

EFFECTS OF FILTERED AND UNFILTERED INCANDESCENT,
FLUORESCENT, AND QUARTZ LIGHTING SYSTEMS
ON COTTON DYED WITH NATURAL DYES

by

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B.S., North Texas State University, 1975

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Clothing, Textiles, and Interior Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas
1979

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ACKNOWLEDGMENTS

I express sincere gratitude and appreciation to the following, without whom this research project would not have been possible:

Dr. Barbara Reagan, my major professor, for her guidance in this research and consistent interest in my program of study.

Dr. Margaret Ordonez, for her interest throughout my graduate program and suggestions for this study.

Dr. Robert Taylor and Mr. Ludwig Villasi, my committee members, for their interest and helpful suggestions for this research project.

Dr. Arlin Feyerherm and Jeff Rayenkamp, for their assistance with the statistical analysis of data.

Ms. Zoe Annis for her interest and encouragement in all areas of my graduate program and research.

Mrs. Joan McCabe Moore for typing this thesis.

My family, Bob Bowman, Lt. Col. (Ret.) Billy Gilliland, and Mrs. Hildreth Gilliland, for their consistent and indispensable support and faith in my achievements.

J. G. B.

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INTRODUCTION

A primary function of museums is to preserve and exhibit objects having historical or archaeological significance, such as historic textiles and costumes. Museum display techniques should be judiciously chosen to maximize the benefits obtained from display without causing unnecessarily adverse effects (44).

Light is indispensable for displaying objects, but it also can be a potential environmental hazard since radiant energy may induce reactions that result in the deterioration and/or color change of historic artifacts. Textiles often are damaged during display when the radiation emitted by the light source is rich in ultraviolet and high-energy, visible regions of the electromagnetic spectrum and these regions are absorbed by the object (24, 34, 179, 194). In museums and art galleries, it is essential to control the spectral distribution of lighting systems and to select display techniques which will not accelerate textile deterioration needlessly (172).

All wavelengths of electromagnetic radiation emitted by museum light sources have been shown to contribute to fading and photodegradation, including ultraviolet, visible, and infrared (50, 73, 99, 193). Though the spectral distribution of the radiant energy upon objects affects fading and deterioration, total incident radiant energy, expressed by the reciprocity principle (light intensity multiplied times exposure

time) is recognized as the major factor which determines the extent and rate of fading and degradation of artifacts. According to a 1976 Canadian Museum's survey, however, only 25 percent of the museums surveyed were aware of lighting levels being used in their textile exhibition areas, and only 12 percent maintained illumination at acceptably low values. This suggests insufficient concern in museums today for the potential hazards of lighting and display techniques on fragile artifacts (141, 158).

Light is not an isolated factor, but part of the total museum environment. Environmental factors, including temperature, relative humidity, atmospheric composition, and physical state of dye and substrate, have been investigated and found to affect degradation and fading in varying amounts. Suggestions for controlling radiant energy and environmental factors that accelerate degradation have been made to aid museums in selecting optimal display techniques for aged and fragile artifacts (72, 73, 101, 117, 118, 192). As an example, a maximum illumination level of about 50 lux has been established as acceptable for adequate visibility with minimal deterioration (51, 96, 151, 156).

The Illuminating Engineering Society's 1966 Lighting Handbook (24) thoroughly explains theories of light physics, color and vision, radiant energy measurement and technology, and the design of lighting systems. IES Report 14 (132) applies these principles to museum lighting and display techniques. Research in museum lighting has explored the effects of emission spectra of natural and artificial light sources on fading, deterioration, and color rendering of textiles and other artifacts. Specific lighting sources investigated include daylight,

incandescent, fluorescent, and quartz (83, 120, 141, 172). Research utilizing ultraviolet- and infrared-filtered quartz lamps as a possible museum lighting source is scarce, even though they possess such attractive characteristics as superior color reducing properties, good energy conservation characteristics, and small lamp size for high light output (34).

This research compared the effects of six lamp and filter systems on the lightfastness of natural dyes and chemical properties of the cotton substrate. The six systems investigated were: incandescent lighting with and without an infrared filter, fluorescent lighting with and without an ultraviolet filter, and quartz lighting with and without infrared and ultraviolet filters. Cotton samples were evaluated for color change by visible spectrophotometry and the presence of cellulose deterioration products were evaluated by the copper number test.

REVIEW OF LITERATURE

Radiant Energy

Electromagnetic Spectrum

Radiant or electromagnetic energy is produced when excited electrons revert to stable positions within their atoms, releasing energy (24). Electromagnetic energy emitted by artificial and natural light sources varies in intensity and spectral distribution, both of which influence the color of the lighting source and its ability to degrade organic textiles and other objects. The spectral distribution of a light source may range from ultraviolet to infrared radiation (10, 24, 28, 99, 151).

Early attempts to explain the nature of radiant energy included the Corpuscular Theory, advocated by Newton, which postulated that energy particles were ejected intermittently from luminous bodies and transmitted to the retina of the eye, resulting in the sensation of light. Huygen's Wave Theory stated that light resulted from molecular vibration in luminous material and these vibrations were transmitted as wavelike movements to stimulate the optic nerves of the eye. Maxwell's Electromagnetic Theory suggested that radiant energy was propagated through space in the form of waves. The modern Quantum Theory, similar to the Corpuscular Theory, is based on the premises that energy is

emitted and absorbed in particles or quanta which, in the case of radiant energy, are called photons. The Unified Theory, proposed by DeBroglie and Heisenberg, combines ideas of both the Electromagnetic and Quantum Theories and these three theories now form the basis of current ideas on the physics of light (13, 24, 50).

The electromagnetic spectrum (Figure 1) represents all forms of radiant energy plotted as a function of wavelength (the distance from wave crest to crest). Every moving element of mass has an associated wavelength, the length expressed by:

$$\lambda = h/mv$$

where: λ = wavelength of wave motion
 h = Planck's constant (6.62×10^{-27} ergs/sec.)
 m = mass of the particle
 v = velocity of the particle.

Wavelength and frequency (the number of wave crests passing a point in one second) are two characteristics which distinguish one type of electromagnetic radiation from another, and indicate chemical and optical properties and utility of the radiation (13, 24, 25, 151, 179). Frequency is inversely proportional to wavelength. Waves with higher frequency, and thus shorter wavelength, contain photons of greater energy than lower frequency, longer wavelengths. Gamma and cosmic rays have the shortest wavelengths which are measured in million millionths of a meter; whereas, low energy radio and television waves are measured in hundreds of meters (101, 154, 179). The relationship between wavelength, frequency, and velocity of wave motion is expressed by the formula:

$$c = f\lambda$$

where: c = velocity of light (3×10^{10} cm. per second in free space, or 186,000 mi. per sec.)

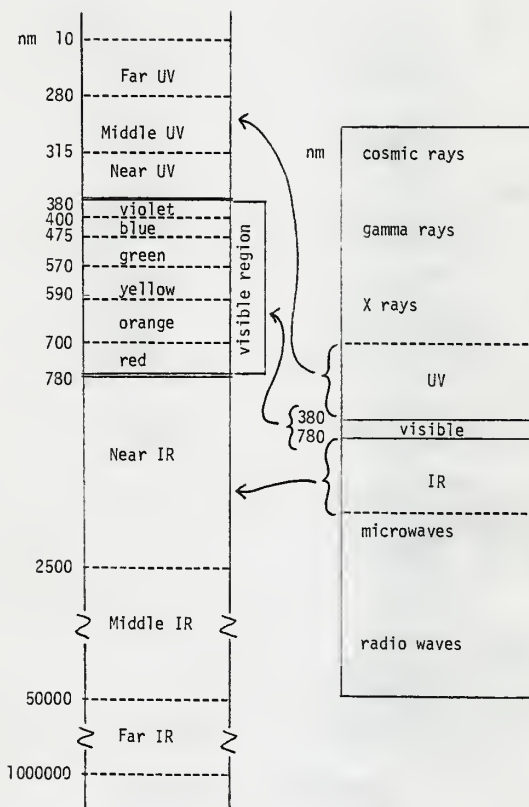


Figure 1

Electromagnetic Spectrum (10, 22, 25, 50).

f = frequency of radiation in vibrations per sec.
 λ = wavelength in cm. (13, 25, 151).

Changes in wavelength are accompanied by changes in radiant properties.

As shown by the following formula, the amount of energy per photon varies in direct proportion with wavelength (13):

$$E = hf = hc/\lambda$$

where: E = energy of a single quantum (photon) in ergs
 h = Planck's constant
 c = velocity of light
 f = frequency of radiation
 λ = wavelength of radiation in cm. (13, 25, 34, 101, 151).

Visible light comprises only a small portion of the electromagnetic spectrum. White light is the basis of all colors of the spectrum, and these colors may be obtained by the suppression or adsorption of one or more parts of white light. The visible spectrum contains as many as 200 full-intensity colors in its progression through violet, blue, green, yellow, orange, and red (22, 85, 146, 154). The exact points at which the eye becomes sensitive to radiant energy varies slightly with each individual, but the limits established by the International Commission on Illumination (CIE) are 380 to 780 nanometers (nm). The nanometer ($1 \text{ nm} = 10^{-9}\text{m}$ or 10 \AA) is an international wavelength measurement adopted by the International System of Units (SI) (10, 25, 59).

Color and Vision

All matter lacks color and is not directly visible. The three phases and major disciplines of color vision are: 1) the spectral nature and intensity of the light emitted by the light source and how it is reflected from, transmitted through, or emitted from the object or light source to the eye, as explained by the science of physics, 2) the

response of the eye to the light and transmittance of signals to the brain, as explained by physiology, and 3) the mental image of apparent color perceived by the individual, as explained by psychology (23, 64, 95, 114, 189). The combination of these sciences in relation to color vision is called psychophysics (i.e., the study of the physical nature of the light and the repeatable and measurable effects produced) (95).

Color results from visible radiation being either reflected from an opaque object, transmitted through a transparent object, or emitted from a light source (23, 157). Light, and thus color, as it reaches the eyes of two people viewing the same object from the same position at the same time, are identical and have the following three attributes which are necessary for its physical description: hue or color name, brightness or lightness, and saturation or intensity. These three characteristics are governed by the amount of light of each wavelength in the electromagnetic spectrum falling on the object, and the proportion of each wavelength reflected or transmitted to the eye (24, 59, 71, 95, 149). The physical and molecular properties of the object determine which wavelengths are absorbed and which are reflected or transmitted through the object (27, 41, 84). The light adsorption characteristics of many objects such as textiles often are modified by the addition of dyes or pigments which selectively adsorb various portions of incident light.

The photoreceptors in the eye (i.e., rods and cones) generate nerve impulses by photochemical mechanisms in response to visible radiant energy (24). The rods perceive brightness and darkness, are sensitive to small amounts of light, and are affective in scotopic, or night

vision. Three types of cones, concentrated at the central foveal region, are sensitive to detail and color, operate at higher levels of illumination, and are used in photopic, or daytime vision (51, 71). Each type of cone has a spectral sensitivity to one of the three additive primary colors, red, blue, and green. Though their absorption bands overlap to some extent they are generally known as: "r" type which absorb the red end of the spectrum, "g" type which absorb the green region of the spectrum, and "b" type which absorb the blue end of the spectrum. The light energy is transformed into chemical energy which triggers the optic nerves into activity. By nerve cell synapses, a pattern of activity is transferred to the occipital lobe in the cortex (23, 45, 59, 184, 202).

The eye has the ability to integrate stimuli at different wavelengths of the visible spectrum to produce the sensation of a single color (71). A person with normal color vision has maximum photopic sensitivity to the visible spectrum in the green/yellow region at about 554-555 nm (12, 23, 101, 146, 151, 195). The luminosity function of the eye, or variation of the eye's sensitivity to color, plotted as a function of wavelength, yields a basically bell-shaped curve called the luminous efficiency curve. This accounts for the great color discrimination near the middle of the visible spectrum, and poor discrimination at the violet and red ends of the spectrum, reaching zero at ultraviolet and infrared beginning points (12, 22, 23, 101, 195).

The eye is not simply a physical instrument which gives identical responses to the same light source. In addition to variations in individual physiological and/or psychological characteristics, physiological factors may influence the visual signals received by the optic

nerves, such as state of health, eye disorders, and the darkening of macular pigment with age (24, 71, 202). The appearance of a stimulus to the individual observer may be influenced as much by psychological as by physiological factors. The mental picture and colors produced are influenced by experience, recognition, and attitudes and are not necessarily a true representation of the stimulus or of what others see (95, 202).

Color Measurement

The human eye and brain are almost unequalled in discerning precisely whether two colors are alike. As many as 500,000 to 10,000,000 colors and variations of lightness/darkness and intensity may be distinguished by the eye. Color cannot be expressed, measured, or matched accurately, however, solely by individual description due to differences of opinion in comparative color evaluation (22, 62, 149).

Color is expressed in one of three ways. Colorant-mixture systems, for example, are based on subtractive pigment mixing. Color-appearance systems are based on color change progressions which look uniform in difference to the normal human eye, such as the Munsell numerical method of color description. Color-mixture systems, or additive light mixing systems, are based on a set of colored lights which can be mixed in expressed amounts to match specific colors. The CIE method of instrumental color measurement is based on the last system (22, 71).

A spectrophotometric curve produced by a recording spectrophotometer also can be used to characterize a color. Spectrophotometers

measured the light reflected or adsorbed by an object as a function of wavelength (24, 71, 137, 154). Spectrophotometry eliminates many variables in the measurement of color by controlling the following factors which influence apparent color: 1) geometry of illumination and viewing, which is generally non-specular, that is 45° and 0° , respectively, in order to eliminate gloss or surface reflectance; 2) character, color, and intensity of light incident on the sample by using standard illuminants A, B, C, or D; and 3) response of the "observer" or recording mechanism by employing standard observer characteristics (51, 59, 86, 95, 136).

Additional variables which affect instrumental color measurement and should be controlled in order to obtain comparable color measurements include: gloss and reflectance characteristics of specimens; uniformity of size, shape, and surface texture of specimens; relative transparency (two layers may be required in measurement of textiles); atmospheric conditions such as content, temperature, relative humidity, and air current; manner in which specimens are prepared, mounted, and exposed for measurement; complete specifics and history of specimens; and specific measurement scales employed (51, 86, 130, 136).

CIE System. Colorimetric analysis of the spectrophotometric curves is a means of numerically evaluating the color appearance of an object (23). In 1931, CIE developed a method of color description based on computation of colorimetric data from spectrophotometric measurement which permits precise mathematical definition and description of all manifestations of color (24, 64, 71, 86). This system has become one of the most frequently employed methods used internationally by industries

relying on precise and objective standardized color measurement. It also has been recommended by the Optical Society of America since 1943. Color expressed in CIE terms can be converted or compared to any other color-designating system in use today (23, 24, 186).

The CIE system is based on tristimulus values (Y, X, and Z) which numerically represent the amounts of the three additive primaries that are required to produce a match with a color stimulus. Two color specimens having the same X, Y, and Z values will always match if lighting and viewing conditions are the same. The relative amounts of the three additive primaries have to be adjusted mathematically for a standard light source and a standard observer (22, 27, 39, 59, 64, 86).

The two dimensional color space in the CIE system is called the chromaticity diagram (Figure 2). Since the sum of the tristimulus values equals unity ($X + Y + Z = 1$), a color in the chromaticity diagram can be located by plotting the chromaticity coordinates derived by calculating the relative amounts of each tristimulus value required to match a color stimulus (22, 23, 45, 64, 86). To obtain chromaticity coordinates mathematically from the tristimulus values, the following formulas are employed:

$$\begin{aligned}x &= X/(X + Y + Z) \\y &= Y/(X + Y + Z) \\z &= Z/(X + Y + Z).\end{aligned}$$

Since $X + Y + Z = 1$, chromaticity can be described and plotted in terms of only X and Y, which also designate chromaticity (hue and chroma) (22, 64).

Located near the center of the diagram, equi-energy white represents the location of a color or light source having an equal energy

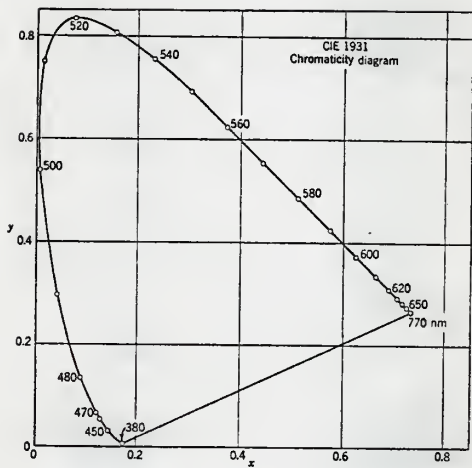


Figure 2

CIE (Commission International de l'Eclairage) x,y-Chromaticity Diagram
Taken from Judd and Wyszecki, p. 31 (23).

spectrum with neutral chromaticness (hue and saturation), and chromaticity coordinates of $x = .3333$, $y = .3333$, and $z = .3333$ (59, 81). The tristimulus value Y represents luminous reflectance (luminance or lightness) of the sample and may be plotted on the third-dimensional achromatic axis which begins at the equi-energy point or illuminant point and rises above the X, Y plane. The x , y , and Y axes form an irregular cone color solid (22, 24, 27, 59, 64, 71). Since the Y value is not visible on a two-dimensional chromaticity diagram, it may be stated numerically. A color located high above the x, y plane on the Y axis would have a higher numerical value and be lighter in appearance than a color plotting closer to the x, y plane. The x, y chromaticity coordinates plus the Y value represent a specific position in the CIE color solid for each color and are sufficient to specify any color (22, 39, 64, 86, 202).

The spectrum locus is the limit of the x, y plane formed by connecting the points representing the chromaticness of the spectrum colors. The farther a color is located from the equi-energy point on the x, y diagram, and the closer to the spectrum locus, the more intense or saturated it will be. The most saturated colors are located on the spectrum locus (22, 59, 64).

In the CIE system, color also can be specified in terms of dominant wavelength and excitation purity. Dominant wavelength is roughly synonymous with hue, and excitation purity with saturation (45, 59, 71). The CIE standard illuminants are all close to white in color (have little saturation) and are located in approximately the central portion of the x, y -diagram. The dominant wavelength of a color is determined by running a straight line through the x, y point of the illu-

minant and specimen location and extending it to spectrum locus. Excitation purity is calculated as the percentage relative distance of the graphed line from the illuminant to the specimen, compared to the distance from the specimen to the spectrum locus (24, 64). Spectral colors have 100 percent excitation purity. A color specimen plotting halfway between the x,y point of the illuminant and the spectrum locus would have an excitation purity of 50 percent (23, 24, 64).

Uniform Color Solids. Color difference systems are based on increments of change required to produce equal amounts of change in color stimulus to the human eye under standard psychophysical conditions (87). The Munsell color space used for visual evaluation of color is based on equal steps of perceptible change (124). In the CIE chromaticity diagram, however, a distortion exists with respect to equal change in visual perception (22, 39, 71, 103). For example, if two pairs of colors of equal visual difference were plotted on the diagram and the distances between the colors of each pair measured, a pair in the upper right portion of the x,y-diagram would be greater in distance than a pair in the lower left portion of the diagram. Therefore, Y,x,y, alone are not a means of specifying equal perceptible color difference, and formulas which transform the CIE space into a uniform chromaticity space must be employed so that equal numerical differences are attached to equal visual differences (22, 59, 64, 86).

Over 20 different uniform transformations of CIE space have been established. A uniform scale which converts CIE coordinates to equal-difference Munsell notation is the ISCC-NBS Method of Designating Colors.

Two other systems which assess uniform tri-dimensional differences are the CIElab system, which is considered best by Morton (161) for determining color difference in color matching, and the Hunter ΔE combined chromaticness and lightness scale (22, 24, 45, 139). The CIElab scale is specified in dimensions, called L^* , a^* , and b^* , which can be approximately related to lightness (L), redness-greenness (a), and yellowness-blueness (b). These scales are correlated to the eye's ability to judge differences, and represent the magnitude of the perceived difference of the combined tristimulus values of the colors by reducing the tri-dimensional CIE coordinates to an adjusted single number (45, 59).

Light Measurement

Several measurable qualities of energy emitted by light sources are important in the selection of museum lighting systems. These include: illumination value, total incident energy, relative damage factor, and lamp efficacy (24, 131). Illuminance (E), or illumination value, represents the total luminous or visible energy reaching a surface from a light source at a specific moment. The lumen is a unit of luminous energy. Though footcandle (fc), or lumen per square foot, is commonly used in the United States to measure illuminance, SI has adopted the lux which is equal to one lumen per square meter. For a light source, the footcandles emitted may be computed by the following equation:

$$E = \frac{.214 I}{h^2}$$

where: E = maintained illumination in footcandles
 I = manufacturer's listed, initial candlepower

h = height of lamp above sightline or object
(based on an 80 percent maintenance factor),

and converted to lux by the conversion equation: $1 \text{ fc} = 10.764 \text{ lux}$ (24, 32, 101, 131, 193).

While illumination describes light delivered to an object, luminance or photometric brightness is the brightness of an object or surface, and is the result of incident illuminance and the reflectance characteristics of the object. Because of differences in physical characteristics of objects, the same illumination may achieve different luminance values. It has been suggested that luminance, rather than illumination, is the ultimate factor determining the ability of a viewer to perform a visual task. The SI unit for luminance measurement is the candelas per square meter (cd/m^2) and this value should be taken into consideration when determining visibility of exhibits (131, 199).

The reciprocity principle states that total visible energy (or photoperiod) emitted from a light source, or illuminant, is equal to the product of the intensity times the exposure period (33, 34, 99, 107, 121, 132, 150, 190, 195):

total visible energy = light intensity x exposure time.

Whenever possible, both illumination level and exposure time should be kept to a minimum in museum environments. Research has shown that the reciprocity principle may not hold true for all situations, such as in high intensity light sources used in accelerated light fastness tests or in low intensity accelerated light used for testing light sources used in museums for long exposure periods (32, 99, 106, 110, 170).

Total museum exposure to light is sometimes expressed in

millilux-hours (1,000,000 lux hours), which takes into account both light intensity and exposure time. A museum illuminating at intensities of 100 lux, or approximately 10 footcandles, for an average of six hours daily for five years would amass a total quantity of illumination of one millilux-hour (1MLxh). Carefully controlled low illumination levels, and total exclusion of light whenever possible can result in annual exposures as low as .005 MLxh, or 5,000 lux hours (106, 193).

Instruments available for measuring illumination levels include photocells and light meters which register in footcandles or lux. Radiometers can be used to determine amount of total radiation. Care should be exercised in choosing a museum light monitor because some instruments measure accurately only at higher illumination levels than are reasonable for museum requirements. Others must be color-corrected for each light source and are affected by oblique light (132). Illumination measurements always should be taken as close to the position of the object as possible, with the monitor placed in the chief plane of the object and with all display case doors shut so that all light incident upon the object, radiated or reflected, will be measured (24, 132, 140, 156).

An important factor in light measurement for conservation purposes, as opposed to visibility purposes, is total visible and invisible radiant energy reaching the specimen over time, since this governs the amount of potential damage attributed to a specific illuminant. Total visible and invisible radiant energy incident upon an object may be measured in kilojoules though this measurement is not equal to or interchangeable with illumination level (34, 101, 134, 193).

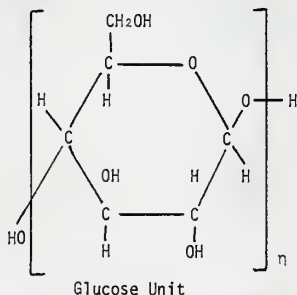
Though no exact prediction of the degrading effects of specific lamp/filter systems can be made, Harrison (50) and others suggested using the Probable Relative Damage Factor ($D\lambda$) which is a function of total radiant energy and is inversely related to wavelength (24, 50, 51, 150, 156, 188). Spectroradiometers are used to determine the spectral distribution and relative intensities of light sources. When multiplied times the $D\lambda$ for each wavelength, Probable Relative Damage per Footcandle (D/fc) for a light source can be determined (24, 101, 151, 192). Since light sources emit ultraviolet, visible, and infrared radiation, and possible damage to objects is dependent on all three regions of the electromagnetic spectrum, D/fc is a more meaningful factor than illumination level. Charts have been prepared listing specific light sources, filters, and combinations and their D/fc values. D/fc times intensity of illumination yields "Relative Degree of Hazard" expected for that light source. Relative Degree of Hazard increases with increase in intensity as well as with increase in output of high frequency wavelengths by light sources (50, 101, 188).

Lamp efficacy is a measure of the efficiency of the conversion of energy input to light output and, for electric lamps, is expressed in lumens per watt. This value is dependent on power efficiency and luminance efficacy, the amount of visible light output per unit of energy consumption at each wavelength. Since the eye is most sensitive to yellow/green wavelengths, lamps emitting the greatest amount of their light in this region and with the least amount of energy input dissipated in invisible wavelengths would exhibit the highest efficacy (24, 132, 184).

Chemistry of Cotton

Cotton, a seed-hair fiber, has been used in textiles since antiquity (38, 69). Babylonian cotton tapestries were mentioned by Greek and Roman writers, and tablets from 2200 BC record weavers of cotton in Ur (38). Other historic peoples that used cotton textiles include the Hebrews, Phoenicians, Egyptians, Persians, Greeks, Romans, Byzantines, Indians, Japanese, East Indians, and the early American Cultures (38).

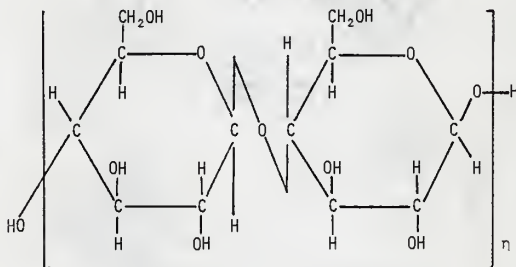
Cellulose ($C_6H_{10}O_5$) is a complex, long-chain carbohydrate polymer. The basic component of cellulose is the glucose unit (30, 69):



Through a condensation reaction glucose molecules combine to form a long-chain, high molecular weight polymer with a degree of polymerization (DP) of approximately 10,000. The repeat unit in cellulose is anhydro- β -cellobiose, which is illustrated as two glucose units joined together by glycosidic or oxygen linkages (30, 32, 34, 126).

The composition, structure, and size of a molecule account for its chemical reactivity and physical characteristics. The chemical and physical stability of cellulose fibers depends on both the primary

valency forces within the molecule and the secondary valency forces exerted by the quadrivalent oxygen atoms between molecular chains (27, 127).



Anhydro-β-cellobiose Unit

The cotton fiber is hydroscopic. A rise in relative humidity increases moisture regain of the fiber; it will swell in diameter, and contract in diameter when moisture content drops. Very low relative humidity causes drying and embrittlement of the fiber, yet relative humidity above about 60 percent encourages microorganism growth which may prove detrimental. High temperatures can cause damage to the fiber (32, 119). Like most organic materials, cellulose is susceptible to degradation by environmental factors (44, 194). Cellulose is degraded by concentrated mineral acid. Acid hydrolysis results in a cleavage of the glycosidic linkages and the formation of hydrocellulose, a degradation product of cellulose. Cleavage of the glycosidic linkage results in a lower DP and strength and an increase in solubility and reducing power due to the formation of aldehyde groups. Oxidative degradation of cellulose occurs at the primary and secondary hydroxyl (OH) groups, resulting in the formation of oxycelluloses as degradation products (34, 127).

Dyes and Dyeing

History

The earliest evidence of dyes used by man dates from the Neolithic Period (about 7000-2000 BC) (7). Peoples in several areas of the world had learned to spin, weave, and cultivate and were using vegetable dyes primarily as fugitive stains. Forbes (14) suggests that the first dyes were berry and fruit juices, crushed flowers, and roots and bark. Evidence of the earliest use of madder, woad, indigo, and some animal dyes date from this era (23, 70, 129, 154).

China may have originated the true craft of dyeing; 5,000 years ago the Chinese had attained fairly fast dyeings with indigo and alizarin from madder, and were impregnating yarns with mordants. Middle Kingdom Egypt also used mordants in textile dyeing. The first Western dyers were probably the Swiss Lake Dwellers who lived about 2000 BC (3, 14, 102).

During the Hellenistic era (approximately 500 BC), dyeing was a major industry but was monopolized by the state. Since dyeing was one of the earliest technical arts, the search for better dyeing techniques was a major factor in the development of a new science--chemistry. The art of dyeing increased in knowledge and sophistication until the fall of the Roman Empire, at which time the industry temporarily stagnated (14, 31).

During the late Middle Ages in Europe, guilds were responsible for fostering the dye industry and standardizing quality (38, 165). The earliest printed book on dyeing was written by Aillerley Matkel and contained recipes to improve colorfastness to light (102).

From 1500 AD, India had more influence on Western dyeing than any other country. Renaissance Italy and, in particular, the city-state of Venice were known for superior dyeings. In 1540, Rosetti, a Venetian, wrote Plictho de Larti de Tentori, which was the best source of dyeing information of the period (3, 30, 70).

Since dyeing methods and recipes had traditionally been handed down from father to son and the information was carefully guarded, recipes were seldom written, or if they were, they appeared as cryptic and obscure documents (14, 165, 166). The first organized synthesis and dissemination of dyeing theory occurred in the second quarter of the 18th century in Europe, when French chemists began to organize information and experiment with dye methods and lightfastness tests. Basic understanding of the physical and chemical mechanisms of dyeing led to the formulation of a theoretical framework, and the dye industry became the first industry to be based on knowledge gleaned from continuous scientific research and publication (3, 102, 159).

Colbert, minister to France's Louis XV, commissioned Charles Francois Dufay (1698-1729) to revise and organize all dyeing recipes and information. Dufay also performed controlled lightfastness tests (102, 166). Jean Hellot (1685-1766) published Application of Chemistry to Dyeing and L'Art de la Teinture des Laines. Other dye manuals of the 18th century from Europe include Le Teinturier Parfait and Le Nouveau Teinturier Parfait in 1708 and 1769, respectively, Pierre Joseph Macquer's (1718-1734) Elements de l'art de la Teinture, J. N. Bischoff's 1780 History of Dyeing, and two other manuals, The True and Proper Art of Dyeing, and The New Dyer's Manual (102, 166). Bancroft, in 1794, produced Experi-

mental Researches Concerning the Philosophy of Permanent Colours, the best survey of dye materials and methods available at that time (102, 166).

Elijah Bemiss' 1806 Dyer's Companion listed "Five Material Colors" (i.e., blue, yellow, red, brown, and black) and "Three Powers" (i.e., alkali, acid, and corrosive) (1, 69). Sigismund Hermbstadt (1760-1833) published Outline of the Art of Dyeing and J. A. Claude Chaptal (1756-1832) the Traite de la Teinture au Coton en Rouge (166). Parnell, in 1844, produced the first list of all dyes in use at the time, and Slater in 1870 contributed the first comprehensive dictionary of dyes (102). David Smith's The English Dyer (1882) was a widely circulated British dye manual (78).

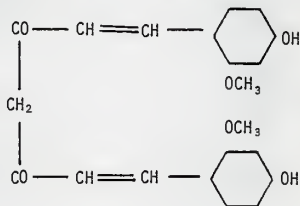
The head of the dyeing department of the Gobelin factory, Michel Eugene Chevreul (1786-1889), carried out extensive lightfastness tests, finding that some dyes vary in fastness to light on different fibers (102, 166). Natural dyes, in general, exhibit poor lightfastness by modern standards, with the exception of some mordanted and vat dyes. Yellow dyes were notoriously fugitive (172, 179, 188). Since few natural green dyes were known, this color was often obtained by mixtures of yellow and blue dyes (14, 154).

Most historic textiles found in museums are dyed with natural dyestuffs, since the first synthetic dyes were not discovered until the latter half of the 19th century. In 1856, William Henry Perkin's discovery of aniline mauve marked the beginning of the end of the use of natural dyes (14, 154, 155, 171). The synthetic dyes generally were purer, easier to obtain and use, and produced dyeings that were more pre-

dictable than its natural counterparts. Though most early synthetic dyes were unreliable in lightfastness, this disadvantage was soon corrected. Today, except for indigo which is still used in the production of some cotton denims, natural dyes are seldom used in the dye industry (3, 200).

Natural Dyes

Turmeric. Turmeric, tumeric, or curcuma is a yellow dye used on cotton, wool, and silk. It is obtained by grinding the root of the *Curcuma longa* plant, also called Indian Saffron, which yields a waxy powder containing the dye substance curcumin (3, 9, 14, 29, 37):

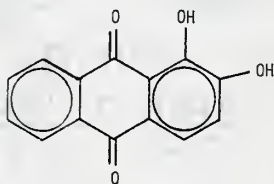


Curcumin

The plant grew primarily in the Middle East, East Indies, India, and Asia and was used as an edible source of starch and as a medicinal spice, in addition to a dye substance. The unmordanted color is yellow, with a range from orange to brown obtainable with mordants. It also has been used to improve reds, and to obtain greens. Though turmeric was considered the finest yellow by many dyers in the 18th and 19th centuries, it is notoriously fugitive to light and alkaline solutions (1, 26, 29, 34, 37, 43).

Madder. Madder is a mordant dye that was used widely on cotton and wool to obtain many shades in the red family or was used in combination with indigo and other dyes to obtain madder blacks or purples. Also known as "dyer's root" to the ancients, it is obtained mainly from the roots of the plant *Rubia tinctorum*, a herbaceous perennial, though 34 other variants are known (3, 14, 29, 37, 43, 102, 128).

Alizarin, the dyestuff in madder, is obtained from glucosides located between the core and the outer layer of the root (7, 26, 29):



Alizarin

Roots of plants 18 to 28 months old and taken in late autumn yield the best dye when dried, beaten, and pulverized (1, 14, 26, 43).

Indigenous to tropical and temperate zones, it was cultivated originally in Syria, Turkey, Egypt, and India (3, 14, 29). Egyptian mummy cloths and textile fragments from the third millennium BC have been found which were dyed with madder. Ancient Hebrews, Persians, and Libyans used madder and it is mentioned in the Old Testament. The Classical Greeks and Romans were familiar with madder and used it extensively (26, 29, 31, 37, 43).

By Medieval times, it was cultivated in much of Europe (i.e.,

Holland, France, and Italy) and Asia and was an important element in Asiatic commerce. From the fifth to seventh centuries AD, madder decreased in commercial importance as a crop in Europe, but was revived when Charlemagne decreed its cultivation in the seventh century. The Moors revived the use of madder in Spain about 900 AD and during the Crusades it was reintroduced into France. From 1500, Dutch madder was considered superior to other varieties until France took over the market after Louis XV aroused interest in its production (26, 29, 43, 159). England passed legislation to encourage cultivation of madder in 1757. Though it never reached commercial proportions, it was used widely, such as to dye the British "Redcoat" uniforms. The crop was introduced into America and widely used there in the 18th century. A complicated process of mordanting madder on cotton produced a scarlet called "Turkey Red," one of the most sought-after colors of 19th century Europe and America. Graebe and Lieberman synthesized alizarin in 1868, which soon replaced natural madder because it was less expensive (1, 2, 29, 37, 155, 200).

Madder usually is applied in conjunction with a mordanting agent, such as soluble salts of aluminum, chromium, iron, or tin (14, 69, 200). The mordanting process generally results in relatively permanent colors (69). Several sources state that madder, or any dyestuff taken from the ground, should not be boiled or heated for a prolonged time or the recipe will be "killed" and the red madder tone turn to brown (1, 43).

Indigo. Indigo, one of the oldest and perhaps the most important blue dye in history, is a naturally occurring vat dyestuff. It is obtained from plants of the genus *Indigofera*, mainly *Indigofera tinctoria*,

a leguminous plant which contains the dye substance indican in the leaves (9, 11, 14, 70, 94, 189). India was the birthplace of indigo and the main supplier until 1500 AD, but it has been cultivated in China, Japan, West Indies, Central America, Brazil, South and Central Africa, Madagascar, Java, Philippines, and North America as well. Sanskrit manuscripts tell how the dye was prepared and transported along ancient trade routes to Egypt 5,000 years ago. Mummy wrappings dyed with indigo have been discovered from ancient Egypt. Asia has used indigo for over 4,000 years, and Peruvian Inca graves contain indigo-dyed textiles (5, 15, 26, 29, 174).

Indigo was introduced to the Mediterranean countries in the last century BC and it was used extensively by the Greeks and Romans. The name indigo is derived from the Latin "indicum" which referred to all imports from India (15). Pliny the Elder mentioned indigo in his Historia Naturalis. The Venetian Marco Polo (1254-1324) mentioned the dye and its preparation in his books of trade with the East, and the Venetians were the first Western Medieval people to use it. In the Americas, Indians were using indigo long before the Spanish arrived (29, 168).

In Medieval and Renaissance Europe, strong objections to the use and cultivation of indigo arose because of the extensive revenue gained from the production of woad (*Isatio tinctoria*), a plant which contains indican, but in much smaller quantities than *Indigofera* (112, 168). By the 14th century, indigo had replaced woad in Europe, despite the label of "ruffian's color" and "devil's color," and King Henry IV of England's decree that indigo dyeing constituted a capital crime. Efforts in France to revive woad continued until 1737, and Napoleon briefly and

unsuccessfully tried to stimulate woad cultivation in 1811. In the early 16th century, after the discovery of the all-water route to India, the Portuguese and Dutch imported large quantities of indigo to Western Europe (15, 29, 168, 169).

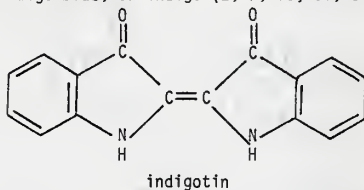
In the 17th century, the East India Company imported indigo into Europe and England began to cultivate the plant in her colonies (159). For a brief period, 1747-1776, indigo was a lucrative crop in the Carolinas and was the first major export item from the colony. Political conditions signaled the decline of indigo production, but only after American indigo had reached the superior quality of French indigo which had enabled the British to undersell France in 1773. After the war, rice became a more lucrative crop in the Carolinas and indigo cultivation was transferred to the British West Indies (174). Indigo was extensively used to dye American and British sailors' uniforms and became the most important American dyestuff of the 18th and 19th centuries (3, 29).

The year 1893 marked the peak of world indigo production, shortly after which synthetic indigo began to supplant the use of the natural material. The chemical structure of indigo had been discovered by A. von Baeyer in the 1880's and by 1897 the synthetic dyestuff "Indigosol" was being marketed at a very low price compared with natural indigo (9, 92, 112, 155, 168).

Since the dye substance in indigo is present in water-insoluble and colorless form, a special reducing process, called vatting, is necessary to yield a usable dye (69, 169). Originally the dye was extracted by the natural fermentation of vegetable matter and human urine (15, 169, 189). The plants were harvested while in bloom and steeped in water

until fermentation and reduction had extracted the dye-yielding substance, the glucoside indican, from the plants and reduced it to indoxyl. The solution was then drawn off, the plants disposed of, and the liquid beaten to incorporate oxygen into the vat and, with the help of ammonia, precipitate indigo, the oxidized form of the dye. A boil was then reached to arrest fermentation, and the precipitated indigo was dried into cakes or a powder, ready to be dissolved in a dyeing vat (3, 5, 15, 112, 174).

In the application of vat dyes, the dyestuff first was reduced to its soluble, sodium leuco state (3, 29, 94, 189). The fibers were entered into the bath at this point, and the water-soluble reduced dye substance was absorbed into the fiber; when exposed to oxygen in the air or treated with an oxidising agent, the dye reverted back to a water-insoluble form, indigo blue, or indigo (2, 7, 15, 31, 94, 112):



To create deep shades, the fabrics were dipped and exposed to air several times (69, 189). As an aftertreatment to help develop the true shade, remove loose dye particles, and further crystallize the dye in the fiber, soaping at the boil was sometimes performed to increase lightfastness (5, 9).

Indigo vats used historically include: the lime and copperas vat (ferrous sulfate), oldest and most commonly employed historically;

the bran and madder vat; zinc-lime vat; zinc powder vat; and, first used in 1873 and most common thereafter, the hydrosulfite vat (2, 37, 112, 189).

Since the leuco form of the dye is water-insoluble, properly applied vat dyes show good washfastness. They also exhibit superior lightfastness, unless used as a pigment. Indigo is generally faster on wool than on cotton, due to a greater chemical potential on cotton. Some extant textiles dyed with indigo centuries before the time of Christ still hold their color (2, 29, 70, 101). In general, vat dye-stuffs have good lightfastness properties, but certain vat dyes, especially in the yellow-orange hues, may accelerate photo-oxidization of the fabrics.

Mordants. Colour Index (9) suggests that the classification of "mordant dyes" has little logical basis since a wide range of heterogeneous dyestuffs may require or be assisted by a mordant, including most natural dyes (172, 183). The mordants may be applied before dyeing (i. e., the on mordant process), during dyeing (i. e., the metachrome process), or after dyeing (i. e., the afterchrome process). Mordants influence the ultimate hue of the dyestuff and make possible a range of colors or shades from one dye (3, 43, 69, 102).

The word mordant comes from Latin "mordere," to bite, which indicates the ability of the mordant to create a bond between dyestuff and fiber or to create a larger, insoluble dye molecule. Commonly used mordants with historical significance include (3, 43, 69, 70, 78):

<u>Common name</u>	<u>Technical name</u>	<u>Formula</u>
alum	aluminum potassium sulfate	$KAl(SO_4)_2$
chrome	potassium dichromate	K_2CrO_7
iron	ferrous sulfate or copperas	$FeSO_4$
tin	stannous chloride	Na_2SnCl_6
blue vitriol	copper sulfate	$CuSO_4$
Glauber's salts	sodium sulfate	Na_2SO_4
oak galls, sumach leaves	tannic acid	$C_{14}H_{10}O_9$
acetic acid	acetic acid	$C_2H_4O_2$
ammonia	ammonia	NH_3
cream of tartar	potassium bitartrate	$C_4H_5KO_6$
certain oils.		

Chemistry of Dyeing Cellulose

The chemical constitution of a dye influences its color and coloring potential. The presence of certain chemical groups within a dye molecule facilitate the adsorption of visible light and, hence, increase color potential. These groups are called chromophores and include nitro (NO_2), nitroso (NO), azo (N_2), and carbonyl groups (CO). Additional groups, called auxochromes, impart water solubility to the dyestuff and give it affinity for the fiber substrate. These include amino (NH_2), substituted amino (NHR), hydroxyl (OH), sulphonic (SO_3H), and carboxyl ($COOH$) groups (35, 68, 132, 143, 196). The color potential of a molecule also is increased by resonance or the existence of alternating states of distribution of valencies within a ring molecule, bi-symmetry of molecular geometry, and conjugation. A highly conjugated molecular system of alternating single and double bonds absorbs in the visible spectral region, producing color. Compounds with only a few conjugated or double bonds tend to absorb in the ultraviolet region. Compounds containing easily excited electrons (i.e., non-bonding or pi (Π) electrons) absorb longer-wavelength (red region) visible wavelengths

and tend to appear blue in color, whereas molecules containing less easily excited electrons (i.e., sigma single bonds), absorb toward the blue end of the spectrum and appear red in color (35).

Factors which influence the dyeing and fastness properties of the dye include size and chemical structure. For example, a small molecule may be easily absorbed and as equally easily released from the fiber, whereas a molecule larger than the fiber interstices may not be able to enter the fiber at all. Fading characteristics also rely partially on chemical constitution. Symmetrical molecules exhibit greater lightfastness than non-symmetrical dyes, and in vat dyes lightfastness increases as planer length:breadth (axial) ratio decreases (85, 143). In addition, a dye with greater molecular weight is generally less susceptible to fading than a low molecular weight compound (179).

Though fastness is not dependent entirely on specific groups, certain chemical groups and auxochromes may accelerate fading, such as hydroxyl (OH), amino (NH₂), and thiol (SH) groups and the quinoline ring (85, 143). Fade-retarding components and chromophores include nitro (NO₂), sulfate (SO₄), the carboxyl hydrogen ion, and bromine and chlorine atoms (85, 143).

Dyeing proceeds in three basic steps: 1) migration of the dye from the solution to the fiber surface, governed by dye concentration, electrical charge of fiber due to presence or absence of hydroxyl ions (pH), and temperature of the dyebath; 2) diffusion of the dye molecules from the surface toward the center of the fiber, which is dependent on dyestuff molecule size, crystallinity of the fiber, number of attractive sites in the fiber, dye concentration, and number of substituents on the

dye molecule; and 3) type of chemical bond or physical force which anchors dye and fiber together (35, 164).

The chemical structure of both the dye and the fiber influence the method of dye fiber association and, hence, the dyeing characteristics and colorfastness properties of the dye (75). Most dye-fiber bonding associations may be classified into: mechanical, hydrogen bonding, ionic bonding (salt links), and covalent bonding (35, 59). Vat dyes rely on mechanical or physical entrapment, whereas direct, acid, basic, mordant, and reactive dyes are held more by chemical means (34, 59, 69). Other factors affecting the formation of a dye-fiber unit levelness, quality, lightfastness, and other dyeing characteristics include acidity of the dyebath, electrolytes, rate of exhaustion, temperature, degree of agitation, ratio of fiber weight to volume of dyebath, and dye content (16, 44, 163, 179).

Museum Lighting Environments

The museum should employ lighting systems which eliminate unnecessary ultraviolet and infrared radiation by controlling spectral emission and intensity, and by limiting exposure time. The museum environment also must provide an inconspicuous, energy-efficient, and visually comfortable surrounding for the viewer with proper color rendition, luminance, contrast, modelling, and suitable visibility. Efficacious lighting systems provide maximum effect with minimum risk, extend the lifetimes of museum objects, and encourage close study of exhibits (24, 119, 132, 157, 176).

Daylight versus Artificial Light

Daylight is difficult and costly to control, especially at low illumination levels. Fenestrations and skylights may cause disabling glare, as well as loss of display space. Psychological considerations require that daylighted galleries be brighter than those artificially lighted, especially with the trend in architecture for highly illuminated rooms with glass walls (60, 117, 118, 119, 120, 139, 193).

Direct sunlight reaches intensities of 10,000-100,000 lux and should never be used to illuminate objects susceptible to actinic degradation (121, 151). Even diffuse or reflected daylight generally is too intense and contains too high a percentage of ultraviolet radiation for proper conservation of susceptible objects. Of six light sources listed by the National Bureau of Standards (NBS) (zenith sky, sunlight, cool-white deluxe fluorescent, warm-white deluxe fluorescent, and incandescent) all types of natural lighting possessed the highest ultraviolet content and resulted in the greatest photochemical damage in light-exposure research, followed by unfiltered fluorescent, then unfiltered incandescent, though sometimes warm-white deluxe fluorescent rated better than incandescent (42, 73, 98, 151, 157, 192). Taylor (191), comparing relative footcandle hours required to produce equal fade, reached similar conclusions:

sunlight and skylight	1.00
daylight fluorescent	1.68
tungsten filament	1.80.

Zenith skylight is known to have a greater percentage of ultraviolet content than any other source listed above (about 25 percent), and

ultraviolet content percentages decrease in the same order as listed above. All factors considered, for strictest control of intensity and spectral distribution, and for lower ultimate installment and operation costs, total exclusion of daylight has been suggested (67, 101, 120, 139, 150).

Light Sources

Lighting systems may be either general (lighting a whole area with even illumination) or localized (lighting directed at specific small areas only). Many museums concerned with maintaining low illumination levels while achieving adequate visibility use localized lighting systems (119).

Though the cause of light emission for all light sources is fundamentally the same (i.e., electronic transition from higher to lower energy states) there are two main classes of artificial light sources: 1) those which are based on the principle of incandescence (matter heated to the point of glowing), such as filament lamps, and 2) those which are based on luminescence (glow caused by an electric discharge passed through an inter gas, and phosphorescence of powders deposited inside a tube) such as fluorescent lamps (12, 13, 24, 45, 82, 107).

Emission spectra produced by lighting sources are either continuous (containing some energy of each wavelength within its range), or discontinuous (emitting energy in isolated wavelengths or groups of wavelengths with areas of abrupt discontinuity). Natural and incandescent sources characteristically emit continuous spectra, whereas gaseous discharge lamps generally emit predominantly discontinuous line or band

spectra (24, 25, 106, 132). Total radiation emitted by an artificial lamp depends upon spectral emission, electric power input and power efficiency, luminous efficacy, and operating efficiency and maintenance (21, 179, 184).

Incandescent. Incandescent lamps consist of a filament, usually tungsten, which is located within a glass bulb filled with inert gas (i.e., argon and nitrogen) or evacuated. The filament is heated to approximately 2600°C, causing violent molecular agitation and the emission of light having a long-wave, continuous visible spectrum of warm colors (reds to yellows). As wattage and, therefore, operating temperature increases, the wavelength of maximum intensity shifts to higher frequency, the emission shows less red/yellow color, and the light becomes whiter in appearance (13, 21, 106, 132, 156). Incandescent light emits 4 percent or less ultraviolet radiation and generally contains no wavelength below 320 nm. As much as 90 percent of emitted energy is in the infrared region of the spectrum, resulting in excessive heating which is the major disadvantage of incandescent lamps. A light source emitting a high percentage of invisible light operates at low efficacy, producing relatively small amounts of visible light for a specific amount of energy input (21, 24, 34, 45, 57, 150, 160).

Incandescent illumination can cause rapid and uneven heating of objects, especially when used in display cases. Maximum illumination value at the beam axis as it reaches an object should not exceed about 125 lux (12 fc.) in showcases containing textile objects (24, 96, 151). Ventilation and cooling of air in a room or showcase may decrease local

heating. Other precautions include the use of infrared filters between the lamp and artifacts, or the use of incandescent lamps with dichroic reflectors which direct the heat produced in the bulb backward, and reduce the heat energy emitted toward an object and the amount of dust collection on the bulb (44, 72, 96, 132).

Advantages of incandescent lighting include sparkle and good modelling (planes illuminated in such a way as to show form well), ease of light control, and the possibility of localized accenting. In addition, incandescent lights are available on moveable track systems (118, 119, 132).

Quartz. Quartz (tungsten halogen) lamps are incandescent lights which contain halogen gases inside a quartz bulb. The quartz bulb is necessary because of high operating temperatures. Quartz characteristically is an efficient radiation transmitter in the infrared, visible, and ultraviolet regions above 210 nm (145, 179). Quartz lamps may emit a considerable amount of infrared and ultraviolet radiation, and often require heat- and ultraviolet-absorbing filters (28, 34, 175, 178).

The disadvantages of quartz lighting include high heat output and ultraviolet content, and the discoloration of the quartz bulb if touched directly. Advantages include high intensity light output for small size, low voltage requirements, higher efficacy than regular incandescent bulbs, and extremely white light emission due to the presence of halogen or iodine (24, 25, 34).

Fluorescent. Fluorescent, or electric discharge, lamps consist

of a thin glass tube lined with fluorescent powders (called phosphors) and sealed with electrodes at both ends. The lamp is filled with mercury vapor and a small amount of inert gas. Light from fluorescent lamps is produced in two ways. When electric energy is passed from electrode to electrode through the mercury gas, mercury electrons are driven from orbit and emit energy as they return to stable states. As a result, the radiation spectrum of mercury is emitted, which consists of discontinuous bands high in ultraviolet, and a very small amount of visible light called luminescence. The ultraviolet energy produced excites the phosphors, or fluorescent powders, lining the tube which respond to ultraviolet radiation, particularly at 253.7 nm. The phosphor absorbs and re-emits the ultraviolet energy in longer wavelength to produce radiant energy consisting of a fairly continuous spectrum of visible and ultraviolet light. The emission of light by the phosphors during excitation is called fluorescence, and light emitted by the phosphors after excitation ceases is called phosphorescence (13, 24, 43, 45, 101).

Though clear window glass characteristically absorbs radiation below about 320 nm., the glass tube of a fluorescent lamp is so thin that radiation below about 280 nm. is allowed to pass. Therefore, the total spectrum emitted from a fluorescent lamp consists of: 1) invisible ultraviolet from the direct line spectrum luminescence of mercury vapor, which is about 7 percent of total energy output; 2) 5 to 10 percent of visible light from the same; and 3) 90 to 95 percent of visible light from the indirect continuous spectrum of phosphor coating fluorescence and phosphorescence. A negligible amount of ultraviolet also may be produced by the phosphor powders (33, 106, 107, 148, 151, 157, 179).

Different electrode materials, combinations and thicknesses of phosphors, vapor pressures, current densities, and glass tube compositions yield fluorescent light having different spectral emissions and different amounts of ultraviolet content (24, 45, 101, 106, 132). Even though the ultraviolet output may vary as much as a factor of 10 for different makes of the same type of fluorescent lamp, the level is sufficient enough to justify using ultraviolet filters (106, 132).

High ultraviolet content is the major disadvantage of fluorescent lighting; it contains ultraviolet energy of such short wavelengths (below 340 nm.) that no other museum lighting source, even sunlight through glass, allows passage of wavelengths as short. The appreciable amount of 280-310 nm. ultraviolet radiation from unfiltered fluorescent lamps may result in substantial fade and deterioration, and life of susceptible objects is extended up to 100 percent by its removal (79, 107, 132, 193). Because of the presence of discrete, radiant energy bands in fluorescent lamplight, the spectral emission is different from relatively continuous, spectral emission sources such as incandescent and natural light; thus, color rendering properties must be carefully evaluated. The characteristically bluish color of most fluorescent lamplight may appear too cold at low illumination values, since the eye is adjusted to natural light which becomes warmer in color as illumination level decreases toward sunset. Special fluorescent lamps are available with relatively low ultraviolet content and warmer color light, which may be better suited to the needs of museums. Localized, low-illumination light is difficult to achieve with fluorescent tubes (13, 98, 106, 148, 151, 195).

The advantages of fluorescent lamps are many. They exhibit luminous efficacy up to four times greater than incandescent lights with much less heat for equivalent light output. Fluorescent lamps are used with current-limiting devices called ballasts which may generate heat, but total heat radiation is vastly lower than incandescent, which is desirable for showcase lighting. Fluorescent lamps also have a long operating life and are ultimately more economical than incandescent, though initial installation cost may be higher (148, 185). Lamp life varies from 1,000 to 20,000 hours of operation, though visible and invisible radiant energy output efficiency may be decreased by 15 to 25 percent by excess dust accumulation. The first hours of operation may emit unsteady radiation, which should be considered if a fluorescent lamp is being used for testing purposes. The tubular shape of fluorescent lamps, though unsuitable for local or spot lighting, ensures good spatial distribution of light. A variety of color tones of fluorescent lamps are available, though some, due to type of phosphors used in the coating to obtain a specific color, may be fairly low in luminous efficacy compared to fluorescent lamps in general. The metal-halide lamp yields improved color-rendering properties obtained by the addition of metal-halide to the mercury. This modification of the mercury lamp is still in developmental stages as a museum light source (24, 34, 72, 99, 134, 160, 178).

Filters

A filter may be any material that selectively absorbs or transmits certain wavelengths of radiant energy (41, 79). Total incident

radiant energy upon a filter is divided into three parts:

$$P_i = P_t + P_a + P_r$$

where: P_i = total incident power from a light source
reaching a filter
 P_t = amount of energy transmitted
 P_a = amount of energy absorbed
 P_r = amount of energy reflected (41).

Filters which absorb invisible radiation only (i.e., infrared or ultraviolet) are colorless, but any filter which absorbs a portion of visible light must be at least slightly colored (41, 79, 179). Both inorganic and organic materials are used as light filters (i.e., glass, plastics, and varnishes).

Main considerations in selection of filters for museum light sources include: the range of wavelength transmitted and filtered and sharpness at which transmittance falls, filter life (transmittance shift or embrittlement with age), production of undesirable volatile by-products during use, and heat resistance or decomposition due to heat energy from light sources (101).

Infrared filters. Necessary for regular incandescent and quartz lamps, infrared filters are generally heat-absorbing glasses. Most plastic filters would be distorted or decomposed by the substantial infrared heat output of incandescent or quartz lamps. Ordinary glass used for incandescent bulbs transmits little radiant energy of wavelength longer than 3500 nm., therefore, the major concern for filtering purposes is near infrared radiation. Glasses are available from several sources which efficiently filter near infrared radiation. Dichroic reflecting filters, available in special incandescent bulbs, transmit

visible light to the object while reflecting infrared energy toward the back of the bulb where it may be dispersed by moving air. Infrared filters may reduce heat incident on objects by 11-22°C (20-40°F), but also may result in a slight loss of candlepower (41, 45, 50, 57, 96).

Colored filters. Eliminating invisible radiation does not make a susceptible material safe from harm. Visible radiation also causes fading and deterioration and, in some cases, may be partially filtered to reduce potential harm (105, 150). Colored filters have been used to separate the effects of different wavelengths. Research has suggested that actinic degradation, though affected by many factors, is substantially less under colored filters which absorb toward the blue, high frequency, end of the visible spectrum (55, 73, 150, 172, 190). A filter absorbing blue radiant energy would transmit red/orange radiation, thus causing the apparent color of objects viewed beneath it to shift toward the orange region of the spectrum. Research has revealed that, in general, filters in the following colors allow progressively more fading: red, yellow, blue-green, blue, and clear. Several sources, however, noted greater degradation under the blue than under the clear filter, due possibly to greater passage of ultraviolet light under the blue filter (32, 46, 50, 51, 101, 190).

Since filters may produce by-products harmful to organic objects and a colored filter has the least effect on object color when placed between lamp and object, colored filters should not be placed between viewer and object or in close proximity to artifacts (101). Because of their influence on object color, colored filters are seldom used in

actual museum display situations.

Ultraviolet filters. Effective ultraviolet filters must absorb efficiently in the ultraviolet region, remain stable during performance by dissipating the absorbed ultraviolet energy in such a way as to cause minimal degradation and color change in the filter, and be resistant to heat (79, 105). Quartz and fluorescent lamps often require removal of ultraviolet components. Materials used as ultraviolet filters include: glasses, polyvinylchloride plastics, acrylic sheets, cellulose acetate films, and varnishes of various kinds. Several sources recommend rigid cast acrylic plastics which may be placed above louvers under fluorescent lamps (50, 105, 121, 132).

Ultraviolet absorbers are compounds or chemicals incorporated into filters which cause the absorption of ultraviolet radiant energy. They include substituted benzophenones, titanium dioxide, and ferric oxide. Many white pigments used in paint (lead, titanium, and zinc) also absorb ultraviolet energy, and light reflected from paints containing these pigments is lower in ultraviolet content than direct light (13, 33, 79, 88, 101, 105, 151). There is no strongly-defined cut-off point between ultraviolet and visible regions of the spectrum. The most efficient filters absorb all ultraviolet and a proportion of wavelengths up to 400 nm ; these filters are slightly yellow in color, but generally not enough to affect object appearance noticeably. Padfield (32) and others suggest that sacrificing a small portion of the energetic, blue component in museum lighting by using slightly yellow filters or employing warmer color lamps may reduce the degradation of susceptible artifacts.

Filter life is generally five to ten years (42, 73, 120, 121, 141, 160, 178).

Adaptation, Contrast,
and Glare

Adequate ease of seeing, with respect to necessarily low illumination levels, may be achieved most effectively when adaptation, contrast, and glare are properly controlled. Adaptation is the ability of the eye to change its sensitivity to brightness, which plays an important role in the visibility of objects illuminated at the low levels suggested for textiles. Because of adaptation, the visual image transmitted to the retina is not directly related to the amount of light that initiates the image. The eye adapts to its visual environment and is, therefore, no judge of absolute illumination level. Response of the retina to illumination level depends on previous stimulation. The amount of light pleasing to the eye and necessary for visual acuity is lower if the illumination level of light falling on the eye preceding that instant was low. Apparent brightness of a surface or object is increased when viewed by the dark-adapted eye. There are limits, however, to the adaptation capacities of the eye, and the viewer should be gradually exposed to progressively lower illumination levels to facilitate gradual adaptation and reduce the discomfort of eyestrain (24, 95, 101, 132, 151, 195).

Since the eye responds automatically to the brightest area in the visual field, ambient lighting should be reduced to direct the eye to accented exhibits (138, 158). Distracting brightness of light sources may upset adaptation and cause difficulty in visualizing detail, and, therefore, should be eliminated by concealing lamps with louvers or

shutters or recessing them in ports so that the viewer is not aware of their location or placement. Absolute intensity is less important in determining visibility of displays than provision for proper adaptation and lighting objects at higher intensities than background illumination levels (44, 60, 138, 139, 158). Care should be taken to avoid too great a contrast between object and background illumination, and some diffuse or reflected light may be employed to prevent impairing visual performance (24, 178). Background materials should be unobtrusive in color and glare, as well as low in luminance. Proper contrast is aided by allowing for adequate space between artifacts, by placing objects at eye level or slightly below, and by good display of form and proper illumination of all planes of three-dimensional objects. Deep shadows may be avoided by correct placement of lamps (120, 138, 158, 176).

Good lighting and modeling for complete costumes may be difficult to achieve with overhead lighting. If the garment is illuminated to 50 lux at eye level, for example, the floor level may be 10 lux or below. Vertical directional lighting, if well-screened, would emphasize modelling and produce even luminance over the entire length of the object (117, 118).

The eye also adapts to color. In chromatic adaptation, areas in the visual field can change the appearance of each other. When a group of color receptors is subjected to stimulation for a prolonged period of time, the sensitivity is diminished through decomposition of chemicals within the receptors and the eye becomes adapted to that color. Therefore, variation in color or spectral distribution of light sources within the visual field causes a conscious reaction to color difference and

diminishes the efficiency of vision. All light sources within a room should have about the same spectral distribution (95, 139, 202).

A distracting problem in low-intensity galleries may be discomfort glare, occurring when a bright area (i.e., a light source or reflecting background or showcase) in the visual field prevents proper adaptation and reduces perception of detail. Highly reflecting materials on floors, ceilings, and backgrounds should be avoided. Internally lighted showcases produce discomfort or disability glare when reflected by neighboring showcases. The problem is compounded in galleries containing showcases viewed from more than one side. The effect may be alleviated by using vertical screens to separate cases, by sloping the front glass slightly, by concealing light sources in the cases, and by using as low luminance as is efficacious. The brightness of any exterior object, including floors, ceilings, and windows, should be substantially less than the luminance of artifacts within the case in order to reduce reflected glare (24). External lighting often is a source of glare on glass showcase surfaces, but it has the advantages of generally producing less heat inside the case and creating greater distance between artifact and light sources, thus decreasing intensity. Because desk-type, horizontal cases are difficult to light externally without producing glare from ceiling lamps, IES suggests the use of angled lectern showcases for textiles. Several sources consider internal showcase lighting most effective, provided ventilation is adequate to remove heat from lamps, illumination level is kept low, and proper filters are placed between lamps and artifacts. High-intensity, external lighting or sunlight should not be used to illuminate unventilated showcases, due

to a deleterious buildup of heat, called the "greenhouse effect," which may occur. Objects within the case are warmed by absorbed, high-intensity light and give off blackbody radiation in longer wavelengths than the glass can retransmit (60, 96, 132, 134, 150).

Color Temperature and Rendering

A method of expressing the color of light emitted by a light source is color temperature, which is based on the principle that a perfect heat absorber and radiator (i.e., a theoretical "blackbody") incandesces or emits absorbed energy as heat and visible radiation, due to violent molecular agitation, when it reaches 600°C (873°K) and beyond (24, 96, 151). Subsequent heating of the blackbody produces energy emission in progressively shorter wavelengths, ranging from dull red to bright red (about 900°K), orange to yellow (about 3000°K), white (about 5000°K), and finally bluish-white (about 9000°K) and sky-blue (about $100,000^{\circ}\text{K}$) (Table 1) (24, 51). This principle accounts for the color of the heated tungsten filament in an incandescent lamp, though the color of any light source may be compared to blackbody color and specified in degrees Kelvin (24, 96). Color temperature refers only to amount of light at various wavelengths produced by a light source and is not synonymous to intensity of illumination or "warmness" and "coolness" of color. High color temperature (blue-white) light indicates "cool" colors, and low color temperature indicates "warm" colors (i.e., red, orange, yellow) (132, 151).

If a light source is moved closer to an object, the illumination will increase, but color temperature will remain constant. Electrical

Table 1
 Color Temperature Ranges and Predominant
 Color of Various Light Sources,
 Daylight, and CIE Standard
 Illuminants

Light source	Color temperature ranges	Color
incandescent	2400 to 3400°K	yellowish
fluorescent	2800 to 6500°K	yellowish to white
daylight	6500 to 100,000°K	white to blue-white
lamp with white light the color of interna- tional white point	5500°K	white
CIE standard illuminant A	2854°K	orangish, color of incandescent light
CIE standard illuminant B	4870°K	neutral, color of direct noon sun- light
CIE standard illuminant C	6770°K	bluish, color of average daylight
CIE standard illuminant 065	6500°K	color of daylight

dimmers alter the color of lamplight by decreasing color temperature as electrical power is reduced. Placing a mesh screen in front of a lamp reduces intensity, without altering color temperature (151, 178). As color temperature increases, the proportion of shorter wavelengths increases. A lamp emitting short, visible wavelengths would appear blue to the eye and be potentially more injurious to dyes and fibers than lamps with more of the yellow or red component (24, 73, 121). Harris (21) states that warm color (low color temperature) lamps are potentially less destructive than cooler color (higher color temperature) lamps, and probably would cause less fading for equal illumination values (121). Characteristic color temperature ranges for various light sources are given on Table 1 (23, 45, 135, 169).

Object color appearance is influenced by lamp color, since materials can reflect only those rays present in incident light (3, 23, 83, 120, 132, 151, 156). Color rendering refers to the effect of a light source on object color appearance. An efficient museum lighting environment should provide proper color rendition, which is governed by the color temperature or spectral distribution of the light source, to enhance both the color and appearance of an object (120, 138, 184). Since many artifacts were made in yellow candlelight (color temperature about 1700°K), the question often arises as to whether illumination should imitate color rendering properties of daylight or candlelight (160). Most sources seem to support the idea that white daylight, with a color temperature of a cool-white of approximately 4200 to 4500°K, is ideal (50, 90, 120, 138, 157, 160, 180).

Two light sources may have the same color temperature and yet

vary in spectral emission, showing evidence of their differences only when their effects on object color are compared. White light may be produced by even wavelength distribution, mixing of two complementary wavelengths, or many other combinations. Some research suggests that best color rendering properties are achieved by lamps containing all wavelengths of visible light (24, 120, 134, 151). Other researchers suggest good color rendering also may be achieved by using three-line prime color lamps composed of three primaries, at about 450, 540, and 610 nm. (184). Though fluorescent lamps with good color rendering properties generally have lower luminous efficiency than most fluorescent, prime-color lamps achieve relatively high luminous efficiency (132, 184).

The Test Color Method, utilized by CIE, measures and specifies color rendering properties of light sources in terms of R, color rendering index. Color rendering properties increase as R approaches 100 (45, 184). Incandescent lamps rate low on the scale and generally are inadequate for portraying accurate color appearance. Several fluorescent lamps have superior color rendering properties (72, 117, 118, 178, 180).

There are psychological dimensions to color rendering that may influence desired color temperature (151). For each color temperature, there exists a level of illumination at which the color temperature is considered pleasing to the eye. Daylight color may appear too "cold", dull, and depressing at the illumination levels suggested for textiles (i.e., about 50 lux) (82, 83, 101, 118, 132, 151, 156). Crawford (83) suggests that warmer color temperature, with lower rendition capabilities, may be best for illumination at low light levels, and Mantle (156) and Harris (118) recommend 2200 to 3000°K as preferable to higher color

temperatures. Since low color temperature light usually includes less high frequency, blue wavelengths than high color temperature light, it may result in less photo degradation (73, 101, 117).

Though Ruhemann (180) and others suggest that mixing cool fluorescent with warm incandescent lamps may lead to unpleasant results, other sources recommend "warming" fluorescent lamplight with incandescent light and mixing cool-white and warm-white fluorescent lamps (50, 60, 83, 138, 180).

Photochemical Deterioration of Fibers and Dyes

All textiles will eventually discolor and deteriorate, regardless of the environment. Any organic object located in an oxygenated atmosphere will suffer degradation by photodecomposition when radiation is absorbed (156). The rate and extent of degradation is influenced by the intensity and wavelength distribution of the light source and by other environmental factors such as temperature, relative humidity, and atmospheric pollutants. There is no threshold light level below which fading ceases to occur, and the effects of light are both irreversible and cumulative (35, 50, 110, 121).

Photochemical or actinic degradation (i.e., deterioration caused by radiant energy) of dyed textiles may result in either a change in color or of the fiber substrate. Research has shown that a correlation often exists between fading and fiber deterioration (51, 52, 146). The types of color changes that may occur during light exposure include: one-tone fading or lightening and graying of color without hue change, off-tone fading or hue change, or an increase in yellowness (23, 179).

Fibers vary in their susceptibility to deterioration by light because different configurations of atoms are capable of being affected by energies of different quanta or wavelengths. Silk, for example, is the most light sensitive fiber, whereas acrylics and polyesters have good sunlight resistance (101, 107, 150, 151). The actinic degradation of cotton may result in the production of oxycelluloses and hydrocellulose, rupture of oxygen bridges, a decrease in the degree of polymerization and viscosity, changes in crystallinity, an increase in fluidity and solubility, an increase in copper number due to formation of carbonyl groups, an increase in methylene blue absorption due to formation of carboxyl groups, shortening of staple length, reduction in abrasion resistance and a loss of strength, embrittlement, and alterations in hand (3, 32, 34, 44, 48, 51, 58, 101, 173, 198).

Photodegradation of Fibers and Dyes

Radiant energy affects dyed cotton cellulose in three ways. These include direct photolysis, photosensitization (i.e., both photochemical changes caused primarily by ultraviolet and visible radiation), and thermo-dynamic action (i.e., changes caused primarily by infrared radiation) (6, 173, 179). A molecule will be directly affected by radiant energy only if the energy is absorbed, which is possible only if the radiation has a frequency which closely corresponds to the mode of vibration within the receptor molecule (46, 85, 99, 101, 175). Absorption of high frequency, ultraviolet and visible radiation may cause changes in electronic energy levels of substances, whereas low frequency, infrared radiation results in an acceleration of molecular vibrations (10).

Direct photolysis. Direct photolysis is the rupture of inter-atomic bonds by direct absorption of electromagnetic radiation of sufficient quantum energy (32, 179). The energy of photon bombardment must, in order for chemical reactions to be initiated, be of sufficient energy to raise a molecule in the irradiated substance from ground state to excited state. This amount of energy required, which differs depending on molecular structure, is called the "activation energy" (98, 194). An excited molecule may dissipate the absorbed energy by: dissociating, transferring energy to another molecule at collision, rearranging into a new substance, giving off light by fluorescence, or producing heat (105, 143, 151).

Most organic materials absorb in the far and middle ultraviolet region, which often results in photochemical decomposition. Wavelengths below 486 nm are capable of breaking the C-C bond in many materials, and ultraviolet energy is generally capable of breaking the C-H and C-O bonds (13, 50, 56, 147, 194). Pure cellulose only absorbs light energy below about 270 or 340 nm and, therefore, cannot be affected directly by radiation of higher wavelengths. Effects of near ultraviolet radiation on cellulose are of lesser magnitude than those at 253.7 nm. Since near ultraviolet of about 300 to 400 nm may be present in light sources in much greater quantities than shorter wavelength ultraviolet, the near ultraviolet region may account for more ultimate damage (32, 33, 177, 179).

Photosensitization. Though visible and near ultraviolet radiation has little effect on pure cellulose, it is seldom completely free

of impurities and additives (42, 73). The reaction of light energy upon a sensitizer (i.e., impurities or additives such as dyes and finishes), and the resulting chemical action between the oxidation products and cellulose, or between the additive and the fiber, constitutes the photochemical action called photosensitization (33, 42, 92, 99, 132).

Impurities, foreign matter, and additives such as dyes, mordants, pigments, and sizings, often increase cellulose deterioration in the presence of light, since these types of matter may absorb longer wavelengths of radiation (i.e., near ultraviolet and visible) than the fiber substrate (32, 132). Though energy must be absorbed to affect reaction, absorbed energy does not, in all cases, cause photochemical changes, and much of the absorbed light is dissipated as heat (59, 179). The sensitizer may suffer decomposition and change the water or oxygen molecules present to hydrogen peroxide (H_2O_2) or ozone (O_3), which are capable of oxidizing cellulose, resulting in chain scission and/or rupture of the pyranose ring. Light and oxygen may convert the cellulose in cotton to oxycellulose, which may further degrade into strongly colored, low molecular weight compounds capable of staining and yellowing the fibers (32, 42, 99, 132, 179). Bleached cellulose may be more susceptible to light than raw cotton because impurities which could have a light filtering effect are removed, and the bleaching process may weaken the fibers (51).

Thermo-dynamic degradation. Thermo-dynamic energy affects cotton by increasing the vibrational activity of atoms and molecules, disturbing the chemical bonds, and thus increasing the rate at which

chemical reactions take place (98, 101, 150, 179). Much of the light energy reaching the surface of an object is converted to heat. The temperature of an irradiated object varies with light intensity, ventilation, relative humidity, and object color, with dark areas being about 30 percent higher in temperature than light areas (132, 162, 194). Though ultraviolet and visible radiant energy cause deterioration mainly on the surfaces of objects to a distance of only about 154 microns, infrared heat energy has a greater penetration potential, which may result in bond cleavage, embrittlement, and strength loss (96, 150).

Research has shown that an increase in temperature during light exposure may result in faster rates of fading and fiber deterioration. Feller (96, 98), for example, reported that a 10°C rise in temperature increased the fading of some fugitive pigments by a factor of 1.3, and a 12°C rise in temperature doubled the deterioration rate of selected textiles.

Factors Affecting Deterioration and Fading

Intrinsic and Extrinsic. The following are recognized factors influencing the fading and/or deterioration of textile objects:

Environmental Factors:

- Atmospheric composition and contaminants (oxygen, pollutants)
- Temperature
- Relative humidity
- Air currents
- Microbial and enzymatic attack
- Mechanical stress

Radiant Energy:

- Spectral distribution per wavelength
- Light intensity
- Exposure time

Fabric Characteristics:

Fiber type

Thickness of yarn, yarn twist, weave construction

Presence of foreign substances or additives

Type of dye (chemical constitution) and dyeings conditions (dyebath additives, pH, concentration)

Type of dye-fiber bond

Physical state of dye in substrate

Aftertreatments

Spectral sensitivity and absorption characteristics of substrate and dye (luster, reflectance)

Deterioration already occurred (42, 45, 46, 108, 110, 145, 146, 162, 188).

Environment condition and radiant energy characteristics are extrinsic elements and should be controlled in a museum environment. Intrinsic elements, or the nature of the medium, are generally beyond museum control (44).

Light Source. Though isolated portions of the spectrum present in light sources are known to cause specific effects on materials, there is no simple relation between spectral distribution of radiant energy emitted by light sources and fading or deterioration rate (110). The wavelength causing most damage varies depending upon the dye (172, 190, 195). In general, however, for equal number of wavelengths of radiant energy, as wavelength decreases through infrared, visible, and ultraviolet regions, fading and deterioration increase (45, 117, 118, 132, 172, 195). Ultraviolet and blue rays are potentially more injurious than longer wavelength red or infrared (50, 59). Absorbed ultraviolet radiation, containing photons of energies, is potentially more potent than absorbed visible or infrared energy (150, 195). It is generally accepted that, relatively, ultraviolet radiation is the most potentially harmful component of daylight, sunlight, and museum lighting sources,

though each of the three regions alone may cause fading and ultraviolet elimination does not ensure the safety of objects (42, 50, 123).

Light sources vary in their spectral emission characteristics, some emitting light with a greater proportion of short wavelengths than others. Ultraviolet radiation, however, is often present in light sources in low or negligible amounts (150). It has been established, therefore, that fading is principally due to visible radiation in most lighting situations (50, 139, 190, 192). The visible region is responsible for causing photochemical damage to many textile impurities or additives, and may cause indirect damage to the fabric itself. All dyes absorb and reflect radiant energy in the visible spectral region, reflecting most energy in the region of the color of the object (3, 154). All substances, except those most intensely colored, are capable of absorbing some of all visible wavelengths. Even bright blues absorb some radiant energy within the blue region. Ultraviolet and infrared energy also may be absorbed by dyes, finishes, impurities, and the fiber substrate (73, 192).

Fading often is caused primarily by a narrow band of wavelengths near the absorption maximum of the dye (50, 85, 162). A bright blue dye would absorb maximally in the red region, reflecting the blue. A red dye, absorbing high energy blue wavelengths would be expected to, and often does, fade more readily than a blue dye (172). Many factors are involved, however, and it is important to consider the fiber-dye-environment system as a whole. An object's color is not a fail-safe guide in determining the spectral region causing greatest damage (73, 145, 195).

McLaren (73) states that short wavelengths, if absorbed, can cause fading of a dye if longer wavelengths do so. Every dye-fiber system seems to possess a threshold wavelength, such that only shorter wavelengths, if absorbed, can cause photochemical activity. This critical wavelength is toward the red end of the spectrum for fugitive dyeings and toward the blue end for fast dyeings. Therefore, fugitive dyes may be faded by a greater range of wavelengths than fast dyeings, and, therefore, primarily by visible light (73, 172, 176, 179). For the faster dyes, visible light above the blue region may be inactive even if absorbed, and ultraviolet and short wavelength visible radiant energy may be the main factors in fading (33, 105, 190, 192). Thomson (195) states, "The more resistant a material is to deterioration by light, the more its eventual deterioration will be caused by ultraviolet rather than by visible light" (42, 195). Filtering out ultraviolet radiation may, therefore, benefit relatively light-stable objects more than fugitive ones. Some organic dyestuffs fade so rapidly that removal of ultraviolet has almost no retarding effect on fading (79, 101, 150). Both ultraviolet and infrared energy are invisible; they contribute nothing to the visibility of objects and, consequently, should be eliminated (42, 44, 132, 141, 160, 193, 195).

Total luminous energy (visible light intensity times exposure time) is more operative in affecting fading rate and deterioration than spectral distribution of the light source or spectral characteristics of energy absorbed by the object. Lowering illumination intensity reduces the number of photons per second reaching the surface of the illuminated object, thereby decreasing the potential rate of fade and deterioration

(110, 121, 151, 192).

Light intensities allowing adequate visibility and comfortable viewing will be affected by the size of the object, the reflection factor, color and brightness contrast between object and background, adaptation time for the eye, and individual visual differences. If the eyes were not previously excited by strong light, and if the background were recessive in color and brightness, illumination levels as low as 10 to 30 lux (about 1 to 3 fc.) can be acceptable for comfortable, adequate viewing (42, 120, 132, 141, 151, 157). Detail discrimination suffers below about 10 lux (approximately 1 fc.) and color discrimination below about 32 lux (3 fc.). The generally accepted limit for the most susceptible organic materials, including leather, feather, textiles, dyestuffs, and hair is 50 lux (about 5 fc.), while other sources recommend a minimum of about 125 to 160 lux (12 to 15 fc.) (72, 97, 101, 117, 118, 138).

Due to variation in individual vision and other conditions, levels cannot be fixed at exactly the same number of lux for all museums (42). Electrical dimmers allow systems to fluctuate with changing needs and to keep a relatively constant service value of illumination, which may vary due to dust collection and lamp depreciation over time (119, 121). Devices which limit exposure time, according to the reciprocity principle, reduce total energy reaching specimens as well. Rooms or showcases which illuminate only when a viewer walks into the area or operates a switch which automatically turns off, reduce unnecessary exposure time (151, 172). Special curtains which eliminate light and ultraviolet radiation may be placed over cases, to be moved and replaced by the viewer (44, 151). Especially sensitive objects, or those showing

noticeable fade should be transferred to storage to reduce exposure time (151).

Atmospheric Conditions. The influence of temperature on hydroscopic materials is interdependent with relative humidity (98). Relative humidity directly affects moisture content of natural fibers (194). Most dyes, especially on cotton, show an increase in fading with an increase in relative humidity and moisture content (53, 73, 110). Total elimination of moisture causes almost total elimination of fading in many cases. Though fibers and dyes differ in their sensitivity to moisture, the increase in rate of fading on cotton is often as much as 50 percent, with an increase in relative humidity from 45 to 50 percent to 80 to 90 percent (53, 73, 122). Therefore, relative humidity ideally should be kept low for textiles, though not low enough to cause dehydration and, thus, mechanical embrittlement (73, 101). Considering all factors (i.e., microbial growth, textile embrittlement, fading, and deterioration rates) Leene (33) suggests a relative humidity range of 45 to 65 percent for museums containing textile objects, and a temperature range of 19 to 22°C.

Due to their interdependence of temperature and relative humidity (i.e., relative humidity increases with a decrease in temperature and vice versa) it is difficult to establish a direct pattern of effect on fading of either one separately. Relative humidity is known to affect fading more than temperature and, thus, should be more carefully controlled. Especially at high temperatures, high relative humidity encourages fading. Only in the presence of moisture may hydrogen peroxide be formed to bleach and/or deteriorate dyes and fabric (33, 91, 106).

Lighting objects with lamps emitting large quantities of heat can raise the temperature of the object, thus lowering the effective relative humidity in the immediate area (73). The end results, even in a museum with carefully controlled climate, may include dimensional change, dehydration of the fabric, or increase in fading (119). A reduced fading rate may, in some cases, also result from lowered relative humidity, but extreme localized heating is not justified by this possibility (33, 73, 162).

Temperature and relative humidity fluctuation cause dimensional changes in absorbant objects, such as textiles, resulting in a mechanical strain on the object and ageing (96, 119, 152, 194). When light adjustments are made for day and night conditions, especially if heat-producing, high-intensity lighting is used, temperatures vary twice daily and produce inverse fluctuations in relative humidity, causing climactic fatiguing (150, 178, 194). In time, old and progressively ageing textiles become increasingly embrittled and inelastic until a point is reached when the object can no longer accommodate the daily dimensional changes (194).

The presence of oxygen in the atmosphere is an important factor in both deterioration and fading. Radiant energy often causes cellulose to become sensitive to oxidation, perhaps as a result of modifications in the glycosidic linkage, so that the linkage becomes susceptible to rupture by oxidation. Oxygen atmospheres usually accelerate actinic degradation, but direct photolysis of cellulose also can occur in the absence of oxygen, especially with high-intensity, ultraviolet radiation (89, 179, 190). An evacuated or inert environment, however, is not

recommended for all objects, since oxygen is essential to the stability of some chemical structures (32, 51, 73).

Gases found in polluted atmospheres, such as sulphur dioxide (SO_2), ozone (O_3), carbon dioxide (CO_2), also may increase fading. Museum climate control systems should eliminate these pollutants effectively without the production of ozone, which is a by-product of some climate control systems (101).

Cotton is most stable in neutral condition. When irradiated in the presence of oxygen, it often suffers a reduction in pH, and is more susceptible to photodecomposition. Photochemical damage also increases the susceptibility of cellulose to damage by weakly alkaline solutions often used in wet-cleaning (42, 51, 73, 132).

Fading Rate. The rate of photochemical decomposition of cellulosic materials diminishes with time. This may be due to a screening effect in which the uppermost layer of a substance absorbs damaging radiant energy, forming a protective barrier, and because penetration of textiles by visible light energy occurs to a very shallow depth. The same is true for fading rate of dyes; the rate of fading decreases as the dye is progressively destroyed (73, 132, 172). Possibly, this results because only accessible dye particles are faded by light energy, causing a progressive increase in lightfastness when most small particles have been affected. In one test, the most rapid fading occurred within the first two hours of accelerated light exposure (by quartz 360-watt "Uviarc" lamp at two feet distance), the fading rate being nearly constant for 130 subsequent hours under the same exposure. Therefore, the

point at which fading of different dyes is compared is important because of this inconstant rate of fading (134, 153).

A fading rate curve may be constructed by plotting increase (or decrease) in reflectance at the wavelength of maximum absorption as a function of exposure time (145). A fugitive dyeing generally will yield a curve displaced to the left, a dye of higher fastness will yield a curve displaced to the right (Figure 3), but the shape of the curves should be about the same (50, 162, 188).

As depth of dyeing or dye concentration increases, fading decreases (64, 101, 133). In addition, discoloration of a substrate generally results in a more or less uniform change in reflectance at all wavelengths, whereas fading of a colorant yields a greater reflectance change at selected wavelengths only (135).

Off-tone fading of a dye may affect fading rate curves by causing a reddening of water-soluble dyes and a blueing of water-insoluble dyes (108). Slight color increase in the early stages of the fading rate curve is sometimes noted and may be due to heat energy breaking down large aggregated dye particles to smaller particles, causing an apparent rise in depth of color and counteracting the effects of fading (108).

Individual fading curves consist of reflectance spectra of the dye before and after light exposure, as shown in Figure 4 (59). Berger and Brackes (59) state that a reduction of relative reflectance at the region of maximum absorption and a slight increase in reflectance at the region of minimum absorption is the general activity of dyes faded by light. An individual spectral curve, or some indication of color of artifacts before exposure may be obtained without relying simply on

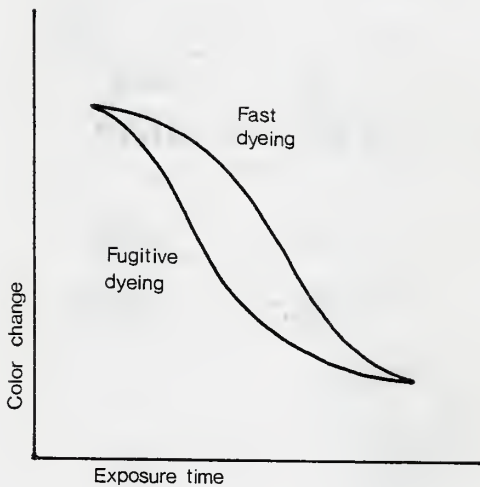


Figure 3

Fading Rate Curves for a Fugitive Dyeing
and a Fast Dyeing
(Taken from 50, 188).

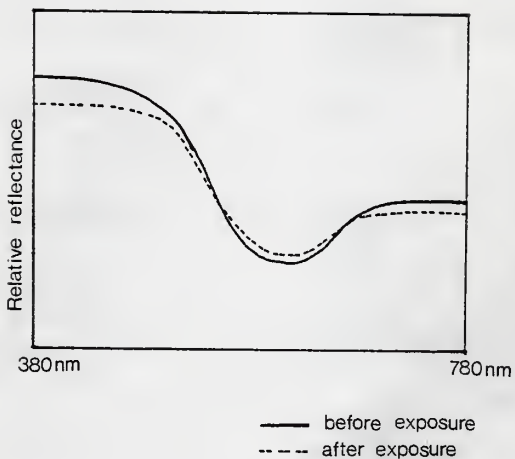


Figure 4

Individual Fading Curve
(Taken from 59).

memory of original artifact color (172).

Quantitative Tests

Copper Number

Aldehyde or potential aldehyde groups are formed in cellulose as a result of acid hydrolysis and oxidative degradation. As the number of aldehyde groups in degraded cellulose increase, its reducing power also increases. The copper number test is a quantitative method for determining the reducing power of cellulose and, hence, the extent of degradation (34, 35).

Pure, undegraded cellulose reduces .2 to .3 grams of copper (Fehling's solution) from the cupric to the cuprous state, resulting in a copper number of 0.02 to 0.03. Degraded cellulose may attain a copper number as high as 14 (32, 34).

K/S Value

The Kubelka-Munk equation defines the relationship between spectral reflectance data and dye concentration. K/S values may be used to express color change quantitatively. The function is as follows:

$$\frac{K}{S} = \frac{(1-R)^2}{2R}$$

where: R = decimal reflectance
 S = coefficient of scatter (constant)
 K = coefficient of absorption (proportional to concentration of dye).

Since the region of maximum absorption exhibits the greatest change in reflectance with a change in color, the percentage reflectance at point of maximum absorption, read from the spectral reflectance curves of

colored samples, is used to obtain K/S value data.

PLAN OF PROCEDURE

The purpose of this study was to evaluate and compare the amount of color change and deterioration which occurred on undyed and dyed cotton samples exposed to incandescent, fluorescent, and quartz lighting systems. Samples were exposed to incandescent lamps with and without infrared filters, to fluorescent lamps with and without ultraviolet filters, and to quartz lamps with and without infrared and ultraviolet filters. After light exposure, the samples were evaluated for color change with a Cary 219, recording, ultraviolet/visible spectrophotometer. Chemical degradation was ascertained by determining changes in copper number.

Questionnaire

Prior to selecting the lighting systems to be evaluated in this study, the following letter and questionnaire were mailed to 80 textile museums and galleries in the United States (see Appendix A). The purpose of the questionnaire was to determine the types and brands of lighting and filter assemblies and general environmental conditions that were being used or that had been used by museums. The lamps and filters evaluated in this study were those listed most often by museums as the types of lamps used in textile exhibits or planned for use in the immediate future.

November 24, 1977

Dear _____

I am a graduate student in textile science and conservation at Kansas State University. I feel it is important to produce a thesis which is timely and useful to industry and/or organizations. As my field is conservation, feedback from museums will help me to investigate timely problems and produce a viable manuscript which has potential for actual contributions to the field. The topic I am investigating is museum lighting, more specifically, the effects of available fluorescent lights and filters on the fading of certain historical dyes on textiles.

Response from you would be greatly appreciated. A short questionnaire is provided as well as a stamped, addressed return envelope.

Thank you.

Sincerely,

Janet Bowman
Clothing/Textiles/Interior Design
Department
Justin Hall
Kansas State University
Manhattan, Kansas 66506

These questions refer to your textiles and/or costume galleries:

Temperature _____

Relative Humidity _____

Type of fluorescent lamp most often used and producer

Filter(s) used with this light and producer

Distance of objects from light source

For general gallery lighting

For general gallery lighting

For showcase lighting

For showcase lighting

General level of illumination (footcandles) _____

Have you considered using any new or different light sources and/or filters? If so, what kind and who is the producer? _____

Are there any particular groups of colors, dyes, or objects for which you notice an unusually intense fading problem?

Are there any specific questions which you think need investigating concerning museum lighting as related to deterioration of objects?

Please include any other comments on the reverse side of this sheet.

Experimental Fabric

The fabric selected for this research was an 80 x 80, bleached, cotton print cloth (Style #400) manufactured by Testfabrics, Inc. All samples were scoured in a 0.5 percent solution of AATCC Detergent 124 prior to dyeing. Randomly selected samples were dyed with three natural dyes. Within each dye type, samples, measuring 5 x 8.25 cm., were randomly assigned to the six lighting/filter systems. Undyed (control) cotton samples also were prepared for light exposure.

Application of Natural Dyes

The three dyes chosen for this research, turmeric, madder, and indigo, are all vegetable in origin. They represent three of Bemiss' "five material colors", and three of the major dye application classes (i.e., direct: turmeric; mordant: madder; and vat: indigo). Turmeric was known to be a fugitive dye, whereas indigo and madder were reported as having greater lightfastness. All three were commonly used throughout history to dye both cotton and wool textiles and are well represented in current museum textile collections. The procedures given by Weigle (43), Adrosko (3), and Colour Index (9) were used in applying the turmeric, madder, and indigo dyes, respectively.

Turmeric

To extract the turmeric dyestuff, 14 g of turmeric powder was placed in a cheesecloth bag, soaked overnight in one liter of distilled water, and then boiled gently for one hour. After removing the cheese-

cloth bag containing the turmeric powder, the level of the bath was brought up to the one liter mark with distilled water. Cotton samples weighing 50 g were entered into the dyebatch (pH 5.8) and then the temperature was raised slowly to 60°C. After dyeing for 45 minutes at 60°C, the samples were removed, rinsed thoroughly, and allowed to dry at room temperature.

Madder

Prior to applying the madder dyestuff, the cotton samples, weighing 50 g, were pre-mordanted by the alum (aluminum potassium sulfate) and tannic acid procedure described by Adrosko (3). The samples were each wetted out thoroughly in distilled water, and immersed in an alum mordanting solution containing 113.4 g alum and 28.35 g sodium carbonate dissolved in 15.14 liters of distilled water. Samples were gently boiled for one hour. After remaining in the solution overnight, the samples were rinsed in distilled water, and placed in a bath containing 28.35 g of tannic acid dissolved in 15.14 liters distilled water. The samples were soaked in the tannic acid solution overnight and then rinsed briefly. The alum mordanting process was repeated and excess moisture was removed from samples just before dyeing.

A 15.14 liter dyebath was prepared using 56.7 g of madder which had been soaked in distilled water overnight and strained through cotton muslin. After adjusting the pH to 6.0, the cotton samples were immersed in the dyebath, the temperature was raised to 35°C, and the dyeing was continued for one hour. The dyebath was cooled to room temperature and the samples were allowed to soak overnight. The dyeing process was

repeated twice more using 85.05 g of madder for the second and third dyebaths. After dyeing, the samples were rinsed well and allowed to dry at room temperature.

Indigo

Colour Index (9) Method IV (hydrosulphite vat) was used to dye the cotton samples, weighing 50 g, with indigo. The first vat contained 18 ml of sodium hydroxide (30 percent), 4 g of sodium hydrosulphite, 7.78 ml liquid indigo, and 2.663 liters of distilled water. Samples were entered into the dyebath set at 50°C and dyed for 20 minutes. The second dye vat was similar to the first, except 9.98 ml of indigo was used and the temperature was maintained at 80°C for 20 minutes while the samples were immersed.

The dyed samples were allowed to oxidize in air for 30 minutes between dyeings and were scoured at the boil in a 0.5 percent solution of AATCC detergent after the second vat.

Lamps and Filters

The incandescent lamp/filter systems used in this study were an unfiltered, Sylvania 300-watt, spot-lamp and a Sylvania, 300-watt, PAR/56, dichroic filter, heat reflecting lamp with Corning Noviol 0 glass heat (infrared) filter. The filter was placed 30.5 cm. below the lamp.

The quartz systems used were an unfiltered, Sylvania, Super Q Clear, Tungsten Halogen Quartz, 250-watt lamp and the same lamp with both Corning Noviol 0 glass infrared filter and Rohm and Haas rigid UF3, Plexiglass, ultraviolet filter. The infrared filter was placed 30.5 cm.

below the lamp and 716 cm. above the ultraviolet filter to reduce the amount of heat reaching the ultraviolet filter.

The fluorescent systems used were an unfiltered, Verilux F40T12-VLX, 40-watt, 40-inch, medium, bi-pin lamp and Verilux F40T12VLX/M, low ultraviolet, 40-watt, 40-inch, medium bi-pin lamp with a Rohm and Haas rigid UF3, Plexiglass, ultraviolet filter. Tables 2 and 3 list the spectral power distributions per lumen per 10 nm for the lamps and the manufacturer's transmittance specifications for the two filters used in the study. Appendix B lists lamp and filter suppliers.

Exposure

Lamps and filters were arranged in plywood light boxes, painted matte black to reduce light reflection, so that light intensity reached 150 footcandles (1615 lux) at sample level (see Figure 5). The temperature and relative humidity of the ambient air during light exposure were $21 \pm 1^\circ\text{C}$ and 65 ± 2 percent, respectively. To ensure constant light intensity, all lamp and filter systems were preaged for 100 hours prior to sample exposure as suggested by the manufacturers. Undyed and dyed cotton samples were assigned randomly to lamp and filter systems, and positions in light exposure boxes. Berger and Brackes (59) reported a 50 percent fading of certain dyed textiles after 50,000 footcandle hours of exposure; therefore, 60,000 footcandle hours of exposure was selected as the maximum exposure time in this study, which was achieved by an exposure period of 400 hours with light intensity at 150 footcandles for each lamp and filter system. Samples were exposed to alternating periods of 100 clock hours (15,000 fc hours) of light and 68 hours of darkness. Black bulb temperatures recorded are listed in Table 4.

Table 2. Spectral Power Distribution of Incandescent, Quartz, and Fluorescent Lamps (Microwatts/sq. cm./10 nm/lumen) (Taken partially from Thomson (34)).

Wave-length, nm	Incan-descent	Low IR Incan-descent	Quartz	Fluorescent	Low UV Fluorescent
250			1		
260			1		
270			2		
280			3		
290			4		
300			6	0	
310	0		7	20	
320	3	0	8	0	
330	4	1	10	4	
340	5	2	13	0	
350	6	7	16	2	0
360	8	9	19	3+44	1+8
370	10	10	22	6	6
380	13	13	26	9	15
390	16	16	31	12	17
400	20	18	36	15	19+45
410	24	19	41	19+87	20+3
420	28	20	47	23	25
430	33	22	53	28	35
440	39	27	59	33+160	54+135
450	46	29	65	36	75
460	52	32	71	38	94
470	59	37	78	40	106
480	66	41	84	40	108
490	74	49	91	40	110
500	82	57	98	40	110
510	90	68	105	41	108
520	99	72	112	47	107
530	107	84	119	57	107
540	117	101	125	85+113	108+111
550	127	105	132	124	112
560	137	118	138	165	119
570	146	120	145	197	126
580	156	123	151	210+39	134+35
590	166	125	157	205	142

Table 2. (Continued)

Wave-length, nm	Incan-descent	Low IR Incan-descent	Quartz	Fluorescent	Low UV Fluorescent
600	176	126	163	184	150
610	185	127	169	156	155
620	195	128	175	124	158
630	205	130	181	99	165
640	217	130	187	74	165
650	225	133	192	55	172
660	234	135	198	39	175
670	244	137	202	30	136
680	252	137	206	22	102
690	261	138	210	17	81
700	270	140	214	13	67
710	278	147	217	10	58
720	286	152	221	8	50
730	295	142	224	6	40
740	302	130	228	4	30
	309	110	231	2	20
750	316		234	1	12

Table 3. Spectral Range Distribution Transmitted through Lamp Filters.

Percentage Transmittance			
Wave-length, nm	Corning Noviol 0	Wave-length, nm	Rohm and Haas UF3
680-720	60	370-380	0
720-760	45	380-390	1
760-800	33	390-400	3
800-840	20	400-410	22
840-880	12	410-420	60
880-920	7	420-430	85
920-960	3	430-440	91
960-1000	1	440-450	97
1000-1040	1		
1040-1080	1		
1080-1120	1		
1120-1160	1		
1160-1200	1		
1200-1240	1		

Table 4. Black Panel Temperatures for Lamp and Filter Systems During Sample Exposure.

Lamp and Filter System	Black Panel Temperature, °C
Fluorescent	
Unfiltered	26.5
Filtered	25.5
Quartz	
Unfiltered	36.5
Filtered	32.0
Incandescent	
Unfiltered	35.0
Filtered	32.0

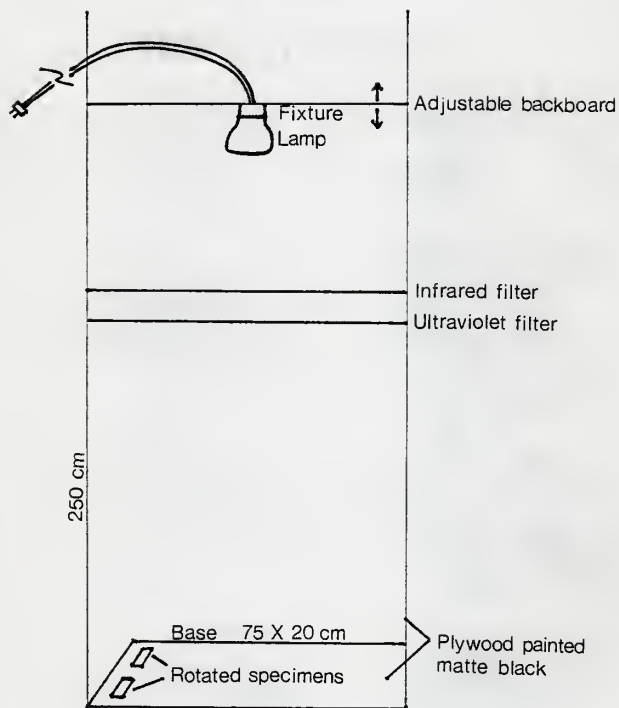


Figure 5
Light Boxes

Color Measurement

After 0, 100, 200, 300, and 400 clock hours of light exposure, reflectance readings (380-480 nm) were taken on the undyed and dyed cotton samples with a Cary 219 uv/visible recording spectrophotometer with a D₆₅ illuminant. Percentage reflectance readings at λ_{max} for each sample were converted to K/S values according to the procedures outlined by Judd (23, 108, 109, 110). Scanning parameters were recorded on the original reflectance spectra, presented in Appendix C.

Quantitative Tests

Copper Number

Copper number was determined on the undyed and dyed cotton samples before exposure and after 400 clock hours of exposure. Because of the small sample size available for testing, Skinkle's (40) micro-copper number procedure was adapted for this test.

Calculations were based on the bone dry weight of the test samples. The following solutions were prepared for the test:

- Solution A: 100 g of crystalline copper sulfate dissolved in 1 liter of distilled water,
- Solution B: 50 g of sodium bicarbonate and 150 g of sodium carbonate dissolved in 1 liter of distilled water,
- Solution C: 100 g of ferric alum (ammonium sulfate) and 49 ml of concentrated sulfuric acid in 1 liter of distilled water,
- Solution D: 0.5 percent sodium carbonate solution (5 g of sodium carbonate in 1 liter of distilled water),
- Solution E: 1 liter of two normal sulfuric acid solution (55 ml of concentrated sulfuric acid in 1 liter of distilled water), and

Solution F: .04 normal potassium permanganate solution (128 g of potassium permanganate in 1 liter of distilled water).

Micro samples, weighing 0.25 g each, were placed in individual test tubes. A boiling mixture of 0.5 ml of solution A and 9.5 ml of solution B was poured over each sample. The test tubes were covered and placed in a boiling water bath for two hours. The contents of each test tube were filtered by suction through a fritted glass filter, then washed with 10 ml each of solution D and distilled water. Filtrate and washings were discarded. Next, 5 ml of solution C, and 5 ml of solution E were poured over the residue. The ferric acid and alum washings were titrated with solution F.

In addition, 5 ml of unused solution C and 5 ml of unused solution E were titrated as a control.

The following equation was used to determine copper number:

$$\text{Copper Number} = [(B \times C \times (D/A))] \times 100$$

where: A = dry weight of sample (moisture regain 3.178 percent for undyed specimens, 3.199 percent for turmeric-dyed specimens, 3.306 percent for madder-dyed specimens, and 3.178 percent for indigo-dyed specimens),
 B = true volume of KMnO_4 (volume of KMnO_4 used for blank was subtracted from volume of KMnO_4 used for specimen),
 C = normality of KMnO_4 (0.0395), and
 D = milliequivalent weight of copper (0.0636).

PRESENTATION OF DATA WITH DISCUSSION

Museum lighting systems should be selected carefully so that the characteristics of the art objects are enhanced and viewing is facilitated, while minimizing the rate of deterioration. Textiles as well as many other types of art objects are susceptible to color change and deterioration during light exposure. The rate of change is determined by the light sensitivity of the object being illuminated, in addition to environmental factors such as the spectral characteristics and intensity of the light source.

Evaluated in this study were the effects of six lighting systems on the rate and extent of colorfastness and deterioration of cotton fabric dyed with selective natural dyestuffs commonly found on historic textiles. The three dyes selected for this study were turmeric, madder, and indigo; undyed cotton samples also were evaluated. Samples were exposed for 0, 100, 200, 300, and 400 clock hours to the following lighting/filter systems:

- incandescent lamp, unfiltered,
- incandescent lamp, filtered with an infrared filter,
- quartz lamp, unfiltered,
- quartz lamp, filtered with ultraviolet and infrared filters,
- fluorescent lamp, unfiltered, and
- fluorescent lamp, filtered with an ultraviolet filter.

After light exposure, color change was assessed by comparing the K/S values of the light-exposed cotton samples with those from unexposed

controls. K/S values were calculated based on the percent reflectance at the point of maximum absorption read directly from the reflectance spectra. Actinic degradation of the cotton substrate was evaluated by the copper number test. The undyed and dyed cotton samples were evaluated for both color change and actinic degradation after 0, 100, 200, 300, and 400 clock hours of exposure to the six lighting/filter systems.

The Kansas State University Computing Center performed the statistical analysis for this study. The Synscort IV-and-a-half program developed and copyrighted by Whitlow Computer Systems, Inc., in 1977 was used.

Null Hypotheses

1. There was no significant difference in color change among the undyed samples exposed to incandescent, fluorescent, and quartz lighting/filter systems.
2. There was no significant difference in color change among the undyed samples exposed to unfiltered and filtered lighting/filter systems.
3. There was no significant difference in color change among the undyed samples exposed to light for 0, 100, 200, 300, and 400 clock hours.
4. There was no significant difference in color change among the dyed samples exposed to incandescent, fluorescent, and quartz lighting/filter systems.
5. There was no significant difference in color change among the dyed samples exposed to unfiltered and filtered lighting/filter

systems.

6. There was no significant difference in color change among the dyed samples exposed to light for 0, 100, 200, 300, and 400 clock hours.

7. There was no significant difference in color change among the samples dyed with turmeric, madder, and indigo.

8. There was no significant difference in deterioration among samples exposed to incandescent, fluorescent, and quartz lighting/filter systems.

9. There was no significant difference in deterioration among samples exposed to unfiltered and filtered lighting/filter systems.

10. There was no significant difference in deterioration among samples exposed to light for 0 and 400 clock hours.

11. There was no significant difference in deterioration among undyed samples and samples dyed with turmeric, madder, and indigo.

Evaluation of Color Change

Table 5 shows the K/S values of the undyed cotton samples before and after 100, 200, 300, and 400 clock hours of exposure to the six lighting/filter systems evaluated in this study. The mean differences in the K/S values after each exposure level also are presented in Table 5. The sources of variation were lighting (three levels: incandescent, quartz, and fluorescent), filter type (two levels: unfiltered and filtered), and exposure time (five levels: 0, 100, 200, 300, and 400 clock hours of exposure). The analysis of variance results showed that filter type and exposure time had a significant effect on the extent of color change which occurred in the undyed samples during light exposure. Light source and all second order interactions were not significant (see Table 6).

According to the Duncan's Multiple Range Test, a significantly greater amount of change occurred in the cotton samples exposed to the unfiltered light sources than to those samples exposed to the filtered light sources (see Table 7). However, even though the mean differences in the K/S values for the unfiltered and filtered treatments differed significantly, the actual differences were small, and there were no perceivable differences in the color of the cotton samples before and after light exposure (i.e., no significant yellowing).

As exposure time increased, the mean differences in K/S values for the undyed samples progressively increased (see Table 8). Results from the Duncan's Multiple Range Test showed no significant change in the mean differences in K/S values between 100, 200, and 300 clock hours of exposure. The 400 hour exposure level produced K/S values dif-

Table 5. Differences in K/S Values of Undyed Cotton Samples after Light Exposure.

Light	Filter	Exposure Time, Clock Hours	K/S Value		Differences in K/S Values
			Initial	After Exposure	
Incandescent	Unfiltered	100	0.0294	0.0330	0.0036
		200	0.0294	0.0314	0.0020
		300	0.0294	0.0327	0.0033
		400	0.0294	0.0334	0.0040
	Filtered	100	0.0294	0.0330	0.0036
		200	0.0294	0.0330	0.0036
		300	0.0294	0.0330	0.0036
		400	0.0294	0.0334	0.0040
Quartz	Unfiltered	100	0.0294	0.0323	0.0029
		200	0.0294	0.0327	0.0023
		300	0.0294	0.0330	0.0036
		400	0.0294	0.0354	0.0060
	Filtered	100	0.0294	0.0323	0.0029
		200	0.0294	0.0361	0.0067
		300	0.0294	0.0333	0.0039
		400	0.0294	0.0354	0.0060
Fluorescent	Unfiltered	100	0.0294	0.0317	0.0023
		200	0.0294	0.0310	0.0016
		300	0.0294	0.0310	0.0016
		400	0.0294	0.0337	0.0043
	Filtered	100	0.0294	0.0317	0.0023
		200	0.0294	0.0334	0.0040
		300	0.0294	0.0350	0.0056
		400	0.0294	0.0344	0.0050

Table 6. Analysis of Variance (ANOVA) for K/S Value Differences for Undyed Samples.

Source of Variation	Degrees of Freedom	Sum of Squares	F	PR>F*
Light (L)	2	0.00000553	4.37	0.0675
Filter (F)	1	0.00000672	10.62	0.0173*
Exposure Time (E)	3	0.00001212	6.39	0.0269*
L X F	2	0.00000174	1.38	0.3219
L X E	6	0.00000687	1.81	0.2445
F X E	3	0.00000601	3.17	0.1066
Error	6	0.00000380		
Total	23	0.00004280		

*Significant groups at the 0.05 level of confidence are marked with an asterisk.

Table 7. Ouncan's Multiple Range Test for K/S Value Differences in Filter Type Associated with Undyed Cotton Samples.

Filter	Mean	Grouping*
Unfiltered	0.004267	A
Filtered	0.003208	B

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

Table 8. Ouncan's Multiple Range Test for K/S Value Differences of Exposure Time Associated with Undyed Cotton Samples.

Exposure Time	Mean	Grouping*
100 Hours	0.002933	A
200 Hours	0.003533	A
300 Hours	0.003600	A
400 Hours	0.004883	B

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

ferences that were significantly greater from all other exposure levels, but these differences were not visually perceptible.

K/S values for the undyed cotton samples at each exposure level are shown in Figure 6. The curve indicates the greatest change in K/S values after 100 hours of exposure and between 300 and 400 hours of exposure.

The K/S values and differences for the cotton samples dyed with turmeric, madder, and indigo after 0, 100, 200, 300, and 400 hours of exposure to the six lighting/filter systems are shown in Table 9. Analysis of variance results showed the significant independence variables to be dye type, light source, filter type, and exposure time (see Table 10). However, the following second order interactions also were significant: dye type X light source, dye type X exposure time, and light source X exposure time.

The Duncan's Multiple Range Test performed on K/S value differences for dye type showed that indigo exhibited the greatest amount of color change, whereas madder had the least amount of color change (see Table 11). These values correlate with visual difference perceived in the samples after light exposure. In general, the samples dyed with indigo and turmeric exhibited a greater color loss (i.e., a greater change in K/S values) after 400 hours of exposure than did the madder-dyed samples (see Figure 7). This effect was expected since mordanted dyes generally exhibit less color loss during light exposure than more fugitive and unmordanted dyes.

Among the three light sources, the differences in K/S values for the incandescent lamps were not unlike those which were recorded for

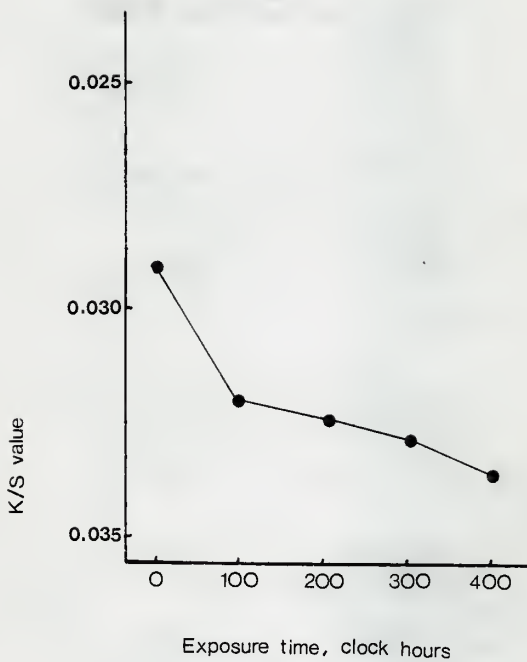


Figure 6

Effect of Light Exposure on K/S Value Differences
of Undyed Cotton Samples

Table 9. Differences in K/S Values of Dyed Cotton Samples after Light Exposure.

Dye	Light	Filter	Exposure Time, Clock Hours	K/S Value		Difference in K/S Values
				Initial	After Exposure	
Turmeric	Incandescent	Unfiltered	100	1.125	0.914	0.221
			200		0.812	0.313
			300		0.641	0.484
		Filtered	400		0.604	0.521
			100		0.926	0.199
			200		0.792	0.333
	Quartz	Unfiltered	300		0.723	0.402
			400		0.641	0.484
			100		0.802	0.323
		Filtered	200		0.768	0.357
			300		0.641	0.484
			400		0.569	0.556
Fluorescent	Unfiltered	100	0.926	0.199		
		200	0.832	0.293		
		300	0.723	0.402		
	Filtered	400	0.641	0.484		
		100	0.817	0.308		
		200	0.701	0.424		
400	Unfiltered	300	0.641	0.484		
		400	0.569	0.556		
		100	0.869	0.256		
	Filtered	200	0.745	0.380		
		300	0.680	0.445		
		400	0.641	0.484		

Table 9 (Continued).

Oye	Light	Filter	Exposure Time, Clock Hours	K/S Value		Difference in K/S Values
				Initial	After Exposure	
Madder	Incandescent	Unfiltered	100	0.792	0.749	0.043
			200		0.731	0.061
		300	0.680		0.112	
		400	0.660		0.132	
		100	0.782		0.010	
	Quartz	Unfiltered	200		0.768	0.024
			300		0.723	0.069
		400	0.680		0.112	
		100	0.768		0.024	
		200	0.759		0.033	
Fluorescent	Unfiltered	Filtered	300	0.723	0.069	
			400	0.736	0.056	
		100	0.792	0.000		
		200	0.817	-0.025		
		300	0.759	0.033		
	Filtered	Unfiltered	400	0.745	0.047	
			100	0.782	0.010	
		200	0.777	0.015		
		300	0.777	0.015		
		400	0.777	0.015		

Table 9 (Continued).

Oye	Light	Filter	Exposure Time, Clock Hours	K/S Value		Difference in K/S Values
				Initial	After Exposure	
Indigo	Incandescent	Unfiltered	100	2.080	1.795	0.285
			200		1.600	0.480
		300	1.289		0.791	
		400	1.187		0.893	
		100	1.767		0.313	
	Quartz	Filtered	200		1.542	0.538
			300		1.433	0.647
		400	1.289		0.791	
		100	1.883		0.197	
		200	1.795		0.285	
Fluorescent	Unfiltered	Filtered	300	1.289	0.791	
			400	1.325	0.755	
		100	1.977	0.103		
		200	1.853	0.227		
		300	1.228	0.852		
	Filtered	400	1.363	0.717		
		100	1.687	0.393		
		200	1.542	0.538		
		300	1.383	0.697		
		400	1.383	0.697		
Filtered	100	1.713	0.367			
	200	1.542	0.538			
	300	1.486	0.594			
	400	1.486	0.594			

Table 10. Analysis of Variance (Anova) for K/S Value Differences for Dyed Samples.

Source of Variation	Degrees of Freedom	Sum of Squares	F	PR>F*
O	2	3.27970436	1811.79	0.0001*
L	2	0.02032353	11.23	0.0018*
F	1	0.03129168	34.57	0.0001*
E	3	0.79718515	293.23	0.0001*
O x L	4	0.04781139	13.23	0.0002*
O x F	2	0.00243503	1.35	0.2971
O x E	6	0.39434697	72.62	0.0001*
L x F	2	0.00078419	0.43	0.6582
L x E	6	0.09152847	16.85	0.0001*
F x E	3	0.00296560	1.09	0.3899
O x L x F	4	0.00369122	1.02	0.4359
O x L x E	12	0.09942328	9.15	0.0003*
O x F x E	6	0.00447319	0.82	0.5729
L x F x E	6	0.01193936	2.20	0.1157
Error	12	0.0108612		
Total	71	4.79886465		

*Significant groups at the 0.05 level of confidence are marked with an asterisk.

Table 11. Duncan's Multiple Range Test for K/S Value Difference of Dye Type Associated with Dyed Samples.

Dye	Mean	Grouping*
Turmeric	0.390917	B
Madder	0.035417	C
Indigo	0.545125	A

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

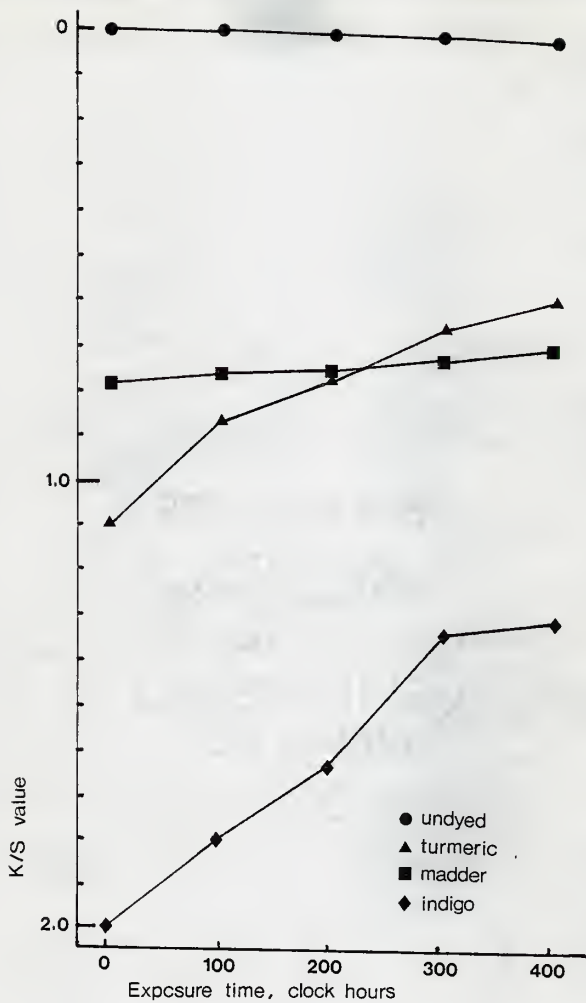


Figure 7

Effect of Light Exposure on K/S Values of the Undyed and Dyed Cotton Samples.

fluorescent lamps, whereas the mean differences in K/S values for the quartz lamp was significantly different from both the incandescent and fluorescent lamps (see Table 12). The quartz lighting/filter systems caused the least amount of color change and incandescent caused the greatest.

According to Ouncan's Multiple Range Test applied to the mean differences in K/S values for the unfiltered and filtered lighting systems, the filters significantly reduced the extent of color change in the dyed cotton samples during light exposure (see Table 13 and Figure 8). Thus, the filters reduced the amount of harmful radiation reaching the dyed samples and the extent of fading.

A significant increase was observed in mean K/S value differences after 100, 200, 300, and 400 hours of exposure (see Table 14), thus a significant change in color occurred after each exposure level. Though the change from 200 to 300 exposure hours was unexpectedly large, the general trend indicates a reduction in fading rate from 100 to 200, and 300 to 400 exposure hours. This trend was expected since most dyes show a reduction in rate of fade throughout exposure (59, 76). The small amount of change from 300 to 400 hours may indicate that the dye had reached approximately 50 percent fade after 50,000 footcandle exposure hours, as predicted by Berger and Brackes (59), after which rate of fade generally decreases.

The significant second order interaction of light source X dye type (see Table 15) indicated that turmeric samples faded least under incandescent light and most under fluorescent. Madder and indigo samples faded most under incandescent lamps, madder fading least under

Table 12. Duncan's Multiple Range Test for K/S Value Difference for Light Source Associated with Dyed Samples.

Grouping*	Mean	Light
A	0.343667	Incandescent
B	0.302583	Quartz
A	0.325208	Fluorescent

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

Table 13. Duncan's Multiple Range Test for K/S Value Difference for Filter Type Associated with Dyed Samples.

Grouping*	Mean	Filter
A	0.344667	Unfiltered
B	0.302972	Filtered

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

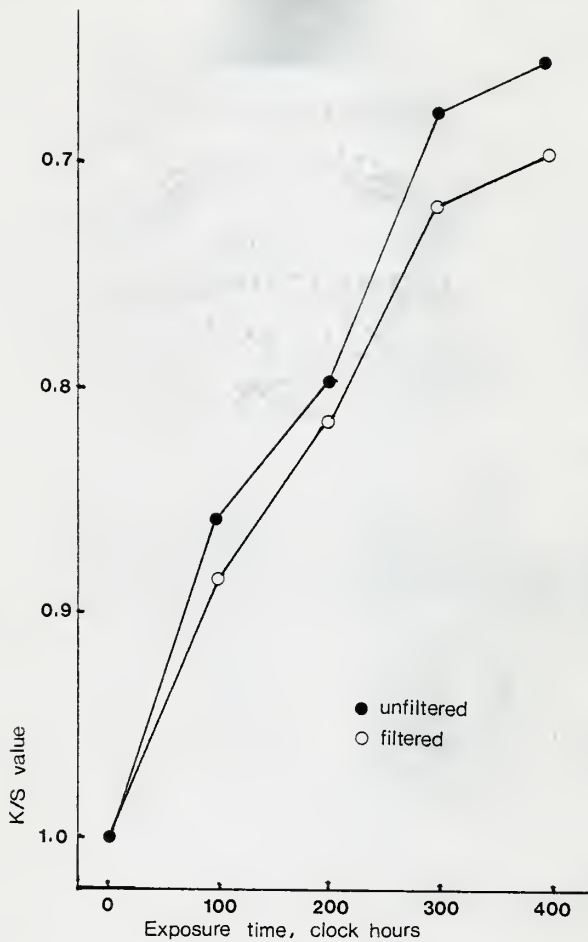


Figure 8

Effect of Light Exposure on the K/S Value Differences for Cotton Samples Exposed to Unfiltered and Filtered Lighting/Filter Systems.

Table 14. Duncan's Multiple Range Test for K/S Value Difference for Exposure Time Associated with Dyed Samples.

Grouping*	Mean	Exposure Time
A	0.438278	400 Hours
B	0.409500	300 Hours
C	0.267444	200 Hours
D	0.180056	100 Hours

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

Table 15. K/S Value Differences for Light Source and Dye Type Associated with Dyed Samples.

Dye Type	Light Source		
	Incandescent	Quartz	Flourescent
Turmeric	0.36837500	0.38725000	0.41712500
Madder	0.07037500	0.02962500	0.006250000
Indigo	0.59225000	0.49087500	0.552250000
Ranking			Mean
Indigo under Incandescent			0.5923
Indigo under Fluorescent			0.5523
Indigo under Quartz			0.4909
Turmeric under Fluorescent			0.4171
Turmeric under Quartz			0.3873
Turmeric under Incandescent			0.3684
Madder under Incandescent			0.0704
Madder under Quartz			0.0296
Madder under Fluorescent			0.0063

fluorescent and indigo fading least under quartz. The fast dye, madder, was expected to fade most under light sources containing high energy invisible radiation, since fast dyes often do not respond to low energy invisible radiation as readily as do fugitive dyes (195). In this respect, the results of this study did not reveal trends published in the current literature. Incandescent lamps, showing greatest K/S value differences in Table 12, caused greatest amount of color change for two dyes in Table 15, whereas quartz, showing least K/S value difference in Table 12, caused greatest amount of color change for no dyes in Table 15.

Each dye showed progressively greater total color change from 100 to 400 hours (see Table 16); indigo and turmeric, the most fugitive dyes in this study, showed greater K/S value difference after 100, 200, and 300 hours of exposure than the least fugitive dye, madder.

K/S value differences for exposure time \times light source (see Table 17) showed greatest total color change for all light sources after 400 hours of exposure, except for quartz which showed greater total change after 300 hours. The incandescent lighting/filter treatments caused greatest increments of color change at 100 and 400 hours of exposure, with fluorescent showing greatest change at 200 hours, and quartz greatest change at 300 hours. Quartz showed least K/S value difference after 100, 200, and 400 hours of exposure.

Figure 9 shows actual K/S means for each light source, filtered and unfiltered, plotted against exposure time. The reversal of curves (i.e., quartz and incandescent showing least color change at 100 and 200 hours of exposure and fluorescent showing least change at 400 hours) may indicate the reason for the non-significance of light source \times filter type \times

Table 16. K/S Value Difference for Exposure Time and Oye Type Associated with Oyed Samples.

Oye Type	Exposure Time			
	100 Hours	200 Hours	300 Hours	400 Hours
Turmeric	0.24933333	0.35000000	0.45016667	0.51416667
Madder	0.01450000	0.01800000	0.04966667	0.05950000
Indigo	0.27633333	0.43433333	0.72866667	0.74116667

Ranking	Mean
Indigo, 400 Hours	0.7412
Indigo, 300 Hours	0.7287
Turmeric, 400 Hours	0.5142
Turmeric, 300 Hours	0.4502
Indigo, 200 Hours	0.4343
Turmeric, 200 Hours	0.3500
Indigo, 100 Hours	0.2763
Turmeric, 100 Hours	0.2493
Madder, 400 Hours	0.0595
Madder, 300 Hours	0.0497
Madder, 200 Hours	0.0180
Madder, 100 Hours	0.0145

Table 17. K/S Value Difference for Exposure Time and Light Source Associated with Dyed Samples.

Light Source	Exposure Time			
	100 Hours	200 Hours	300 Hours	400 Hours
Incandescent	0.17683333	0.29150000	0.41750000	0.48883333
Quartz	0.14100000	0.19500000	0.43850000	0.43583333
Fluorescent	0.22233333	0.31583333	0.37250000	0.39016667

Ranking	Mean
Incandescent, 400 Hours	0.4888
Quartz, 300 Hours	0.4385
Quartz, 400 Hours	0.4358
Incandescent, 300 Hours	0.4175
Fluorescent, 400 Hours	0.3902
Fluorescent, 300 Hours	0.3725
Fluorescent, 200 Hours	0.3158
Incandescent, 200 Hours	0.2915
Fluorescent, 100 Hours	0.2223
Quartz, 200 Hours	0.1950
Incandescent, 100 Hours	0.1768
Quartz, 100 Hours	0.1410

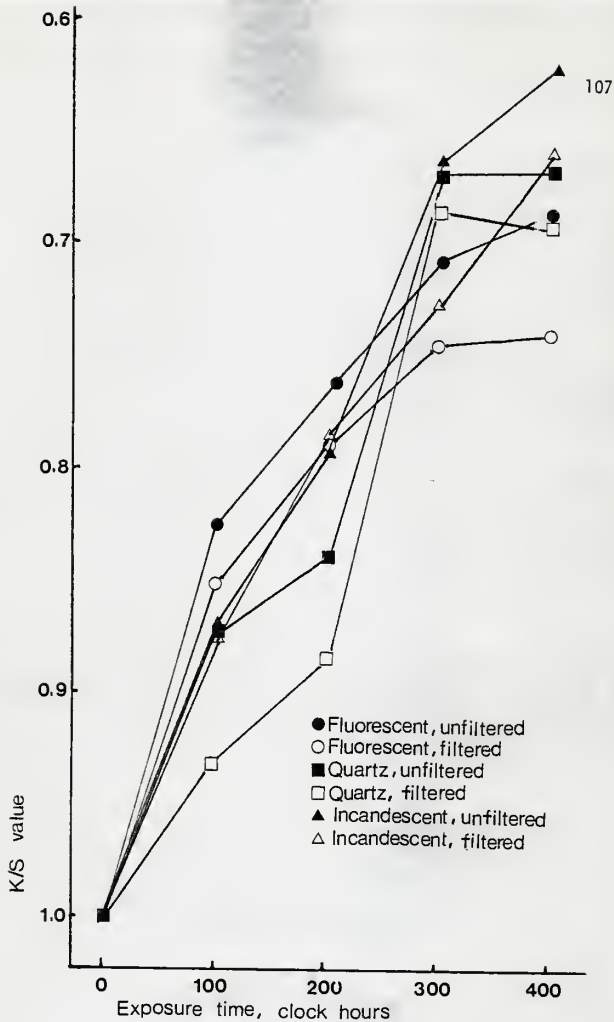


Figure 9

Effect of Light Exposure on K/S Values of Undyed and Dyed Cotton Samples Exposed to the Six Lighting/Filter Systems.

exposure time and light source X filter type.

The ANOVA for K/S value differences of the undyed samples indicated that light source was a non-significant independent variable at the 0.05 level of confidence. Therefore, null hypothesis 1 was accepted. Since filter type and exposure time caused significant color change, null hypotheses 2 and 3 were rejected. Unfiltered systems caused greater color change than filtered systems, indicating that the filters were effective in blocking spectral radiations which can cause a decrease in K/S value (increase in color or yellowing) of undyed cotton samples. Exposure time results showed the greatest amount of change in K/S values from 0 to 100 and from 300 to 400 clock hours of exposure.

The second ANOVA (K/S value differences for dyed samples) indicated that all four independent variables (i.e., light source, filter type, exposure time, and dye type) were significant; null hypotheses 4, 5, 6, and 7 were rejected. Light source was a significant variable, with incandescent and fluorescent causing significantly greater color change than quartz. Filtered systems caused significantly less color change than unfiltered systems, indicating the effectiveness of the filters used in this study. Exposure time was a significant independent variable, each level (100, 200, 300, and 400 clock hours) causing a significant and progressive decrease in color. Each dye type was significantly different from the others, indigo fading most and madder least.

Evaluation of Copper Number

Main sources of variation for copper number were dye type (four levels: undyed, turmeric, madder, and indigo), light source (three

Table 18. Differences in Copper Number Values of Dyed and Undyed Samples after Light Exposure.

Dye	Light	Filter	Copper Number		
			Initial	After 400 Hours Exposure	Difference in Copper Number Values
Undyed	Incan- descent	Unfiltered	0.0904	0.2210	0.1306
		Filtered		0.2010	0.1106
	Quartz	Unfiltered	0.0904	0.3015	0.2111
		Filtered		0.2412	0.1508
	Fluores- cent	Unfiltered	0.0904	0.3417	0.2513
		Filtered		0.2613	0.1709
Turmeric	Incan- descent	Unfiltered	0.1005	0.2210	0.1205
		Filtered		0.2110	0.1105
	Quartz	Unfiltered	0.1005	0.3115	0.2110
		Filtered		0.2412	0.1407
	Fluores- cent	Unfiltered	0.1005	0.3718	0.2713
		Filtered		0.2713	0.1708
Madder	Incan- descent	Unfiltered	0.1206	0.2412	0.1206
		Filtered		0.2311	0.1105
	Quartz	Unfiltered	0.1206	0.3216	0.2010
		Filtered		0.2512	0.1306
	Fluores- cent	Unfiltered	0.1206	0.4120	0.2914
		Filtered		0.3115	0.1909
Indigo	Incan- descent	Unfiltered	0.1105	0.2311	0.1206
		Filtered		0.2210	0.1105
	Quartz	Unfiltered	0.1105	0.3115	0.2010
		Filtered		0.2512	0.1407
	Fluores- cent	Unfiltered	0.1105	0.3920	0.2815
		Filtered		0.3015	0.1910

Table 19. Analysis of Variance (Anova) for Copper Number Differences for Dyed and Undyed Samples.

Source of Variation	Degrees of Freedom	Sum of Squares	F	PR>F*
O	3	0.00006736	0.85	0.5163
L	2	0.04892697	923.61	0.0001*
F	1	0.01945982	734.70	0.0001*
O x L	6	0.00137246	8.64	0.0095*
O x F	3	0.00006734	0.85	0.5164
L x F	2	0.00667860	126.07	0.0001*
Error	6	0.00015892		
Total	23	0.07673147		

*Significant groups at the 0.05 level of confidence are marked with an asterisk.

levels: incandescent, quartz, and fluorescent), filter type (two levels: unfiltered and filtered, and exposure time (two levels: 0 and 400 hours).

The actual copper number data and copper number differences for the six lighting/filter systems and after 0 and 400 hours of exposure for the dyed and undyed cotton samples are presented in Table 18. Analysis of variance for the copper number difference data (see Table 19) showed light source and filter type as the significant independent variables. Dye type X light source and light source X filter type were the significant second order interactions. All other independent variables and second order interactions were non-significant at the 0.05 level of confidence.

Differences in copper number values for light source are presented in Table 20 and show that all three light sources showed significant change. Fluorescent systems showed greatest difference and incandescent least. Though this ranking is opposite to the K/S value difference ranking for light source, the fluorescent and quartz lamp/filter systems were expected to produce greater deterioration than incandescent due to presence of high energy invisible radiation.

Filter type also was a significant independent variable, as presented in Table 21. Unfiltered lighting/filter systems caused greater change in copper number than filtered systems, indicating the filters were effective in blocking harmful invisible radiation from the samples, as was expected.

The second order interaction of light source X dye type (see Table 22) was significant and showed all dyes suffering greatest change

Table 20. Ouncan's Multiple Range Test for Copper Number Difference for Light Source Associated with Undyed and Oyed Samples.

Light	Mean	Grouping*
Incandescent	0.116800	A
Quartz	0.173362	B
Fluorescent	0.227387	C

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

Table 21. Ouncan's Multiple Range Test for Copper Number Difference for Filter Type Associated with Oyed and Undyed Samples.

Filter	Mean	Grouping*
Filtered	0.144042	A
Unfiltered	0.200992	B

*Non-significant groupings at the 0.05 level of confidence are marked with the same letter.

Table 22. Duncan's Multiple Range Test for Copper Number Difference for Light Source and Dye Type Associated with Dyed and Undyed Samples.

Dye Type	Light Source		
	Incandescent	Quartz	Fluorescent
Undyed	0.12060000	0.18095000	0.21110000
Turmeric	0.11550000	0.17585000	0.22105000
Madder	0.11555000	0.16580000	0.24115000
Indigo	0.11555000	0.17085000	0.23625000
Ranking	Mean		
Madder under Fluorescent	0.2412		
Indigo under Fluorescent	0.2363		
Turmeric under Fluorescent	0.2211		
Undyed under Fluorescent	0.2111		
Undyed under Quartz	0.1810		
Turmeric under Quartz	0.1759		
Indigo under Quartz	0.1709		
Madder under Quartz	0.1658		
Undyed under Incandescent	0.1206		
Madder under Incandescent	0.1156		
Indigo under Incandescent	0.1156		
Turmeric under Incandescent	0.1155		

in deterioration under fluorescent lighting systems and least under incandescent systems. For dyed samples, the madder deteriorated most and the turmeric least under fluorescent lighting systems. Since fast dyes generally respond less to low energy radiation than do fugitive dyes, and since fluorescent lighting exhibits minimal low energy infrared but considerable high energy ultraviolet radiation, this result was expected. Samples exposed to incandescent lamps showed only minute variance in copper number differences, undyed samples exhibiting greatest deterioration. Undyed samples also showed greatest difference in copper number for quartz lighting systems. Perhaps the masking effect of the dyes protected the dyed samples to some extent, allowing greater substrate damage to the undyed samples; the amount of energy expended to cause color change in the dyes could not be used to deteriorate the substrate.

Light source X filter type was another significant second order interaction (see Table 23). Unfiltered systems for incandescent, quartz, and fluorescent lamps showed greater change in copper number differences than the three filtered systems. Fluorescent, unfiltered, showed greatest deterioration and incandescent, unfiltered, least (see Figure 10). These results were anticipated, since lamps with harmful invisible radiation removed should produce less deterioration on objects than lamps with infrared or ultraviolet rays present.

The third ANOVA, copper number differences for dyed and undyed samples, revealed light source and filter type as significant independent variables, therefore, null hypotheses 8 and 9 were rejected. Since light source was a significant independent variable, copper number showed significant differences in the third Anova among incandescent,

Table 23. Duncan's Multiple Range Test for Copper Number Difference for Light Source and Filter Type Associated with Dyed and Undyed Samples.

Filter Type	Light Source		
	Incandescent	Quartz	Fluorescent
Unfiltered	0.12307500	0.20602500	0.27387500
Filtered	0.11052500	0.14070000	0.18090000
Ranking	Mean		
Fluorescent, Unfiltered	0.2739		
Quartz, Unfiltered	0.2060		
Fluorescent, Filtered	0.1809		
Quartz, Filtered	0.1407		
Incandescent, Unfiltered	0.1231		
Incandescent, Filtered	0.1105		

fluorescent, and quartz lighting/filter systems. Fluorescent systems produced greatest deterioration and incandescent least.

All unfiltered systems caused greater deterioration on dyed and undyed samples than filtered systems, indicating filter effectiveness in blocking harmful invisible radiations. Null hypothesis 10 was rejected since there was a significant difference in deterioration from 0 to 400 exposure hours. Since dye type was a non-significant independent variable, null hypothesis 11 was accepted; no dye deteriorated significantly more than any other.

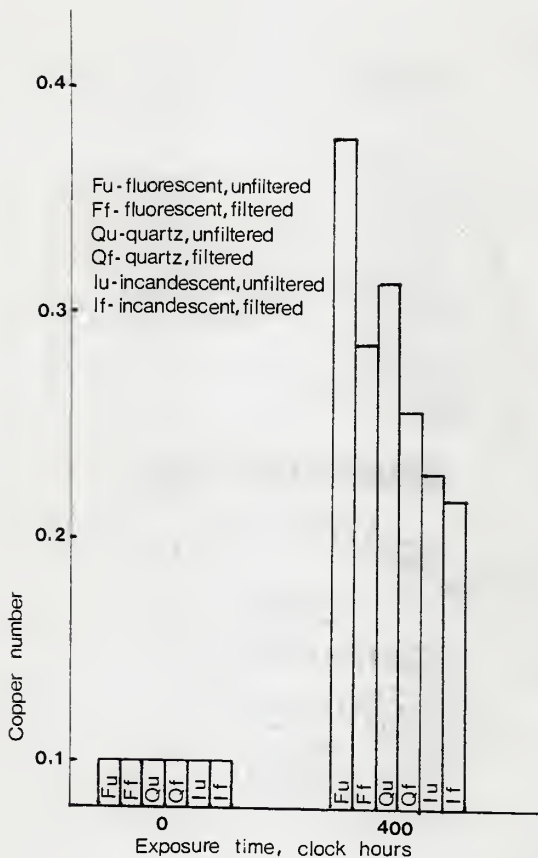


Figure 10

Effect of Light Exposure on Copper Number of Undyed and Dyed Cotton Samples Exposed to the Six Lighting/Filter Systems.

SUMMARY AND CONCLUSIONS

Evaluated in this study were the effects of six lighting/filter systems on the colorfastness and deterioration of cotton fabrics dyed with turmeric, madder, and indigo. A survey sent to museums aided in the selection of lighting systems that are currently being used or are being considered for use in museum environments. Undyed and dyed cotton samples were exposed for 0, 100, 200, 300, and 400 clock hours and evaluated for color loss by calculating differences in K/S values. Chemical deterioration was assessed by the copper number test.

Results showed that the filtered lighting/filter systems caused more color loss and deterioration than the unfiltered systems. These results indicate that the amount of harmful, invisible infrared and ultraviolet radiation can be reduced by the use of specially-designed lamps and filters, reducing color loss and deterioration of textile objects.

All independent variables (i.e., dye type, light source, filter type, and exposure time) produced results anticipated, but light source variation indicated incandescent and fluorescent systems caused greatest color change with quartz causing the least amount of change. Incandescent systems were expected to cause the least color loss since the only invisible radiation produced by these light sources was low energy infrared. Light source X filter type was a non-significant interaction for K/S value differences, therefore no conclusions could be drawn concerning the desirability of one filtered lighting system over another.

Light source also had a significant effect on the extent of deterioration in the dyed and undyed cotton samples, with fluorescent lighting causing the greatest deterioration and incandescent the least. The light source X filter interaction was significant, indicating unfiltered fluorescent and unfiltered quartz systems caused greater deterioration than filtered fluorescent and filtered quartz systems. Incandescent, filtered and unfiltered, caused the least deterioration, with filtered incandescent causing less than unfiltered.

K/S values and copper number differences for the independent variable light source revealed different rankings. Incandescent systems caused the greatest amount of color change and quartz caused the least, whereas fluorescent systems caused greatest deterioration and incandescent caused the least. Literature in the field of textile conservation generally indicates a direct proportion between deterioration and color change.

RECOMMENDATIONS

Much of the research regarding the effects of radiant energy on dyed textiles has been performed under accelerated conditions. Tests performed under "normal" museum conditions, though necessarily time-consuming, would perhaps be more accurate in establishing fading/deterioration rates and relative hazards under varying conditions (98, 182). Because quartz lighting is being included in some museum lighting design, its exact and relative long-term effects should be evaluated.

Further research is needed to compile accurate and complete lists of relative susceptibilities of materials and expected color change and deterioration rates of specific dye-fiber systems under various lighting and atmospheric conditions. This information might provide a practical guide for determining optimum exposure and display conditions of artifacts (101).

The exact relationship between fading and deterioration is influenced by many conditions. Research leading to the estimation of deterioration rate by fading rate for specific dye-fiber-environment systems may, however, provide a practical document for museum personnel.

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APPENDICES

APPENDIX A

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 Old Sturbridge Village
 Sturbridge, Massachusetts 01566 * by D. L. Colglazier, Conservator

Elizabeth P. Benson
Center for Pre-Columbian Studies
Dumbarton Oaks
1703 32nd Street, N. W.
Washington, D. C. 20007 *

Richard C. Nylander, Curator
SPNEA-Harrison Gray Otis House
141 Cambridge Street
Boston, Massachusetts 02114 *

Joseph Peter Spang III, Curator
Historic Deerfield, Inc.
Route 5
Deerfield, Massachusetts 01342

Elsie McGarvey, Curator of Textiles
Philadelphia Museum of Art
Parkway at 26th Street
Box 7646
Philadelphia, Pennsylvania 19101 *

Eva Burnham, Chief, Textiles Division, Conservation Services
National Museums of Canada
Canadian Conservation Institute
1030 Innes Road
Ottawa, Ontario, Canada K1A 0M8 *

APPENDIX B

Suppliers for Materials Used

Rohm and Haas ultraviolet filter UF3:	Rohm and Haas Distributor Westlake Plastics Company West Lenni Road Lenni, Pennsylvania 19052
Corning infrared filter Noviol 0:	Corning Distributor Fred S. Hickey 9601 River Street Schiller Park, Illinois 60176
Sylvania incandescent and quartz lamps and incandescent fixtures:	Sylvania Distributor Endacott Lighting 309 Moro Manhattan, Kansas 66502
Verilux fluorescent lamps:	Verilux 35 Mason Street Greenwich, Connecticut 06830
Quartz fixtures:	Bill Scaletty Lighting Associates 4102 Truman Road Kansas City, Kansas 64055
Dyes:	Straw into Gold 5509 College Avenue P. O. Box 2904 Oakland, California 94618
Fabric:	Testfabrics, Inc. P. O. Drawer 0 200 Blackford Avenue Middlesex, New Jersey 08846

APPENDIX C

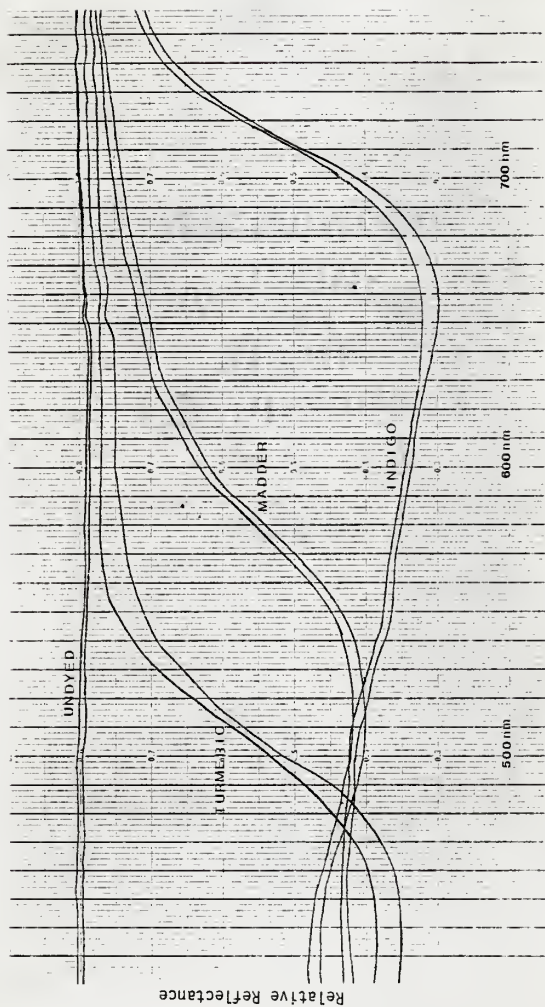


Figure 11

Spectral Reflectance Curve for Dyed and Undyed Samples Before Exposure and After 400 Clock Hours: Incandescent, Unfiltered Lamp.

EFFECTS OF FILTERED AND UNFILTERED INCANDESCENT, FLUORESCENT,
AND QUARTZ LIGHTING SYSTEMS ON COTTON DYED WITH NATURAL DYES

by

JANET GILLILAND BOWMAN

B.S., North Texas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Clothing, Textiles and Interior Design

Kansas State University
Manhattan, Kansas

1979

Light sources used by museums for the display of textile artifacts must be chosen judiciously to reduce fading and deterioration by ultraviolet, infrared, and visible radiation during light exposure. Two light sources used by museums are incandescent and fluorescent lamps. Incandescent lamps emit high levels of infrared radiation in addition to visible radiation; fluorescent lamps generally emit substantial quantities of ultraviolet radiation. Quartz lamps, which are used by museums to a lesser extent, emit high levels of infrared and a substantial amount of ultraviolet radiation.

This study assessed the effects of six lighting/filter systems on the color change and deterioration of undyed cotton and cotton dyed with three natural, vegetable dyestuffs (i.e., turmeric, madder, and indigo), commonly found on historic textiles. The lighting/filter systems evaluated were unfiltered incandescent, low infrared (dichroic reflector) incandescent with an infrared filter, unfiltered quartz, quartz with infrared and ultraviolet filters, unfiltered fluorescent, and fluorescent with an ultraviolet filter.

Color change was determined by calculating differences in K/S values from reflectance spectra after 0, 100, 200, 300, and 400 clock hours of light exposure. Deterioration of the cotton substrate was evaluated by the copper number test.

The filtered lighting systems produced significantly less color change and fiber deterioration than did the unfiltered lighting systems. The incandescent and fluorescent lighting/filter systems produced significantly greater color change than did the quartz lighting/filter

systems.

Results from the copper number test showed significant differences among the six lighting/filter systems in the extent of deterioration on the undyed and dyed cotton fabrics, with fluorescent causing the greatest amount of deterioration and incandescent the least. The light source by filter interaction was significant for copper number as evidenced by the unfiltered fluorescent and unfiltered quartz lighting systems causing greater deterioration than did the filtered fluorescent and filtered quartz lighting systems. In addition, unfiltered and filtered incandescent lighting systems caused the least amount of deterioration, with filtered incandescent causing less than the unfiltered.