# New Evaluation Method for the Lightfastness of Colored Papers by Radiant Energy

THIS PAPER WAS PRESENTED AT
THE 1999 IESNA ANNUAL CONFERENCE

*Hoon Kim (1), Hong-Bum Kim (2)*

***Authors' affiliation: (1) Division of Electrical and Electronic Engineering, Kangwon National University, Korea, (2) The Corps of National Museum Construction Project, Korea***

## Introduction

The recommended illumination levels for the display lighting of museums and art galleries are based on a compromise between artifacts' conservation needs and visitors' needs for good viewing conditions. While these two needs are contrary to each other, both of them are to be satisfied. But the original idea of balancing the amount of light needed for looking at exhibits against the damage which it causes[1] was changed, and they have been transformed into absolute figures. Most people involved in museum affairs misunderstand it as a safe-deposit box. Fortunately, the aim of museum display lighting has been newly defined as satisfying visitors with the least possible amount of optical radiation energy being absorbed by the displayed object.[2] In case of highly sensitive materials, the illuminance of 50[lx] is reviewed as being too dim for visitors whose vision has deteriorated due to age.[3] The Montreal Museum of Fine Arts raised this illuminance to 75[lx] accepting this review.[4]

The categories of photochemical stability are based on the BS1006.[5] The exposure limits have their origins in the lx-hours which cause just perceptible color change. However as 'Harrison's probable relative damage factor'[6] is not the representative activation spectrum covering all the museum objects, they are not fixed figures to be applied equally to whole artifacts classified in a certain category. The color change of the natural organic dyes on textiles had been measured by the method suggested by CIE, and found that the lightfastness of a good many samples is ISO class 1 or below.[7] Moreover each of them had a different activation spectrum.

According to the IESNA classification of museum objects for susceptibility, roughly speaking, all of the colored objects except oil paintings or textiles with stable dyes are highly susceptible.[8] But each of them has its inherent exposure limit. Lightfastness ratings of colored materials are given for a typical middle shade. Tints and thin glazes of a given pigment are 1 to 2 ISO levels more sensitive, while heavy colors may be more durable.[9]

Artifacts should be maintained in the best possible condition. The surface is the very essence of colored objects. Particularly the color change of Korean paintings is the loss of value as museum collections, and once lost, it is almost never to be recovered. Accurate evaluation of the artifacts' sensitivity to light is, especially in case of highly susceptible materials, obviously of critical importance. If lightfastness is underestimated, the flexibility and the possibility to be open to public is restricted within narrow limits. In case of extremely sensitive artworks, overestimation brings about unexpected photochemical damage.

In this paper, a new method of evaluating the lightfastness of colored objects is proposed. Under the assumption that density of a dye or pigment reduces by the absorption of radiant energy and density change induces color change, a model and equations that relates color change and radiant energy is developed. The factors in the equation was established and verified by experiments.

## Model for Color Changing

To make an equation that predicts the color change of a sample, it is assumed that a material C, which is originally on the surface of the sample, is transformed into material D by the effect of the radiation

energy. Area $A_C$[$m^2$], which is the area of material C on the surface, is same to the sample's total surface area at first and becomes smaller as radiation is applied. Area $A_D$[$m^2$] of the material D, is same to the total surface area at final stage of the color change.

If radiation energy of which the center wavelength is $\lambda_1$[nm] in relatively narrow wavelength range is applied on the sample, the time change of $A_C$ is as follows.[10]

$$\frac{dA_C}{dt} = -a_1 P_1 A_C \tag{1}$$

where $\alpha_1$ = factor for material transformation(damaging factor)[$m^2$/W·hour] and $P_1$ = radiation power density [W/$m^2$]. The equation was for the density of the materials originally, and it is transformed into the equation for surface area because radiation energy affects the outer layer of artifacts.[11]

Solving equation (1), the area $A_C$ at time t[hour] is,

$$A_C(t) = A_C(0)\, e^{-a_1 P_1 t} \tag{2}$$

,where $A_C(0)$ is $A_C$ at t=0 (same to the total surface area). If radiation of rather wide wavelength range is applied on the sample, it can be divided into several continuous narrow range radiation energy each of which above equation is applicable to. So the above equations can be written as follows:

$$\frac{dA_C(t)}{dt} = (-a_1 P_1 - a_2 P_2 - \cdots - a_N P_N) \cdot A_C \tag{3}$$

$$A_C(t) = A_C(0)\, e^{-(a_1 P_1 + a_2 P_2 + \cdots + a_n P_n)t} \tag{4}$$

And area $A_D$ at time t is

$$A_D(t) = A_C(0) - A_C(t) \tag{5}$$

To relate the area changes of the materials with the color change, the reflection coefficient $\rho_T(\lambda, t)$ of the sample at time t is calculated as:

$$r_T(l, t) = \frac{A_C(t)\, r_C(l) + A_D(t)\, r_D(l)}{A_C(0)} \tag{6}$$

where $\rho_C(\lambda)$ and $\rho_D(\lambda)$ are the reflection coefficients of the material C and D. Calculating color coordinates of $L^*_T$, $a^*_T$, and $b^*_T$ of the sample in CIELAB color space from $\rho_T(\lambda, t)$, these coordinates can be represented as follows because the equations for the calculation are linear and homogeneous.

$$L_T^*(t) = \frac{A_C(t)\ L_C^* + A_D(t)\ L_D^*}{A_C(0)} \tag{7}$$

$$a_T^*(t) = \frac{A_C(t)\ a_C^* + A_D(t)\ a_D^*}{A_C(0)} \tag{8}$$

$$b_T^*(t) = \frac{A_C(t)\ b_C^* + A_D(t)\ b_D^*}{A_C(0)} \tag{9}$$

where $L^*_C$, $a^*_C$, and $b^*_C$ are color coordinates of material C, and $L^*_D$, $a^*_D$, and $b^*_D$ are color coordinates of material D in CIELAB color space.

The difference of the L* of the sample at time t as defined in equation (7), from its original value is

$$L_T^*(t) - L_T^*(0) = \frac{A_C(t)\ L_C^* + A_D(t)\ L_D^*}{A_C(0)} - L_C^*$$

$$= \frac{(A_C(t) - A_C(0)) \cdot L_C^* + A_D(t)\ L_D^*}{A_C(0)} \tag{10}$$

, because the color of the sample is same to the color of material C at t=0.

Using equations (4) and (5), equation (10) is reduced to:

$$L_T^*(t) - L_T^*(0) = (1 - e^{-(a_1 P_1 + a_2 P_2 + \cdots + a_n P_n)t}) \cdot (L_D^* - L_C^*) \tag{11}$$

And the differences between the a* and b* can be expressed in the same way.

So the color difference $\Delta E^*_{ab}$ at time t is

$$\Delta E_{ab}^*(t) = \Delta E_{ab,CD}^* (1 - e^{-(a_1 P_1 + a_2 P_2 + \cdots + a_n P_n)t}) \tag{12}$$

where $\Delta E^*_{ab,CD}$ is the color difference between material C and D.

If color changes of the samples due to radiation energy of narrow wavelength range are measured, the values of damaging factor $\alpha$ can be calculated using the above equations.

## Apparatus and Experiment

The experimental apparatus, which was originally suggested by Aydinli, et al.[12] was made as in **Figure 1** to induce the color changes of the samples. A Xenon lamp, which emits continuous radiation in UV and visible region, is at the center of the apparatus and samples are hung on the wall beneath high-pass cut-off filters.

The set of fourteen filters used have their cut-off wavelengths at 265, 309, 338, 366, 400, 435, 455, 495, 530, 570, 610, 665, 725, and 780[nm] respectively. **Figure 2** shows the relative spectral power distributions of the Xenon lamp and radiation through filters. If two filters have their cut-off wavelengths at $\lambda_1$ and $\lambda_2$ ($\lambda_1 < \lambda_2$) respectively, the color difference between two sample spots beneath those filters are caused by the radiation energy difference between $\lambda_1$ and $\lambda_2$.

**Figure 1—The arrangements of the irradiating apparatus.**

**Figure 2 —The relative spectral power distributions of the radiation from the Xenon lamp through the filters.**

Direct irradiation on the sample without filter changes the color most rapidly, and its saturated value of color difference can be estimated as the value of $\Delta E^*_{ab,CD}$. Infrared radiation energy through the filter with cut-off wavelength of 780[nm], is assumed as single radiation power density $P_{14}$. Using measured color change under that filter and equation (12), value of $\alpha_{14}$ can be obtained. Radiation power density through the 725[nm] filter is the sum of $P_{13}$ and $P_{14}$, and value of $\alpha_{13}$ is obtained from measured color change under that filter, and all other values of $\alpha$ can be obtained by the same method.

Samples for the experiment are white pulp paper, three colored papers (red, green, and blue), and Korean paper dyed with gardenia nuts. White pulp paper is the kind that is used for copy machines. The three colored papers were selected to investigate the relationship between $\alpha$ and the absorption coefficients in the visible region. Gardenia nuts have been used as yellow dye in Korea and the light yellow color changes very fast into dark yellow by radiation.

The samples with the set of filters were exposed for three weeks, and the colors of the samples were measured for each spot beneath the filters using a Minolta Spectrophotometer CM-2002 before exposure and periodically during the experiment. The plots of color changes as function of lx-hours for some samples are shown in **Figure 3**.

**(a)**

**(b)**

**(c)**

**Figure 3 —The color change of the samples. (a) White pulp paper (b) Red paper (c) Korean paper. (Color changes beneath the filters with longer cut-off wavelength than 495[nm] are omitted to simplify the graph.)**

## Analysis and Proving Experiment

The values of damaging factor $\alpha$ for the samples appear in **Figure 4**. The damaging factor is very large in the UV region, and becomes smaller as the wavelength increases. It does not show an exponential decrease as Harrison's relative damage factor, and shows relatively irregular change especially in the visible range. This result suggests that damage due to the certain wavelength radiation energy would be dependent on the absorption of the radiation by the sample.

**Figure 4—The damaging factors of the samples as function of wavelength.**

The absorption coefficient and the damaging factor in the visible range were investigated for colored papers and is shown in **Figure 5**. For the red paper, the damaging factor is almost in proportion to the absorption coefficient. It shows reducing responsivity for increasing wavelength. The green paper is less affected by the wavelengths between 590 and 630nm, and the damaging factor in subsequent longer wavelength is a little higher than that of those wavelengths. The blue paper is less affected by the wavelengths between 450 and 490nm, and the damaging factor and absorption coefficient are closely correlated.

**(a)**

**(b)**

**(c)**

**Figure 5 —The absorption coefficient and the damaging factor in the visible wavelength range. (a) Red paper (b) Green paper (c) Blue paper.**

Each of the colored papers shows the lowest responsivities at the wavelengths at which spectral absorption coefficients are the smallest while damaging factor was shifted a little to long wavelength. Through the whole visible spectrum, it can be inferred that the damaging factor at a certain wavelength is influenced not only by the energy of a photon but by the spectral absorption coefficient. To investigate this relationship thoroughly, more detailed experiment of color changing by visible radiation with more set of filters is needed.

**(a)**

**(b)**

**(c)**

**(d)**

**(e)**

**Figure 6—The measured and calculated color changes of the samples.**
**(a) White pulp paper (b) Red paper (c) Green paper**
**(d) Blue paper (e) Korean paper dyed with gardenia nuts**

To confirm the effectiveness of the suggested model, a practical experiment was carried out. Samples were irradiated by a common light source, and the measured color change was compared with the calculated value using equation (12). A daylight fluorescent lamp was selected because of its stable light output and commonness in Korea, and an illuminance of 1,000[lx] was applied for 2 weeks.

Measured and calculated color changes as function of lx-hours for each sample were compared in **Figure 6**. Two color changes coincide with each other very well except Korean paper dyed with gardenia nuts. For the Korean paper, calculated values are smaller because of underestimated damaging factor. This sample has problems in factor estimation because of very fast color change in UV region, and needs more study by the exposure of very low illumination level.

The watercolors on paper are more sensitive than oils or tempera, and less responsive dyes fade at constant rate over time.[13] It is expected that above model could be applied to oil paintings and other materials which are moderately sensitive.

## Conclusion

There have been no methods to predict the color change caused by display lighting. To some extent well-disciplined conservation scientists will be able to classify artworks into appropriate lightfastness levels, but precise estimation is no easy matter. This proposed method for estimating color change is useful for museum's twin mandates of artwork conservation and exhibition. The effectiveness of the equation and the method are confirmed.

Special regard will be paid to the fact that in case of highly susceptible materials there will be a need to develop a more functional and practical policy to preserve museum objects. Illumination level tends to rise due to the normal visual changes that occur with aging, and the number of requests to use the collections in loan exhibitions and touring exhibitions is on the increase now. Museum professionals have to accommodate these inevitable requests with a consistent policy.

And it was found that there is a close relationship between the spectral damaging factors and the spectral absorption coefficients of the color samples in visible wavelength range.

## References


1. Thomson, G. 1986. *The Museum Environment*. London: Butterworth. p. 22.

2. Cuttle, C. 1996. Damage to museum objects due to light exposure. *Lighting Research and Technology* 28(No. 1): 1-9.

3. Michalski, S. 1990. Toward specific lighting guidelines. *ICOM Committee for Conservation, Lighting and Climate Control* (Vol.2): 583-589.

4. Colby, K.M. 1996. A suggested exhibition: Exposure policy for works of arts on paper. *http://www.webcom.com/lightsrc/policy*.

5. Feller, R.L. 1975. Studies on photochemical deterioration. *ICOM Committee for Conservation*. Venice. 4-6

6. Harrison, L.S. 1954. Report on the deteriorating effects of modern light sources. *Metropolitan Museum of Arts*.

7. Kim, Hoon. Kim, Hong-Bum. 1996. A study on the measurements of the museum exhibit's color change by lighting. *Journal of the Korean Institute of Illuminating and Electrical Installation Engineers* 10(No. 5): 43-51

8. IESNA. 1996. *Museum and art gallery lighting: A recommended practice RP-30*. p.14

9. Michalski, S. 1990. Time's effects on paintings. *Proc. of a seminar for curators and conservators*. 39-53

10. Feller, R. 1994. *Accelerated Aging*. The Getty Conservation Institute. p.25

11. Michalski, S. 1987. Damage to Museum objects by visible radiation(light) and ultraviolet radiation(uv). *Lighting in Museum Galleries and Historic Houses*. Bristol Seminar, Museum Association. London. 3-16

12. Aydinli, S. *et.al*. 1991. On the deterioration of exhibited museum object by optical radiation. *CIE Publication 89/3* Wein. 25-36

13. Crews, P. C., 1987, A comparison of clear versus yellow ultraviolet filters in reducing fading of selected dyes. *Studies in Conservation*. 33. 87-93


## Discussions

Future research must ask if the absorption in the visible wavelengths by the principal compound responsible for the color invariably leads to the excitation of that colorant molecule which in turn leads to its oxidation or reduction. Might there not be a significant number of cases in which some other component of the system absorbs wavelengths in the radiant flux and thereby is able to initiate processes that ultimately result in the decomposition of the colorant compound? Perhaps highly durable colorant systems may fade by a different mechanism than the fugitive types involved here.

The authors' data in their **Figure 4** do suggest that the ultraviolet may be responsible for a different mechanism of fading. They state that their damaging factor does not follow the exponential behavior of Harrison. Nonetheless, the accompanying replot of their data indicates that at least two of their findings indeed resemble the relationship of Harrison's damage factor, $D_\lambda$, versus wavelength. Moreover, it seems clear that there is an as yet unidentified component that must be associated with the peak response at 350 nm.

Rather than postulating color change in the sense of area as is done here, a number of workers have been investigating fading in terms of the concentration of colorant using instrumental color-matching techniques (Feller, Johnston-Feller and Bailie, 1986, J. Am. Institute for Conservation, 25: 114-129). Moreover, Whitmore and Bailie (1997, J. Am. Institute for Conservation, 36: 207-230) have recently pointed out that, dependent upon concentration, fading may proceed linearly with time rather than decreasing by first-order decay as in the underlying equations used here and by others. These workers have also shown that it is possible to predict the course of fading with considerable precision.

**Figure A1**


*Robert L. Feller*
*Carnegie Mellon Research Institute*

The paper *New evaluation method for the lightfastness of colored papers by radiant energy* by Hoon Kim and Hong-Bum Kim delves once more into the eternal discussion of light-induced damage. The basic medicine we are not willing to accept is that exposing artifacts to light will damage them. Conversely, not exposing artifacts to light will inherently reduce public awareness.

The application of the paper's results intrigues me. I challenge the authors to apply the paper to an exhibition, analyzing the artifacts to be displayed and proposing a lighting design based on the analysis. For example, analyze an impressionist art exhibition that has paintings with many different colors in the same painting and many different types of paper. How can the results and conclusions of the authors be utilized by the average museum?

Finally, I would ask the authors to give further explanation in the use of the xenon lamp for the experiment. Have the authors found this lamp to be used extensively in museums? If not, what lamp is more predominant in the museum? Utilizing the lamp more commonly found in museums, how would the results of the authors' experiment be altered?

*Frank A. Florentine, LC*
*National Air and Space Museum*

I congratulate the authors on their efforts to help preserve precious works of art. In principle this is a sound paper to establish the amount of fading at different wavelengths of incident radiation. The only weak point in the authors' model is the simplification to two states of the pigment – original and bleached. It might be possible that more than one product is formed as a function of the wavelength of incident radiation which would not fit in their calculation scheme.

Practically the method is sound and can be used to check the characteristics of a certain pigment of a specific item. Then from the derived action spectra, damage and color shift due to illumination can be calculated as functions of spectrum, time and intensity. It would however be of more practical value to classify objects and give typical action spectra.

*Dr. Johan van Kemenade*
*Philips Lighting*

Subject paper is a welcome addition to the literature on light damage to museum artifacts. The test apparatus used, similar to that of Sirri Aydinli and Gunther Hilbert of Berlin, is again producing verifiable results. The equations derived and confirmed will be useful, particularly with regard to the kinds of artifacts studied.

The authors could not have known that this very area was under intense discussion within CIE TC3.22, charged with producing an international Museum Lighting Design Guide. At the recent (30 June) meeting in Warsaw, Aydinli forcefully presented both his original work and some recent analyses of earlier work to support his strong contention that there should be a spectral weighting factor within the visible band of 400 – 700 nm in assessing damage potential from radiant energies. The committee had already determined that all radiations outside this band should be excluded, as far as possible.

The Task Committee rejected this approach since it decided that: (1) most displayed materials have more than one colorant and, as the authors correctly point out, different colorants have different spectral responses; (2) it would be extremely difficult for the ordinary museum to apply such standards.

Nonetheless, a museum that knows, in detail, the nature of the displayed material and the exact spectral character of the illuminants would be well advised to be guided by the researches of Kim and Kim, as well as those of Aydinli and Hilbert.

As to the requirements of older viewers, while this reviewer agrees, it is still his experience that, with careful adaptation, objects can be seen and appreciated under as little as 35 lux. This was accomplished at the Smithsonian's National Museum of American History for the display of the First Ladies' Gowns.

*Edwin Robinson, FIES*

The authors develop a model that relates color change and the absorption of radiant energy. The model intuitively makes sense and appears to be verified experimentally – specifically for the case of selected colored papers. The implications for museum lighting design, however, are not clear. How do the authors propose to apply this model to the broad range of materials and dyes found in museum artifacts – often in a single item?

*Mary Beth Gotti*
*GE Lighting*

## Author's response

The authors express their great thanks to the reviewers for their elaborate comments covering a wide scope from the logical appropriateness of the postulation to the general application in the actual display lighting design. Their comments were very helpful for providing additional clarity.

***To Robert L. Feller and Dr. Johan van Kemenade***

This paper focuses originally on the evaluation of the lightfastness of highly susceptible materials. There may be a number of cases in which other components can initiate photochemical reaction such as a photosensitising effect, as this reviewer has pointed out. But in case of highly sensitive materials, the authors think that color change is caused by the principal colorant responsible for the color.

***To Robert L. Feller***

Damaging factor has different characteristic from the Harrison's relative damage factor. From the log scaled graph of damaging factor against the wavelength in UV range (**Figure A2**), large deviations from linear dependency of Harrison's factor is found. And there are some dips and peaks in the graph. From this result, the author supposed that the damaging factor at certain wavelength would be a function of the absorption coefficient and photon energy at that wavelength. Shape of the damaging factor, including the dips and peaks, depends on the multiplication of the absorption and photon energy. Especially in the visible range, where the photon energy is relatively small, the dependence of the damaging factor on absorption coefficient is strengthened.

**Figure A2—The log plot of the damaging factors in UV range**

Upon the postulation about the change of the materials area, it is assumed that the colorant at the outmost surface is responsible for the color change of the highly susceptible sample. Under this assumption, the equation about the concentration change is reduced to the equation about the area change.

***To Frank A. Florentine, Edwin Robinson, and Mary Beth Gotti***

There are three categories on the types of museum materials. The categories of moderate and the least susceptible materials select the lowest ISO value, ISO levels 4 and 7 respectively, as their exposure limits. But the category of the most susceptible materials selects ISO level 2 as its exposure limit, so it does not cover the materials of ISO level 1. The authors think that it is necessary to consider artifacts that are suspected of containing colorants of ISO level 1 or lower as exceptions and to evaluate their lightfastness on a case by case basis.

The purpose of our study is not to talk a desk theory, but to find a solution that satisfies both of the conflicting requirements of display and conservation. The authors think that their model and method can be applied to the traditional Korean paintings with some different colors. There are some colored parts on a white paper in a traditional Korean painting. And the color has a curatorial significance. Therefore, the lightfastness of a painting must depend upon that of the most sensitive color in the painting.

Calculation of lx-hrs for just perceptible color change ($\Delta E^*_{ab}$=1) is possible using damaging factors of each samples. **Table A1** shows the calculated lx-hrs for light sources of which the relative spectral power distribution were given.[1)]

**Table A1–Calculated lx-hrs for various light sources.**

| | I/L (2.854K) | Halogen Lamp (H/L) | H/L through glass | Philips F/L (CRI 84) | Overcast sky | Overcast sky through glass | Sun + sky | Sun+sky through glass | Metal Halide Lamp |
|---|---|---|---|---|---|---|---|---|---|
| White pulp paper | 146,000 | 14,700 | 118,000 | 86,300 | 16,300 | 35,000 | 26,700 | 53,400 | 7,560 |
| Red paper | 148,000 | 13,700 | 126,000 | 105,000 | 29,600 | 53,000 | 44,600 | 72,200 | 14,500 |
| Green paper | 426,000 | 49,000 | 359,000 | 291,000 | 107,000 | 166,000 | 151,000 | 211,000 | 48,300 |
| Blue paper | 9,710 | 4,500 | 10,700 | 12,700 | 3,370 | 6,630 | 4,920 | 8,450 | 1,940 |
| Korean paper+Gardenia nuts | 17,500 | 3,060 | 12,100 | 9,810 | 2,130 | 3,660 | 3,380 | 5,480 | 1,180 |

1) Thomson, G. 1986. *The Museum Environment*. London: Butterworth. p. 168.

***To Frank Florentine***

A Xenon lamp was used to change the color of the samples by continuous wavelength in UV and visible range and to obtain the damaging factor. With the damaging factor, the color change of the material by any light source can be anticipated. The Xenon lamp is not a common light source for display lighting.