected areas of the spectrum increases visibility and presentation (the way the object looks).

A side-by-side visual comparison was made with two blue wool samples. One was illuminated at 10 footcandle by a 2900 K° incandescent light and the other illuminated at exactly the same 10 fc level with bare fiber optics (having a significantly higher blue light content). The samples were separated by a black panel, so there was no light mixing on the samples. The fiber-optics-illuminated blue wool sample looked clearly brighter and slightly bluer. This same comparison was also made with identical green samples, and as expected, the green sample illuminated by fiber optics was visibly appeared brighter and slightly greener.

The fiber optics source was then backed away from the samples to the point where both the blue and green samples appeared to be equally bright. The incandescent illumination was maintained at 10 fc. But at the point where the samples had equal visual brightness, the fiber optic illumination was only 6 fc. Of course, at that point the colors illuminated by the incandescent source were still grayed in chroma because of color mismatch in the light source, but they appeared to have approximately the same luminance (visually-observed reflected brightness).

Figure 17 clearly shows that the spectral power distribution of the incandescent lamp is asymmetrical and out of balance when compared to both the CIE curve and the fiber optic spectrum. Although all of the colors are present in each light source, the incandescent source has poor color balance. “Color balance” is a term common to photography and cinematography. It is seldom used in exhibit lighting where until recently when the choices in lighting sources has grown. Lighting with perfect color balance will have all of the colors present in equal intensity across the visible spectrum. As Figure 17 shows, fiber optic illumination has much better color balance than that of incandescent lighting. This explains the better sight (presentation) at lower footcandle levels.

Over twenty years ago, the conservator of a museum with a large oil painting gallery was installing fiber optic lighting. He discovered that paintings illuminated with the fiber optic lighting looked brighter than those illuminated with dimmed incandescents. He found that paintings lit with fiber optic illumination at 5 fc had the same apparent brightness as paintings lit at 10 fc with halogen tracklights.

Based on this anecdotal information we mounted two identical art prints side-by-side, but separated by a divider to preclude spill light from one print onto the other. Each print had a full range of colors from warm yellows to dark blues. One print was cross lighted with two 50-watt halogen tracklights adjusted to exactly 10 fc. The second print was cross illuminated to an identical 10 fc with 6 fiber optic luminaires. The print illuminated with fiber optic lighting appeared dramatically brighter than the other.

Following the conservator's lead, we reduced the fiber optic illumination to 5 fc, the level where both prints had the same apparent brightness. This balance was a little subjective because of the higher red and yellow of the incandescent lighting. Observers of several different ages viewed the side-by-side prints and consistently judged the fiber optic illumination at 5 fc to be at least as bright as the halogen lighting at twice its intensity.

This further possible reduction in lighting intensity possible with good color rendition, correct color matching and the exact intensity adjustments of fiber optic lighting add an additional factor of 1.6 (10/6) to expected exhibit life. With good color balance, the REM factors described in the tests above can be approximately doubled by subsequent reductions in intensity without any reduction in the visibility of an object.

These tests show that poor color balance or mismatched color between illumination and an object are responsible for more than just photochemical damage. Both color distortion and loss of color perception are caused by non-uniform relative spectral intensity in light sources. Sources that have strong dominant peaks or low-level gaps anywhere in the visible spectrum are incapable of showing the true colors of art works and such sources tend to diminish the visibility of exhibit artifacts.

7.5 LIGHTING TO PROTECT ONE FUGITIVE COLOR

One single pigment is sometimes very fugitive on an artifact that is otherwise reasonably light stable. An example of this is a paper document written in sepia ink, particularly when the ink is already faded. A light REM filter can be employed to tint all the light on the document in the hue of the sepia ink. This emphasizes the ink color, providing more light that is reflected off the sepia pigment.

The end result is that the ink is more visible and the paper picks up a slight tint. But the fugitive ink is protected from fading by removal of the blue end of the spectrum. The natural color accommodation of the human eye will minimize the perception of the sepia-colored light on the paper.

Another practical example are illustrated books printed in black with an additional red plate. The lighting of *the Bird's Christmas Carol* by Kate Douglas

Wiggin, 1912, was lit with fiber optic lighting, a rose REM filter and at a lower light level to match the other books in a case.

The illustrations were by Katharine R. Wireman. The book was printed in black ink with red to create the illustrations. The paper and black ink are more durable than the red ink, so the book was tinted with a light red REM filter to match the ink. Using fiber optic lighting extended life by 3 to 6 times. Lightly filtering for the red extended life by 11.8 times compared to the UV-filtered fluorescents used in the library cases. Dropping the footcandle level to balance the same illuminance visually extend the book by 18.9 times.

The original rotation schedule was to show the book to the public every 10 years for a 2 year exhibit (10 years in archives, 2 years exhibit, 12 years total). Because of the applied science of Reflected Energy Matching, the schedule changed. The math would be every 10 years for a 37 years and 10 months of exhibit (2 x 18.9). The library extended the exhibit life by such a large factor that the book could be displayed for decades with less damage compared to before the technology changes in lighting. The exhibits' contents and subject now drove what was exhibited and what was held in archives. Books, documents and other treasures returned to archives to provide variety and a change of educational content. Conservation requirements no longer demanded removal from the gallery. The improved lighting allowed the library to abandon its rotation schedules into archives.

8.0 CONCLUSIONS

Accelerated fading tests may be conducted to compare fading samples of unknown materials to samples of known fugitivity. A small sample of unknown material may be tested to establish the relative fading rate, compared to known ISO fading sample numbers, thereby predicting fugitivity for the unknown material. This is a much-needed tool for conservators, as a recent article on dye fading states... "one should strongly consider the IESNA recommendation (5 fc level) since there is[17] no known method for determining which colorants will fade until after the fact."

That statement is no longer true, since accurate predictions are now possible. The degree of color matching (or how much of the incident illumination is reflected by the surface instead of being absorbed) establishes the "REM

[17] Henderson, LaGiusa & McGowan, "Dye Fading", *Lighting Design & Applications*, May 1991.

Factor” (Reflected Energy Matching Factor) of the light source. The exhibit life of an object of known or measured fugitivity is proportional to the REM Factor of the light source which is measurable and predictable; and may be used to predict exhibit life directly, in terms of footcandle years.

The REM Factor is directly derived from ISO #2 fugitivity which would produce an average of 70% fading in 100 FcYr under solar illumination with a REM Factor of 1.00. If accelerated fading tests show an artifact to be equivalent to ISO #1, the exhibit life is divided by 2, as ISO #1 is twice as fugitive as ISO #2. If accelerated fading tests show an artifact to be equivalent to ISO #3, the exhibit life is multiplied by 2, as ISO #3 is half as fugitive as ISO #2. Each successively higher ISO number would double the exhibit life for the same degree of fading.

Accelerated fading tests on various colored fugitive dye samples show that photochemical damage is directly related to the amount of radiometric energy absorbed by a surface. Light sources with large components outside the visible spectrum cause significant photochemical damage as do sources with unbalanced and/or mismatched color outputs. Conservation lighting should be limited to evenly balanced, full visible spectrum sources with no energy outside the visible spectrum. Such lighting not only reduces fading and other photochemical damage, but greatly increases color rendition in artifacts, improving appearance and increasing visibility.

A final very simple conclusion of these tests is the ability to evaluate museum lighting sources overall effects of collections by type. Unfiltered fluorescent and incandescent sources have no conservation value. Partial filters can double life depending on their effectiveness. (Insist on full spectral data including both long and short wave UV when evaluating these products.)

Complete elimination of UV and IR decreases the risk of photochemical damage by a factor of 3 to 6. REM filtering can extend life of fugitive artifacts by 70 times. Artifact lighting should follow IESNA guidelines with zero UV and zero IR. Within the visible spectrum, artifact lighting should have constant intensity across the visible spectrum (see Figure 21) with no colors missing or overrepresented. Lastly, this balanced lighting should be filtered where possible to match the reflected energy (color) of the illuminated artifact.

Testing also shows that correct color matching of illumination increases visibility allowing a corresponding reduction in intensity. (Good lighting not only decreases absorbed energy, it increases the reflected energy required for vision.)

The ability to reduce lighting intensity without reducing visibility extends exhibit life by a factor of 1.6 over and above the calculated REM factors.

Properly designed and adjusted artifact lighting will extend exhibit life by 10 to over 100 times. Perhaps it is more important to express this in negative terms. Poor lighting will increase destruction in a collection by 10 to 100 times.

8.1 COMPARISON OF DATA AND CONCLUSIONS TO OTHER STUDIES

The data and conclusions of these tests are generally consistent with the findings of other researchers. However, it is important to note that the experimental data are contradictory to common perceptions of some museum personnel. These people have in the past tended to apply fading test data performed on certain specific materials to generalized applications in museum lighting.

The only safe generalizations are: 1) Every material fades at a different rate; 2) Identical materials can fade at different rates at the same light level (identical footcandle measurements), but under light sources having different spectral distributions; and 3) Different light sources provide different artifact visibility, even at identical measured intensities.

DAMAGE BY WAVELENGTHS SHORTER THAN REFLECTANCE PEAK
The work of Harrison indicates that the greatest damage to low-grade paper is at very short wavelengths, with damage highest at the ultraviolet wavelength of 300 nm (identified as a "Harrison Damage Factor" of 7.7) decreasing linearly to zero at 660 nm.[18] If one looks carefully at the color of low-grade and particularly old papers, it becomes apparent that such papers are not white, but have a relatively high reflectance with a Munsell Notation of YR (Yellow-Red) 8.4. This hue, described as "light yellowish pink (Caucasian complexion)"[19] has a dominant peak wavelength of just about 660 nm, precisely where Harrison indicates the damage to be reduced to zero. In this example, light at 660 nm illuminating

[18] L. S. Harrison, Report on the Deteriorating Effects of Modern Light Sources (Metropolitan Museum of Art, 1954).

[19] *Lighting Handbook of the Illuminating Engineering Society, 8th Edition*, ed. Rea, Mark S. (New York: The Illuminating Engineering Society of North America, 1993), p. 132, Fig. 4-25.

paper of 660 nm is a close Reflected Energy Factor match, which would be expected to cause nearly zero damage.

DAMAGE BY WAVELENGTHS LONGER THAN REFLECTANCE PEAK

The Harrison Damage Factor, being based on the illumination of paper, cannot be universally applied to all organic materials in museum exhibits. As a matter of fact, sometimes it is exactly the opposite end of the visible spectrum that does the damage. Quite often the most harmful aspect is the red light.

As Thomas Brill states: “Yellowing in varnishes is due to oxidation reactions activated by light... An increase in the number of unsaturated fatty acids occurs... The longer wavelengths of visible light (red) and the near infrared region seem to be responsible for the increase in the percentage of unsaturated fatty acids.”[20] Since nearly all organic varnishes tend to have a weak but visible similar yellow hue near 575 nm wavelength, it is mismatched by both the deep, visible red as well as infrared radiation.

Brill continues: “Infrared radiation causes considerable damage to materials made of wood, ivory, paper, parchment, leather and textiles. The most serious effects result from moisture loss as manifested in warping, cracking and peeling. Color changes can occur in varnish and ivory. Incandescent lamps are an important source of infrared radiation in a museum. Spotlighting of particular objects is a practice that needs careful control. The temperature rise of an object’s surface as a result of incandescent illumination can and should be measured if there is a chance that heating may occur." [21]

It should be noted that the air temperature indicated by commonly-used museum thermometers or thermographs does not indicate the surface temperature of the artifacts in display cases or paintings on walls. In addition to photochemical damage, IR-driven cycles in temperature create a number of photomechanical dangers ranging from physical stresses to increased contamination by pollutants. This photomechanical damage is outside the scope of this research. [22]

---

[20] Thomas B. Brill, pp. 188-191

[21] Thomas B. Brill, pp. 188-191

[22] *Protecting Museum Exhibits From Their Environments (and Vice Versa)* by Matthew S. Miller is an excellent treatment of the photomechanical dangers of light, heat, humidity, pollution and infestation. This 153 page book is available from NoUVIR Research.

9.0 A FINAL WORD

It is imperative that conservation personnel understand the physics of light and matter as well as the processes of fading and photochemical damage. The Second Law of Thermodynamics says simply that things tend to break down in time. This is true. It is unavoidable. We must plan for it. But it is also energy-driven. Light absorption accelerates the break-down. In a collection, we can delay the operation of the Second Law of Thermodynamics by reducing and controlling the energy impacting art and artifacts.

While a curator or conservator may pull artifacts off exhibit as soon as fading is detected, the tragedy is that this is only after damage has occurred. Since darkness does not reverse the Second Law of Thermodynamics, sick artifacts do not get well in the archives. If the artifact is later returned to exhibit, it will start out just as faded as when it was put into the archives. Fading will then resume, based on the fading characteristics and light level of the light source used for its illumination. An effective conservator must understand and be able to calculate possible damage before it occurs.

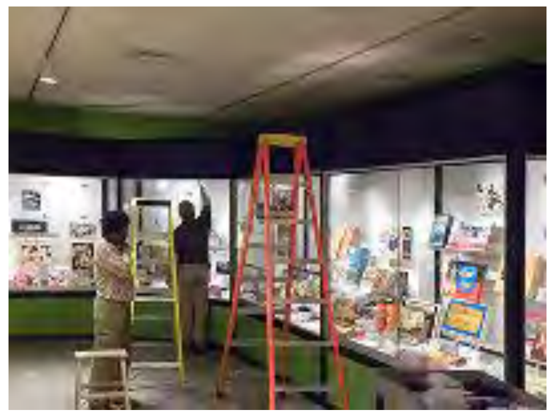
There has also been a tremendous amount of junk science done in the area of lighting. On top of this, marketing has gotten involved and the field is full of unsubstantiated or just flat untrue claims. One that comes to mind is the often-made claim that glass fiber will not transmit infrared. The facts are that glass fiber was specifically designed to transmit data from IR lasers centered around 1400 nm, far into the infrared. A check of the transmission spectrum of glass fiber will show only a 3% reduction in transmission characteristics at 2000 nm.

An electric skillet peaks about 3000 nm. These kinds of claims succeed because no one has taught museum professionals and conservationists to understand the processes and the data available.

Conservation science has for the most part been reactive. We have developed many of our conservation techniques as a result of failures. After damage occurs we learn not to do whatever we did to create the damage.

NoUVIR Lighting is committed to proactive rather than reactive science. It is our mission to save art and artifacts, before damage occurs. We are accomplishing this through research, education, seminars, published papers and books like this one and through an innovative and patented line of lighting and micro-climate products designed specifically for the museum market.

We encourage you to contact NoUVIR Lighting if we can help you further this goal of preserving our art and historical heritage. We are available to answer questions, provide detailed information on light sources, matter, photochemical damage, temperature, humidity, pollution, infestation and micro-climate control systems. Please contact NoUVIR.



Printed in the United States of America.
Unattributed photographs and diagrams are by the authors.