2009-01-01

Art In A New Light: Design And Assessment Of Illuminants To Reduce Photochemical Degradation Of Works Of Art

Monica Fabiola Delgado
University of Texas at El Paso, zafiromon@aol.com

ART IN A NEW LIGHT: DESIGN AND ASSESSMENT OF ILLUMINANTS TO REDUCE PHOTOCHEMICAL DEGRADATION OF WORKS OF ART

MONICA FABIOLA DELGADO RAMOS

Department of Chemistry

APPROVED:

Carl W. Dirk, Ph.D., Chair

Katja Michael, Ph.D.

Geoffrey Saupe , Ph.D.

Kathryn A. Bonansinga, M.A., M.B.A.

Patricia D. Witherspoon, Ph.D.
Dean of the Graduate School

Dedication

To my daughter Marina for whom I work even harder than before to be a better person at every possible level. Thank you for being in my life.

To my sister Vanessa who helped me take care of my daughter, while finishing this endeavor; thank you for all your love, help and support.

To my husband, thank you for being in my life.

To my parents Claudio and Guadalupe Delgado who made me the woman that I am today. Thank you for all your unconditional love and support.

To my sisters who have been with me in this journey. Thank you for listening, for loving me, for your help, for your advice, for your support.

To all my teachers and professors from whom I have learnt in the classroom and in life form kindergarten all the way to graduate school. Thank you for your support, your discipline, your patience, your hard work, your advice, your dedication, your inspiration, your time, I respect all of you deeply, I was always listening; you were all key people in my life. Thank you this is for you.

To all those people that did not believe I could do it, those who hurt me and made it almost impossible for me to get here; this is for you, Thank you those obstacles made me work harder for this and made me stronger.

To my beloved grandmother Juanita Ramos, who raised me and loved me unconditionally, I know that where ever you are, you are crying, out of happiness and you are very proud of me. I have missed you every day that you have been gone.

ART IN A NEW LIGHT: DESIGN AND ASSESSMENT OF ILLUMINANTS TO REDUCE PHOTOCHEMICAL DEGRADATION OF WORKS OF ART

by

MONICA FABIOLA DELGADO RAMOS

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

Department of Chemistry

THE UNIVERSITY OF TEXAS AT EL PASO

December 2009

Acknowledgements

To Dr. Carl W. Dirk, my mentor and my academic father. Who believed in me from the very beginning. He saw my potential, which I did not know I had yet. Without his academic, educational, moral, and monetary support this achievement would not have been possible. Thank you for believing in me, for your teachings, your guidance, you advice, your patience and you time. Thank you for all you support.

To Jim Druzik, Senior Scientist at the Getty Conservation Institute. 1200 Getty Center Drive, Suite 700 Los Angeles, CA 90049-1684. Thank you for this opportunity. Without your monetary and moral support this achievement would not have been possible. Thank you for your guidance, your advice, and collaboration.

To the Getty Conservation Institute for the funding of this research. This would not have been possible without your help. Thank you for supporting projects like this.

To the Getty Foundation for the financial assistance. This project and research was possible because of the ability of the Foundation to see the potential in these kinds of projects. Thank you.

Abstract

The purpose of this research is to design the best lighting that will minimize long term photochemical degradation of Old Master Drawings and/or other works of art, while maintaining the patron's appreciation of the object's color and detail. The present approach is a technological refinement to the basic underlying earlier work on fluorescent lighting by W. A. Thornton, W.A. at General Electric[1]. Thin-film dielectric, multi-coating technology is used to create filters that eliminate ultraviolet light, near infrared light and significant unnecessary parts from the visible spectrum, thus maximizing the reduction in photochemical degradation, while maintaining optimal color rendering. Three interference filters, were designed and manufactured successfully. The filters are designated Mark 1, Mark 2, & Mark 3. In this dissertation, the filters are analyzed with regard to their performance parameters. This includes color rendering, retardation in fading or color change, beam angle effects, filter stability, perceived brightness, and visual appreciation parameters.

To a high confidence level, all three filters are perceived as being indistinguishable from Unfiltered light with regard to the color confusion index parameter (CCI). Subjective assessments by tests subjects suggest the Mark 3 filter may display some distinguishability with a confidence level for distinguishability of 35% for the overall satisfaction parameter. The Mark 3 filter is the most complex three-color type spectral profile and this might be expected due to beam angle effects or departures in accuracy of color theory. Beam

angle affects suggest that the Mark 1 and Mark 2 filters do not display significant color rendering aberrations due to Newton's colors interference effects, except possibly at the periphery of the broadest (55-60+°) beam angle lamps.

Filtered and Unfiltered light are effectively of the same perceived brightness, though to a low confidence level, Unfiltered light might be perceived brighter. Accelerated aging studies of the filters indicate useful mean time before failures of >20 years. In fact, no failure was observed in any of the accelerated studies, The Mark 2 and Mark 3 filters were evaluated in equal-luminosity studies with regard to their effect on limiting fading of both standard fading samples such as the ISO Blue Wool series, and also other commercial pigments or stains. Within experimental error, the Mark 2 filter either slowed fading or had no effect on fading for all pigments relative to Unfiltered light and Optivex® filtered light, Optivex® being a common commercial filter used to protect works of art. Mark 3 protected in many cases, but for some pigments it was less protective than Optivex® filtered light. This failure is interpreted in terms of the wavelength dependence of the excess light in certain wavelength regions on an equal luminosity condition, and suggests that more subtle wavelength dependent optimizations have to be undertaken for filters which possess significant band separation.

Table of Contents

List of Tables

List of Figures

List of Illustrations

List of Photographs

General Introduction

The main reason this Museum Lighting Research project started is the increasing recognition of the photochemical damage to works of art. On October 21-22 of 2002 the Department of Science of the Getty Conservation Institute conducted a meeting with experts on lighting from different backgrounds. This group of experts included art curators, art conservators, conservation scientists, scientists, and lighting engineers from around the world. Some of the questions discussed in this meeting include the following: Can a new light source be engineered that can be safer and possibly provide longer exhibition periods than any other existing light source? Can a light source be engineered that has a satisfactory or superior color temperature? Can pre-existing light sources be modified to a point where they can simultaneously provide adequate color rendering and offer photochemical protection? By the end of this meeting, the group had identified eight possible solutions or eight possible strategies to extend the lifetime display of the works of art.

Four of these strategies are already being used by the museums and art galleries around the world. They are the following: to reduce the illumination levels of existing light sources; the use of interrupted illumination with the aid of switches and motion detectors; to remove ultraviolet and infrared light; and to adjust exhibition display periods according to the sensitivity of the artifact. The other four strategies needed further research and they include the following: to

use new light sources, like LED's; to use filters that cut out unnecessary light from existing light sources; to further investigate anoxic environments; and to implement of risk management methodologies based on radiometric monitoring techniques. A filter solution to attenuate unnecessary light on existing lamp sources was the birth of this Museum Lighting Research project.

In order to fulfill its educational and exhibition mandates, a museum usually displays the major works of art from its permanent collection, sometimes for indefinite periods. Consequently, works of art may be exposed to light for years and even decades or centuries. Light exposure is among the greatest environmental risks because it cannot be eliminated or easily controlled. The light exposure represents the transmission of energy, which will often cleave chemical bonds or stimulate other chemistry. Photochemical degradation is an inevitable outcome of seeing and appreciating a work of art. Most of this damage is irreversible, and the consequence is that great works of art will lose their luster within decades and be destroyed within centuries. Works of art on paper or those using watercolor pigmenting are among the most susceptible and could be destroyed in years or months of exposure to light. The main area of concentration for this project has been on Old Master Drawings (OMDs), this being the most immediate need of the J. Paul Getty Museum. The technology that has been developed can be applied to any work of art.

The purpose of this research is to design the best lighting that will minimize long term photochemical degradation of OMDs and/or other works of art, while permitting visibility and, therefore, the patron's appreciation of color and detail. There are several well-known approaches to the reduction of photochemical damage to works of art. Some of these include eliminating UV photons, reducing illumination levels, interrupting illumination, extreme cold, and inert atmosphere[1, 2, 3]. This approach is a technological refinement to the idea of removing unnecessary illumination in the visible spectrum. The basic concept is based on earlier work on fluorescent lighting by Thornton, W.A. at General Electric[1].

Thin-film dielectric, multi-coating technology is used to create filters that eliminate ultraviolet light, near infrared light and significant unnecessary visible regions of light, thus maximizing the reduction in photochemical degradation, while maintaining optimal color rendering.

1.1 Controlling Environmental Factors

All cultural works are sensitive to environmental conditions. Some objects are more sensitive than others. The sensitivity to environmental stress includes temperature, humidity, light, oxygen, sound, and vibrations. All cultural objects need to be preserved using different conservation methods. There are two types of art conservation: preventive conservation and interventive art conservation.

Preventive conservation attempts to protect cultural works from potential damage. The objects must be put in a controlled environment. In this controlled environment, the temperature, humidity, light, oxygen, noise, and vibrations are maintained within a range of damage-limiting levels. An example of preventive conservation is when a watercolor is shielded from sunlight in order to prevent pigment fading. Preventive conservation is a key element in museum policies regarding the care of collections. This type of conservation includes the objects on display, in storage and in transit to other museums.

Interventive conservation is done by an art conservator. This involves the conservator working on a specific cultural object. The most important feature here is that the work done on an object should be as noninvasive and as reversible as possible. The intervention by a conservator can be any of the following or a combination of the following. The conservator can clean, stabilize, repair, in-paint, or replace part or parts of the cultural object. Before an art conservator works on an object, extensive preparation, documenting, testing and research needs to be done. The conservator needs to document all the work before, during, and after the designed treatment. In this type of conservation, there is controversy among art conservators around the world. The main controversy is often the methodology of conservation.

1.2 Humidity and Temperature

Humidity is a factor that affects the preservation of art. Water is everywhere, in our bodies, the environment, plants and animals. Products made from plants and animals retain moisture. Moisture can play a destructive role or a conservation role in art. In the following example humidity acts as a protector. Wood, ivory and bone contract, slip and wrap when moisture is subtracted from the atmosphere they are in. Paper, parchment, leather, and textiles that come from a natural source become less flexible and their fibers break easier. Moisture can act as a destructive force not only because it creates the right conditions for mold and fungi, but also because it impacts the form of the object due to moisture absorption.

There are three basic types of deterioration caused by Relative Humidity (RH): change in the size and shape, chemical reaction, and bio-deterioration. The first type of deterioration that is caused by RH that will be discussed is the change of size and shape. In general all materials that absorb moisture expand when the RH is high and they contract when the RH goes down. But different objects, because they are composed of different materials, react, expand and contract in many ways, directions, and angles, thus making the problem more complicated.

The second type of deterioration is chemical reactions favored by relative humidity. Some objects require higher and some lower RH for best stability. If the

museum or art gallery has a collection that contains paintings, furniture, textiles, metals, etc., then the RH has to be averaged for the entire collection between 55-60%. If it is a pure textile museum, the conditions can be specific for the textile collection; for example at a RH of 45%.

The third type of destruction caused by moisture is bio-deterioration. Mold, bacteria, and most insects require different levels of RH in order to flourish. Therefore, in order to completely eradicate this problem, different levels of RH need to be applied. This is unrealistic, expensive, and impractical. It has been concluded by experts that insect damage cannot be prevented by control of relative humidity, and other methods should be employed.

The other factor that affects art preservation is heat or temperature. Achieving both an ideal and a non-fluctuating relative humidity is more important than temperature. The ideal and stable relative humidity should be achieved first before setting the temperature. Even though there are standards that suggest a safe temperature, disagreement between the conservators, curators, and conservation scientists will arise.

There are several mechanisms on how a rise in temperature can affect exhibits including the following: the rates of chemical reactions increase, the rates of physical processes increase, there is thermal expansion and contraction,

the biological activity increases, drying is accelerated, and fading accelerates in some textiles.

With a rise in temperature the rates of dark (absence of light) chemical reactions increase. The following example is to further illustrate the severity of this problem. The rate of deterioration of cellulose can increase in the dark with a temperature change even if the relative humidity is kept constant. This rate of deterioration of cellulose can increase to two and a half times with a temperature increase of 15 to 25 °C[2].

Increases in temperature increase the rates of other physical processes. These other physical processes can be the movement of water and air through solids. A change of temperature of 5° centigrade higher can make these processes one and a third times' faster[2]. The embrittlement that is caused by age is related to this process.

The expansion of materials caused by heat is small. The swelling due to heat for the following materials can be ignored; bone, leather, ivory, paper, wood and textiles. The expansion of these materials can be ignored because the swelling due to water for these materials is much more dangerous. There are other materials that are brittle, that do not absorb moisture and their components expand at different rates, such as enamel in metal. For these kinds of materials, a sudden change in temperature can be extremely detrimental[2].

One very important fact regarding temperature rise is that in warm weather the biological activity increases. Under these conditions, RH needs to be kept constant, independently, at all times. Wood, paper, animal glue, and leather are particularly susceptible rises in temperature [2]. In some cases, this rise in temperature that causes dryness can actually be helpful. Dryness can in fact decrease the rate of fading of most dyes. Although this effect is good, it is not good enough to be taking into consideration for actual use in museums or in art galleries. An example of this would be textiles. Textiles can benefit from being in dry conditions, but their flexibility may be affected, therefore the benefit is not surpassing the damage[2].

The last and possibly the most significant effect of all is the rise in temperature caused by radiant heat. This dangerous radiant heat can come from two sources: sunlight or a robust spotlight. This type of rise in temperature, even if the RH is kept constant independently, will cause drying[2].

In general it can be said that digressing from the specified temperatures affects art pieces in two essential ways. The first effect is the possibility of altering chemical processes. The second is the possibility of triggering mechanical stresses and strains. Also, severe changes in temperature have adverse effects on the visitor's comfort level. Therefore, museums and art galleries have to set an ideal temperature for their collections without affecting the comfort and experience of the visitors.

The next two factors that affect the preservation of artwork are sound and vibration. Sounds that travel through the air can cause an object to vibrate or shake, this kind of vibration can be caused by alarms, planes, earthquakes, heating and ventilation equipment, traffic, and construction work done in the building or outside the building. The traveling exhibits are at higher risks of getting damaged due to this kind of vibration, and even though there are proper ways of packing the objects so that the effect of vibrations can be diminished, there are other external factors that cannot be controlled.

1.3 Light and Oxygen

Light sources utilized in museums vary from room to room and within the museum or gallery itself. Some of the light sources available in museums and galleries are: sun light, fluorescent, incandescent and light emitting diodes (LED). This exposure to light in museums or art galleries is still a special case among the other environmental risks because is cannot be completely removed for objects on display, and its control is limited.

Exposing a work of art to any of the mentioned light sources for viewing purposes always involves the transmission of energy to the artwork. This transmission of energy is known as the absorption of photons. This absorption of energy increases the potential for many various and complex chemical interactions, not only on each layer of the materials making up the artifact but

also between the layers. Some of these chemical interactions between all or some of the materials can cause irreversible damage to the art piece.

It should be clarified that the absorption of photons does not mean that a chemical change will happen. When a molecule absorbs a photon many things can happen. Some of the known possible scenarios are: fluorescence can occur as energy is emitted from the molecule; the energy from the molecule can be transformed into heat; the energy from the molecule can be transmitted to another molecule; the molecule can go to a lower excited state that might be longer lived; or a bond in the molecule can break. A chemical change in the excited molecule can only occur when a bond breaks or is made between atoms within the molecule.

Different light sources cause different rates and levels of photo degradation. Sunlight causes the most photochemical damage. The least damaging energetically and the most commonly specified for museums or galleries are incandescent light sources. Some photochemical degradation processes are unimolecular. Some are bimolecular. For instance, oxygen also is sometimes involved as a component of a photochemical degradation. Bimolecular processes can be far more complicated to understand than unimolecular processes.

Reactions that happen with the utilization of oxygen are called photooxidation reactions. Some of these damaging reactions can happen with

as little as 0.06% oxygen. Oxygen has long been recognized as a cause of deterioration of many organic materials found in objects in museums and art galleries. The different oxidative processes vary depending upon much oxygen is available, from pigment to pigment, the time when the pigments where made, what they were made of and how and to what they were applied to. The general nature of these processes is complex and only a hand full of materials have been studied and fully understood[3].

In the case of reactions with oxygen, an anoxic environment can be created, but unfortunately some important pigments or colors have been shown to be susceptible to changes even under these conditions[2].

Another form of oxygen that is a powerful oxidant is ozone. Ozone can be found in museums from three main sources: 1) from the conversion of car exhaust gases with sunlight, 2) from the natural production in the atmosphere and 3) from a selection of lamps and electrical equipment used in museums. In unsaturated organic compounds ozone has a very specific role. This role is to break double bonds that are in the carbon chain, in other words to destroy the material[2]. This means that ozone is a slayer of the majority of organic materials. Museum art collections are composed mainly of objects like paintings, watercolors, drawings, textiles, furniture, leather, fur, paper documents and biological specimens all made mostly or wholly by organic materials. Therefore ozone poses a great threat in these environments.

1.4 Background on methods for protecting art from light

All organic materials that are part of collections are at risk under light. The term organic for museums and art galleries refers to anything that originated from animals and plants, for example wood, leather, paper, silk, feathers, glues, dyes, etc. In order to reduce photo degradation, light in museums and art galleries must be controlled. In museums light is a form of energy that can act as the activation energy necessary to initiate a chemical reaction.

Luminance is measured with a light meter. There are three basic light units: The first basic unit is the candela that measures luminous intensity, which are the lumens that emanate from a point source per unit solid angle[2]. The second basic unit is the lux that measures illuminance on to a surface of unit area. Lux is the international unit which means 1 lumen per square foot that is also called foot candle. One foot candle is equivalent to 10.76 lux. The third basic light unit is Apostilb (asb) that measures luminance from a square meter of diffusing source or lumens reflected from a square meter of an area. It should be clarified that luminance is defined as a measure of the energy flow of light as the human eyes sees it.

According to the Handbook of Applied Photometry the luminous intensity of a light source is defined as a measure of the luminous flux per unit solid angle in[4] a specific direction. The illuminance is defined as the luminous flux per unit area that is occurring on a plane. In other words illuminance is when the

luminous flux gets divided by the area of the plane when this plane is uniformly irradiated. The luminance is defined as the ratio of the luminous intensity and the surface of the source.

Relative to the visible, light can be defined for three wavelength regions: ultraviolet (300-400nm), visible (400-760 nm) and infrared (beyond 760 nm). The basic rule is the shorter the wavelength of the light the more damaging the radiation. All visible light sources often emit in one or both of the other two regions. Some light sources have more of the ultraviolet or more of the infrared.

In the 1980's there were three types of light sources that were appropriate for museums and art galleries: tungsten or incandescent (with inert gas), fluorescent, and metal halide lamps. The incandescent light source is the ordinary domestic light bulb, and is referred to as incandescent due to the fact that it yields light because of blackbody radiation. A fluorescent lamp is a tubular body that contains mercury vapor. The inner surface glass of this body is coated with of mixture of materials. These materials have the capability of fluorescing in the radiation that is emitted by the mercury vapor[2]. Some fluorescent lamps are better than others regarding color rendering. The metal halide lamp is a modification of the high-pressure mercury bulb. This modification is in order to enhance its color rendering. This improvement is done by the addition of small quantities of metal halides to the mercury. If necessary color can be further improved by enclosing the lamp with a fluorescent powder

coated envelope. This lamp has good color rendering and is quite conservative in its electricity usage, therefore a good candidate for museum use [2].

The recommended maximum illuminance levels were created by the U.K. Chartered Institute of Building Services, the French National Committee of ICOM, ICCROM, The U.S.S.R. Ministry of Culture, and the Canadian Conservation Institute. These light sources had to be adjusted to the following recommended maximum illuminance levels: 200 lux levels for oil and tempera paintings, un-dyed leather, horn, bone and ivory, oriental lacquer and the 50 lux levels for textiles, costumes, watercolors, tapestries, prints, drawings, manuscripts, paintings in distemper media, gouache, botanical specimens, fur and feathers[2].

Until electricity, the most common lighting for museums was daylight, candlelight, and gas or gas-mantle light. Today in the 21st century, the use of incandescent sources, LED, and fiber optics are common, and have developed their own traditional use. These "new" light sources also have to be adjusted in order to follow the recommended maximum illuminance levels.

Ultraviolet radiation causes more damage overall than the equivalent amount of blue radiation. The blue radiation causes more damage than yellow radiation. It is known that there is less ultraviolet radiation than visible radiation in commonly used light sources. Many materials only fade with radiation at particular wavelengths. Small quantities of UV or blue light can cause more damage than the radiation from the whole visible spectrum.

The 200/50 lux illuminance level mentioned above is followed by most museums and art galleries around the world, though achieving these levels is much more complicated than just setting the light to these levels. The 50 lux level is specifically for artificial light, and more specifically for warm (less blue light) rather than cool (more blue light) fluorescent lamps.

Glare must be strictly controlled, by planning carefully and adjusting the positions of light. The other variable that needs to be wisely designed and planned is how the visitors' eyes are going to adapt to the light before they enter the room. Light should also follow the pattern that the eyes are accustomed to, that is the light should be partially directional and partly diffused.

The 200 lux level applies to both artificial and natural daylight. To achieve the 200 lux level illumination three combinations can be used. It can be sunlight alone, artificial light alone and a mixture of both lights. Out of these three possible combinations, more problems arise when dealing only with sunlight. This is because there are more variables involved with sunlight, which varies with weather and time of day. There are two specifications for very light sensitive materials: at the center of the exhibit it can vary from 150 to 250 lux and for large to very large objects, a ratio of no more than 2 to 1 among the brightest and darkest parts. In photograph galleries this applies to the whole picture hanging area.

Even though these practices of 200/50 lux were created originally for all collections for all museums and art galleries to follow, a new policy has been created by the Montreal Museum of Fine Arts (MMFA) regarding works on paper. The MMFA has concluded that works on paper should be classified in one of three specific categories based on the uniqueness of their susceptibilities. Exposure to light is measured by a unit known as lux-hour. A lux hour is defined as one lux that falls on an area of one square meter per hour[3]. The three categories are: Category 1 pieces suffer noticeable fading in 1.2 million lux-hours; therefore these pieces can be exhibited 4 weeks every year at 75 lux for 100 years. Category 2 classifies objects that suffer noticeable fading in 10 million lux-hours; therefore they can be exposed for 10 weeks a year at 100 lux for 250 years. Category 3 objects are the most durable; they suffer noticeable changes after 10 million lux hours of exposure. Therefore, these objects can be exhibited for 20 weeks per year at 100 lux hours for 250 years[2].

When it comes to reducing the time of exposure, four common practices are followed. The first is that illumination should only exist during operating hours. The second is that collections should only be illuminated while on view. The third is that replicas can be used for extremely light sensitive objects. The forth practice is to limit the amount of material that is exhibited from a large collection.

Earlier in this dissertation, it was mentioned that light is a form of energy that can act as the activation energy necessary to initiate a chemical reaction. Chemical reactions that occur with just the absorption of energy are known as photolysis. These reactions typically occur with UV radiation at wavelengths shorter than 300nm.

In table 1.1 obtained from The Museum Environment book, by Garry Thomson, one can appreciate the wavelength and approximate activation energies[2].

Table 1.1

Wavelength	300 nm	400 nm	500 nm	600 nm	700 nm	760 nm
Activation Energy in kcal/mol	95	72	57	48	41	38
Activation Energy in kJ/mol	400	300	240	200	170	157
Activation Energy in electron volts	4.1	3.1	2.5	2.1	1.8	1.6

There are several solutions on how to slow, prevent or avoid photochemical oxidation in museum and art galleries. The options that are available are the following: low illumination levels that have been discussed previously, extreme cold, inert atmospheres, free radical scavengers, and

removing unnecessary illumination in the visible spectrum. In the following paragraphs the other methods mentioned above will be discussed.

Reducing temperature can dramatically reduce the rate of chemical reactions, including photochemical reactions. Extreme cold of -195 C can be considered for extremely susceptible objects. However, extreme cold is impractical due to expense and problems with moisture.

An inert atmosphere involves creating display cases where oxygen has been removed and replaced by inert gases like nitrogen, argon, or helium. The best-known examples of pieces that are protected by this solution are the Declaration of Independence, the Bill of Rights and the Constitution, it should be clarified that these documents are also protected with yellow filters. Only those pigments, colorants, inks, that have oxygen dependent photochemical reactions can benefit from this solution. When a piece has a combination of oxygen independent reactions with oxygen dependent reactions; the protection from inert atmospheres is not that beneficial, and in some cases it can be detrimental. Therefore the detailed identification of each material in a particular piece needs to be made to evaluate whether it can be benefit from this solution.

Free radical scavengers involve using a molecule or a group of molecules that combine with the free radicals to reduce their reactivity. In other words, the scavengers trap the free radicals that have been created. This solution has only

been explored in theory. There are no museums or art galleries that have applied this solution. Currently, research on free radical scavengers for museum and gallery use is carried out at Lubljana at the National and University Library[5].

Removing unnecessary illumination in the visible spectrum is classified as an engineering solution, and it involves as its names implies to remove unnecessary parts of the visible spectrum from a light source. This solution is based on the notion that the human eye does not need the entire distribution of radiant power within the visible to correctly perceive an image.

Background Theory and Methods

Understanding the procedure of how a light stimulus becomes a color such as pink, blue or yellow is extraordinarily complex. To start understanding the complexity of this conversion procedure one needs to have a basic knowledge of the eye and its parts. In general light enters our eyes, the light is sent to the retina. The retina has light receptors that absorb part of this light and generate a signal that gets interpreted by the brain. The image that the retina produces and the quality of this image depends almost completely on the selection, distribution, and focus properties of the eye lens, the eye cornea, and the fluids that fill the eyeball.

2.1 Human Vision

2.1.1 Rod Cells

There are two kinds of photoreceptors, the rods cells, and the cone cells. The rod cells take their name form their unique shape. There are about 120 million rods and they are 1000 times more sensitive than the cones[6]. The main and most important function of the rods is detection at low light levels. A single photon is enough to produce a signal. Detection at low light levels is called scotopic vision. The rod cells are not part of the color sensitivity mechanism. The rods stop sending signals to the brain as soon as the amount of light increases because they become desensitized. This means that the rods are not active in a very well lit room or space.

2.1.2 Cones Cells

The cones are the other class of photo-receptors located in the eye in the back of the retina. The cone cells like the rods also take their name from their unique physical shape. One of the most important differences between the cones and the rods is that the cones are less sensitive to light in comparison to the rods. There are around 6 to 7 million cones[6.] These photo receptors are responsible for providing the sensitivity to color and spatial acuity. The cones are mainly concentrated in the retinal area that is named the macula. And just as the amount of light increases and the rods start to lose sensitivity the cones start sending the signals to the brain. This is what is known as photopic vision. The level of light where both the cones and rods are active is called mesopic vision. There are three types of cones, each cone responds to different wavelengths of light. A stimulus that causes many colors produces distinct cone signals. The sensitivity of the cones to the wavelengths is classified as short-wavelength, middle-wavelength, and long-wavelength. Each of these wavelengths is represented by the letters S, M, and L respectively. In illustration 2.1, adapted from *The human eye: structure and function*[6], it can be appreciated the spectral sensitivities overlap, particularly in the L and M sensitivity cones.

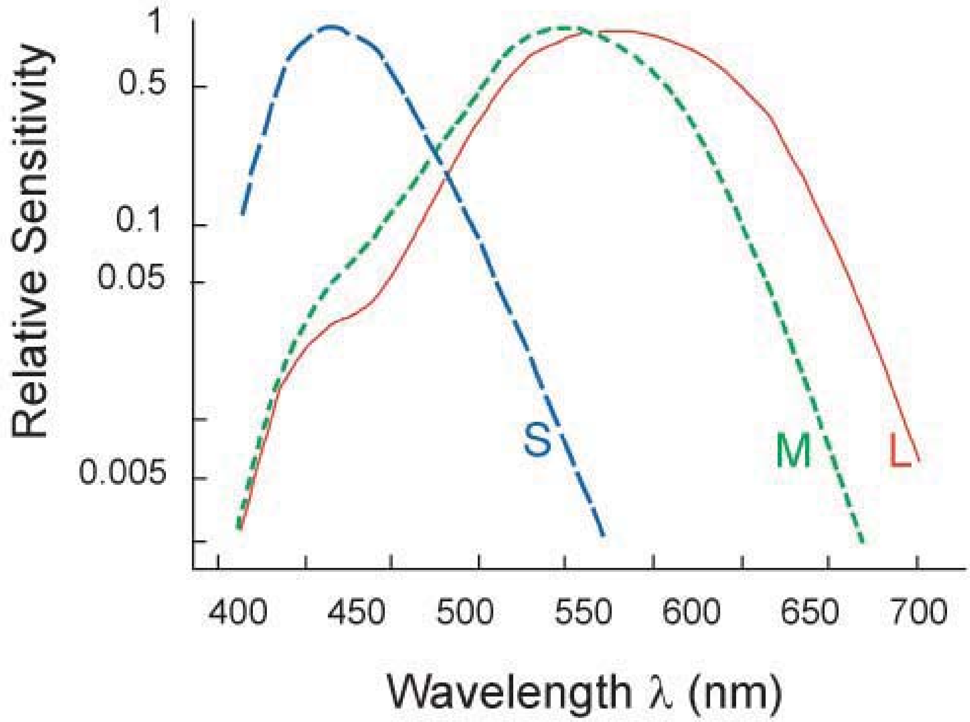


Illustration 2.1

It is because of the overlap that color discrimination is achieved, if these overlaps did not occur, one would only perceive three hues in the spectrum. The proportion of the cones according to Hecht, Eugene in his book *Optics*[7] is as follows: red sensitive cones (64%), green sensitive cones (32%), and blue sensitive cones (2%). According to the same author, the fovea centralis contains the highest concentration of red and green cones. The cones that have the highest sensitivity are the blue cones. The majority of these cones are found outside the fovea.

In illustration 2.2, one can appreciate the shape of the cones and rods. This image was adapted from *Optics*[7].

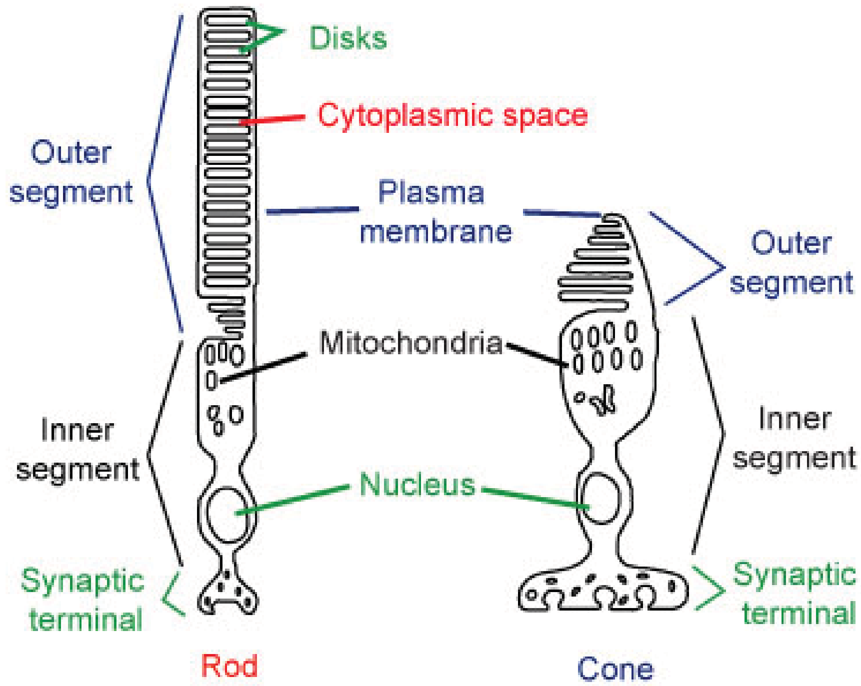


Illustration 2.2

2.2 Radiometry and Photometry

2.2.1 The Photopic function

The photopic function[8] represents the wavelength dependence of the sensitivity of the eye to the perceived brightness of light under well-lit lighting conditions, typically > 30 Lux. The scotopic function represents the wavelength sensitivity in poorly lit circumstances, typically < 20 Lux. In figure 2.1, the CIE

spectral luminous efficiency functions for scotopic[9] vision, V' (λ) and photopic vision, V (λ) are illustrated.

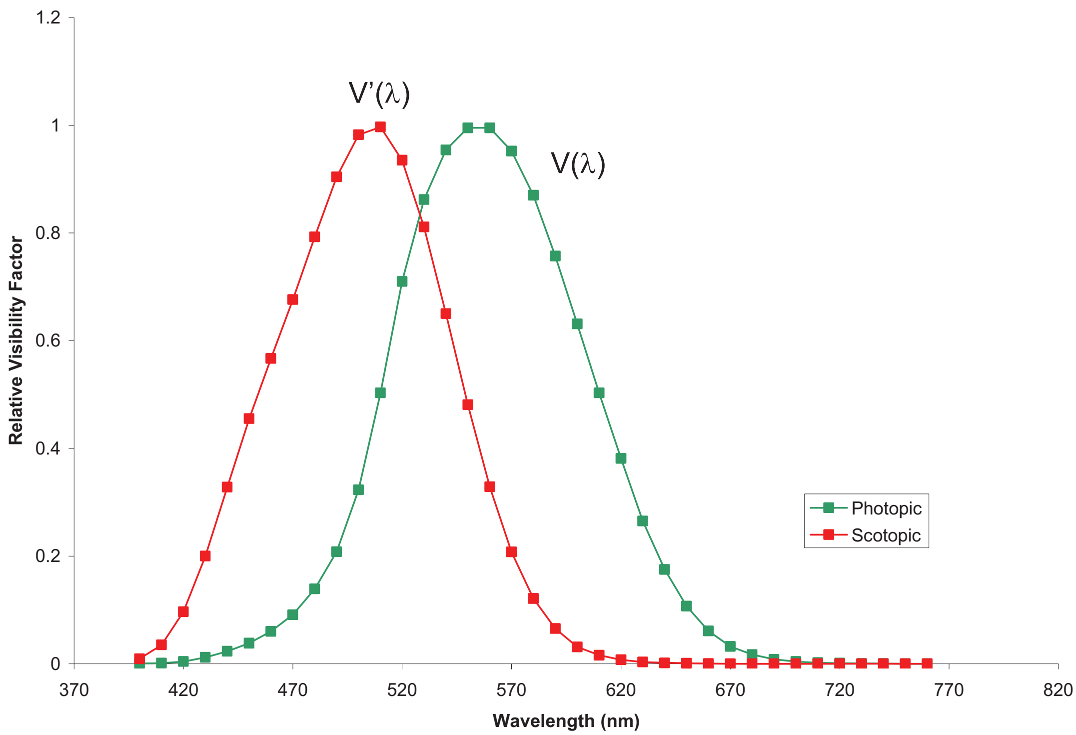


Figure 2.1

A standard photopic luminous efficiency function for 2° angular sub tense photopic viewing conditions was implemented by the CIE. This standard was adopted in the year 1924. This is known as the CIE 1924 *V* (*λ*) [10]. This standard is still used to this date in order to define luminance. This function was first proposed by Gibson & Tyndall (1923). Regrettably, the *V* (*λ*) is a speculative hybrid function that was artificially smoothed and symmetrized from very

divergent data. This function was measured under very different procedures at numerous laboratories[9, 10, 12]. This function proposed in this year also underestimates the sensitivity at wavelengths below 469nm.

2.2.2 Luminosity

Luminosity is a photometric[4] quantity that is represented by L_v or L. Luminosity is defined in photometry as light intensity factored by the sensitivity of a normal average human eye. Luminosity is important because it is associated with brightness, but it is not completely understood due to its complexity. The photopic function (which we will reintroduce as one of the color matching functions, Y; *vide supra*) is used to determine luminosity. In the following charts, an example on how to calculate the luminosity of a source is illustrated. In this example the luminosity of D65 (sunlight) is determined. Figure 2.2 shows the spectral profile of sunlight.

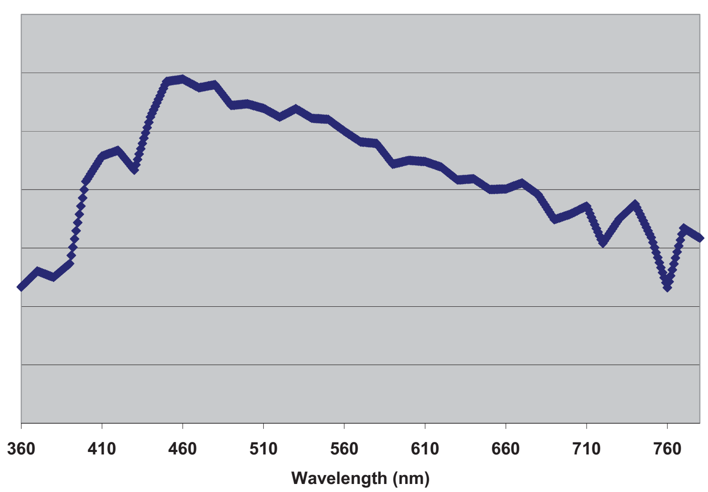


Figure 2.2

Figure 2.3 shows the multiplication of the spectral distribution of sunlight and the photopic function.

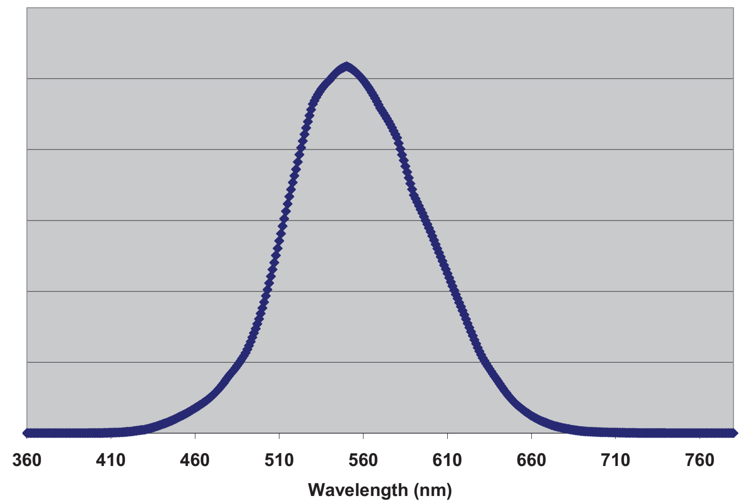


Figure 2.3

The subsequent integration of figure 2.3, shown in figure 2.4 yields a quantity directly proportional to luminosity.

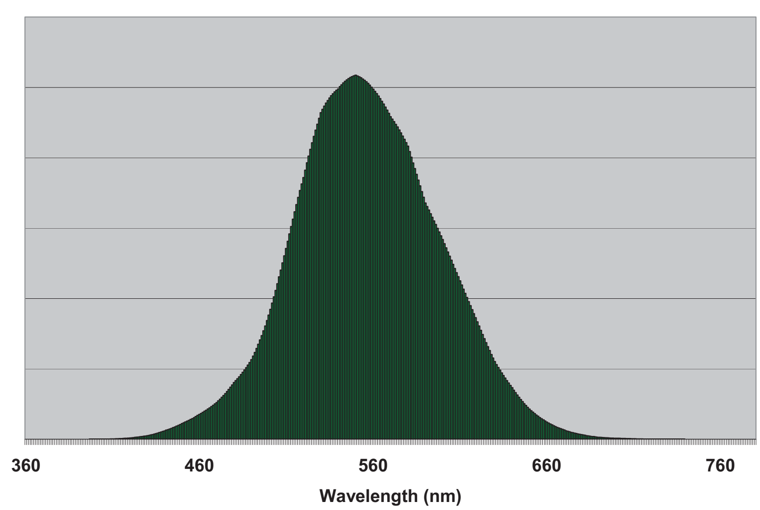


Figure 2.4

2.2.3 Definition of 2 degree tristimulus functions

According to the CIE there are two sets of color matching functions. The first one is the 2 ° color matching function[10] and the second is the 10 ° color matching function[10]. In 1931 the CIE established the standard colorimetric observer utilizing different experiments and a visual field of 2 degree[11]. Using a visual field of 2° denotes that the corresponding stimuli were imaged onto the retina entirely inside the fovea. It is known that within 2° of the fovea, rods do not contribute significantly to the perception of brightness. This is shown in illustration 2.3. This image was adapted from *Color appearance models*[11].

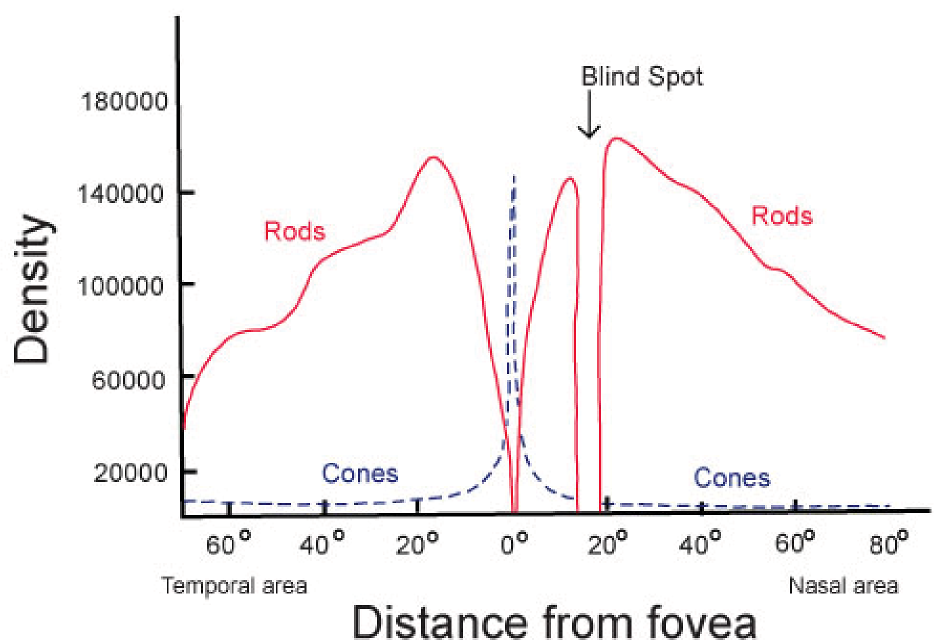


Illustration 2.3

The color matching functions for the 2 ° observer are shown in illustration 2.4.

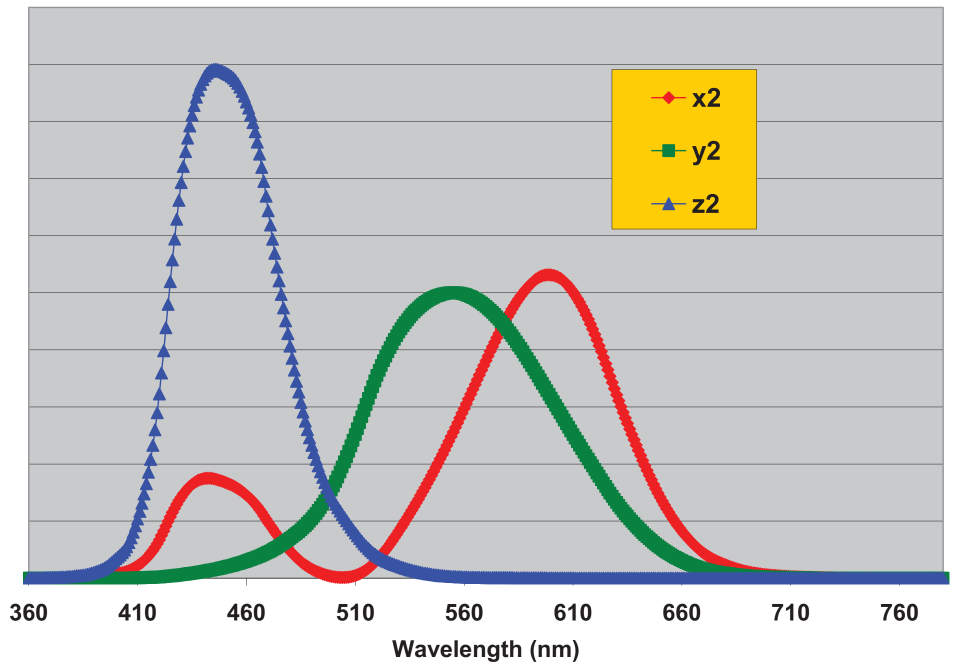


Illustration 2.4

These types of color matching functions based on this visual field are employed in color appearance modeling. In the 1931 CIE[10] experiments for the 2 ° color matching functions were based on only 20 participants, later in the 1950's this set of experiments was completed with the use of more participants and better instrumentation[11].

The second color degree matching function is the 10° function[12]. In 1959 Stiles and Burch conducted more experiments for large visual fields. In these experiments the central fovea was excluded, therefore this color matching function does not include the influence of the macular absorption. This function was officially adapted by the CIE in 1964. It is important to note that the cone

density peaks within 10° either side of the fovea, though rods contribute to color brightness. Because of the difference in the degrees used to calculate each color matching function, the results will be different based on what set is used, Therefore, it is important to state what function was utilized when reporting colorimetric data, or in colorimetric analysis. In this work, all analysis is done with the 2 ° color matching functions.

To simplify some colorimetric analyses, the y2 color matching function was forced to be coincident with the photopic function, which it closely matches. In other words, in the creation of the color matching functions, there were forced transformations of the x2, y2 and z2 (the color matching functions) so that the y2 color matching function would equal the CIE 1924 photopic luminous efficiency function. The purpose of forcing one of the color matching function to be equivalent the $V(\lambda)$ function serves the purpose of integrating the CIE system in photometry into the CIE system of colorimetry[11].

2.3 Color Theory

2.3.1 Trichromatic Color Theory

Because of the complexity of color vision, there have been many different theories that work together or separate from each other in order to explain the function of color vision. The first color theory to be discussed here is the trichromatic theory. This theory emerged towards the second half of the 19th

century, and it was created using the works of Helmholtz, Young, and Maxwell[13]. In simple words, this theory believes that there are three different types of receptors and that each is sensitive to the red, green and blue regions of the spectrum. Originally this theory believed that three images of the object being observed were formed, one image in red, one image in green and one image in blue, then these three images would be sent to the brain. The brain would later balance out or make the necessary adjustments to correctly perceive that object. In this day and age, the trichromatic theory still stands, but the idea of the three images being formed and then sent to the brain to sort out, has long been proven to be wrong.

In trichromatic theory, there is a direct or implied relationship between the three color sensitivity of the eye with the three color matching functions, x2, y2, and z2.

2.3.2 Color Spaces

The CIE (*Commission Internationale de l'éclairage*) which translates in English to International Commission on Illumination was created in 1931[15], and took over the responsibilities of the earlier Commission Internationale de Photometrie (International Commission on Photometry). The CIE is the international authority on light, illumination, color, and color spaces. The CIE is a technical, scientific, and cultural non-profit organization that is formed presently

by 38 countries. The CIE main headquarters are located in Vienna Austria.

According to the CIE, these are the following color spaces, the CIE 1931[10, 14, 15], the CIEUVW [16], the CIELAB[17,] and the CIELUV[15].

2.3.2.1 1931 XYZ color space

The CIE color space from 1931 is also known as the CIE 1931 XYZ color space. As it was mentioned in an earlier section, the human eye has receptors known as cone cells. These cone cells are sensitive to short (S), middle (M), and long (L) wavelengths. The S, M, and L parameters are the ones that describe a color sensation. The CIE 1931 XYZ color space is very important because is the

basis of all the color spaces that developed after it. This color space was the result from a series of studies and experiments done by W. David Wright and John Guild in the late 1920's [14]. The results from their studies and experiments were complied into the specification of the RGB color space from where the CIE 1931 XYZ color space is derived from. It should be clarified that the S, M, and L stimuli of the human eye are not the tristimulus values for this color space. The tristimulus [10, 14] values for this color space are represented by the letters X, Y and Z; where X is nearly red, the Y is roughly green and the Z is approximately blue. Note that X, Y, and Z are not the coordinates of the CIE 1931 XYZ color space.

The three tristimulus values are defined by the following equations:

$$X = \int_{360nm}^{830nm} S(\lambda)\, x2(\lambda)\, d\lambda$$

$$Y = \int_{360nm}^{830nm} S(\lambda)\, y2(\lambda)\, d\lambda$$

$$Z = \int_{360nm}^{830nm} S(\lambda)\, z2(\lambda)\, d\lambda$$

Due to the coincidence of the y2 color matching function with the photopic function, Y is directly related to Luminance.

The coordinates for the CIE 1931 color space are chromaticity coordinates x and y, defined below,

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

and the Y tristimulus function along the remaining Cartesian axis. The color space defined by these transformations and which are referred to as the CIE 1931 XYZ color space or the CIE 1931 xyY color space is shown in Illustration 2.5. This image was adapted from *The reproduction of Colour*[16] and *Color Appearance Models*[11].

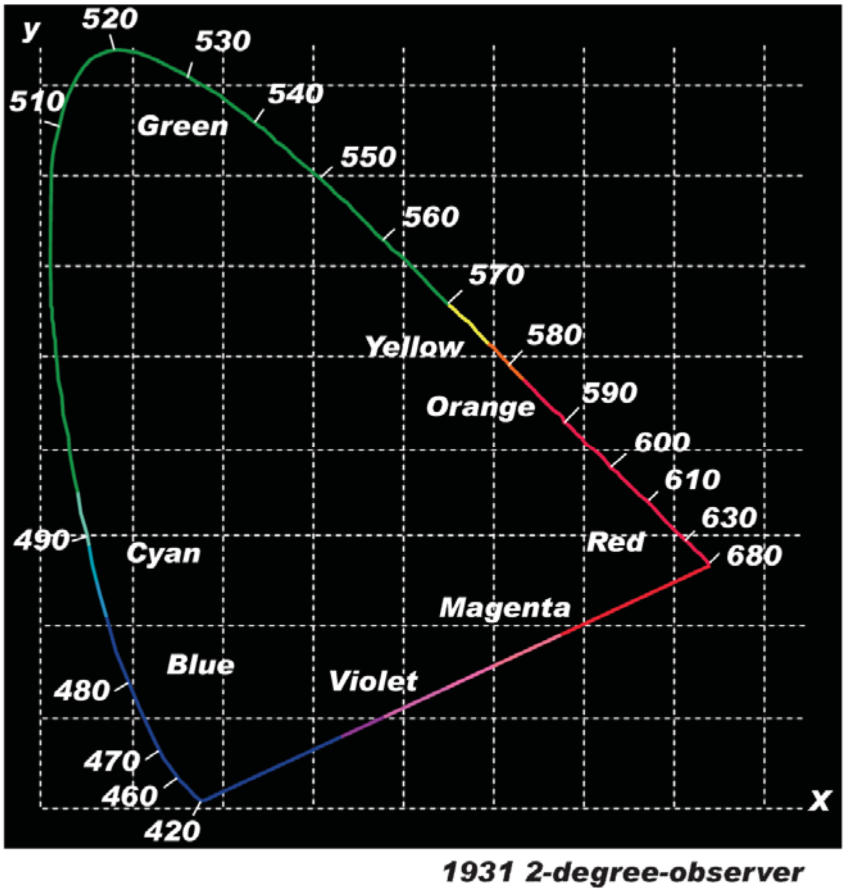


Illustration 2.5

The CIE 1931 xyY color space diagram is the representation of all the attainable chromaticities that are visible to an average human eye. The shape looks like a human tongue, and is often referred to as the "tongue diagram".

The area represented in illustration 2.5 is called the gamut of human vision. The curved line that includes this gamut is known as the spectral locus. In the diagram it can be observed that all the visible chromaticities are related to non-negative values of x, y, and Y.

2.3.2.1.1 Gamut

Gamuts are denoted as areas in the CIE 1931 xyY chromaticity diagram [10, 14]. Gamuts represent the regions of color space that can be captured or simulated by color rendering devices. For instance, the typical computer can only render colors within the triangular gamut. This is shown in illustration 2.6. The image was adapted from *The reproduction of Colour*[16] and *Color Appearance Models*[11].

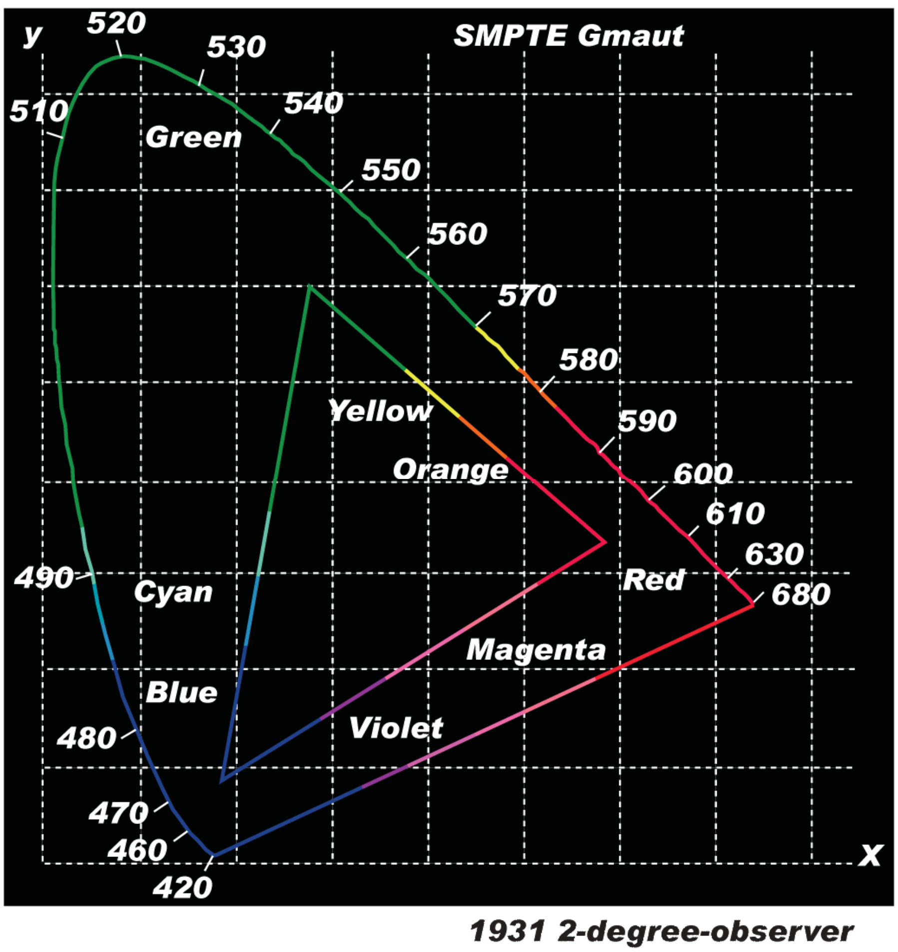


Illustration 2.6

Many gamuts are represented by triangles. This is done because the majority of color reproduction is done with three primaries. It should be clarified that the

accessible gamut is dependent on the brightness, and a full gamut needs to be represented in a three dimensional space.

In 1964, the CIE introduced[12, 16] another color space, the CIEUVW or the U*V*W* color space. This color space has its foundation on the (u,v) coordinates of the earlier CIE 1960 color space, which itself was an improvement over the 1931 CIE color space in creating a more uniform color space. Uniformity is defined as an equivalent change in color from any point in a color space in any direction of the color space for an equivalent shift in color "difference".

The equations for the U*V*W* [16] color space are the following:

$$U^* = 13W^*(u - u_O)$$

$$V^* = 13W^*(v - v_O)$$

$$W^* = 25Y^{1/3} - 17 \quad (1 \leq Y \geq 100)$$

Where $u = 4X/(X+15Y+3Z)$

$v = 6Y/(X+15Y+3Z)$

or $u = 4x/(-2x+12y+3)$

$v = 6y/(-2x+12y+3)$

The coordinate of the illuminant is given by (u_0, v_0). The Y is the luminous tristimulus value of the object. The asterisks that are next to the letters UVW are

placed to indicate that these variables represent a more perceptually uniform color space than the previous color space.

The CIELAB and the CIELUV spaces transform the tristimulus colorimetry to three-dimensional spaces with dimensions that approximately correlate the apparent lightness, color, and hue of a particular stimulus.

The objective of the development of these last two color spaces was to offer uniform practices for the measurement of color differences. It was in 1976 that the CIELAB and the CIELUV were proposed for use. The first color space of these last two to be disused in the following section is the CIELAB.

2.3.2.2 CIELAB Color Space

This color space was designed to be used for the specification of a Euclidean color differences. This Lab color space is what is known as a color-opponent space with dimension L* for luminance, with a***** and b***** for the color-opponent dimensions. Where *L** = 0 yields black and L* = 100 indicates white; *a**= to a negative value indicates green while a positive value indicates magenta and the *b**= to a negative value indicates blue and positive value indicates yellow. In illustration 2.7 this opponent color theory, which is the inspiration of the CIE 1976 *L**, *a**, *b** color space [17], is shown.

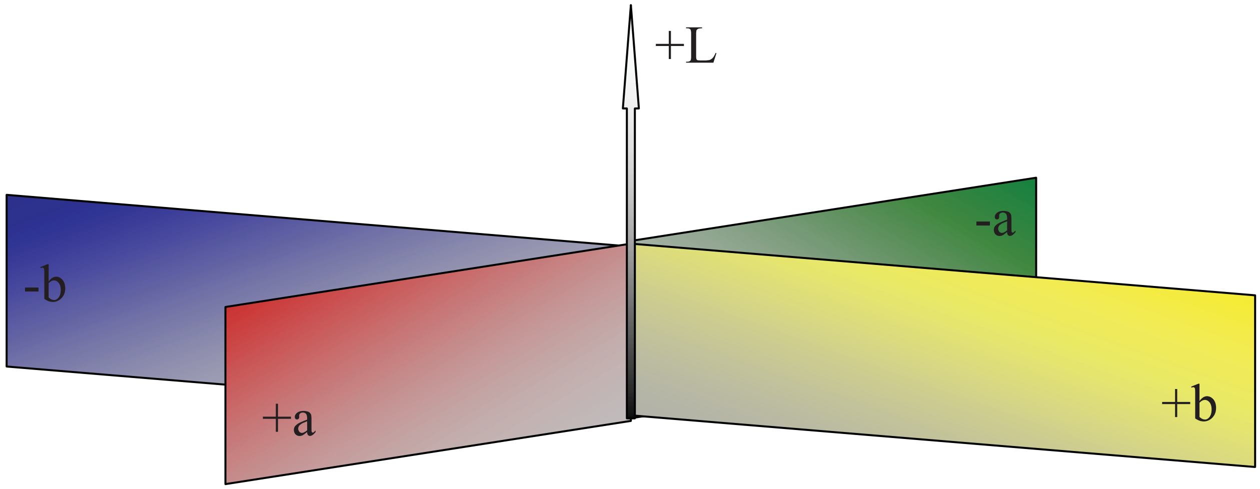


Illustration 2.7

This CIE 1976 *L**, *a**, *b** color space should not be confused with the Hunter 1948 **L, a, b** color space, now that the *Lab* abbreviation without the asterisks is used more and more to denote the CIELAB from 1976. It should be mentioned that this color space is deeply influenced by the Munsell color system[17, 18].

This color space is defined by the following equations[16]:

$$L* = 116\,(\frac{Y}{Yn})^{1/3} - 16$$

$$a* = 500\,[\left(\frac{X}{Xn}\right)^{\frac{1}{3}} - \left(\frac{Y}{Yn}\right)^{\frac{1}{3}}]$$

$$b* = 200\,[\left(\frac{Y}{Yn}\right)^{\frac{1}{3}} - \left(\frac{Z}{Zn}\right)^{\frac{1}{3}}]$$

In the above equations the X_n, Y_n and Z_n variables are the CIE XYZ tristimulus values of the reference white point.

2.3.2.3 CIE LUV color space

This color space is also known as CIE 1976 (L*, u*, v*) color space. This model was adopted by the CIE in 1976. This model is widely applied in different applications especially in computer graphics. Even though the L*, u*, v* has many of the same properties as the LAB, it differs in two main aspects. CIELUV is a rather than a multiplicative normalization of tristimulus values (X/X_n, Y/Y_n and Z/Z_n) this model uses a subtractive shift in chromaticity coordinates ($U'-U'_n$, $V'-V'_n$). This subtractive shift makes it inaccurate with respect to predicting visual data, and can predict imaginary colors which cannot exist.

The LUV coordinates are defined by the next group of formulas[16]:

$$L^* = 116 * (Y/Y_n)^{1/3} - 16$$

$$u^* = 13L * (u' - u_n')$$

$$v^* = 13L * (v' - v_n')$$

The variables u_n' and v_n' refer to the white reference or the light source, and are defined in the following equations[16]:

$$u'_n = 4X_n/(X_n + 15Y_n + 3Z_n)$$

$$v'_n = 9Y_n/(X_n + 15Y_n + 3Z_n)$$

The u' and v' variables are defined the following equations[16]:

$$u' = 4X / (X + 15Y + 3Z) = 4x / (-2x + 12y + 3)$$

$$v' = 9Y / (X + 15Y + 3Z) = 9y / (-2x + 12y + 3)$$

2.3.3 Opponent Color Theory

The trichromatic theory helps explain many of the processes that are involved in color vision, but fails to explain all aspects of color vision. The opponent-process color vision theory was created by Ewald Hering. His observations and research done between 1872 and 1874 lead him to disagree with the leading theory of his time created by Thomas Young and Hermann von Helmholtz[19]. In 1878 he published this opposing theory in the publication *On the Theory of Sensibility to Light*[19] at the Academy of Science in Vienna.

Helmholtz states that yellow is produced from a mixture of red and green. Now Hering's theory states that yellow is a sensation that is not a mixture, that red and green mixtures never occur and that these two colors cancel each other. He further states that a red-green is not possible. Hering concluded from his research that there are six primary colors that are paired. These 3 pairs are red with green, yellow with blue and white with black. Therefore this theory suggests that color perception is dominated by the action of two opponent systems that is a red-green mechanism and a blue-yellow mechanism. In 1878,

Hering[19] wrote: "Yellow can have a red or green tinge, but not a blue one; blue can have only either a red or a green tinge, and red only either a yellow or a blue one. The four colors can with complete correctness therefore be described as simple or basic colors, as Leonardo da Vinci has already done".

Hering's way of ordering colors formed the basis of what now is called NSC[20] or the Natural System of Color. This system orders the colors in a middle circle were it positions the four elementary colors (green, red, blue and yellow) and in between them the proportions to which any two can be mixed. And above this middle circle the other two elementary colors (white and black) opposite to each other. This can be appreciated more clearly in illustration 2.8; the image was adopted from NSC:

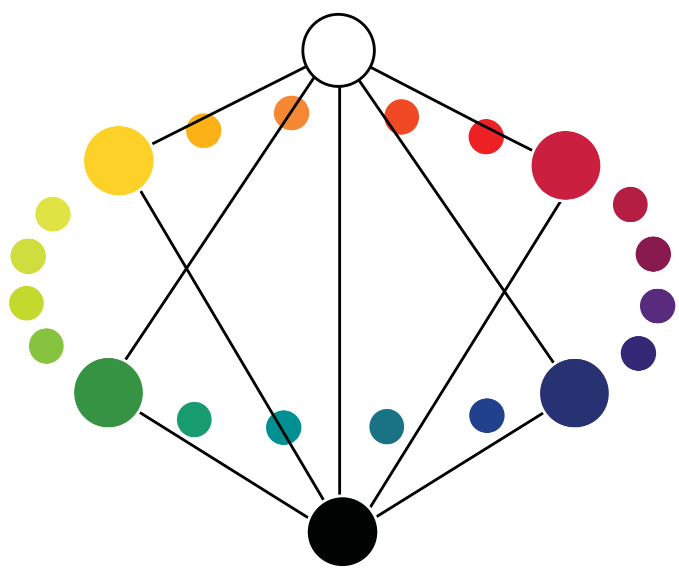


Illustration 2.8

The opponent color theory works via a process of excitatory and inhibitory responses, with the two components of each mechanism opposing each other. To further illustrate this, here is an example. The color red creates an excitatory (or a positive) reaction while the color green created an inhibitory (or a negative) reaction. All of these response or reactions are regulated by opponent neurons. These neurons have an excitatory reaction to some wavelengths and an inhibitory reaction to wavelengths in the opponent part of the spectrum.

As it was mentioned above the opponent color theory is the basis of many color systems and color spaces, including the following: the Munsell[18] color system created in 1929, Hunter's first color space in 1942, Adams chromatic-value space, Scofield color space in 1943, Nickerson's modification of Adams chromatic-value space in 1944, ANLAB in the 1950s, and CIELAB and CIELUV in 1976. Only the last two have been covered in this study because only these have relevance on the research methods used in this work[21].

It should be clarified that the trichromatic theory and the opponent theory do not cancel or contradict each other but complement each other. The receptors indeed are trichromatic as proposed by Helmholtz, Maxwell, and Young but the brain does not receive three color-separated images directly, instead the neurons found in the retina converted into opponent signals.
This means that the retinal neuron processing transform the information into

opponent signals and then send the information to the brain. The illustration 2.9, that was adapted from *Principles of color technology*[21], will help to further understand how these two theories complement each other.

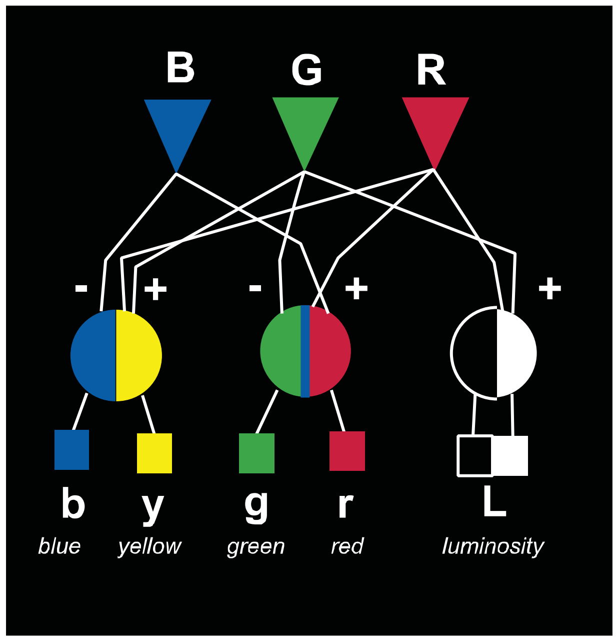


Illustration 2.9

2.3.4 Color Adaptation

With respect to understanding and modeling color appearance the most significant property of the human visual system is chromatic adaptation. The greatly independent perception control of the three mechanisms of color vision is chromatic adaptation. This just means that the spectral responsivity curves of the three cones can fluctuate independently. The illustration 2.10, that was

adopted from *Color Science: concepts and methods, quantitative data and formulae*[22], shows the sensitivity variation of the human visual system.

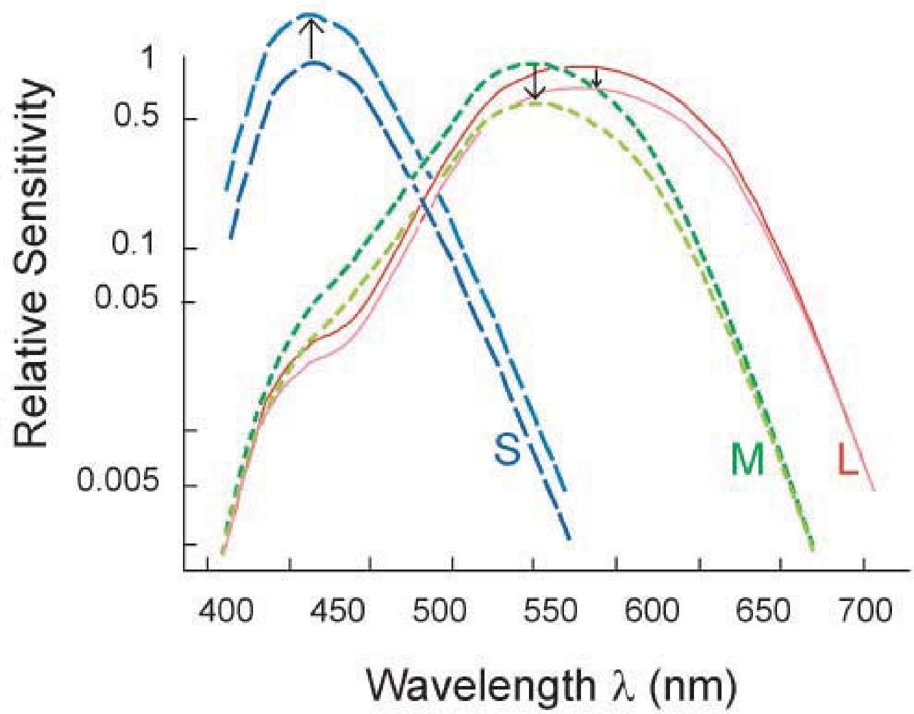


Illustration 2.10

The concept of chromatic adaptation can be further understood with the following exercise. Take a white object, like a sheet of white paper, view this paper under different types of illumination (daylight, fluorescent, incandescent and candle light). Even though the different light sources used have varied wavelengths, the paper retains its white appearance under all the light sources employed. The explanation to this relies on the fact that under daylight the cone system becomes comparatively less perceptive in order to compensate

for the extra short wavelength energy. The long wavelength cone system under incandescent illumination turns less perceptive in order to compensate for the additional long-wavelength energy.

2.3.4.1Von Kries Model and CIE 109.2

Although there are many color adaptation models that can be discussed in this section, only the von Kries model and CIE 109.2 model will be presented in this segment. Johannes von Kries is considered to be the father of Chromatic Adaptation Models. His hypotheses and concepts from 1902 are the basis of all the possible modern chromatic adaptation models of today. Though von Kries did not leave a detailed group of equations that represent what today is known as the von Kries model, he left a collection of hypothesis that have been interpreted into mathematical equations. The following quote is the foundation of the first set of equations. "This can be conceived in the sense that the individual components presents in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function"[11,23].

$$L_a = \kappa_L L \quad (1)$$

$$M_a = \kappa_M M \quad (2)$$

$$S_a = \kappa_S S \quad (3)$$

The explanation for the above equation is found in *Color Appearance Models* by Mark D. Fairchild[11]. The initial cone responses are represented by L, M, and S. The coefficient that are used to scale the initial cone signals are represented by κ_L, κ_M, and κ_S. The post-adaptation cone signals are represented by L_a, M_a and S_a. The equations 1-3 calculate a non-complex gain control model of chromatic adaptation. In these equations a separate gain coefficient is assigned to each of the three cone types.

A very important feature for any adaptation model is the way the values of κ_L, κ_M, and κ_S are calculated. In the majority of the modern interpretations of the von Kries model. The inverse of S, M, and L cone reactions of the greatest sensation or the scene white are taken in order to compute these coefficients[11] as shown in the following equations:

$$\kappa_L = 1/L_{max} \quad or \quad k_L = 1/L_{white}$$

$$\kappa_M = 1/M_{max} \quad or \quad k_M = 1/M_{white}$$

$$\kappa_S = 1/S_{max} \quad or \quad \kappa_S = 1/S_{white}$$

This model can be used to compute corresponding colors under two very different conditions. This can be determined by working out the signals for the post adaptation of the first condition. Then these signals are set equal to the

signals of the post adaptation of the second condition. Then the model can be reversed for the second condition. In special cases it is more suitable to express this adaptation model in the form of a matrix, as it if in the following image[11]:

$$\begin{bmatrix} X_2 & Y_2 & Z_2 \end{bmatrix} = \begin{bmatrix} X_1 & Y_1 & Z_1 \end{bmatrix} \left[[M] \begin{bmatrix} L_2/L_1 & 0 & 0 \\ 0 & M_2/M_1 & 0 \\ 0 & 0 & S_2/S_1 \end{bmatrix} [M]^{-1} \right]$$

Where $\begin{bmatrix} L_{max} & M_{max} & S_{max} \end{bmatrix} = \begin{bmatrix} X_{max} & Y_{max} & Z_{max} \end{bmatrix} [M]$. This matrix representation is called the Bradford model and is used in the computer program Photoshop.

The next chromatic adaptation model to be discussed is the CIE 109.2[31] or also known as the Nayatani et al. Model, represented as follows[11]:

$$L_a = a_L (\frac{L + L_n}{L_0 + L_n})^{\beta_L}$$

$$M_a = a_M (\frac{M + M_n}{M_0 + M_n})^{\beta_M}$$

$$S_a = a_S (\frac{S + S_n}{S_0 + S_n})^{\beta_S}$$

The $L_a,\ M_a,\ and\ S_a$ coefficients are the cone signals after adaptation. The $L, M, and\ S$ coefficients are the cone excitations. The $L_n, M_n\ and\ S_n$ coefficients are the noise terms that were added to the cone responses. The $L_0, M_0 and\ S_0$ coefficients are the cone excitations for the adapting field. The $\beta_L, \beta_M\ and\ \beta_S$ coefficients are exponential functions that correspond respectively to the cone excitations of the adapting filed. The last coefficients are $a_L, a_M\ and\ a_S$ these are calculated based the following rule: if a sample that is nonselective; has a luminance factor that is equivalent to that of the adapting background then the exact color constancy holds for this nonselective sample. The Nayatani et al. model is a non linear improvement of the von Kries model. It was created based on a colorimetric background but in the realm of illumination engineering.

Refinements to the model were made and submitted to the CIE to form the 1994 CIE publication[24].

2.3.5 Color Difference Formulae

There have been many discussions, debates, and calculations in order to come up with a satisfactory color difference formula, up until now there is no single one that is completely accurate. Many formulas have been developed throughout the years, the formulas keep getting more and more complicated

but also more accurate. There are five formulas from the CIE; the pre-LAB from 1960, one for LUV from 1976 and three LAB from 1976, 1994 and 2000.

The observer's judgment of color difference is affected by several factors like: the conditions of the observation, the kind of stimuli presented, volumes, forms, luminances, the test stimuli's spectral power distributions, and the stimuli that surrounds them and the makeup of the display situation[16, 22]. The experimental data regarding color distinction and uniform color balance emphasizes how complex it is to judge, quantify and explain the perception of stimuli of an observer, this the observed color differences in specific investigative circumstances.

2.3.5.1 CIE 1964 (U*V*W*) Color Difference Formula

The total color difference ΔE among two color stimuli in the 1964 CIE[12] U*V*W* color space is given by the following formula[16]:

$$U^* = 13\,W^*\,(u - u_n)$$

$$V^* = 13\,W^*(v - v_n)$$

$$W^* = 25\,Y^{\frac{1}{3}} - 17$$

$$\Delta E = \sqrt[2]{[(\Delta U^*)^2 + (\Delta V^*)^2 + (\kappa \Delta W^*)^2]}$$

Where κ=1 for samples that are in close proximity, but will have lower value for other specific situations.

2.3.5.2 CIE 1976 (L*u*v*) Color Difference Formula

The CIE 1976 L*u*v* color space[17] is among the most uniform, and suggested that Euclidean color differences could be accurately defined. The color difference $\Delta E*_{UV}$ among two color stimuli, each color stimuli given in terms of L*, u*, v* is obtained from the following formula[16]:

$$\Delta E^*_{uv} = \sqrt[2]{[(\Delta u^*)^2 + (\Delta v^*)^2 + (\kappa \Delta L^*)^2]}$$

Where κ=1 for samples that are in close proximity, but will have lower value for other specific situations.

2.3.5.3 CIE 1976 (L*a*b*) Color Difference Formula

As it was discussed previously, the CIE published in 1976 the CIELAB (L*a*b*) color space[17]. This color space is considered the second perceptually nearly uniform color space, and resulted in the definition of another Euclidean color difference formula.

The whole color difference $\Delta E*_{ab}$ among two color stimuli, each color stimuli given in terms of L*, a*, b* is obtained from the following formula[16]:

$$\Delta E^*{}_{ab} = \sqrt[2]{[(\Delta a^*)^2 + (\Delta b^*)^2 + (\kappa \Delta L^*)^2]}$$

Where κ=1 for samples that are in close proximity, but will have lower value for other specific situations.

2.3.5.4 CIE 1994 (L*a*b*) Color Difference Formula

As time passed by it turned out to be evident that the color difference formula from 1976 was not an adequate perceptual color difference quantity. In the year 1995 the CIE determined to publish another color difference formula, the CIE 1994[25]. The CIE 1994 color difference formula uses the 1976 L*a*b* color space, but is no longer Euclidean in this space[11]:

$$\Delta E^*{}_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*\,2}]^{1/2}$$

$$\Delta E^*{}_{ab} = [\Delta L^{*2} + \Delta C_{ab}{}^{*2} + \Delta H_{ab}{}^{*\,2}]^{1/2}$$

$$\Delta H^*{}_{ab} = [\Delta E_{ab}{}^{*2} - \Delta L^{*2} - \Delta C_{ab}{}^{*2}]^{1/2}$$

$$\Delta E^*{}_{94} = [\left(\frac{\Delta L^*}{\kappa_L S_L}\right)^2 + \left(\frac{\Delta C^*{}_{ab}}{\kappa_C S_C}\right)^2 + \left(\frac{\Delta H^*{}_{ab}}{\kappa_H S_H}\right)^2]^{1/2}$$

$$S_L = 1 \qquad S_C = 1 + 0.045\, C^*{}_{ab} \qquad S_H = 1 + 0.051 C^*{}_{ab}$$

2.3.5.5 CIE 2000 (L*a*b*) Color Difference Formula

The CIE 2000[26] color difference formula is mathematically much more complicated compared to the previous color difference formulas, and also is based on the L*a*b* color space:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

The calculations can be divided into three main groups; the groups are in order of precedence. In other words the first groups of equations are calculated first. The following equations are part of the first group.

$$G=\frac{1}{2}\left(1-\sqrt{\frac{C_{ab}^{*\ 7}}{C_{ab}^{*\ 7}+25^7}}\right) \qquad C_{ab}^*=\frac{C_{ab,r}^*+C_{ab,s}^*}{2} \qquad C_{ab,i}^*=\sqrt{\left(a_i^*\right)^2+\left(b_i^*\right)^2}$$

$$C'=\left(a'^2+b'^2\right)^{0.5} \qquad a'=a^*\left(1+G\right)$$

$$b'=b^* \qquad h'=Arc\tan\left(\frac{b'}{a'}\right)$$

The following equations are part of the second group. Where r is the reference r=2 and s is the source s=1.

$$\Delta L'=L^*_r-L^*_s \qquad \Delta C'=C'_r-C'_s$$

$$\Delta L'=L_2^*-L_1^*$$

$$\Delta C'=C_2'-C_1'$$

$$\Delta h'=\begin{cases}0 & C_1'C_2'=0\\ h_2'-h_1' & C_1'C_2'\neq 0;\ \left|h_2'-h_1'\right|\leq 180^\circ\\ (h_2'-h_1')-360 & C_1'C_2'\neq 0;\ (h_2'-h_1')>180^\circ\\ (h_2'-h_1')+360 & C_1'C_2'\neq 0;\ (h_2'-h_1')<-180^\circ\end{cases}$$

$$\Delta H' = 2\sqrt{C_1' C_2'} \sin\left(\frac{\Delta h'}{2}\right)$$

The following equations are part of the third group. Where r is the reference r=2 and s is the source s=1.

$$\bar{L}' = (L_1^* + L_2^*)/2$$

$$\bar{C}' = (C_1' + C_2')/2$$

$$\bar{h}' = \begin{cases} \dfrac{h_1' + h_2'}{2} & |h_1' - h_2'| \leq 180°;\ C_1'C_2' \neq 0 \\ \dfrac{h_1' + h_2' + 360°}{2} & |h_1' - h_2'| > 180°;\ (h_1' + h_2') < 360°; \\ & \qquad C_1'C_2' \neq 0 \\ \dfrac{h_1' + h_2' - 360°}{2} & |h_1' - h_2'| > 180°;\ (h_1' + h_2') \geq 360°; \\ & \qquad C_1'C_2' \neq 0 \\ (h_1' + h_2') & C_1'C_2' = 0 \end{cases}$$

$$T = 1 - 0.17\cos(\bar{h}' - 30°) + 0.24\cos(2\bar{h}')$$
$$+ 0.32\cos(3\bar{h}' + 6°) - 0.20\cos(4\bar{h}' - 63°)$$

$$\Delta\theta = 30\exp\left\{-\left[\frac{\overline{h'} - 275^\circ}{25}\right]^2\right\} \qquad R_C = 2\sqrt{\frac{\overline{C'}^7}{\overline{C'}^7 + 25^7}}$$

$$S_L = 1 + \frac{0.015\left(\overline{L'} - 50\right)^2}{\sqrt{20 + \left(\overline{L'} - 50\right)^2}}, \qquad S_C = 1 + 0.045\overline{C'}, \qquad S_H = 1 + 0.015 * \overline{C'}T$$

$$R_T = -\sin(2\Delta\theta)R_C$$

The CIE 2000 color difference formula is both more complex, and subtlety much more difficult to implement since hue angle is directly implemented within this calculation. This leads to the need to define direction of angles very carefully, and to consider the effects of discontinuities introduced by the trigonometric operations.

For all the color difference formulas discussed above, the ΔE represents the change in color. The minimum value for ΔE, in order for the naked eye to just

notice a perceptible difference in color, is equal to one. If the value for ΔE is less than 1, this mean that we cannot see the color difference with our naked eye, but there is a change and in order to appreciated it would need to be measured with an optical instrument (like a uv-vis spectrophotometer).

2.3.6 Color Rendering

According to the CIE definition of 1974[27], color rendering of a source is how the light source makes the color of an object to appear when is evaluated against how the reference source makes the color of the same object appear. The first step in calculating the color rendering index (CRI) [28] is to select a standard light source to which to compare the given test light source. Once the standard light source has been selected the object-color perceptions and the differences between them need to be known.

Color rendering differences are a combination of color difference and color adaptation. Under difference illuminants, the color difference is perturbed by the eye and brain's attempt to adapt to the color difference produced by the two illuminants.

Standard color rendering theory can be traced back to the CIE 13.3[30] implementation of defining the color rendering difference. This method combined the U*V*W* color difference expression with the von Kries adaptive

color model. Its main utility was to define the color rendering differences of incandescent and fluorescent lamps for the lighting industry. The CIE 13.3 method has severe limitations. It cannot compare lamps of significantly different color temperature, and the adaptive color difference model by von Kries is too primitive to accurately represent the adaptation necessary for widely different luminosities or spectral distributions.

All color rendering method require defining test color samples, either real or theoretical. The CIE 13.3 method defined two sets of test color samples. One set was of eight varying hues given in Table 2.1 in their Munsell notation.

Table 2.1

No.	Approximate Munsell Notation	Colour appearance under daylight
1	7,5 R 6/4	Light grayish red
2	5 Y 6/4	Dark grayish yellow
3	5 GY 6/8	Strong yellow green
4	2,5 G 6/6	Moderate yellowish green
5	10 BG 6/4	Light bluish green
6	5 PB 6/8	Light blue
7	2,5 P 6/8	Light violet
8	10 P 6/8	Light reddish

An expanded set, for more diverse colorimetric uses added six more colors. This is shown in table 2.

Table 2.2

No.	Approximate Munsell Notation	Color appearance under daylight
9	4,5 R 4/13	Strong red
10	5 Y 8/10	Strong yellow
11	4,5 G 5/8	Strong green
12	3 PB 3/11	Strong blue
13	5 YR 8/4	Light yellowish pink (human complexion)
14	5 GY 4/4	Moderate olive green (leaf green

These standard sets encompass colors of relative similar high saturation. Objects of lower saturation are not represented.

Due to the weaknesses in the CIE 13.3 method and the relatively narrow saturations of the reference color set, new color rendering methods were defined which varied either or both the color difference and adaptation theories with more modern and accepted theories, and also varied the basis reflection data to be other than the standard Munsell sets described above. For instance, the Von Kries[11, 23] adaptation method was replaced with the CIE 109.2 (Nayatani) [31] method, and replace the U*V*W* color difference with either the CIE 1994[25] or CIE 2000[26] color difference methods. In addition, the color reference set is replaced by reflection spectra from actual pigments of objects used for which the color matching must apply.

The advantages of the modifications made in the color rendering methodology are:

1) Illuminants of varying luminosity can be compared
2) Illuminants of varying spectral distribution can be compared
3) Lighting can be tailored to specific objects

The color rendering index for a given test pigment is represented by *Ri*. For the standard CIE 13.3 method[30], the color rendering index (CRI) is given by[30]:

$$CRI = \frac{1}{8}\sum_{i=1}^{8} R_i$$

The relationship between the color rendering index and color difference is given by the formula[30]:

$$CRI = 100 - 4.6(\Delta E)\, i$$

To get perfect color rendering for a test color sample would mean that *Ri* =100, or CRI=100 for all colors, in other words, no perceived color difference.

2.3.7 Luminosity versus Brightness

Luminosity is a photometric quantity that is represented by Lv or L. Luminosity is defined in photometry as light intensity factored by the sensitivity of a normal average human eye. The color matching function Y, which is the photopic function, is used to determine luminosity. Brightness is the actual perception of luminosity, apart from the mathematical operation to generate

luminosity. The main difference between brightness and luminance is that brightness can only be perceived by the human eye and it cannot be measured by an instrument.

In the following equation the relationship between brightness and luminance is estimated[32].

$$B = \alpha L^{p} - Bo$$

In the above equation **B** represents the measure of the brightness that is estimated by a subject that is presented with a stimulus of luminance **L** under very specific conditions of observation. The exponent denoted by the letter p has a rough value of 1/3, some researchers believe that p can vary between the following range of values p=0.31 plus or minus 0.03. The values of the variables **a** and **Bo** are dependent of the observing conditions and they include a biased weighing factor.

2.3.8 Helmholtz-Kohlrausch effect

Most photometry assumes that brightness is given strictly by luminance. The Helmholtz-Kohlrausch[8, 33] effect suggests that as a spectral color becomes more saturated, at a constant luminance, will look to the human eye as brighter. Therefore it should be noted that the brightness and the lightness that are perceived should not be believed to be exclusively depending only on the

relative luminance. In a straightforward explanation this effect depends on luminance and chromaticity, the higher the saturation the higher the perceived brightness.

The Optimization problem

The optimization of a potential filter is done using a complex Excel spreadsheet that has links to programs done in visual basic. This sheet was designed by Dr. Carl Dirk and is being constantly updated.

This Excel spreadsheet compiles all the theory that was described in previous sections of this document. The theory described in previous sections is what helps design the desired filter and controls all the variables for the desired filter. The theory behind the filter design includes: radiometry, photometry, luminosity, the 2 degree tristimulus functions, the trichromatic color theory, color spaces, opponent color theory, color adaptation, the color difference formulas, the adaptation, the color rendering formulas and sets, the relationship between luminosity and brightness. The variables than can either be fixed or varied include: the filter efficiency, the lumens per watt efficiency, a graph that includes the source lamp, the reference lamp and the possible filter curves (the filter curve changes as the variables change) the overall efficiency, the power, the transmission, and the 1st and 2nd derivative of the smoothing function. Other parts of the Excel spreadsheet include the source lamp, the reference lamp, the error analysis, the tolerances, the Gaussian and Lorentzian weighing functions,

The mentioned above items all play a crucial role when an optimization calculation is being processed for a potential filter. Even though all parameters can be adjusted to whatever is needed there are three primary interdependent

constraining parameters in this filter design process. These are color rendering, luminosity, and lumens per watt efficiency.

3.1 Color rendering versus luminosity versus luminosity/radiance

Color rendering is the degree to which a given source illumination of an object matches that of a reference illuminant. The actual process involves the convolution of an adaptive color theory method and a color difference method. Color difference alone cannot be used because the eye is known to force some adaptation when confronted with a different illumination. The eye is not just a color difference instrument, but also has adaptive capability that will render some color differences, as caused by the sensation from different illuminants, as being smaller than they might otherwise be.

Many reference illuminants can exist, both real and theoretical. Typically, the concentration will be on three likely possible reference illuminants commonly in use: fluorescent, incandescent, and sunlight. Each of these can have theoretical, as well as real counterparts. The theoretical illuminants are known as standard Illuminants, and for fluorescent, incandescent, and sunlight, the commonly specified standards are F7[8, 34, 36], A[8, 34, 36], and D65[8, 34, 36] (see Appendix A). No lamps exactly match these standards, and so they are considered theoretical. When designing a new illuminant, and faced with the need to conduct actual comparison tests with human test subjects, one has to

use real lamps as the reference, not theoretical standards. In this work, since many museums commonly use incandescent lighting of about 3000 K in color temperature, a 3000 K Sylvania lamp, #58562 was chosen. This choice was somewhat arbitrary, and is discussed further on.

The determination of Luminosity is based on the mathematical procedure discussed above using the photopic function. One can easily compare luminosity between a reference and test illumination by that method. Luminosity is important because a filter design which attenuates too much light will require a more powerful source lamp. Luminosity is linked to transmitted power to some extent, and one can achieve similar ends in optimization by adjusting transmitted power. They are not identical parameters. In fact the objective is to try to achieve higher luminosity for a given transmitted power.

Lumens per watt efficiency (L/W) is a key parameter for optimizing filter performance. A higher L/W achieves necessary luminosity while reducing total power of light that reaches the target. A higher L/W will usually reduce the rate of photochemical change. One easily calculates L/W by dividing the luminosity by the total integration of the illuminant spectral distribution.

3.2 The Optimization Procedure

Given a reference illuminant, one can calculate luminosity and L/W. With a test illuminant, one can calculate luminosity, L/W, and in conjunction with the

reference illuminant, the color rendering. It was relied in the case of color rendering, on reference reflection spectra from actual works of art for which the lighting is to be optimized rather than the standard Munsell color set specified in CIE 13.3[28]. Optimization then involves varying the test illuminant systematically while constraining the three main parameters, luminosity, L/W, and color rendering.

Ideally, the color rendering index (CRI) would needed to be constrained as close to100 as possible. However, if tradeoffs are necessary to achieve higher L/W, one can choose to compromise CRI to lower values, sometimes as low as about 80. This can be a choice for the conservator or curator. Do they want higher color rendering or do they need to protect the object more.

The value for or L/W, needs to be above 100%, or it is offering more power than the reference. When comparing common illuminants like F7, A, and D65, it was found that if A is designated as unity in L/W, then D65 is at 127% and F7 is at 163%. This, even with common illuminants, there is a substantial range for L/W. One might naturally ask why fluorescent lighting is not more commonly used than incandescent, given this higher L/W efficiency? The main concerns are the mercury emission spikes in the visible, which could potentially be very damaging. The other is the proportion of power at shorter wavelengths is higher for F7 than A, and therefore higher energy, potentially more damaging photons, are more available in F7 than in A.

The range in L/W efficiencies for F7, D65, and A suggest that one wants to reach considerably higher than 163% relative to a standard incandescent. An important question is how high can one reach? If color rendering is not an issue, it appears that if the reference is Sylvania 58562, the best optimizations yield is about 404%. This is with unacceptable color rendering. In fact, in general, the higher the L/W, the more difficulty in achieving higher CRI. There is in fact a tradeoff in L/W versus CRI.

A theoretical study was conducted to define the limits of the tradeoff between L/W and CRI. Included in this was the consideration in variation in transmitted power. In figure 3.1 the relationship among these quantities is shown

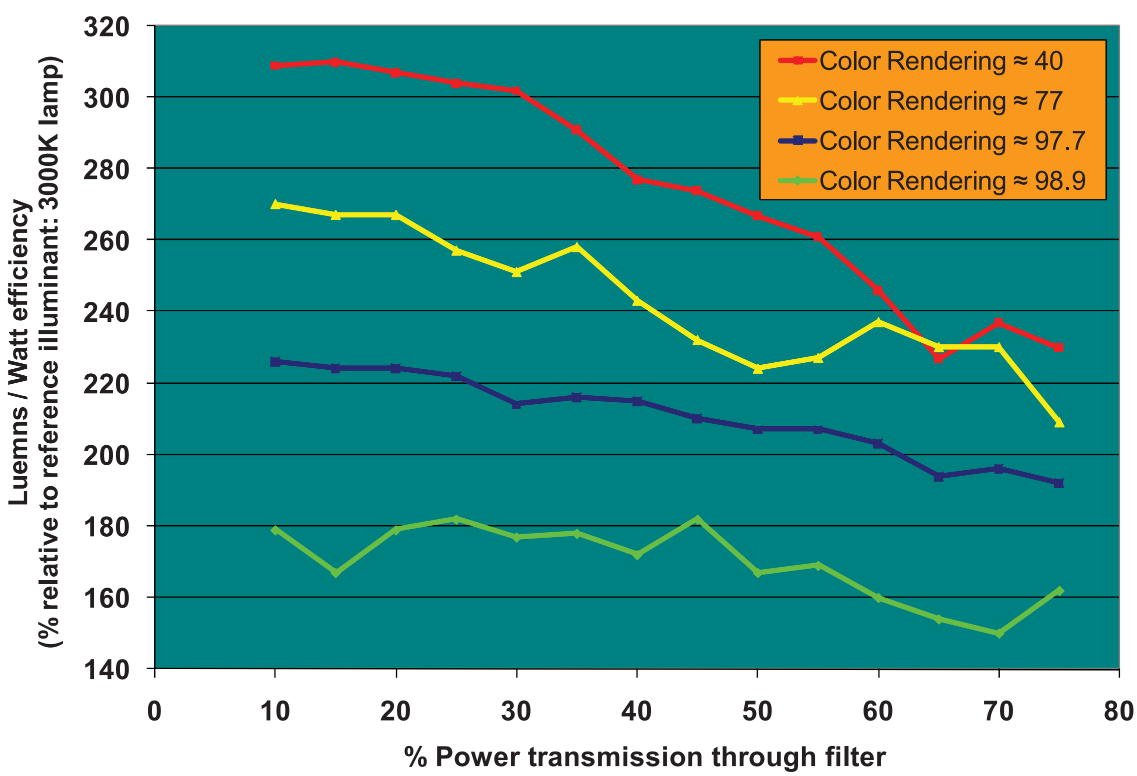


Figure 3.1

Each point in figure 3.1 represents the best optimization that could be done on L/W when power and color rendering are fixed as given. One can clearly see that much better L/W efficiencies can be obtained when CRI is compromised to lower values. Also, as one constrains to lower transmitted powers, there is another improvement in L/W. If one compares the spectral profiles of filters with high CRI (>=95) but with varying power, a trend is seen. The trend is illustrated in figure 3.2. As one reduces transmitted power, the spectral profile takes on structure of several peaks. Depending on the reference and color rendering constraining reference colors, at low transmitted powers below 25%, one obtains four or five peaks for optimal color rendering.

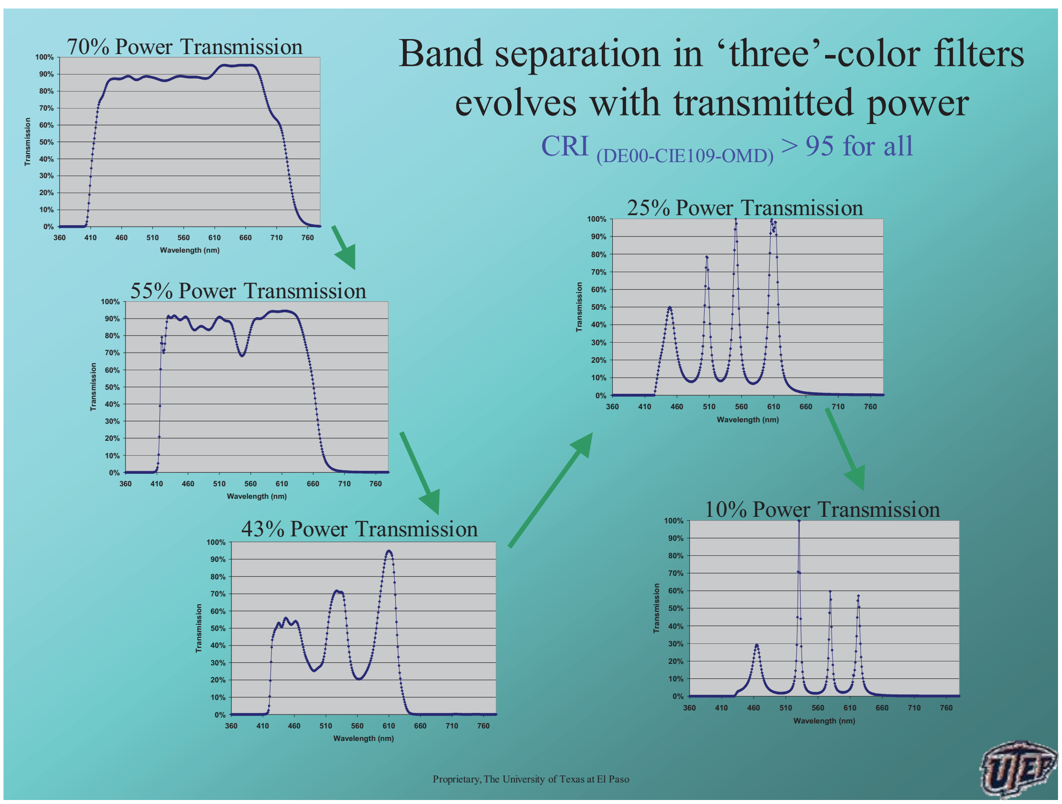


Figure 3.2

Prior to optimization, one has to obtain the primary experimental data used to define the lamps being used as reference or source (lamp behind a filter), and to acquire the reflection spectral data. It is discussed in the following section the methods and procedures to characterize lamps, from among which were selected a reference lamp and a source lamp.

3.3 Construction of Lamp Test Facility (LTF)

Radiometrically accurate spectral profiles of lamps to be used in this study were necessary. Such demanded both spectral accuracy, as well as intensity accuracy. This required both a calibrated detector and a surrounding facility to minimize reflection. The design of this facility had to be effective, practical, and inexpensive.

The LTS was constructed to be black on ceiling and walls to reduce reflected light contributions to the measurement. The most economical route to converting the entire room into an approximately "dark" room was done in three simple ways. First the floor was painted black using black spray paint number 20004 by Endura. This paint was chosen because of its very low reflectivity. Second, movable panels were created using angle iron that was painted with the same flat black, and hung with black fabric tied by black yarn. The black fabric that was used is the BA-05 Sheermist Bati Black c/o China 65% Polyester and 35% Cotton sold in Hobby Lobby. This fabric was chosen because

of its very low reflectivity. Third, a faux ceiling was created using angle iron, black yarn, and black fabric. This angle iron that makes up the ceiling is fixed into the walls of the room. In the angel iron of the faux ceiling the spectrograph was installed. There is an adjacent dark room to this new created dark room, both dark rooms share a wall. In the adjacent dark room, the computer that controls the spectrograph is located.

The floor was easily smudged by footprints, and had to be refreshed periodically with new painting. To minimize the effect of foot traffic, clean room style foot coverings were employed throughout the process of setting up all measurements.

3.3.1Calibration

The detector was radiometrically calibrated against NIST calibrated Oriel Standard 200W Quartz Tungsten Halogen Lamp (#63355) powered by an Oriel regulated power supply (#68931) designed for high stability. The lamp was mounted in an Oriel open mount (#63966) that provided spherical access to the lamp emission. Spectral calibration was performed against an Oriel Hg-Ne pencil lamp (#6030) powered by an Oriel power supply (#6047). The lamp was mounted in Oriel pencil lamp Holder (#63670). Since both lamps emit in the ultraviolet, suitable precautions were made to not expose skin or eyes to the light during measurement. Both lamps were powered for at least 15 minutes before beginning calibration.

The nonlinearity in the detector was investigated by utilizing a series of Oriel fused silica metallic neutral density filters of OD 0.3 (#50510), 0.6 (#50532), 1.0 (#50540), and 1.5 (#50545). Over the anticipated range of intensities of the measurements that were conducted, it was determined that the detector possessed a nonlinear response discrepancy of no more than 5% at maximum.

An Oriel InstaSpec IV CCD array (model DV420-OE 78436) was used in conjunction with an Oriel MS125 1/8m spectrograph (model 77400) equipped with an Oriel ruled (400 lines/mm) grating, #77417, possessing a primary wavelength region of 300-1200nm, a bandpass to the array of 505nm, a spectral resolution of 0.65nm, and a blaze wavelength of 500nm. The spectrograph as equipped with a 2 inch Oriel integrating sphere (#70482), with a 0.5 inch diameter entrance opening. The distance between the lamp filament and the sphere opening was about 2.09m. Thus the entrance opening is small compared to the distance to the lamp. An integrating sphere was used to capture light to ease alignment and focus problems, ensuring better reproducibility between measurements.

The spectrograph as controlled by Oriel InstaSpec software for Windows, version 1.1. For the purposes of calibration, the software was wavelength calibrated using the equipment as described above, and this wavelength calibration was retained within the InstaSpec software to be applied to subsequent measurements. Radiometric calibrations were not relied upon within

the software, and raw count measurements were collected and separately calibrated and computed using procedure within Microsoft Excel. The calibration curve used in this work is presented in Appendix B. For all measurements, the temperature of the CCD array was set to 0°C. The spectrograph has to be on for an hour in order to reach that temperature.

3.3.2 Lamp measurement methods

All the light must be extinguished during measurements. Two lamp fixtures were used to mount the lamps to be tested. One of these fixtures ("A") involved a standard commercial "12V" power supply commonly used for MR16 lamps. In order to better understand the voltage and current characteristics, this device was wired in a way to have both current measuring and voltage measuring capability across the lamp filament circuit. The voltage applied by this circuit was typically about 11.21V for most lamps. The other fixture ("B"; Appendix C) was constructed by the Dirk research group to have more control over either the applied voltage or current, to have greater geometric control for aiming the lamp, and to have a controlled level surface for placing and testing filters on a lamp. For both fixtures, current was measured by a Keithly auto-ranging multimeter, model 176A. Voltage was measured by a Fluke handheld multimeter, model 112. A DC regulated power supply by BK Precision, model 1686A, was used to power the lamp in fixture B.

The lamp is placed on the floor underneath the spectrograph. Without removing the cap covering the opening of the integrating sphere attached to the spectrograph, the center of the lamp filament is aligned with the center of the spectrograph integrating sphere opening. This alignment is done using a self leveling three point laser plumb level from New Pacific Laser Systems; model PLS3, serial number A29399. This aligning tool is attached to a standard photographic tripod. Two of the lasers point vertically. One of the lasers is pointing up, towards the ceiling and the other laser is pointing down towards the floor. The third laser points horizontally, at a 90 ° angle in reference to the other two lasers, and is not used. The tool is moved slowly back and forth, left and right until acceptable alignment is achieved, and then the lamp filament is aligned to coincide with the brightest point of the lower laser. Once close to perfect alignment is achieved the cap of the spectrograph is removed. The researcher exits the dark room, closes all the panels, turns all the lights off, and proceeds to the dark room where the computer that controls the spectrograph is located.

The settings for all the measurements are the following:

- The acquisition mode is set at accumulate.
- The readout mode is set at full vertical binning.
- The trigger mode is set at internal.
- The exposure times is set at 0.021 seconds.
- The number of accumulations is set at 1000.

- The accumulate cycle time is set to 0.021 seconds.
- The units in the y-axis are counts 10^5.
- The units in the x-axis are in nanometers.

All lamps were powered for at least 10 minutes before measurement. This ensures that it has reached temperature stability.

The protocol is to make a dark measurement before and after each light measurement. This is to ensure no significant variation in background during the light measurement. The before and after dark background measurements are averaged to a single dark value that is used to correct the light signal. The spectral output for each lamp is calculated as follows:

$$illuminance = (counts\ light - avg\ counts\ dark) * (calibration\ in\ units\ mW\ m^{-2} nm^{-1} counts^{-1})$$

The illuminance is in units of mW m^{-2} nm^{-1} at the measurement distance of 2.092m between the filament and the opening of the integrating sphere, or 2.1821m to the approximate back of the integrating sphere. The calibration curve is normalized to 1m distance. Therefore, source specific data can be obtained by multiplying by the square of the experimental distance, or a factor of $4.376m^{-2}$ (presuming the distance of 2.092m is applied). The uncertainty in assigning the distance to the detector depends on whether the opening or rear

of the sphere distance is used. Some value in between this may represent the correct effective average distance, so the uncertainty could be as large as about 8%.

The luminance of the lamp is also measured at the opening to the integrating sphere of the spectrograph detector with a lux meter (Oriel auto-ranging light-meter, Goldilux™, #70226, with the Oriel cosine probe, #70231). Meter luminance was recorded as Lux (lumens m^{-2}), but can be converted to candelas by multiplying by the distance correction factor of $4.376m^{-2}$.

3.3.3 Spectral emission of some lamps

A total of 21 lamps were measured. This earlier lamp characterization was done with lamp fixture A. The average measured voltage across the lamps was 11.21±05V. The information for each lamp measured is given in table 3.1.

Each lamp that was investigated is described below:

Table 3.1

		Tungsten Halogen 12V GU5.3 MR16 Lamps			
Manufacturer	**Model #**	**Description**	**Power (W)**	**Beam angle (°)**	**Color Temperature °K**
Sylvania	58533	20MR16/IR/FL35/C; Tru-Aim® IR	20	40	3000
Sylvania	58562	20MR16/T/VWFL60; TRU-AIM TITAN®	35	60	3000
Sylvania	58633	37MR16/IR/FL35/C ;Tru-Aim® IR	37	35	3000

Sylvania	58634	37MR16/IR/NFL25/C, TRU-AIM® IR	37	25	3000
Sylvania	58838	20MR16/IR/WFL60/C; Tru-Aim® IR	20	60	3000
Sylvania	58837	37MR16/IR/WFL60/C; TRU-AIM IR®, Infrared conserving halogen	37	60	3000
Sylvania	54173	50MR16/IR/FL35/C; Tru-Aim® IR	50	35	3000
Sylvania	58551	20MR16/T/FL40(BAB), TRU-AIM TITAN®	20	40	3000
Sylvania	58552	35MR16/T/VWFL60; TRU-AIM TITAN®	35	60	3000
Sylvania	58590	20MR16/B/FL35; TRU-AIM BRILLIANT®,	20	35	3000
Sylvania	54200	20MR16/FL40(BAB); Tru-Aim®	20	40	3000
Sylvania	58570	20MR16/B/FL35/C; TRU-AIM BRILLIANT®,	20	35	3000
Sylvania	58547	35MR16/T/NFL25; TRU-AIM TITAN®	35	25	3000
Sylvania	58557	35MR16/T/FL40(FMW); TRU-AIM TITAN®	35	40	3000
Sylvania	54203	35MR16/FL40(FMW), TRU-AIM®	35	40	3000
Sylvania	58593	35MR16/B/FL35, TRU-AIM BRILLIANT®	35	40	3000
Sylvania	58549	35MR16/T/NFL25/C, TRU-AIM TITAN® Covered	35	25	3000
Sylvania	58572	65MR16/T/VWFL60; TRU-AIM TITAN®	65	60	3000
Ushio	1003225	EXN/FG/WS/5300, WHITESTAR™	50	36	5300

Photograph 3.1 shows what both typical MR16 lamps look like. The image is a photograph taken by Monica F. Delgado of a Sylvania MR-16 lamp.

Photograph 3.1

All lamps that were chosen had a color temperature specification of 3000º K. This was to assure that the blackbody spectral profile did not vary significantly, simplifying design and evaluation of filter prototypes. The USHIO lamp was used in another application and included here only for comparison. All lamps with the possible exception of the USHIO lamp possessed an axial filament. All lamps including the USHIO had a declared specification of a limitation on UV transmission of some type, either “UV-Stop” or “UV-Filter” for Sylvania, or “Integrated UV protection” for the USHIO lamp.

3.3.4 Results of lamp measurements

The objective of these lamp measurements was to select a source (illuminant to be filtered) and a reference lamp, and to obtain the necessary data for spectral profile optimization. Typically, 6-20 lamps of a given product number where measured, and the results averaged. These results are shown in table 3.2.

Table 3.2

Lamp	Manufacturer specified Candela Output	Measured Candela Output by lux meter; {standard deviation; number of lamps n}	Measured Candela Output by spectrograph; {standard deviation; number of lamps n}
Sylvania 58551	700	551{151; n=10}	484{133; n=10}
Sylvania 58533	1000	853 {73; n=20}	653 {71; n=20}
Sylvania 58562	350	365{51; n=10}	324(47; n=10}
Sylvania 54200	700	503{; n=1}	482{; n=1}
Sylvania 58547	3100	2332 {; n=1}	1917 {; n=1}
Sylvania 58557	1250	1140 {; n=1}	917 {; n=1}
Sylvania 54203	1400	1039 {; n=1}	929 {; n=1}
Sylvania 58593	1300	968 {; n=1}	908 {;n=1}
Sylvania 58549	1650	1876{ ; n=1}	1691 {; n=1}
Sylvania 58633	2200	1679{143; n=20}	1507{125; n=20}
Sylvania 58634	4400	3020 {; n=1}	2741 {; n=1}
Sylvania 54173	2850	2037{227; n=20}	1801{129; n=20}
Ushio 1003225	600	384 {0.7, n=2}	335 {2.8; n=2}
Sylvania 58552	650	435 {; n=1}	381 {; n=1}
Sylvania 58570	600	525 {; n=1}	474 {; n=1}
Sylvania 58837	1100	852 {; n=1}	795 {; n=1}

There is a discrepancy between the spectrographic and meter measurements of candela output of the lamps in table 3.2. Spectrographic measurements are systematically low relative to the meter measurement. The meter measurements were performed at 2.0742 m from the estimated location of the filament to the lux meter detection surface, while the spectrographic measurements were made at a distance of 2.1821 m from the estimated location for the lamp filament to the back of the integrating sphere. As discussed above, errors due to assigning the distance to the integrating sphere could range as high as about 8% if the extreme of the rear or the opening applied, but are more likely half this if it is presumed that an effective intermediate value is operable. A 4% error would be insufficient to explain many of the discrepancies between the lux meter and spectrograph. The Oriel Goldilux™ lux meter has a specification of ±3% accuracy, though this would not be expected to be systematic in one direction or another.

The lux meter and spectroscopic results may be systematically off by more than can be explained by an analysis of error. Naively, one might expect the spectrographic measurement of candela output to be more accurate because the photopic function is precisely applied each time, rather than as an average approximation done by the meter, and the spectrograph has been calibrated with the assumption of the distance measured to the back of the integrating sphere, as is utilized for the measurement of lamps.

The spectrophotometric and lux meter candela measurements from this study are systematically lower than that reported by the manufacturers' lamp specifications, and well out of the range that could be explained by experimental error. Possibly, an explanation for this systematic difference is that it is possible that manufacturer powered their lamps at exactly 12 volts, the rated specified voltage for operating the lamps. In this work, the voltage across the lamp filament of many lamps was 11.21±05V using a voltmeter. It is unclear whether the manufacturer measurements were done by spectrograph or meter. The best Lux meters are thought to have errors of 3-15%[35].

The lamps that were measured were found to vary widely in output, not in regards to the spectral profile of the lamp. This variance in output was rare, but it was measured. A wide range of Sylvania MR16 products were measured. These measurements are illustrated in Appendix D.

The output for the average of all lamps measured is shown in Figure 3.3.

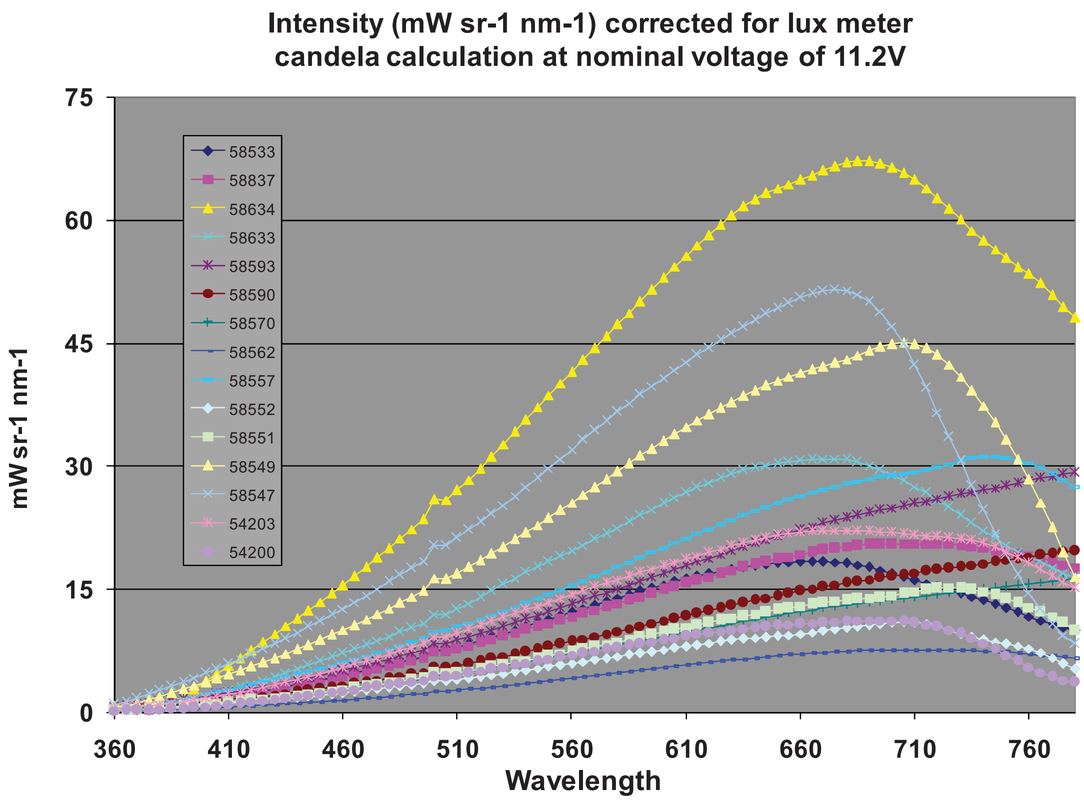


Figure 3.3

However, note that most MR16 lamps are specified at 3000K, and, if power supplies perform at lower specified voltages, as commonly experienced in this study, the typical SOURCE CT will more often be below 3000K, not above.

3.4 Correlated Color Temperature

The correlated color temperature[11] of a specific light source is defined as, the color temperature of a black-body radiator (this is a hypothetical light source that only generates energy through thermal excitation and is the ideal emitter of energy) that is the closest to the color temperature of that light source.

The CIE recognizes seven illuminants for colorimetry[11]. These seven are: A, C, D65, D50, F2, F8, and F11. Illuminant A is a representation of a blackbody radiator with a color temperature of 2856K. Illuminant C is a representation of a daylight simulator with the spectral power distribution of the illuminant A and a color temperature of 6774K. Illuminants D65 and D50 belong to the D-series that have been defined by a significant number of measurements of actual daylight. The D65 has a color temperature of 6504K and D50 has a color temperature of 5003K. The F2, F8, and F11 are representations of spectral distributions of different types of fluorescent sources. The F2 has a color temperature of 4230K. The F8 has a color temperature of 5000K. The F11 has a color temperature of 4000K.

The optimizations of temperature were achieved using the Standard Interval Global model of Frontline Systems Premium Solver Platform version 7.1. This yielded a value for the temperature for which the Blackbody color is closest to the color for the test illumination. The method was tested with D65[8, 34, 36] and Standard A[8, 34, 36], and values for CCT of 6502.6K and 2855.5K were obtained, respectively. The CCT for D65 has previously been reported at 6503.6K and as 2855.5K for Standard Illuminant A.

3.5 Choice of Lamps

The reference lamp is that to which filtered light would be compared.

Upon inquiry with members of the museum community, it was ascertained that there is not a standard lighting fixture, color temperature, or power of lamp that is typically used in museums. This greatly complicated assigning the reference lamp. Most museums do not use fluorescent lighting due both to color rendering effects and the potential for damage from the stronger mercury emissions. Incandescent light, sometimes in combination with daylight are most commonly used. Sensitive objects are most often viewed only under incandescent light because the blackbody distribution significantly reduces the relative contribution of high energy blue photons.

Several criteria were defined for establishing a reference lamp these criteria included:

- Incandescence – blackbody emitters are commonly used in museums
- Color temperature near 3000ºK
- Low power (approximately 20W; discussed below)
- MR16 type

The following lamps were chosen as potential reference lamps: Sylvania #s 58562, 54200, and 58838. Besides incandescence, and a CT of 3000ºK, the main criterion was that they were all relatively low power of 20W. This was to ensure that when filters were used with higher power lamps, the filtered light output would not exceed that of the reference output. This was a logistical

convenience to simplify lamp positioning when anticipating setting up human testing. In practice, the filter would not be limited to use with low power lamps. All of the lamps were of the MR16 type because these are common track lighting fixtures in museums. The MR16 is relatively small, and would require relatively small filters, simplifying manufacturing for the prototype study.

The final lamp to be used as reference (Sylvania 58562) was based on visual perception. A small test facility with replicas of Old Master Drawings was set up, and each lamp evaluated by members of the lighting research group, including Dr. Dirk. It should be clarified that this lamp selection was somewhat arbitrary, and based solely on the Dirk's research group's opinion and perceptions, since there is no established standard illumination in museums.

The source lamp was chosen after the reference lamp was selected. The source lamp can be defined as the starting light from where the excess or unnecessary light will be taken from by use of filtration. The source lamp had to be higher in intensity at every wavelength than the reference lamp so that a negative filtration could not be defined when optimizing filters. Once the reference lamp was chosen, this limited the choice for source lamps. Sylvania 58533 was chosen because it fulfilled the higher power criterion at every wavelength, and was lamp of lower or equivalent power to the reference, philosophically implying that one can filter the light without the need to increase the power of the lamp. Many lamps vary considerably in output when the

power is the same. This is particularly true when comparing the center beam output on lamps which vary in beam breadth. The reference 35 W 58562 lamp has a beam angle of 60°, while the source 20W 58533 has a beam angle of 40°. The 58533 possesses more than twice the center beam candela output as the reference 58562, despite the difference in power. In reality, this difference is also due to differences in lamp technology, filament, reflector type, etc.

3.6 Base Reflection Data for Filter Optimization

Besides the source lamp and reference lamp spectral distribution, the only other experimental information needed to optimize a filter is reflection data from the objects for which the filter will be designed. Some of the color rendering methods used here were based on the standard Munsell reflection pigment sets described earlier. For this work, data was also collected directly from OMDs to use as a more accurate basis than the general eight or fifteen color Munsell colors. This is particularly important because OMDs typically possess significantly lower color saturation than evident for the Munsell sets that were originally designed for color rendering.

A total of 120 reflection spectra were collected in 2004 by J. Druzik of the Getty Conservation Institute and this set was designated the color rendering basis set for this study. Later, additional data was collected using a spectral imaging camera designed and built at UTEP[37] and this supplemented the

original set of 120 reflection spectra. The camera data (*vide infra*) was included for the design of the Mark 3 filter.

The Old Master Drawings selected for this collection were the following. All the photographs that appear in this section of the document were provided by the Getty Conservation Institute.

Photograph 3.2

Number: 83.GB.270

Artist: Paris Bordone

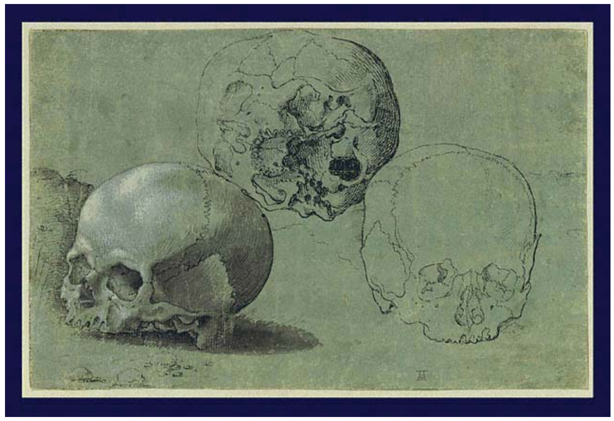
Title: Seated Male Figure with Putto and Armor

Country: Italy

Date: about 1550

Medium: Black chalk on blue-gray paper

Size: 17.3 x 29.5 cm (6 13/16 x 11 5/8 in.)



Photograph 3.3

Number: 89.GA.24

Artist: Barthel Beham

Title: Study of Three Skulls (recto); Architectural Study (verso)

Country: Germany

Date: about 1530

Medium: Pen and black ink, gray wash, and white gouache heightening on green prepared paper (recto); pen and black ink (verso)

Size: 14.9 x 23.2 cm (5 7/8 x 9 1/8 in.)

Photograph 3.4

Number: 90.GG.133

Artist: Joachim Beuckelaer

Title: The Trickery of the Gibeonites

Country: Belgium

Date: 1565

Medium: Oil on paper

Size: 26 x 19.1 cm (10 1/4 x 7 1/2 in.)

Photograph 3.5

Number: 96.GD.337

Artist: Théodore Chassériau

Title: Portrait of Raymond de Magnoncourt

Country: France

Date: 1851

Medium: Pencil heightened with white chalk

Size: 21.9 x 27.6 cm (8 5/8 x 10 7/8 in

Photograph 3.6

Number: 2000.49

Artist: Eugène Louis Lami

Title: A Couple Embracing in an Artist's Studio

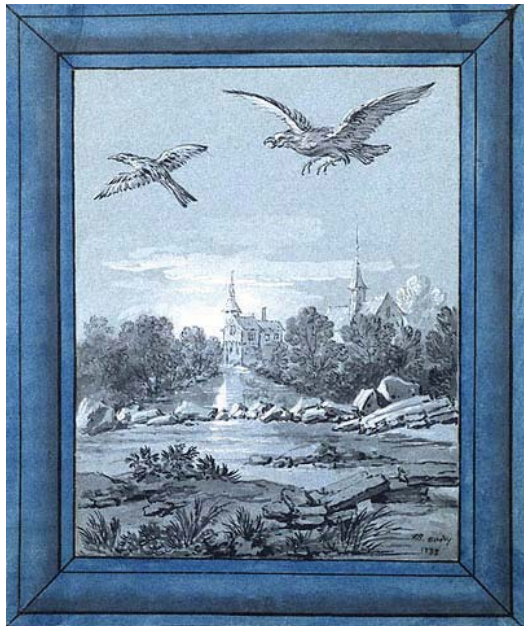
Country: France

Date: 1881

Medium: Watercolor over traces of black chalk, with touches of white gouache

Size: 19.8 x 24.6 cm (7 13/16 x 9 11/16 in.)

Creditline: Gift of Dr. and Mrs. Richard A. Simms in honor of John Walsh on the occasion of his retirement as Director



Photograph 3.7

Number: 2002.52.3

Artist: Jean-Baptiste Oudry

Title: The Eagle and the Magpie

Country: France

Date: 1733

Medium: Brush and black ink, gray wash, heightened with white gouache, on blue paper

Size: 12 1/16 x 10 1/16 in

Photograph 3.8

Number: 89.GD.42

Artist: James Ensor

Title: Christ's Entry into Jerusalem

Country: Belgium

Date: 1885

Medium: Graphite and Conté crayon

Size: 8 7/8 x 6 1/2 in

Photograph 3.9

Number: 91.GA.55

Artist: Circle of Martin Schongauer

Title: Standing Female Saint

Country: Germany

Date: 1490

Medium: Pen and gray and black ink, over traces of black chalk

Size: 9 5/8 x 7 1/2 in

Photograph 3.10

Number: 94.GA.97

Artist: Attributed to Juan Martín Cabezalero

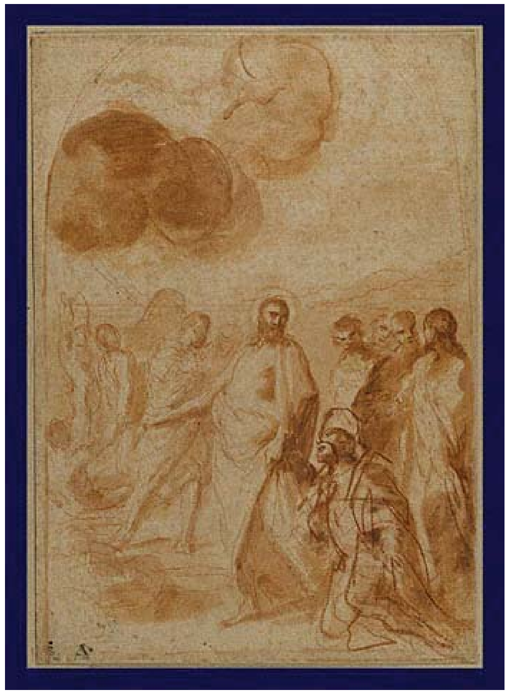
Title: Saint Francis (?) Interceding with the Virgin on Behalf of a Female Saint

Country: Spain

Date: 1665-1670

Medium: Pen and brown ink and brown wash over black chalk

Size: 12 13/16 x 8 5/8 in



Photograph 3.11

Number: 95.GB.42

Artist: Andrea Sacchi

Title: Christ's Command to Saint Peter, "Feed My Sheep!"

Country: Italy

Date: about 1628

Medium: Red chalk and red wash

Size: 10 x 7 1/16 in

Photograph 3.12

Number: 96.GA.332

Artist: Abraham Bloemaert

Title: Studies of a Marrow Plant and Cabbages

Country: Denmark

Date: 1605-1614

Medium: Pen and brown ink, blue wash and heightened with white bodycolor

Size: 9 3/4 x 14 1/2 in

3.7 UTEP camera data

A Prism Grating Prism Line Scan Camera was created to obtain reflection spectra. The camera design[37], construction, and development are provided elsewhere. The reflection spectra collected with this camera were from selected Old Master Drawings. The original intent of this reflection spectra collected from OMD's was to create an Old Master Drawing Color Rendering Basis for the filters. But due to the time constraints, instead the basis for the earliest filters was created with the reflection spectra measured in 2004 by Jim Druzik from the Getty Conservation Institute in Los Angeles California. The data measured with the camera was useful to create a computer program that makes simulations of lighting with hypothetical filters before the filters are actually manufactured. The OMD's scanned for this set were the following: Paris Bordone, Seated Male Figure with Putto and Armor; Barthel Beham, Study of Three Skulls (recto); Architectural Study (verso); Joachim Beuckelaer, The Trickery of the Gibeonites; Théodore Chassériau, Portrait of Raymond de Magnoncourt and Eugène Louis Lami, A Couple Embracing in an Artist's Studio. The complete information of each of the OMD's just listed is given in a prior section.

3.8 Methods of Optimization

There are three categories of optimization. These are linear, smooth non-linear and non-smooth linear or non-linear. Each type of optimization includes

different methods within the category. The simplex method was the first method designed to solve linear optimization problems. The generalized reduced gradient (GRG) and the sequential quadratic programming (SQP) are smooth non-linear methods of optimization. The following methods are under the category of non smooth linear and non-smooth nonlinear: The Tabu search, the Scatter search, and the Evolutionary search methods[38]. These optimization methods were implemented using the Solver designed by Frontline Systems, Inc.

Human Testing

Human subject testing of UTEP designed filtered illumination was undertaken at The Getty Conservation Institute, and UTEP, independently.

The Testing Gallery Facility (TGF) (5.4m x 3.4m x 2.4m {h}) was designed with black walls and ceiling. The carpeting couldn't be changed and it is brown. The black color was chosen to reduce the distractions for the subject while taking the tests and to limit the effect of the reflected light in the testing area. The Getty Conservation Institute built their own testing facility, named the Experimental Lighting Facility (ELF). This testing facility differs in configuration and wall coloring, but the tests employed by both facilities are the same or similar. The main and most important difference is the color of the two testing galleries. The ELF is gray and the TGF is black. For the ELF[35], the ASTM (American Society for Testing and Materials) E 1808-96, "Standard Guide for Conducting Visual Experiments" was used to set the surround and ambient field. The surround is defined as the area immediately surrounding the specimen and it states that it should have a color similar to the specimen. For art, this of often a white or cream colored mat. However, the mat cannot be included in the spectral design of a filter, since it could vary, and it was thought that a more neutral level of gray should be used for testing purposes[35]. For the ambient field, the ASTM standard recommends states that the field of view when the observer glances away from the specimen should have a neutral color that is Munsell Chroma less

than 0.2 and a Munsell value of N6 or N7 with a luminous reflectance of 29-42. The ELF was painted to match this specification.

Unlike the ELF, the TGF had a much more limited budget of $200 for design and construction. Repainting was not an option. Black was chosen for the TGF because it is neutral in chroma; and because fewer of the test age group in UTEP has little or no light adaptation complications between a black ambient field and white or cream mats.

The most economical route to converting the entire room into a "dark" room was done in three simple ways. The first part was to replace all the white ceiling panels with Crescent No. 8 black mounting board. The matte black panels would be cut by hand to the exact size of each white panel that was being replaced. The white divisions between each panel were covered using black duck tape. The second part was to cover all the walls with matte black poster boards. The matte black poster boards were glued directly to each wall using rubber cement in aerosol cans. The poster boards used are 22" x 28" Black Poster-board, Ideal For Posters, Signs & Art Projects, from Royal Consumer Products. The third part was to have a division between the brightness measurements, the color vision testing, and the evaluation of the filters. All the necessary divisions were done using matte black fabric. The black fabric that was used is the BA-05 Sheermist Bati Black c/o China 65% Polyester and 35% Cotton sold in Hobby Lobby. This fabric was chosen because of its very low

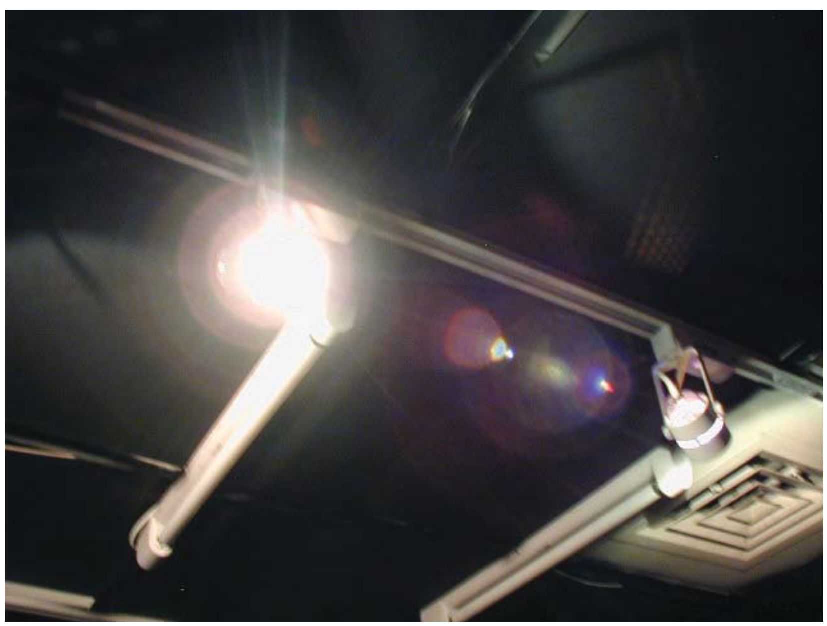
reflectivity. The matte black cloth was cut to the right length and width and hand sown into drapes. The total numbers of drapes used for the testing facility were 8 in total. The drapes were hung from the ceiling using angle iron. The angle iron was painted black spray paint. The black spray paint that was used is Color Place fast dry spray paint, flat black number 20004 by Endura Label and sold in Wal-mart stores. This paint was chosen because of its very low reflectivity. The angle iron was mounted directly into the walls and ceiling of the room.

Now that the construction of the "dark" room was finished the illuminant fixtures had to be put in place. Two sets of tracks were needed to be placed for lighting. The first set of tracks that were needed was for the daylight fluorescent lamps. The fluorescent lamps were needed in order to simulate daylight for all the color vision tests that were going to be done. These set of tracks were glued with epoxy directly onto the ceiling. The second set of tracks that were needed was for the MR -16 lamps. The MR-16 lamps were needed for part of the color vision test and for the evaluation of the filters. These set of tracks were glued with epoxy directly onto the ceiling. In the following images, taken with a digital camera, it can be appreciated what the Testing Galley Facility looks like today.

This is the Testing Gallery Closed with lights on

Photograph 4.1

The ceiling of the Testing Gallery with the MR-16 lamps on



Photograph 4.2

This is the ceiling of the Testing Gallery with the fluorescent lights on.

Photograph 4.3

4.1Human Lighting Evaluation Methods

All methods summarized here were approved by the Institutional Review Board Of the Office of Research and Sponsored Projects at the University of Texas at El Paso.

All human subjects had to first be evaluated with regard to color vision. Within the human population it is known that about 8% of males display some degree of red/green color vision insufficiency, while less than 1% of women have this deficiency. Yellow/blue color discrimination is much rarer as a genetic defect, but it can be an acquired deficiency as one ages and the lens of the

eye yellows and filters more blue light. The consequence of the color vision problems within humans means that one must assure that the test subjects possess adequate color vision when, for instance, when evaluating the difference in perceived color rendering between filtered and Unfiltered light. The methods that were used to assess color vision are summarized below. Note that all subjects were given the option to be informed or not informed of the outcome of the color vision tests. While possibly helpful for some individuals who may not have known of their color vision deficiency, these tests were scientific and not clinical findings. All subjects were advised to consult with a medical vision specialist if they had any concerns raised by the outcome of the testing done in this study.

Following assessment of color vision, several tests were designed to assess perceived differences between filtered and Unfiltered illumination with regard color rendering, spatial acuity, perceived brightness, and subjective evaluation of a set of art represented by high quality prints. The perceived brightness measurement was created to assess the Helmholtz-Kohlrausch effect as it might have been impacted by the variation in spectral distribution of the filtered light relative to the Unfiltered light.

The complete test would be divided into 3 main parts, the brightness measurement, the color vision testing, and the answering of a questionnaire based solely on the opinion of volunteer participant.

When a participant comes into the testing facility he or she is given the following: a detailed explanation of the purpose of the project and a consent form to participate in the research. A copy of these forms is included in the Appendix E.

After the documents have been read and signed by the participant, the subject is instructed to enter the test facility. Here the lights are off and only the light form the brightness instrument is on. The subject is given the proper instructions to begin this test. The subject is given 10 minutes to complete this part. The brightness test procedure, the instrument, the construction of the instrument, how this instrument operates, and how the brightness measurements are made are described in detail in Appendix Q.

4.2 Color Vision testing

The color vision examination was performed under the daylight lighting and consisted of five methods. These methods are mentioned in the order in which they are used in the Museum Lighting Testing Study: the Waggoner HRR Color Vision Test[39], the Ishihara's Tests for Colour Deficiency by Shinobu Ishihara MD[40], the L'Anthony Tritan Album[41], The Farnsworth D-15 Test[42]and the L'Anthony's Desaturated 15-Hue Test[43].

A range of methods were used to improve overall accuracy and as a check of each test. Tests primarily fell into assessment of red/green color

discrimination deficiency or blue/yellow color discrimination deficiency. The Ishihara tests solely for red/green deficiency, while the L'Anthony Tritan Album tests solely for blue/yellow deficiency, while all other tests have some combined methods for testing both. However, the blue/yellow test portion of the Waggoner HRR procedure was relatively limited compared to its more extensive red/green deficiency testing. The methods regarding the administration of these tests are outlined in Appendix F.

4.3 Color Rendering Testing of Filters

Color rendering of an illuminant can be difficult to test. For this study, the adaptation of two color vision disc arrangements tests were used for a check of color rendering of filtered light relative to Unfiltered light. These tests involve arrangement of randomized color discs into the proper order of color change. The test can be quantified by a color confusion index[42, 45], which can be calculated by software which usually accompanies the test. For this study, this software was purchased from Richmond Products Inc. 4400 Silver Ave. SE. Albuquerque NM 87108.

4.3.1Farnsworth D-15 Test

This test was designed by Dean Farnsworth[42, 43]. He designed both the Farnsworth Munsell 100 Hue Test and the Farnsworth Dichotomous Test (D-15).

The Farnsworth D-15 test is designed to screen for congenital and acquired color defects. These color discs were designed in particular to screen for Tritan deficiency. This test is made out of 15 distinct colors and it was specifically designed for The U.S. Navy between 1943 and 1947. It was initially used in 1955 for job placements. The D-15 can only detect severe color vision defects; minor defects can go unnoticed or unidentified.

The D-15 is a subset of the Farnsworth Munsell 100 Hue Test. The D-15 is what is called a color arrangement test. These types of tests can identify if someone is colorblind. These color arrangement tests are made up of a specific number of color discs. In this case for the D-15, the number of colored discs is 16. The D-15 is numbered at the back of the discs from 0 to 15 the 0 disc being just a reference point. The front part of the disc is where the color is located at. The colored paper has a diameter of 1.2 centimeters. The total diameter of each disc is of 2 centimeters. The color of each cap is a Munsell color from the Munsell color system. The administration of the Farnsworth D-15 test is summarized in Appendix G.

4.3.2 L'anthony Desaturated 15-Hue Test

The L'anthony test is a color arrangement test designed to screen for congenital and acquired color defects[43]. The color discs are less saturated than that of the Farnsworth D-15, and can help detect more subtle color vision

deficiencies. The administration of this test is discussed in Appendix H.

4.4 Subjective evaluation of lighting

Subjects were also enlisted to answer a questionnaire for subjective evaluation of the lighting. The questionnaire is described in Appendix I.

Physical Evaluation of Filters

5.1Filter Lifetime Studies Experimental Procedures

There are two types of lifetime study tests being conducted: the constant exposure and the cyclical exposure. In the constant exposure the lamp is on indefinitely. The constant exposure test measures long term constant thermal and photochemical effects. The lamp that is used for this test is the 58533 Sylvania lamp (information for this lamp is given in a previous section). The surface temperature of the filter exposed to this lamp is 190°Celsius.

The filters are evaluated periodically by unaided eye inspection and measurement of transmission. The transmittance of the filters is measured using the Shimadzu UV-VIS-NIR Scanning spectrophotometer, model UV-3101PC. The study is conducted in the following manner. The 1st transmittance measurement is made before exposure to the lamp. The numbers of this transmittance spectrum is saved in a spread sheet. Once this 1st transmittance measurement is done the measured filter is placed in front of the 58533 Sylvania lamp and is left there until the next transmittance measurement. The second transmittance measurement is done after seven days of being in front of the lamp and is saved in the same spread sheet. Then the spectrum was plotted and compared to the 1st measurement. No difference was found between the two transmittance spectrums. The same procedure is still being applied; that is measuring the transmittance and adding the measurement to the spread sheet, plotting it and comparing it to the all the previous measurements.

5.2 Lifetime testing: thermo-mechanical testing

The second lifetime study test is the cyclical exposure. This test evaluates the long term thermal and photochemical effects, measures thermo mechanical stressing of cooling and heating. This test simulates the typical use in a museum or an art gallery, the lamp on for 8 hours and off for 16 hours. The lamp that is used for this test is the 58533 Sylvania lamp (information for this lamp is given in a previous section). The surface temperature of the filter exposed to this lamp is 190° Celsius. This test evaluates the strains introduced by the stress of the filter cooling and heating as typically occurs when lighting is turned on and off.

The transmittance of the filters is measured using the Shimadzu UV-VIS-NIR Scanning spectrophotometer, model UV-3101PC. The study is conducted in the following manner. The 1st transmittance measurement is made before exposure to the lamp. The numbers of this transmittance spectrum is saved in a spread sheet. Once this 1st transmittance measurement is done the measured filter is placed in front of the 58533 Sylvania lamp and is left there until the next transmittance measurement. The second transmittance measurement is done after seven days of being in front of the lamp and is saved in the same spread sheet. Then the spectrum was plotted and compared to the 1st measurement. No difference was found between the two transmittance spectrums. The same procedure is still being applied; that is measuring the transmittance and adding

the measurement to the spread sheet, plotting it and comparing it to the all the previous measurements.

5.3 Human trials experimental procedures

For this section a questionnaire is implemented. This same questionnaire is used for all three filters. The questionnaire was designed by trial and error by the Museum Lighting Study Research Team. A detailed description of this questionnaire, how is administered and how is evaluated is included in Appendix I. Only other details that pertain to this subject matter will be included in the following paragraphs.

After the color rendering tests are finished the subject will be handed this questionnaire. The subject provides the answers; the answers to the questions in the survey are based solely on the subjects' opinion and perception. The subject is asked to come back into the testing gallery where there are three replicas of three Old Master Drawings. The questions in the survey are solely based on these replicas. There is no time limit to answer the questions, the decision on how much time should be spent on this section and on each answer is left to the subject to decide. The subject can choose from two methods on how to answer the survey. The illuminant 1 is the light source with the Mark 1 filters. The illuminant 2 is the light source with not filters. The first method is to have the illuminant 1 on and answer all the questions regarding illuminant 1. Then switch to the illuminant

2 and answer all the questions regarding the illuminant 2. The second method is to have illuminant 1 on and answer the 1st question regarding illuminant 1. Then switch to illuminant 2 and answer the 1st question regarding illuminant 2. Then

proceeding in the same manner for the remaining questions, that is switching back and forth between each illuminant for each question until all the questions are answered. How this questionnaire is answered is completely up to the subject. The total time that a subject has taken to answer this questionnaire has varied from 10 minutes to 60 minutes. The statistical evaluation of the answers for the survey was explained in detail in a previous section of this document.

5.4 Fading studies experimental procedures

All the measurements for this section have been made utilizing the Shimadzu UV-VIS-NIR Scanning spectrophotometer, model UV-3101PC. This product is manufactured by Shimadzu. This UV-3101PC is a high efficiency, ultra-low stray light double monochromator instrument with its unique six-grating system provides a known resolution at every point of the spectrum, 190.0nm ~ 3200.0nm. The UV-3101PC offers the power and precision of the research-grade UV-VIS-NIR spectrophotometer that performs the ease of a PC platform.

Reflection measurements on the Shimadzu spectrometer were made by interchanging the standard solution cuvette transmission/absorption

measurement compartment with the integrating sphere compartment (ISR-3100 CAT No. 206-16450 Serial No. A1055 3500058kL). The integrating sphere compartment consisted of a 50mm integrating sphere with two entrance ports, one for sample irradiation, and one for reference irradiation. The instrument measurement protocol is uncertain as to whether a reference measurement is made while the sample is attached. This could conceivably skew the sample result measurement. In addition, the geometry of measurement appears to be nonstandard, with irradiation of sample appearing to be normal (0 °), which means that the specular components, and a good deal of the diffuse signal is rejected through the irradiation port. Also, the small size of the sphere and numerous ports suggest that diffusely scattered light from the sample is lost either through the reference and irradiation beam ports. This increases the potential error of the measurement.

Other potential problem with use of the integrating sphere compartment is that it was commonly interchanged with the cuvette transmission/absorption compartment. Aligning the instrument perfectly between measurements taken over many months, such as the fading studies dealt with here, can become a problem. It can be a likely source of error for time series measurements involving monitoring changes in samples over long periods.

The standard reference sample used with the integrating sphere was $BaSO_4$ (supplier: 022-00425 Wako Pure Chemical Ind. LTD Lot WTG 3346)). The

reference can become contaminated (and often was by other research groups) or can undergo slight changes with moisture. Consequently this reference sample had to be prepared fresh if measurements were made at widely separated times, or there was evidence of contamination. The reference was made my using a Carver Press to compress the $BaSO_4$ powder into the reference sample holder. Since this was done by hand, and surface finish could not be duplicated exactly from reference to reference, some non-uniformity of reference is to be expected. This will contribute to some variation in data reported for time series studies.

One final issue with the use of the integrating sphere attachment is that the instrument was used by other research groups. This contributed to the alignment problems as different users made changes between reflection and transmission measurements. A much more severe problem was increasing contamination of the compartment by the samples of other users, particularly Maya Blue[46] samples being investigated by another research group. This study began with the sphere in pristine white internal color, and by the end of the study the blue and violet contamination from the Maya Blue work was significant.

For these fading tests special light boxes had to be designed and built at UTEP. All three boxes are exactly the same design, made from the same materials, same measurements, and function in the same manner. There are

three boxes. Each box has four MR16 lamps. In box ONE the lamps have the filter that was designed by the Museum Lighting Research Team (Dirk's Research Team) in front of the lamps. In box TWO the lamps have the Optivex® filter. In box THREE the lamps have no filter; in other words the light is unfiltered.

The irradiated sample platforms of each box were adjusted to display approximately the same luminosity. The platforms can be move up or down to adjust luminosity when necessary. The lamps are arranged by hand in each box to try to achieve reasonably uniform lighting. It is impossible to achieve uniform (<1% variation) luminosity across the platform or even across a relatively small area. Consequently, it was necessary to map luminosities across platforms in the hope of finding matches of <1% difference across all three boxes. To achieve this, each platform has 65 holes. The 65 holes are in rows of 13 holes and in 5 columns. All the holes are numbered starting from left to right. Each hole has a unique luminosity value. The luminosity values for each box are measured using the Ocean Optics (HR 2000CG-UV-NIR High resolution HR2000 HR2B479) cosine corrected probe (CC-3-UV) attached to an optical fiber which feeds into an Ocean Optics (QP400-2-VIS/IR 727-733-2447 sales order 50691). The probe is fed up through the hole until flush with the bottom surface of the platform, and then a measurement is made. After the lamps get adjusted, every single hole in each box has to be measured. The measurements are fed into a computer program. This computer program calculates how many holes are shared in between the

boxes with the same (values are accepted if the difference between them is less than 0.5-1%) luminosity level. A minimum of 15-20 points have to be matched in order to start the fading studies.

The samples are squares of 2 inches by 2 inches. Three samples are prepared or were reference standards, one for each box. Each sample is placed directly on the hole that was matched previously by the computer program. Each sample is measured before it is exposed to the light in the boxes.

Each sample is measured with the Shimadzu UV-VIS-NIR Scanning spectrophotometer, model UV-3101PC. A total of 5 measurements are made on each sample. Once the measurements are made the samples are centered over the corresponding holes on each box for which the luminosity has been matched. The samples are exposed to light for a previously determined time. The samples are taken out of the boxes and then they are measured. The total amount of time exposed to light is calculated and recorded. Then the samples are put back in the boxes to continue the time series of irradiation. The complete procedure is repeated until the sample has reached its t_∞ value, the point at which no further significant change can be measured.

The stability of the lighting in the boxes is checked periodically, twice a week, then once every two weeks, to assure that one box doesn't change its relative illumination.

Fading studies were begun with Sylvania[47] TITAN 58312 MR16 lamps. These

are GU5.3 (base description) 65MR16/T/NFL25/C tungsten halogen lamps with a rated life of 4000hrs. All of the testing of the Mark 3 filters was done with this lamp. Due to lamp burn-outs, instabilities, and cost to replace the Sylvania lamps, later studies utilized the Philips Halogen Long Life lamp[49] (378083) 75MRC16/SP10 EYF. Also, possessing a GU5.3 base to be consistent with the individual lamp power supplies used (ELCO track ELCO lighting ET526-75 black) with the Sylvania lamps; these had a rated life of 6000 hours[49], though depending on Philips literature, this might be rated as 4000(nom.) hrs[50].

Average lifetimes of Sylvania MR16 lamps vary from 2000 hrs to 5000 hrs. For this reason, pigment fading studies often have to be begun with a new set of lamps. To understand why, the mortality curves for MR16 lamps need to be examined as well as lumen maintenance curves for tungsten halogen lamps, of which the MR16 are a subset. Sylvania provides[51] the mortality curve for MR16 lamps and this is shown in Figure 5.1. Search of Philips literature did not provide the mortality curve for the specific Philips lamp that is being used for this study, but mortality curves for similar MR16 lamps are provided in the Philips Halogen Lamps Product Information bulletin[52]. The relevant figure from that bulletin is given in Figure 5.2.

The lamps used for the fading studies possessed a manufacturer specified lifetime of at least 4000 hrs, taking into consideration the potential discrepancies in rated lifetime of the Philips lamp. If it is presumed a fading study may require

800 hrs (some went far longer than this), or 20% of rate life, examination of the Sylvania mortality curve suggests a survival rate of 97%. However, each irradiation chamber holds four lamps, thus the net survivability to the failure of any one lamp can be estimated as $(0.97)^4$ (0.97 raised to the 4^{th} power), or approximately 88.5%. Therefore, in any one box, it might be expect an 11.5% failure rate in 800 hrs. This doesn't take into consideration that such a failure in any one box of the three would halt an experiment. Considering all three boxes, the failure rate can be as high as 30.6%. Thus, 800 hrs. is a long time to run a set of 12 lamps and risks failure of at least one to an uncomfortably high probability. Similar results will be reached from using the data from the Philips mortality curves.

Mortality likely doesn't include "brown-out". Brown-out is when a lamp undergoes a significant decline in output perhaps many hours prior to failure. This has visually been observed, by eye, and measured one instance instrumentally. Occasionally some lamps may dim, but not burn out. The brown-out phenomenon likely occurs well before mortality, and thus mortality prediction does not adequately predict brown-out. The figure 5.1corresponds to the Sylvania lamps used and it was obtained from Sylvania[51].

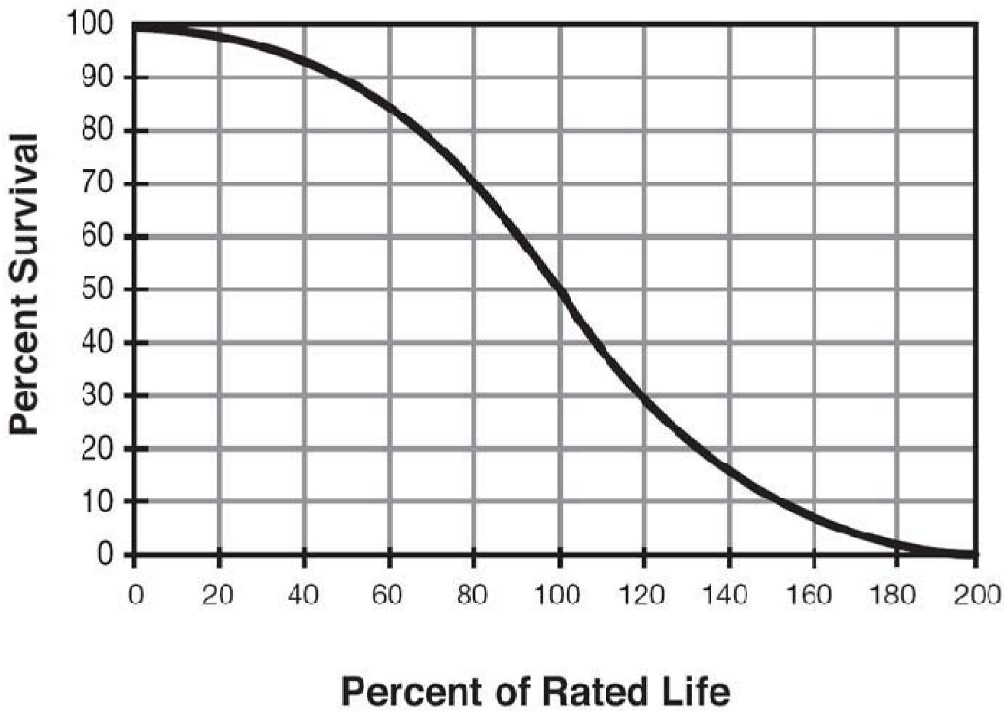


Figure 5.1

The figure 5.2 holds three charts of that show the mortality curves for similar MR16 Philips lamps to those that were utilized in this study. They are provided in the Philips Halogen Lamps Product Information bulletin[52]

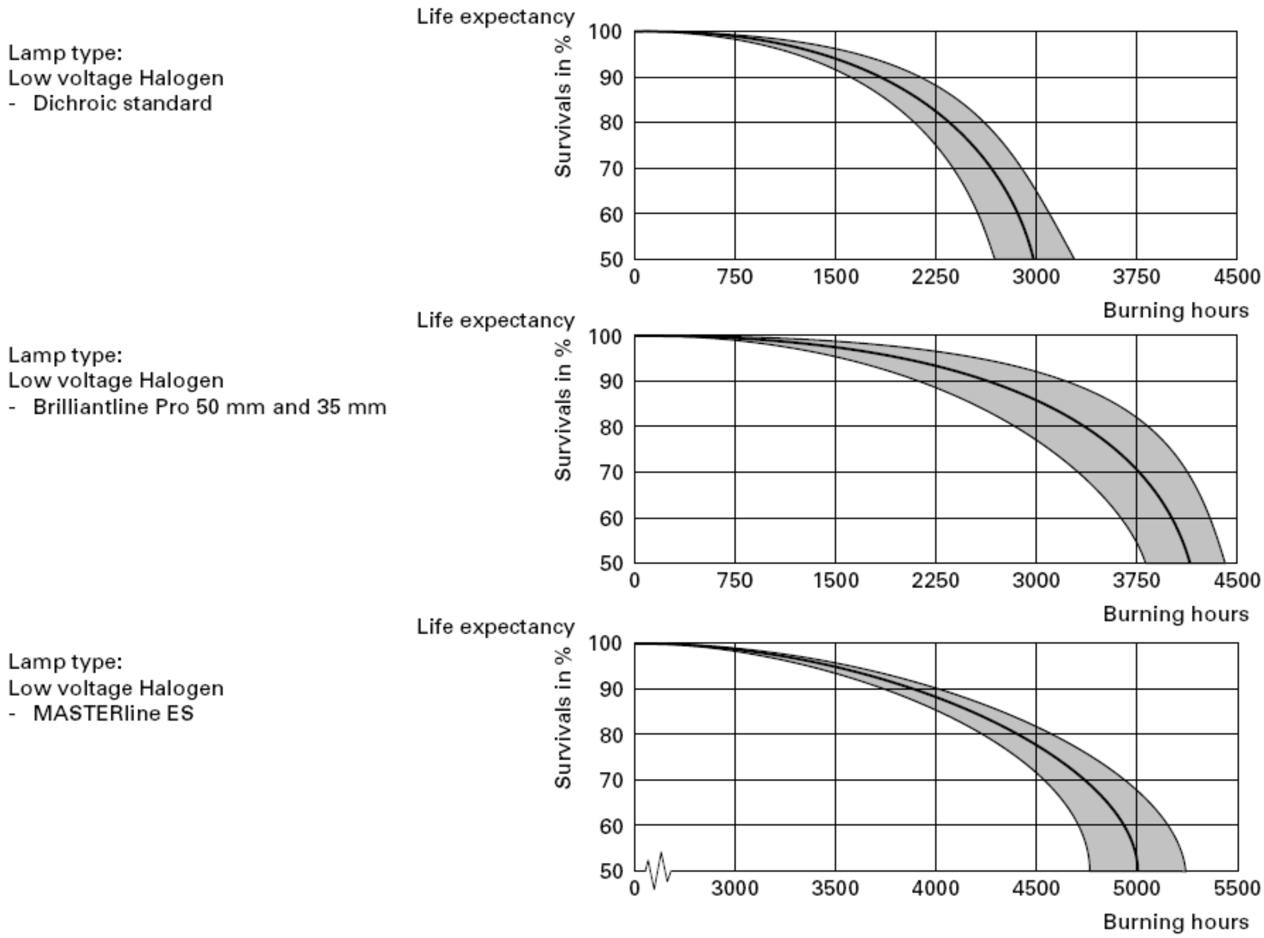


Figure 5.2

Figure 5.3 shows the Sylvania Lumen Maintenance curve for halogen soft glass lamps, specifically Sylvania 18864. The analogous curve could not be found for the Sylvania MR16 lamp that was used. However, mortality curves do not seem to differ between tungsten halogen lamps, so it is presumed the lumen maintenance curves will also not differ.

As can be seen, Sylvania Tungsten-Halogen lamps are rated to maintain their output relatively well over the course of their life compared to other lamp technologies. For the typical lamp at 20% of its rated life, output may decline by 1%. Note that this effect is likely different than the larger declines that were describe as brown-out above. A brown-out lamp is likely close to mortality, while lamps which have been used to establish lumen maintenance relationships probably perform adequately to 100% of their typical mortality. However, the lumen maintenance decline of 1% is likely an average. Some lamps may decline more or less. The standard error for the lumen maintenance curve is not given to ascertain this.

The Lumen Maintenance (LM) curve for the specific Philips lamp that were used could not be located. However, Philips product literature provides LM curves for Philips low voltage halogen capsule lamps, which are essentially an MR16 lamp without the dichroic reflector. These lamps have a 50% rated lifetime of 3000 hrs, which may be comparable to that of the Philips lamp that was used here. The LM curve for these lamps is provided in figure 5.4.

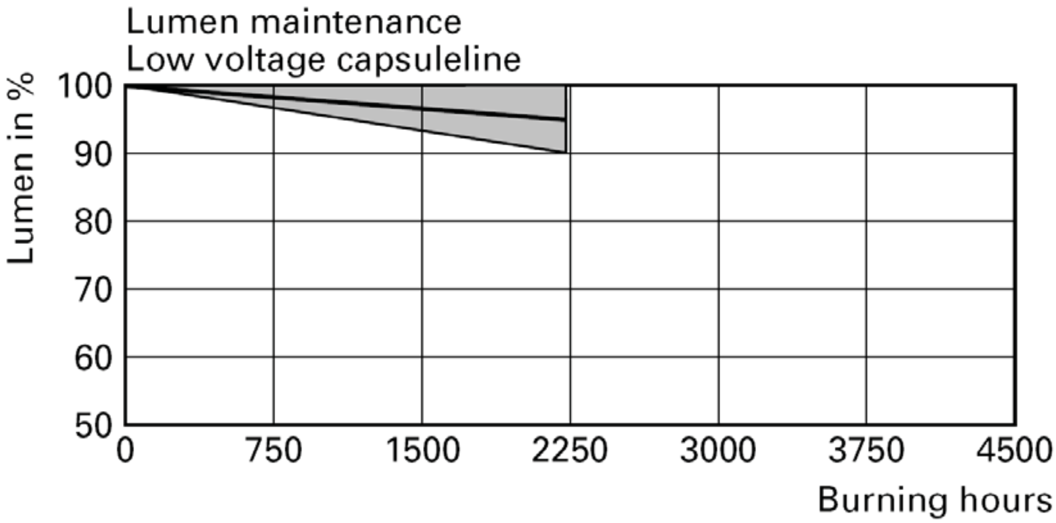


Figure 5.3

The Philips LM curve reveals a distribution envelope around the average LM line which indicates the extremes likely to be expected in lumen depreciation over the life of the lamp. After 2250 hrs, some lamps can be expected to decline by as much as 10%.

The issue of normal lamp decline in performance, and possible variation from average has potential significant impact on the variation in uniform lighting within an irradiance chamber. The abnormal decline of even one lamp could cause some samples to be significantly differently irradiated than anticipated.

The arguments about mortality and lumen maintenance have bearing on the data collected here. Many data sets reported here are collected for periods well beyond 800hrs, to an extreme of more than 2600hrs in the case of some of

the Mark 2 Blue Wool studies. Lamp stability is an issue that needs to be addressed.

Power supplies for the lamps were (ELCO track ELCO lighting ET526-75 black, 12V 75W commercial) MR16 fixtures. These were common commercial devices, and were not assessed for stability, but are also not anticipated to be especially long term stable given the low cost. One of these fixtures burned out over the course of the work and had to be replaced. Apparent instability in output in any one of the boxes could not be fully distinguished as a problem with solely the lamps or power supplies.

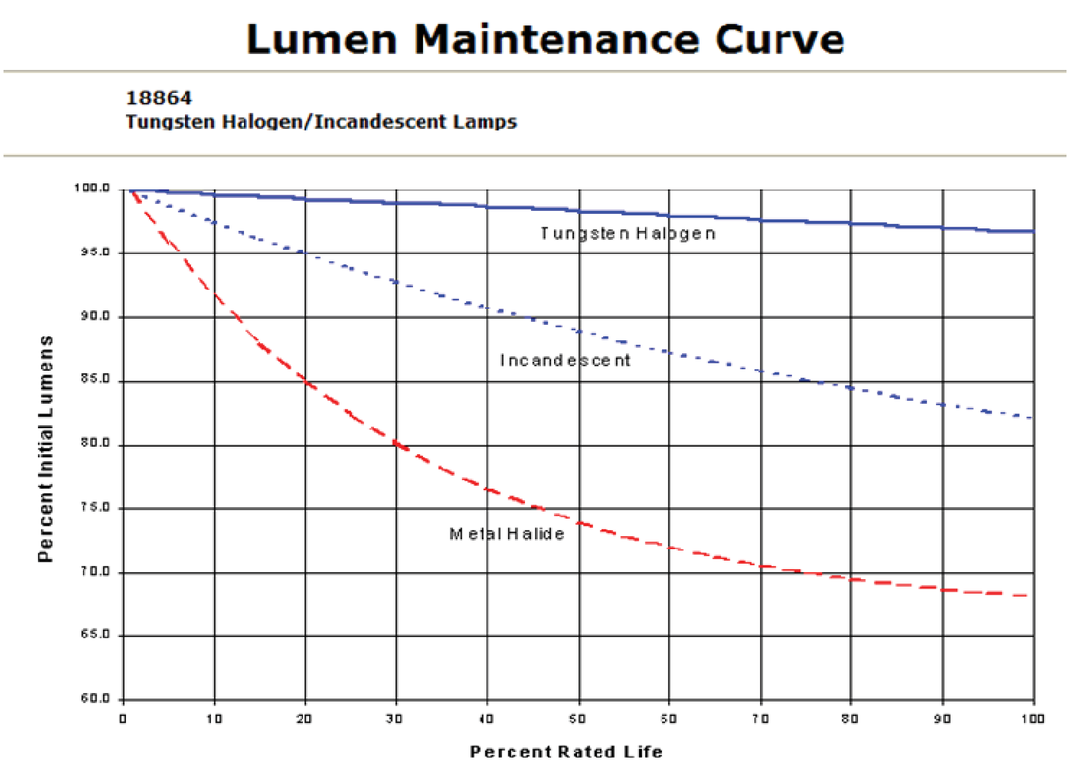


Figure 5.4

The data gathered from the measurements is processed using a computer program. This computer program calculates the DE2000 color difference for each sample from each box. The computer program processes the DE2000's and chooses what method (UTEP filter, Unfiltered or Optivex®) is more efficient in reducing the photochemical damage.

5.5 Transmission and reflection measurements

All the measurements for this section have been made utilizing the Shimadzu UV-VIS-NIR Scanning spectrophotometer, model UV-3101PC. This UV-3101PC is a high efficiency, ultra- low stray light double monochromator instrument. This instrument can both be used for transmission of solids and liquids (with cuvette) and the sample compartment can be interchanged so that an integrating sphere accessory can be incorporated. The reference used for diffuse reflectance measurements using the sphere was a fresh sample of $BaSO_4$.

5.6 Off angle beam angle assessment measurements

All the light must be extinguished during measurements. The lamp fixture used to mount the lamps to be tested was a standard commercial "12V" power supply commonly used for MR16 lamps. The black floor in the testing facility was

marked with small pieces of yellow masking tape at 0 cm, 30 cm, 60cm, 90cm, 120cm, and 150cm. The 0cm was chosen to be the spot directly underneath the spectrograph, exactly in the middle of the opening of the integrating sphere. Each of the yellow tapes has a black dot where the lamp fixture is placed for the measurements.

The lamp is placed on the floor underneath the spectrograph. Without removing the cap covering the opening of the integrating sphere attached to the spectrograph, the center of the lamp filament is aligned with the center of the spectrograph integrating sphere opening. This alignment is done using a self leveling three point laser plumb level from New Pacific Laser Systems; model PLS3, serial number A29399. This aligning tool is attached to a standard photographic tripod. Two of the lasers point vertically. One of the lasers is pointing up, towards the ceiling and the other laser is pointing down towards the floor. The third laser points horizontally, at a 90 ° angle in reference to the other two lasers, and is not used. The tool is moved slowly back and forth, left to right, until acceptable alignment is achieved, and then the lamp filament is aligned to coincide with the brightest point of the lower laser. Once close to perfect alignment is achieved the cap of the spectrograph is removed. The researcher exits the dark room, closes all the panels, turns all the lights off, and proceeds to the dark room where the computer that controls the spectrograph is located.

The settings for all the measurements are the following:

- The acquisition mode is set at accumulate.
- The readout mode is set at full vertical binning.
- The trigger mode is set at internal.
- The exposure times is set at 0.021 seconds.
- The number of accumulations is set at 1000.
- The accumulate cycle time is set to 0.021 seconds.
- The units in the y-axis are counts 10^5.
- The units in the x-axis are in nanometers.

All lamps are powered for at least 10 minutes before measurement. This ensures that it has reached temperature stability.

The protocol is to make a dark measurement before and after each light measurement. This is to ensure no significant variation in background during the light measurement. The before and after dark background measurements are averaged to a single dark value that is used to correct the light signal. The spectral output for each lamp is calculated as follows:

$$illuminance = (counts\ light - avg\ counts\ dark) * (calibration\ in\ units\ mW\ m^{-2} nm^{-1} counts^{-1})$$

The illuminance is in units of mW m^{-2} nm^{-1} at the measurement distance of 2.092m between the filament and the opening of the integrating sphere, or 2.1821m to the approximate back of the integrating sphere. The calibration curve is normalized to 1m distance. Therefore, source specific data can be obtained by multiplying by the square of the experimental distance, or a factor of 4.376m^{-2} (presuming the distance of 2.092m is applied). The uncertainty in assigning the distance to the detector depends on whether the opening or rear of the sphere distance is used. Some value in between this may represent the correct effective average distance, so the uncertainty could be as large as about 8%.

After the 0cm measurement is done; the lamp along with the lamp fixture is moved very carefully across the floor to the next spot (30cm, 60cm, 90cm, 120cm and 150cm). And the same procedure is repeated until all the off-angle measurements are made.

5.7 Fading measurement methods

The interchangeable compartment is replaced with the integrating sphere accessory. The Shimadzu instrument is turned on. While the necessary checks are running automatically in the instrument, the investigator leaves the room to get the samples. The samples that are going to be measured are taken out of the fading boxes. The samples are placed on a cardboard box to protect

them from further light exposure outside the fading boxes. The time at which these samples are taken out is written down. Once all the necessary checks are made the following parameters are set: scan range 200nm-1000nm, range of the axis is set for the y-axis; this is R% from 0-100%, for the x-axis is set to 200nm-1200nm. The instrument is set to measure reflectance and the speed of the scan is set to fast. A baseline is run first. Then a $BaSO_4$ reference sample is run. The first sample can now be measured. The samples are kept in the box at all times except for the one being measured.

There are five measurements made on each sample. Each measurement is saved twice. Once as a spc file, a spectrum bitmap file. The second measurement is saved as a text file. The files are saved in a specific folder created for that sample and for the particular amount of hours that the sample has been exposed to light. The measurement portal of the Shimadzu reflectance integrating sphere is approximately 1.7 cm in diameter. The sample is placed so that the portal of the integrating sphere is in the center of the sample. This is where the 1st measurement is made. The 2nd measurement is made at the far right upper corner of the sample. The 3rd measurement is made on the far left upper corner of the sample. The 4th measurement is made on the far right bottom corner of the sample. The 5th measurement is made on the far left bottom corner of the sample. This is shown in illustration 5.1

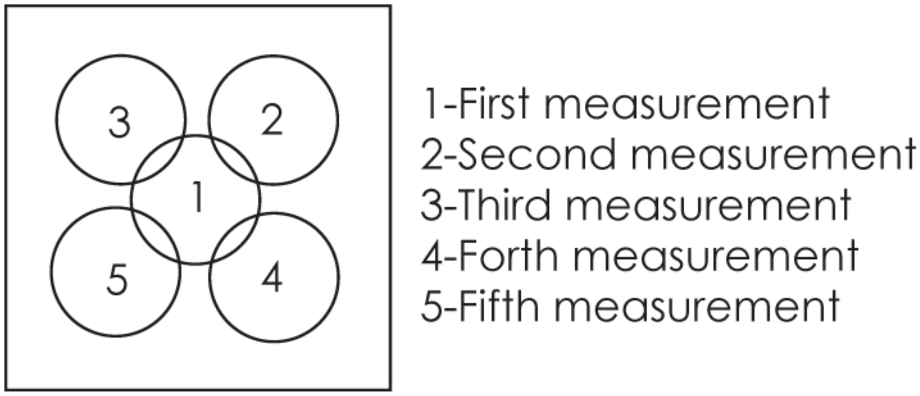


Illustration 5.1

Once all the measurements are made for that sample, the piece is put back in the cardboard box, and a new sample is measured. The same procedure is repeated for all samples until all the samples that needed to be measured have been measured. The samples are put back in the fading boxes. The time is written down. And the whole procedure is repeated whenever the next sets of samples need to be measured.

5.8 Preparation of Samples for Pigment Fading Studies

There is no established method for the preparation of the samples that were used for the pigment fading studies. Therefore a method needed to be created. The pigment sample needed to have the following characteristics:

1. A size of 2 inches by 2 inches. This was dictated by the anticipated uniformity of luminosity within a fading box and physical separation of different samples.

2. The substrate for the pigment sample to be uniform.
3. The substrate for the pigment sample needed to be as stable as possible to light, humidity and to the pigment.
4. A method to provide a uniform coating of the pigment to the substrate
5. The choice of pigment was dictated by the luminosity within the box. Samples which were insufficiently fugitive under the light would not display a significant change to provide a meaningful result. In this regard, some samples were chosen based on perceived light sensitive, while others were selected based on manufacturer specifications as being more or less fugitive. For instance. Winsor & Newton (W&N) provides specifications for samples as being either extremely permanent, permanent, moderately durable, or fugitive. For this work, the W&N pigments in the classifications of moderately durable or fugitive were chosen.

The substrate material chosen for the pigment samples was Crescent 201 Hot Press illustration board smooth surface medium weight (.050-.060) Studio board 30" X 40" and it was chosen because it has the stability characteristics mentioned above.

The pigment and dye materials selected are shown in Table 5.1.

Table 5.1

Name of Pigment or Dye	Manufacturer	Permanence	Obtained from	Type
Methylene Blue				
Cyclamen	Dr. Ph. Martin's®	Fugitive	Salis International, Inc.	Radiant Concentrated Watercolor
Cherry Red	Dr. Ph. Martin's	Fugitive	Salis International, Inc.	Radiant Concentrated Watercolor
Violet	Dr. Ph. Martin's	Fugitive	Salis International, Inc.	Radiant Concentrated Watercolor
Wild Rose	Dr. Ph. Martin's	Fugitive	Salis International, Inc.	Radiant Concentrated Watercolor
Fluorescent Yellow	Windsor & Newton™	Moderately Durable	Art Center El Paso Texas	Designer Gouache
Linden Green	Windsor & Newton	Moderately Durable	Art Center El Paso Texas	Designer Gouache
Orange Lake Light	Windsor & Newton	Moderately Durable	Art Center El Paso Texas	Designer Gouache
Rose Bengal	Windsor & Newton	Fugitive	Art Center El Paso Texas	Designer Gouache
Rose Carthame	Windsor & Newton	Fugitive	Art Center El Paso Texas	Designer Gouache
Rose Tyrien	Windsor & Newton	Fugitive	Art Center El Paso Texas	Designer Gouache
Geranium	Windsor & Newton	Fugitive	Art Center El Paso Texas	Designer Gouache
Periwinkle Blue	Windsor & Newton	Moderately Durable	Art Center El Paso Texas	Designer Gouache
Spectrum Violet	Windsor & Newton	Fugitive	Art Center El Paso Texas	Designer Gouache
ISO Blue Wool Standards 1-8	???	Vary in sensitivity. BW1 is highly fugitive, while BW8 is very stable under even intense illumination	SDC Enterprises, Ltd.	Dye on wool fabric

A method to coat the material with the pigment had to be developed. This was mostly by trial and error. A specific method had to be developed depending on the material that was going to be applied onto the matboard.

5.8.1 The Methylene blue samples

After trial and error it was determined that the best concentration was obtained by dissolving 0.5g of Methylene blue in 1L of DI water. The next step was to coat the matboard. Some exploratory work had to be undertaken to arrive at an acceptable coating method. A variety of samples were prepared that were either dipped into the solution or the solution was applied to the matboard via an ink roller. The samples were dipped either once, twice or three times and for different amount of times into the solution. The different times were: 5, 10, 15, 20, 25, and 30 seconds. The ink roller would stroke the sample either twice, four times or six times.

Due to problems of uniformity, the drying method was varied. Twenty-one samples were prepared and air dried. Twenty-one samples were prepared and oven dried for ten minutes. The temperature of the oven was 85^{o} C. After all the samples were measured by diffuse reflectance via the Shimadzu Spectrometer, it was determined that the samples that were the most uniform are the ones that were dipped twice into the solution for 15 seconds each time, and oven dried.

The final protocol for preparing the Methylene blue samples is the following. The lights are turned off, and under faint light, of less than 10lux, samples are prepared. The oven is equlibriated to 85° C. A solution is prepared by dissolving 0.5g of methylene blue in 1L of DI water. A piece of matboard with a size of 6 inches in length and 2 inches in width is cut. The matboard is dipped into the solution for 15 seconds, and then is dipped again for another 15 seconds. The sample is placed into the oven and is left there for 10 minutes. The sample is now dry. The sample is cut into three pieces of 2 inches by 2 inches, with one of each of these three pieces intended for irradiation by the three different illuminants (UTEP filter, Unfiltered, or Optivex® filter). Taking all three samples from a single piece of dyed matboard assures the best uniformity between these samples.

5.8.2 The Dr. Ph. Martin's Samples

From previous personal (MFD) experience using water colors, it was determined that 3 drops from the concentrated watercolor dissolved in 10 ml of DI water would be adequate. The next step was to determine what tool would be used to yield a uniform sample. The tools used were a paint roller, different sizes of paint brushes (1, 1.5 and 2 inches), and different sizes of foam brushes (1, 2 and 4 inches). Using each tool, samples of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11

layers of paint were prepared. Seventy-seven samples were made, air dried and measured. After the reflectance spectra of all the samples were measured via the Shimadzu Spectrometer, it was determined that the sample with the 11 layers of paint using the 2 inch foam brush gives the most uniform samples.

The final protocol used for preparing the Dr. Ph. Martin's samples is the following. Due to the anticipated light sensitivity, all operations are done under faint light of less than 10 lux. Three drops of the watercolor are dissolved in 10 ml of DI water, and mixed thoroughly with a small paint brush. A piece of matboard with a size of 6 inches in length and 2 inches in width is cut. The 2 inch foam brush is dipped into the solution and 11 layers of paint are applied onto the matboard. Each layer is applied after the last layer is dry. The samples are left to air dry in the dark 5 minutes, which is sufficient for most samples. As above, the sample is cut into three pieces of 2 inches by 2 inches, to be used with each of the illuminants.

5.8.3 The Windsor & Newton samples

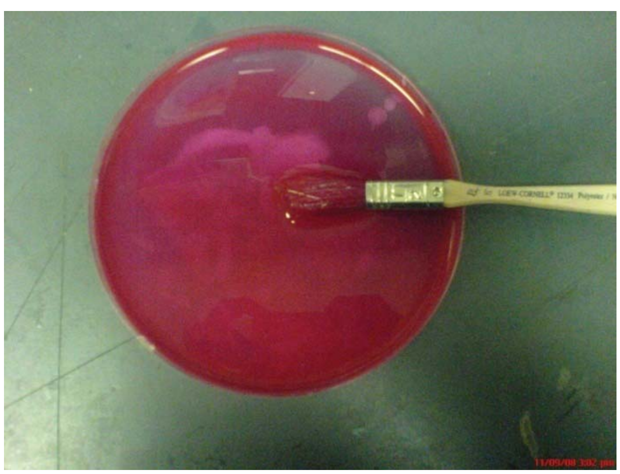
From previous personal (MFD) experience in using gouache, it was determined that a pea size drop of the gouache dissolved in 10 ml of DI water would be adequate. The next step was to determine what tool would be used to give a uniform sample. The tools used were a paint roller, different sizes of paint brushes (1, 1.5 and 2 inches), and different sizes of foam brushes (1, 2 and

4 inches). Using each tool samples of 1, 2, 3, 4, 5, 6 and 7 layers of paint were prepared. Forty-nine samples were made and measured. After the reflectance spectra of all the samples were measured via the Shimadzu Spectrometer, it was determined that the sample with 7 layers of paint using the 4 inch foam brush gives the most uniform sample. The first set of samples that were made and measured were air dried for 3 days in the dark. Later it was found that the samples were not drying uniformly under these conditions. Therefore, it was decided that the samples were going to be oven dried at a temperature of 85ºC or 10 minutes.

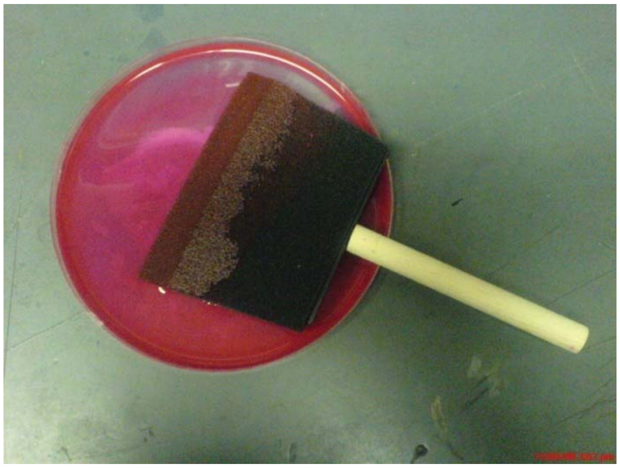
The final protocol used for preparing the Windsor & Newton samples is the following. All operations are conducted under fait light of less than 10lux. The oven is equilibrated at 85º C. A pea size drop of the gouache is dissolved in 10 ml of DI water, and mixed thoroughly with a small paint brush. A piece of matboard with a size of 6 inches in length and 2 inches in width is cut. The 4 inch foam brush is dipped into the solution and 7 layers of paint are applied onto the matboard. Each layer is applied after 1 minute has passed after the application of the last layer. The samples are put into the oven for 10 minutes. The sample is now dry. As before, the sample is cut into three pieces of 2 inches by 2 inches, each of which will be irradiated by the three different illuminants to be tested. In the following photographs 5.1, 5.2, 5.3, and 5.4 the preparation of these samples can be appreciated. The mentioned images were taken with a digital camera.

Photograph 5.1

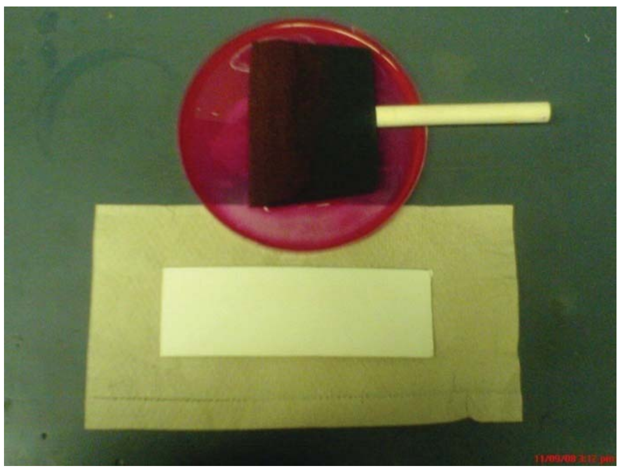
Photograph 5.2



Photograph 5.3



Photograph 5.4



Photograph 5.5

Photograph 5.6

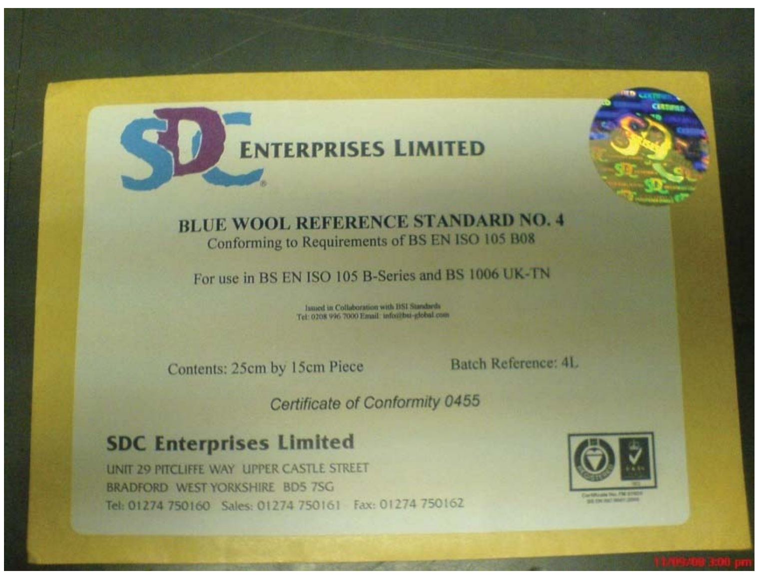
5.8.4 The Blue Wool Standards

These standards were obtained from SDC Enterprises Limited located at Unit 29 Pitcliffe Way Upper Castle Street Bradford, England. The procedure regarding how these standards are made is not disclosed by the company. These tests are used in the ISO 105-B[53] series of tests, and consist of fabrics dyed with a series of blue dyes with increasing sensitivity to light, with Blue Wool 1 being the most sensitive, and Blue Wool 8 being the least. Blue Wool 1 is highly sensitive, and ambient light will produce a change that might be visual in a few hours. The methodology developed here was implemented in lieu of the ISO methodology. The ISO methodology is discussed in detail in appendix M.

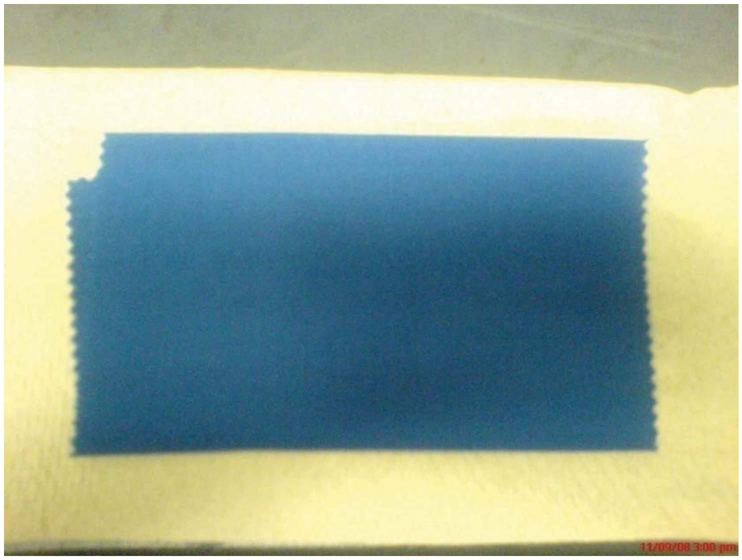
Blue wool standards are used to calculate or approximate the sensitivity of a material to visible light. The sensitivity to light of the material is based on visible-light exposure that is commonly measured in lux-hours. This exposure to light causes the material to fade somewhat similar to a Blue Wool standard. The United States and the United Kingdom have different methods for the production of their Blue Wool Standards. But both standards follow the ISO (International Standardization Organization) guidelines.

The Blue wools samples were prepared in the following manner. All operations are done under faint illumination of less than 10 lux. Three pieces of matboard are cut out. Each piece is 2 inches by 2 inches. The piece of wool

from the standard that is going to be used is taken out from the envelope it came in. Three pieces of cloth are cut out. Each piece of cloth is 2 inches by 2 inches. The pieces of cloth are attached to the matboard using a staple on the edge of each side of the cloth; this is to prevent it from moving and wrinkling. The moving and wrinkling would alter the measurements and the results. In photographs 5.7 and 5.8 the number 4 Blue Wool standard is shown.



Photograph 5.7



Photograph 5.8

Results and Discussions

The results to be considered are as follows:

1) Theoretical design of filter spectral profiles, including tolerances
2) Manufacturing Design of filter structures
3) Manufactured coating outcomes
4) Beam Angle Effects of the filters
5) Estimating the Filter natural life under typical use. Accelerated aging tests of the filters.
6) Pigment fading performance by the filters
7) Human trials for appreciation of the filters.

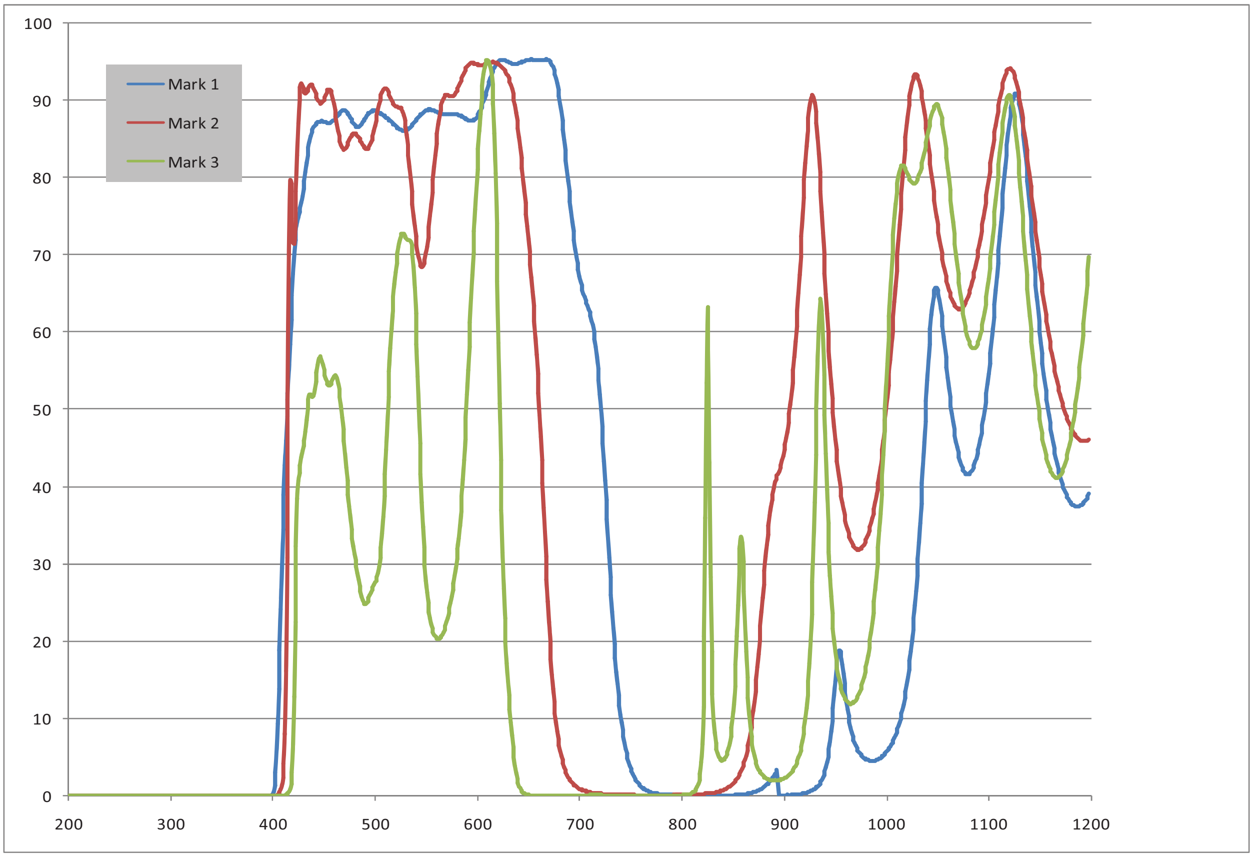
6.1 Theoretical Filter Designs

Three filters were designed that were brought to the stage of manufacturing. All of these filters were referenced to the Sylvania 58562 lamp. All filters were calculated assuming the Sylvania 58533 lamp, though any incandescent lamp close on color temperature would be suitable for actual practice. All filters were optimized using the reflection data from the Old Master Drawing reflection data discussed earlier. Color rendering was calculated and optimized using some of the advanced models discussed earlier, primarily using combinations of the CIE 109.2[24] adaptive color correction with either the U*V*W* color difference formula[12] or the DE00 color difference formula[26]. Note that optimization based on color rendering derived using the DE00 difference based

ethe color difference on a reference of D65[8, 34, 36]. Luminosity and lumens/ watt efficiencies are calculated as described earlier within the optimization procedures.

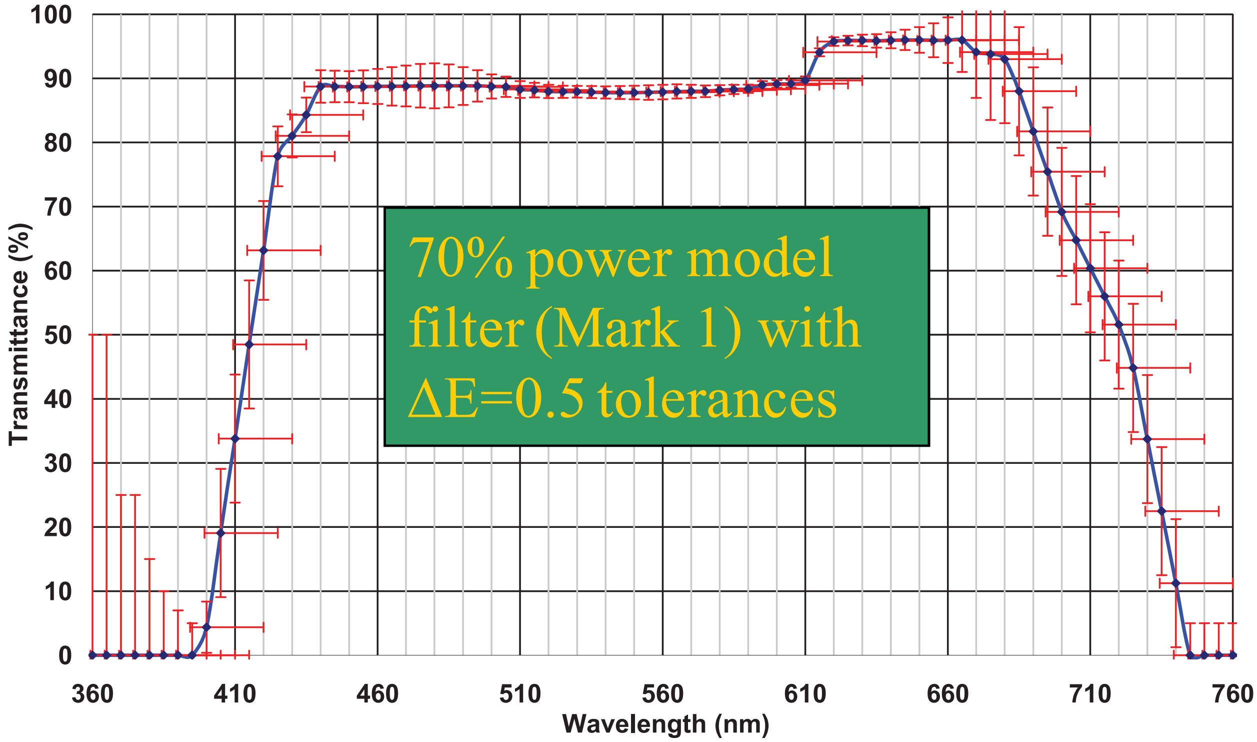
As discussed in the introduction, the transmitted power was varied in order to achieve variations in spectral profile and potentially higher performance in lumens/watt efficiency. The three designs were for percentage (%) power transmissions of 70%, 55%, and 43%, and resulted in filter profiles that were designated Mark 1, Mark2, and Mark 3, respectively. These three theoretical filter spectral transmissions are shown together in figure 6.1. In figures 6.2, 6.3, and 6.4, these plots are illustrated separately with color rendering tolerances. These color rendering tolerances are set at 50% of a just noticeable change in color rendering. This tolerance was set at this rather tight level because it was uncertain to what degree deviations might actually be perceived in the actual filters and caution was exercised in order not waste a filter manufacturing run.

Note that in comparing these tolerances, that as it is proceed to lower % transmission powers, the tolerances become tighter. This is a consequence of the increasing structure in the spectral profile. As more spectral features develop, these become constraints on how far the spectrum could be shifted on wavelength and transmission. This effect will also have a bearing on the beam angle dependence on color rendering (*vide infra*).



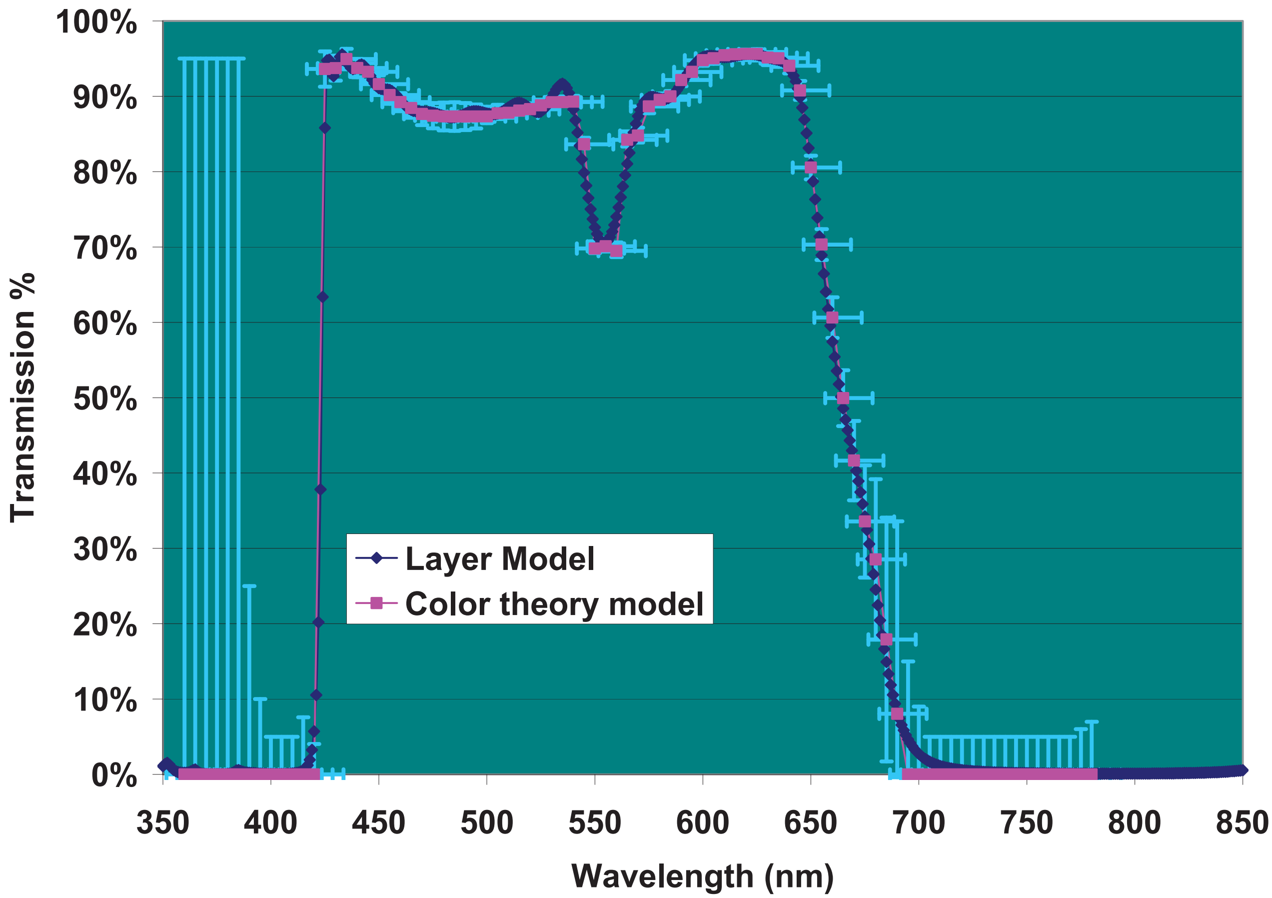
100
90
80
70
60
50
40
30
20
10
0
200
300
400
500
600
700
800
900
1000
1100
1200
Mark 1
Mark 2
Mark 3

Figure 6.1



70% power model filter (Mark 1) with ΔE=0.5 tolerances
Transmittance (%)
Wavelength (nm)
100
90
80
70
60
50
40
30
20
10
0
360
410
460
510
560
610
660
710
760

Figure 6.2



Transmission %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
350
400
450
500
550
600
650
700
750
800
850
Wavelength (nm)
Layer Model
Color theory model

Figure 6.3

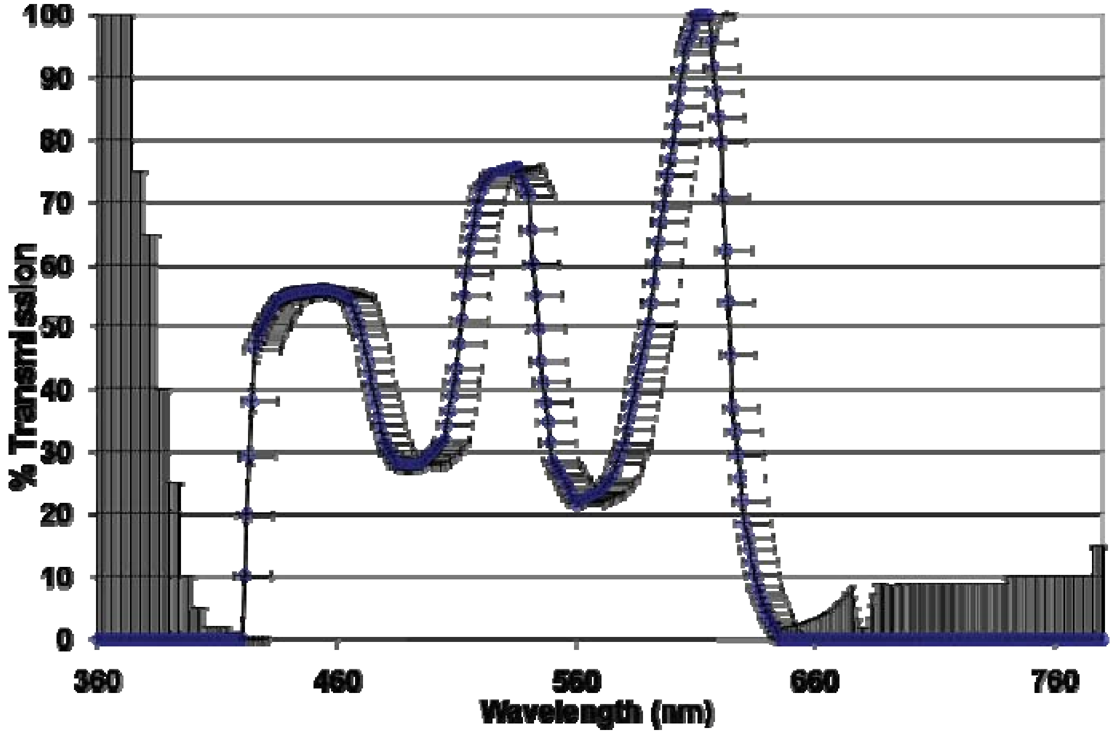


Figure 6.4

6.1.1 Manufacturing Design of Filter Structures

Manufacturing design involves questions of substrate, coating materials, and coating layer structure.

Several substrate materials were considered. Several criteria should be considered:

1) The filter will likely be exposed to high heat when affixed in front of a lamp. Temperatures up to 180-200 C should be planed for. Therefore glasses which can accept thermal cycling on high temperature exposure for long periods are desirable.

2) The glass has to have suitable surface chemistry amenable to bonding with the coating materials. This can't necessarily be fully anticipated. However, any substances in the glass that might react with or diffuse into the coating need to be considered.
3) Ideally, one would like to not need to work hard blocking light in the ultraviolet using the interference effects of the coating. This could greatly complicate coating design. Therefore, a UV-VIS cutoff near 400nm is desirable. This cutoff could vary greatly depending on the filter's application, though variation would normally be to longer wavelength cutoffs, not shorter wavelength. Again, whenever UV or blue light has to be blocked it greatly eases filter design by using the absorptive properties of the substrate rather than the interference properties of the coating.
4) While not a criterion, the complex refractive index needs to be known throughout the spectral design wavelength range for the application of the coating.

Criteria for the filter material components include:

1) Thermally stable under the conditions of use.
2) Photo-chemically stable under the conditions of use.
3) Thermo-mechanically stable in terms of interaction of coating layers with each other, and of coating materials with substrate.
4) Resistant to effects of humidity.

5) Resistant to oxidative effects under normal ambient atmosphere.
6) The coating layers must not react with each other or the substrate.
7) Ideally, some scratch resistance, though appropriate care could permit sensitive materials.
8) While not a criterion, the complex refractive index of all coating materials needs to be known throughout the spectral design wavelength range for the application of the coating. In addition, this measurement needs to be known for the materials as they are deposited by the coating equipment and under the conditions that the coatings will be deposited to create the dielectric filter structures.

With the complex refractive index, it is possible to use standard procedures for the calculation. Commercial programs are available for this task, such as TFCALC (Software Spectra, Inc.). Besides the complex refractive index of the materials, the only other requirement is the need for wavelength and transmission tolerance constraints. The constraints greatly simplify and help focus the optimization to practical solutions.

There are some criteria for designing coatings, some of which can have a bearing on the spectral profile used for the coating design

1) It is difficult to fully attenuate light (0% transmission) by interference alone. Therefore regions where attenuation to below 5% is demanded should be avoided or minimized.

2) Optics can never have 100% transmission. One can build some antireflection into a coating, but even then typically transmissions will not exceed ≈95%. This isn't a constraint; so much as it is an understanding that the theoretical maximum 100% transmission of a spectral profile will be scaled to the maximum transmission possible for the coating. It becomes a constraint when one has more than one peak that has a high theoretical transmission of 100%. It can be difficult to achieve equivalent high transmission on multiple peaks.
3) One should avoid sharp cutoffs. These can require many filter layers to achieve high accuracy when multiple sharp cutoffs are required, as opposed to the sharp cutoffs at either extreme of a broad featureless bandpass or bandstop filter.

Thus, spectral profiles to be considered for coating manufacture must be optimized with these considerations in mind.

For the earliest prototype filters made for this project, simple borosilicate glass was used. The earliest prototype coatings used TiO_2 and SiO_2. This produced a coating with acceptable optical properties, but not acceptable stability. In addition the UV-VIS cutoff for the glass substrate demanded that interference block the light to wavelengths below 370nm. These early prototype materials approaches were abandoned and new materials were considered.

After some searching, Corning 8511 glass was recommended to us by Dr. Lisa Zhang of Ross Optical. This glass possesses a UV-VIS cutoff of about 400nm, and being a borosilicate, possesses enhanced thermal stability. This glass was successfully used throughout the project for all filters reported here. It was discontinued by Corning in 2005, and is no longer available. The complex refractive index of the 8511 glass was graciously done for us by J. A. Woollam, Inc. at no charge. The transmission (T%) of the Corning 8511 can be found in Appendix N.

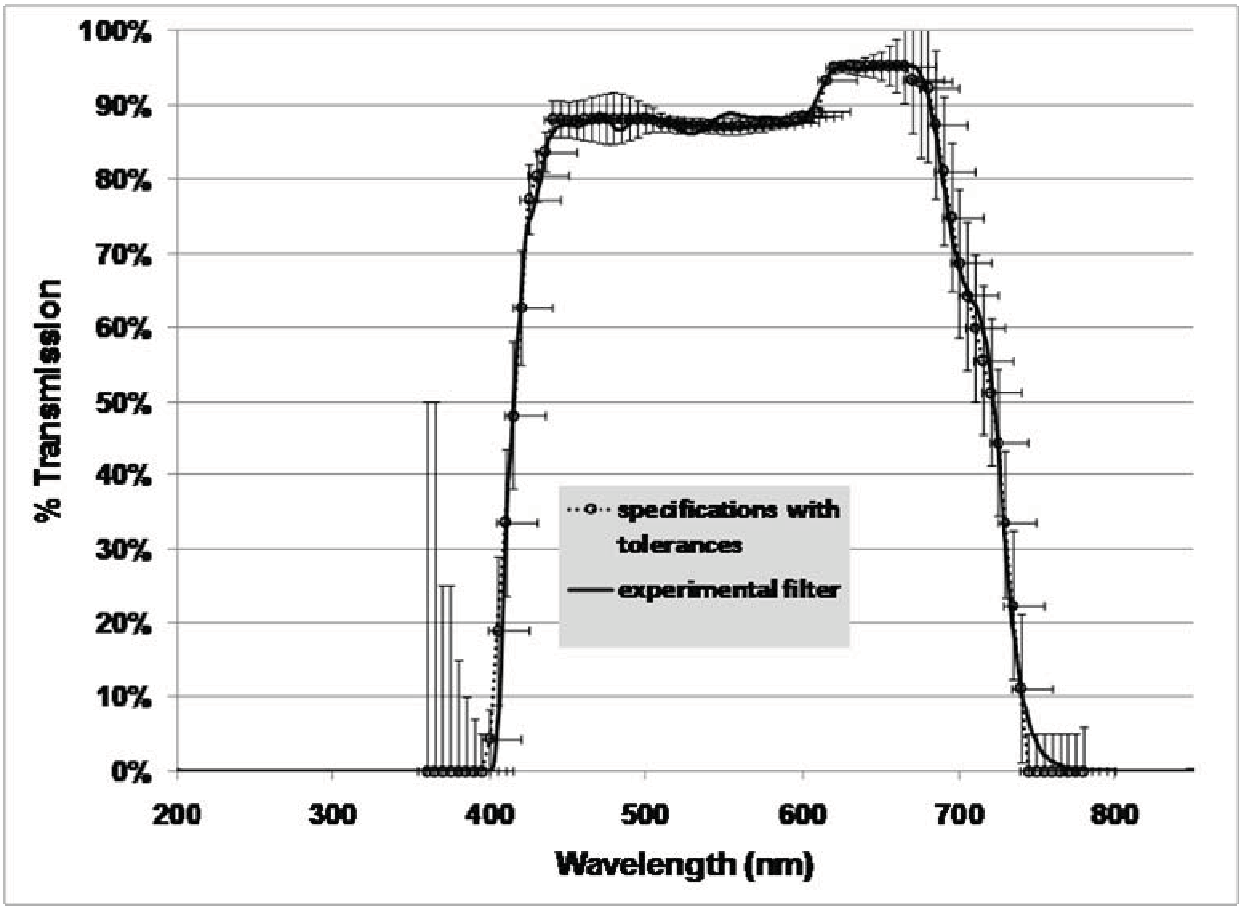
Several manufacturing options were considered or tried. Tolerances are relatively tight for the purposes of manufacturing, and the highest quality coating equipment available at the time had to be considered. This lead to the adoption of Leybold's HELIOS™ coater. This decision lead to the recommendation by Leybold to utilize Nb_2O_5[54] and SiO_2[55] as the coating materials combination. These materials are known to be stable for high heat and light applications. Leybold provided complex refractive index data for their materials as deposited by the HELIOS™ coater.

Using the complex refractive index data and TFCALC, it is possible to calculate candidate filter structures to be considered for manufacture. Candidate filter structures for the Mark 1, Mark 2, and Mark 3 filters were obtained in this fashion. When these filter structures were provided to Leybold, Leybold recalculated new structures based on their own software and optical

models. Comparison of theoretical spectral profiles from the lighting optimization software and that from the theoretical proposed filter structure models are given for the Mark 1, Mark 2, and Mark 3 filter in Figures 6.5, 6.6 and 6.7, respectively.

6.1.2 Manufactured Coating Outcomes

The manufactured coating outcomes for Mark 1, Mark 2, and Mark 3 filter are provided in Figures 6.5, 6.6, 6.7, respectively, along with comparison to the theoretical lighting models, and the structure models. Tolerances are well met for all designs. The deviations that are present do not significantly affect the color rendering or other performance factors. In Table 6.1 are summarized the main optical performance factors for the three filters.



100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Transmission
200
300
400
500
600
700
800
Wavelength (nm)
specifications with tolerances
experimental filter

Figure 6.5

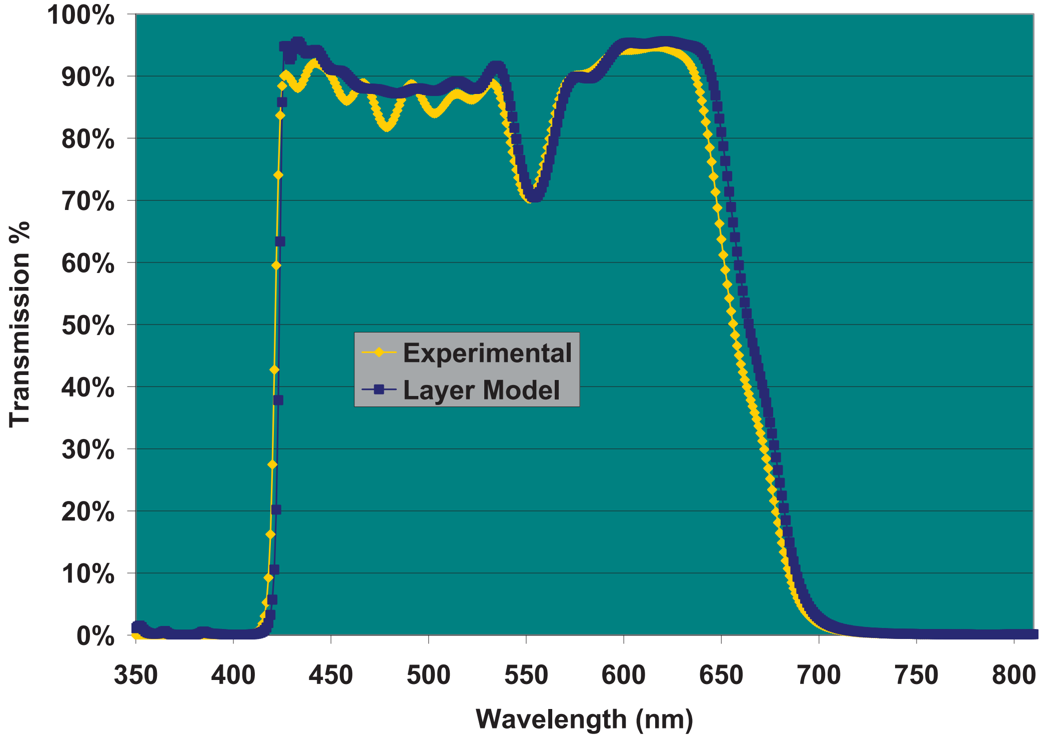
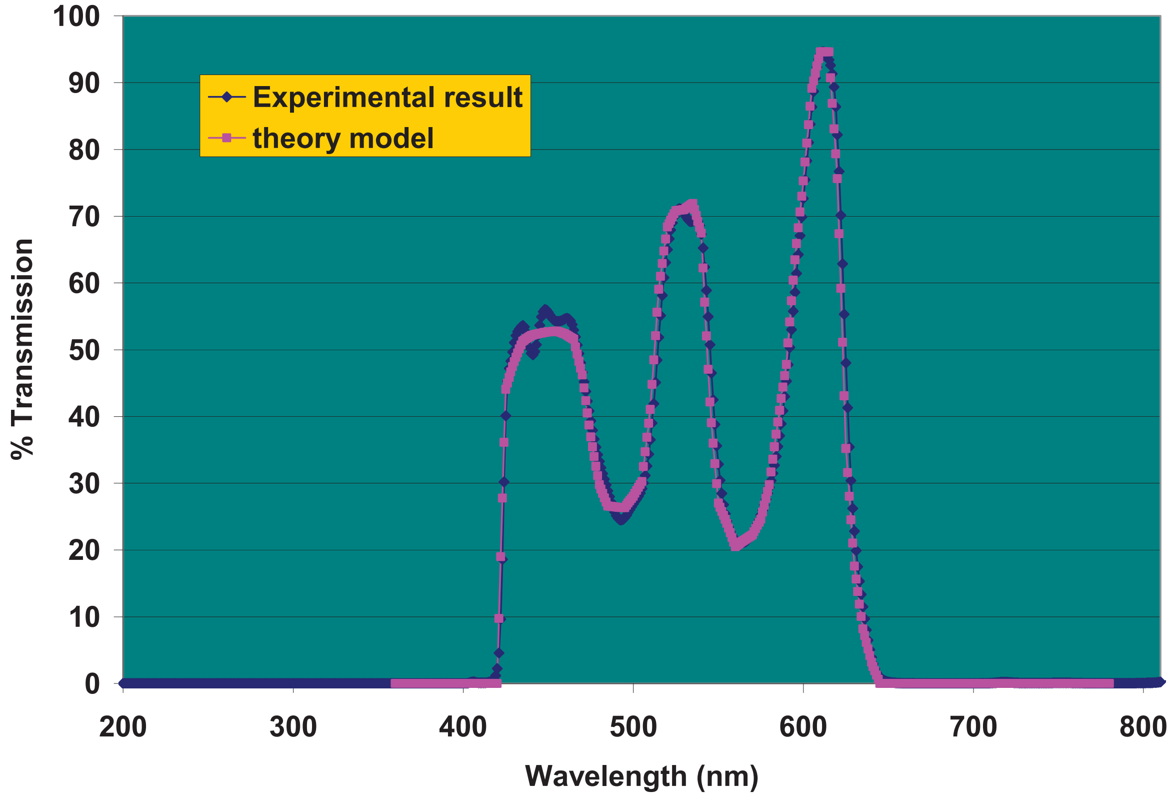

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Transmission %
Experimental
Layer Model
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Figure 6.6



Experimental result
theory model
% Transmission
100
90
80
70
60
50
40
30
20
10
0
200
300
400
500
600
700
800
Wavelength (nm)

Figure 6.7

Table 6.1

	Color Rendering Index	Lumens / Watt Efficiency
Mark 1 (70% power)		
Model	98.9	133%
Actual Filter	99.0	133%
Mark 2 (55% power)		
Model	99.2	183%
Actual Filter	98.9	191%
Mark 3 (43% power)		
Model	97.9	232%
Actual Filter	98.4	229%

Note that performance is either closely met or slightly exceeded in efficacy for all filters. In Appendix O, the spectral transmission for an Optivex® filter (Applied Coatings Group, Inc.) is included for comparison.

6.2 Off Angle Measurements

Figure 6.8 illustrates the anticipated variation in color rendering for the spectral distributions as they vary away from the center beam position.

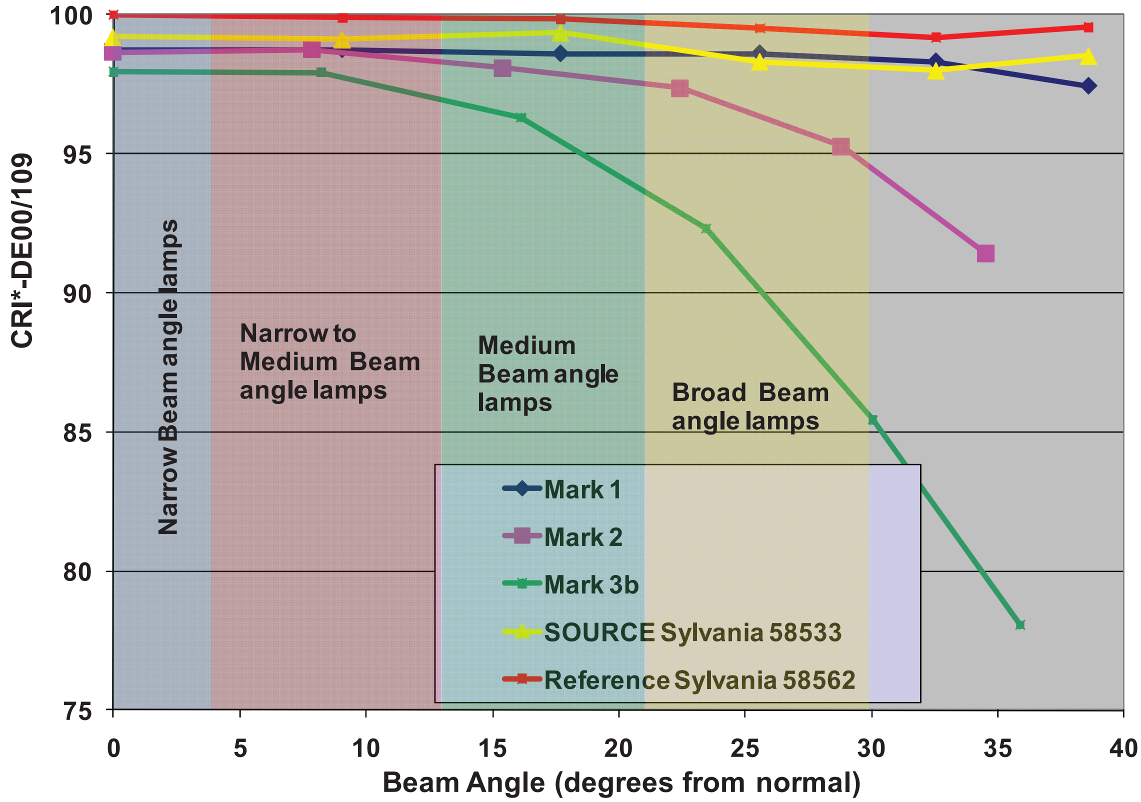


Figure 6.8

Changes in color rendering index less than 4.6 CRI units will normally not be distinguishable. Changes larger than 4.6 CRI units may not necessarily be considered deleterious, sometimes up to deviations as large as 15-20+ CRI units. One has to visualize the lamp's performance in these cases to make this assessment. Note in Figure 6.8 that the reference for all CRI measurements is the Sylvania 58562 lamp at zero degrees. Therefore, the zero degree entry for this lamp on the graph must be exactly at 100.

One can see mild variations in CRI with beam angle for the unfiltered SOURCE and reference lamps. Even far away from the center beam, the resulting light will not display significant color rendering aberrations. For the filters, a progressive increase in color rendering aberration with decreasing power of transmission of the filter (% power transmitted: Mark 1{70%} > Mark 2 {55%}> Mark 3 {43%}) can be seen. Note that the correlation is likely due to the increased complexity in spectral transmission window for each filter, thus making deviations more susceptible to transmission errors. This can be seen in Figure 6.9 where calculate the transmission spectrum as a function of incident angle for a Mark 3 type filter.

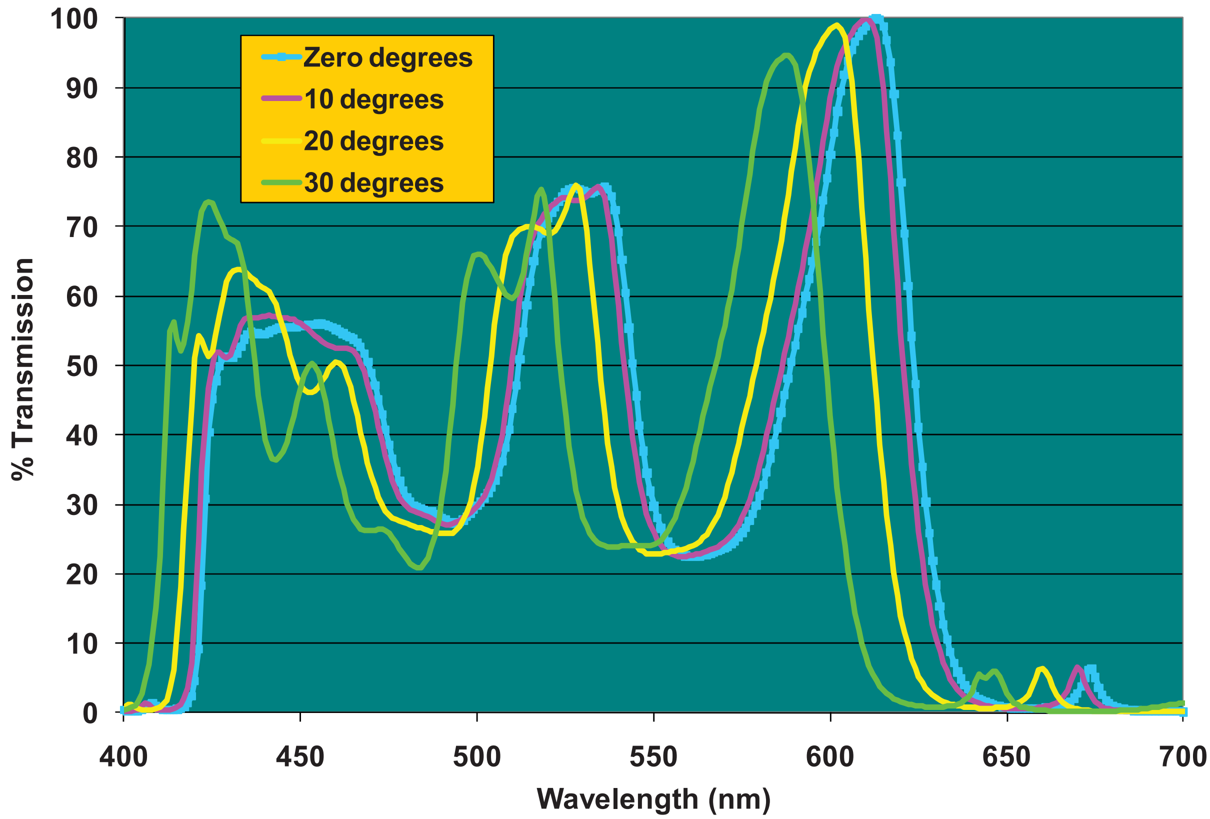


Figure 6.9

For Mark 1 and Mark 2, the results in Figure 6.9 predict and have been confirmed by visualization that there is no aberration in the beam from center point to angles to >30 degrees. The CRI deviations with angle only become relevant for concern for the Mark 3 filter. Visualization does indeed reveal a green halo when projected on an adequately reflective background. Within the UTEP test gallery, with back curtains surrounding the artwork, no aberration is observed. However, within the GCI ELF facility with a neutral gray background, the halo effect can be seen with broad beam angle lamps.

Eliminating the halo involves three possible approaches:

1) Use a more narrow beam angle lamp.
2) Collimate the beam by setting the lamp and filter back into a mounting canister for the lamp fixture. Many lamp fixtures already come with the lamp set back in such a canister.
3) Coat the filter on a gently curving surface such as a lens. This assures that rays that are far off angle pass through the surface of the filter at a normal angle.

In practice, it was found that collimation with the canister of the lamp fixture served adequately.

6.3 Correlated Color Temperature (CCT)

Correlated Color Temperatures have been calculated for the filters and some filter SOURCE illuminant combinations. The SOURCE illuminant is that which is being filtered by the filter. This data, along with CIE 1960 uniform color space chromatcities, is summarized in Table 6.2. CCTs reported in this table are probably within 1-2 ºK of the 'true' color temperature. This uncertainty is based on the calculation of the CCT for standard illuminants, D65 and A, reported above.

Table 6.2

Filter	Lamp	CCT (ºK)	CIE 1960 uniform color space chromatcities	
			U	V
none	Sylvania 58562	2844.7	0.2563	0.3498
none	Sylvania 58533	2931.8	0.2525	0.3499
Mark 1	Sylvania 58533	2833.3	0.2566	0.3505
Mark 2	Sylvania 58533	2881.7	0.2548	0.3495
Mark 3	Sylvania 58533	2908.3	0.2536	0.3498

Recall that Sylvania 58562 is the reference lamp for design of filters, while the Sylvania 58533 lamp is the SOURCE lamp for which the filter has been designed. The data in Table 6.2 is based on the average spectral profile of 20 lamps for 58533 and ten lamps for 58562, and these average spectral profiles were the actual design specifications for the filters. The manufacturer specification for the CCT for the 58562 and 58533 is 3000 ºK. Clearly the reference 58562 spectral profile that was used is significantly different from this specification. This reference was chosen at UTEP by the Dirk research group, and one imagines its 'warmer' lower color temperature may have contributed to this choice. At the time the reference lamp was selected, it was not known that it departed so significantly from its manufacturer specification.

The Sylvania 58533 CCT is much closer to its manufacturer specification. However, the specification of the 2844.7 ºK 58562 forces all filter designs to lower the CCT of the filtered light relative to the 58533. At the time of the filter design, no effort was made to constrain chromaticity or CCT, while CRI was fully optimized. The Mark 1 and Mark 2 filters were designed using the CRI*-109 color rendering model, while Mark 3 was designed using the CRI*-DE00-109 model. The variations in CCT may not be due to changes in the color rendering model used, especially since Mark2 and Mark3 are relatively close in CCT, while the color rendering model varied.

The filters were designed with the spectral profile of Sylvania 58533 as the SOURCE lamp behind the filter. This average (of 20 lamps) spectral profile poss a CCT of 2931.8 ºK. The original intention was that the filters would be designed for SOURCE lamps of color temperature equal to 3000 ºK. Commercial lamps of any given CT specification seem to vary somewhat in this specification. Provided in Figure 6.10 is the variation in transmitted CCT for a range of blackbody emitters at CTs ranging 2900-3100 ºK.

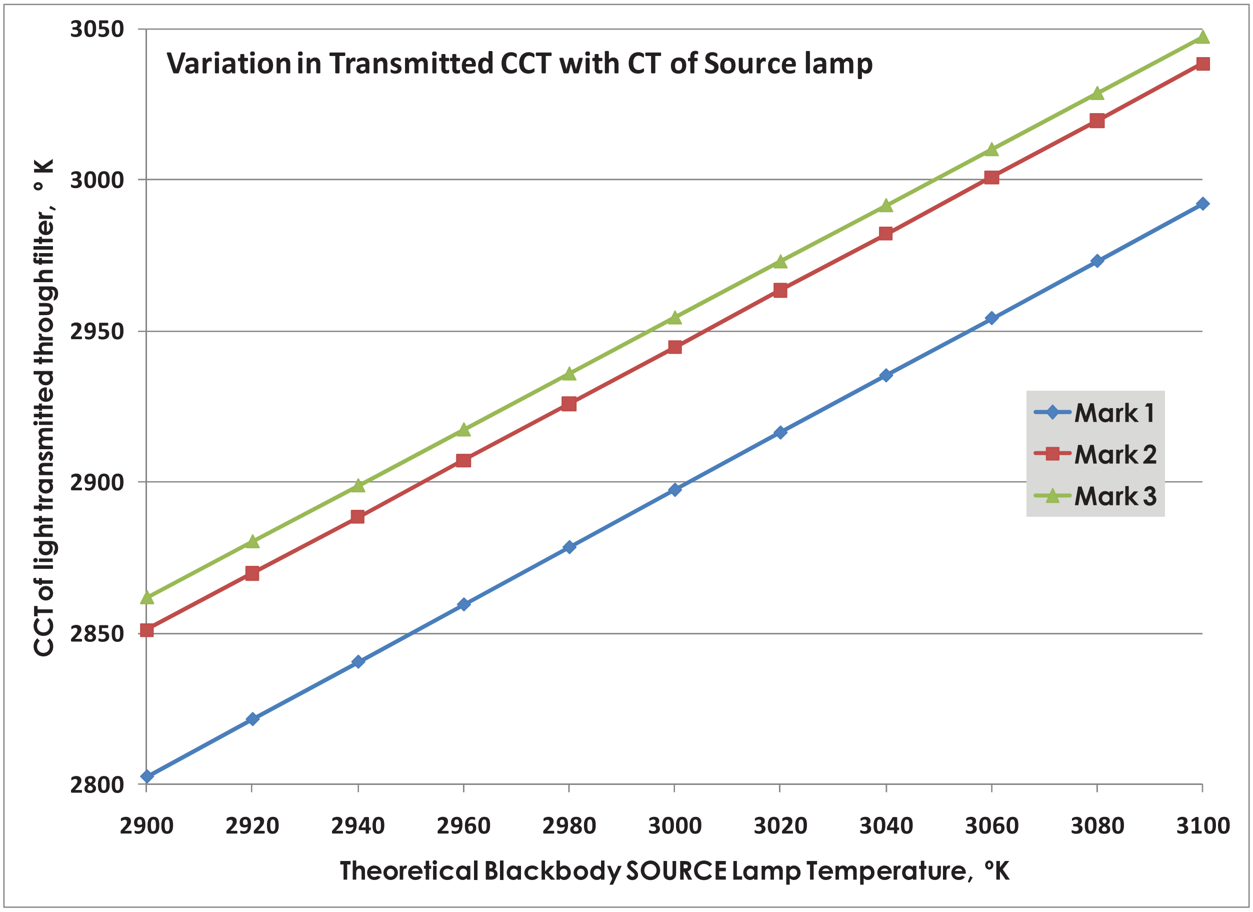


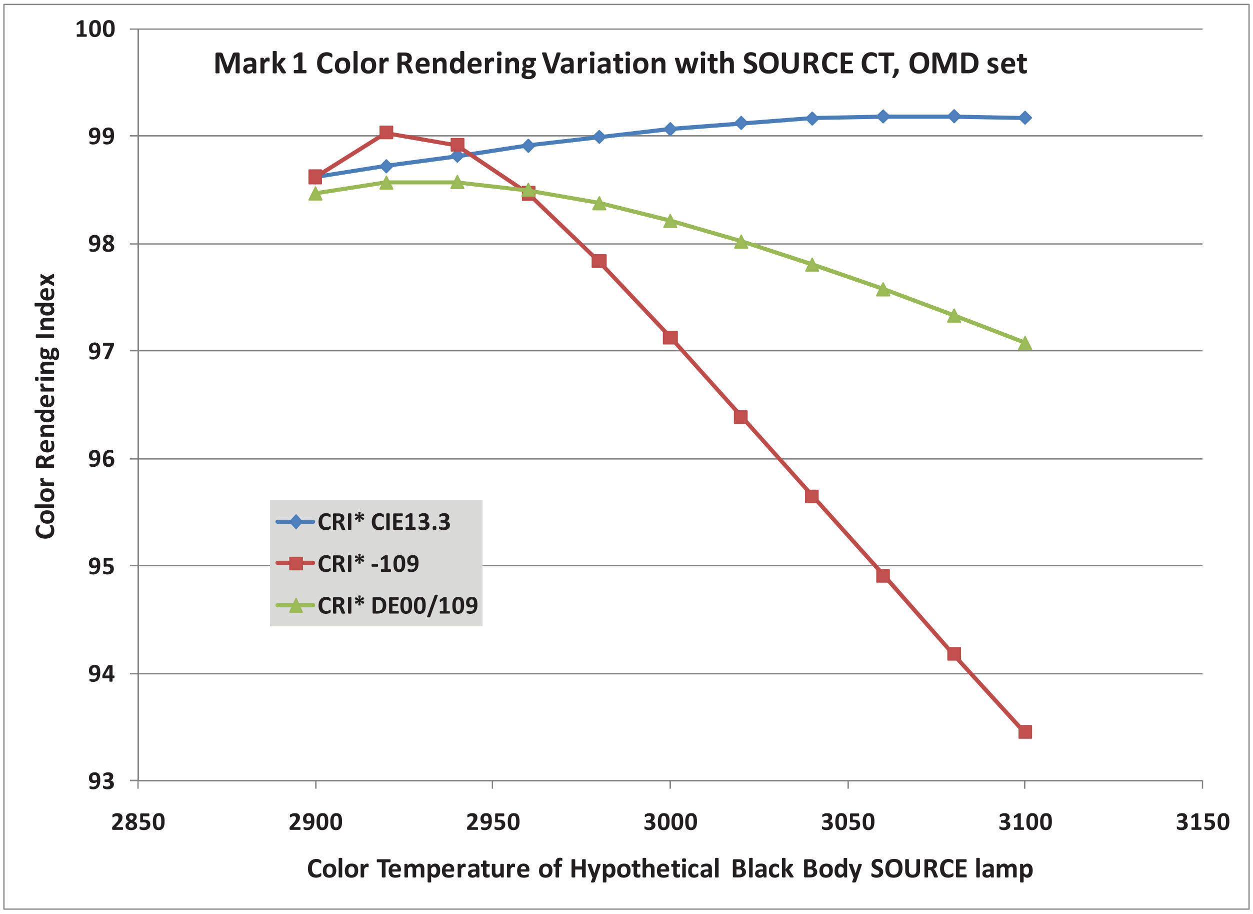
Figure 6.10

6.4 Variation in Filter Color rendering with SOURCE lamp

Equal with concern of the variation in filter color temperature with variation in SOURCE lamp, one would be concerned with how much the color rendering might vary with the SOURCE lamp, In Figures, 6.11, 6.12, and 6.13 are various color rendering indices of each of the filters as they vary with a hypothetical blackbody source of color temperatures 2900-3000K.

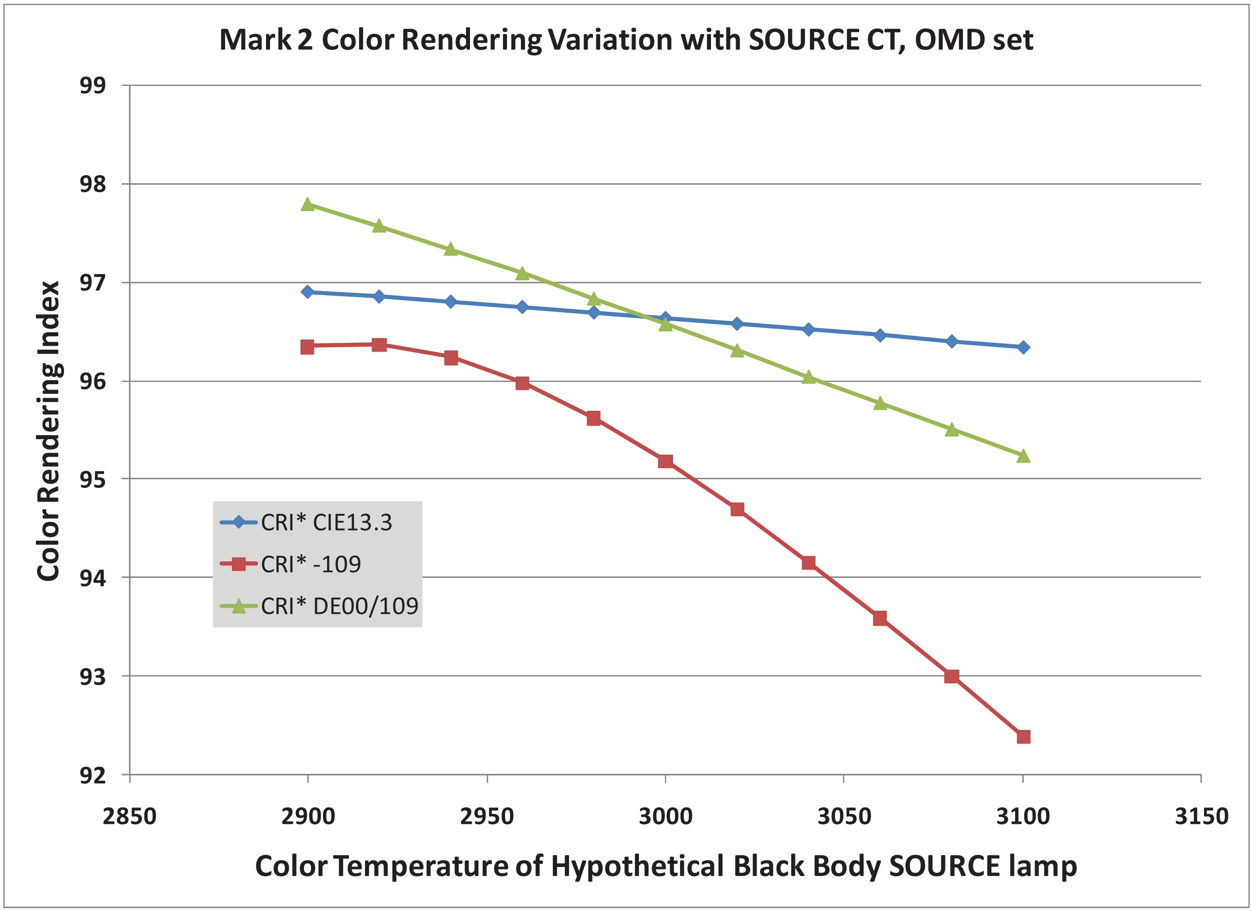
The Mark 1 filter was optimized using the CRI*-109 color rendering model with the 2844.7K Sylvania 58562 as reference and the 2931.8K Sylvania 58533 as SOURCE. The CRI*-109 color rendering model was the variation which included replacing the standard Munsell color set with the OMD reflection data, and replacing the adaptive color correction with the CIE 109.2 method. Figure 6.11 has this data along with that for the CRI* CIE13.3 and CRI* DE00/109 models.

The Mark 1 was optimized with a SOURCE of 2931.8K, and so, it should be no surprise that the CRI*-109 model peaks near this value. The Figure reveals to what extent the color rendering index might vary with SOURCE lamp, and within this graph, the worse case is at 3100K, with a CRI=93.5. This is perhaps 1-2 just-noticeable-differences (JND) in perception, but still acceptable.



Mark 1 Color Rendering Variation with SOURCE CT, OMD set
Color Rendering Index
100
99
98
97
96
95
94
93
CRI* CIE13.3
CRI* -109
CRI* DE00/109
2850
2900
2950
3000
3050
3100
3150
Color Temperature of Hypothetical Black Body SOURCE lamp

Figure 6.11



Mark 2 Color Rendering Variation with SOURCE CT, OMD set
Color Rendering Index
99
98
97
96
95
94
93
92
2850
2900
2950
3000
3050
3100
3150
Color Temperature of Hypothetical Black Body SOURCE lamp
CRI* CIE13.3
CRI* -109
CRI* DE00/109

Figure 6.12

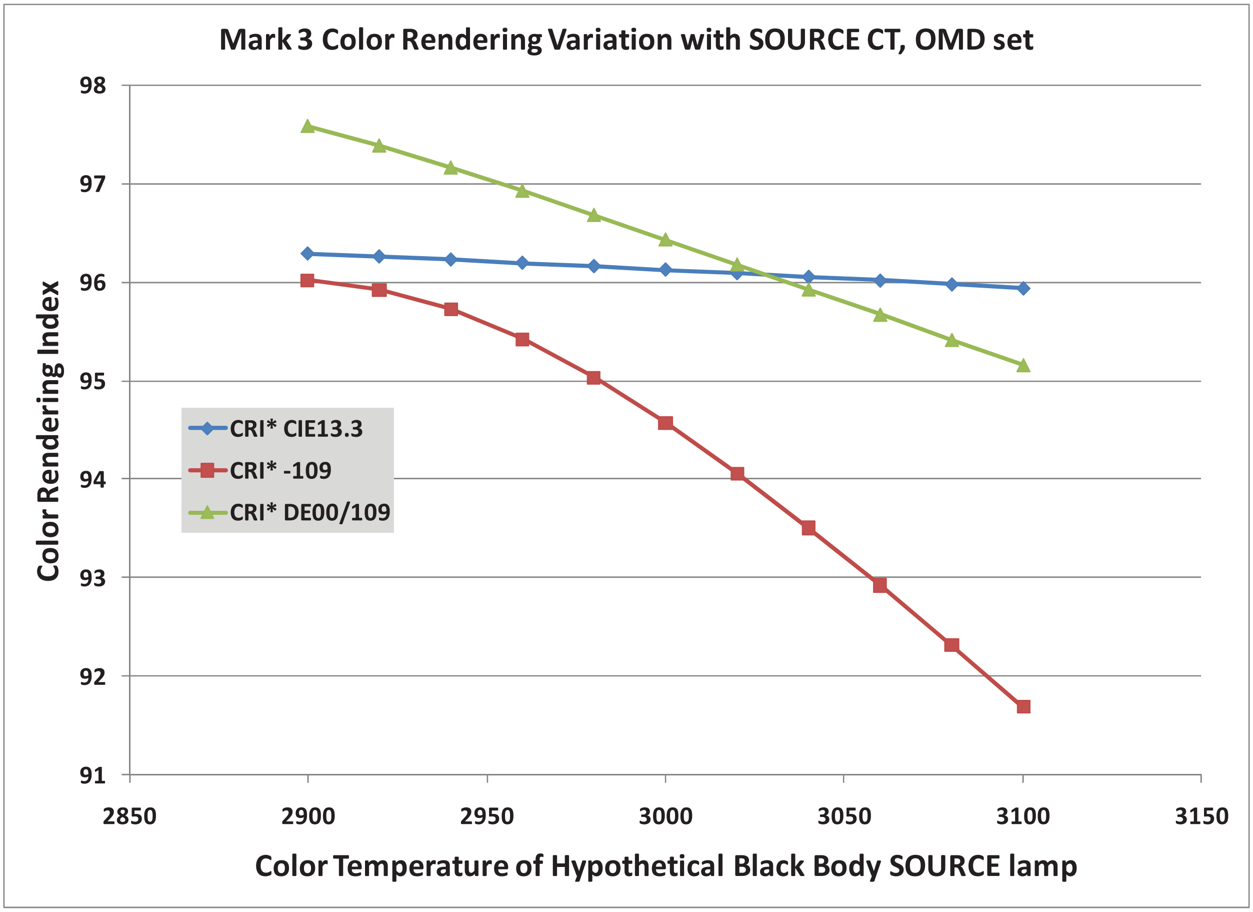
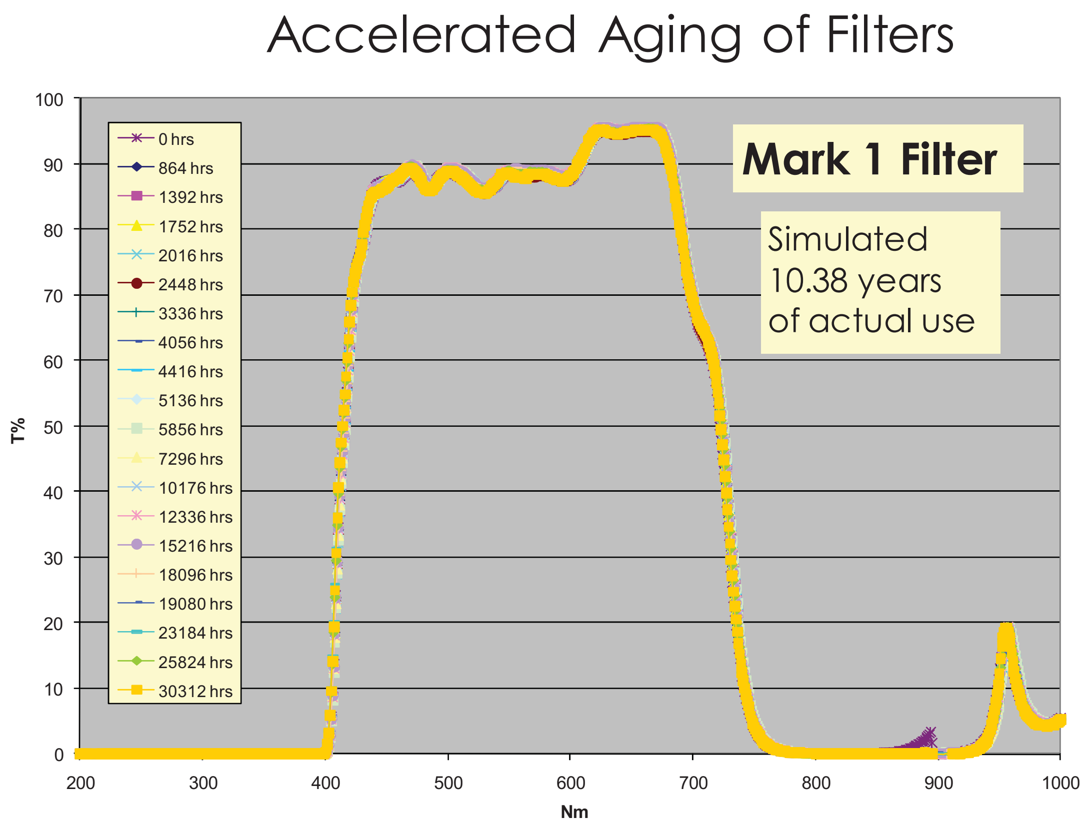


Figure 6.13

6.5 Filter Stability and Lifetime

Dielectric filter coatings are known to occasionally display instabilities. These may be mechanical or chemical in nature. Chemical instabilities could include reaction with moisture or oxygen or air pollutants. Mechanical instability could be related to the adhesion of the coating to the substrate or adhesion of the coating layers to one another. Mechanical instability might be evidenced by de-lamination. Different conditions could accelerate the chemical or mechanical effects, for instance heat or light.

Under normal museum lighting conditions, a filter will be exposed to O_2, atmospheric moisture, and air pollutants. Accelerated aging of these effects is difficult to carry out, and consequently, these effects will be tested as constants for any other accelerated aging that are carried out. It is likely that if these effects are a serious concern, they will arise under the normal conditions of the other kinds of testing that were carried out. As described above, the tests that were carried out were the constant-exposure and cyclical exposure tests which evaluated long term thermal, photochemical, and thermo-mechanical effects. These were accelerated aging tests because light was either kept on indefinitely (constant exposure) or cycled (on for one hour, off for one hour) at a faster rate than normal (thermo-mechanical). Since lighting in museums is probably switched on for an average of eight hours per day, the constant exposure test was accelerated by a factor of three, and the cyclical them-mechanical test was accelerated by a factor of 12. These filters were assessed periodically by both subjective visual inspection, and by transmission spectroscopy. The results are presented in Figure 6.14, 6.15, and 6.16 for the constant-exposure test for the Mark 1, Mark 2, and Mark 3 filters, respectively, and in Figures 6.17 and 6.18 for the cyclical thermo-mechanical test for the Mark 2 and Mark 3 filters respectively.



Accelerated Aging of Filters
Mark 1 Filter
Simulated
10.38 years
of actual use
0 hrs
864 hrs
1392 hrs
1752 hrs
2016 hrs
2448 hrs
3336 hrs
4056 hrs
4416 hrs
5136 hrs
5856 hrs
7296 hrs
10176 hrs
12336 hrs
15216 hrs
18096 hrs
19080 hrs
23184 hrs
25824 hrs
30312 hrs
T%
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
1000
Nm

Figure 6.14

Accelerated Aging of Filters

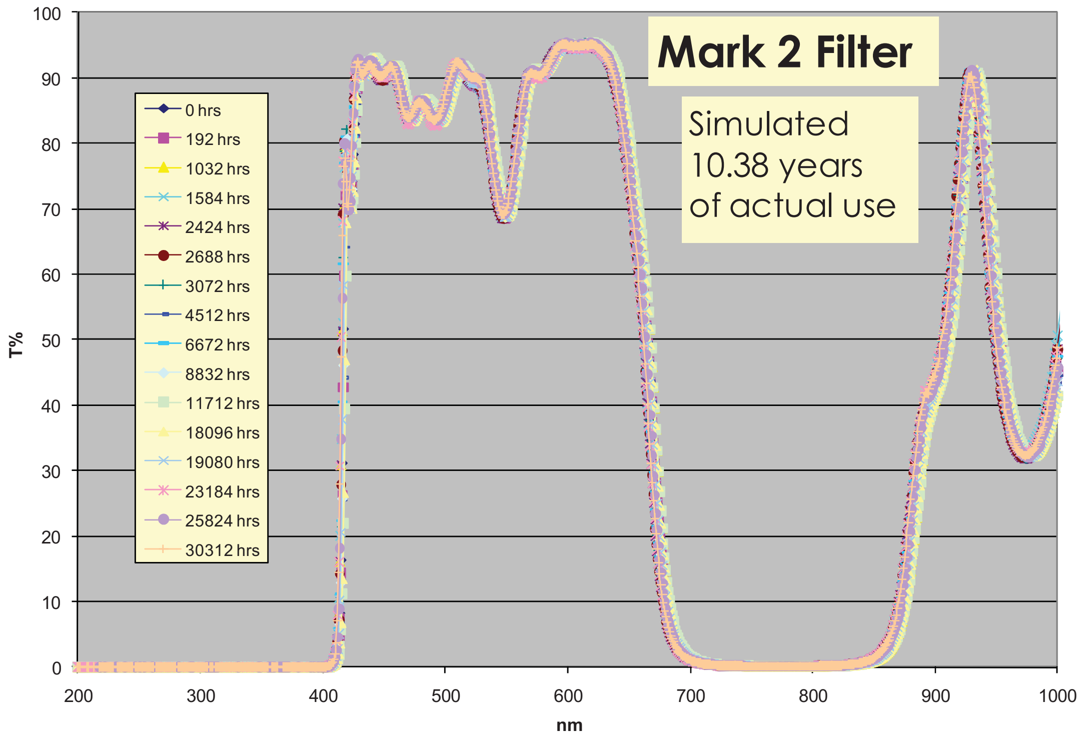


Figure 6.15

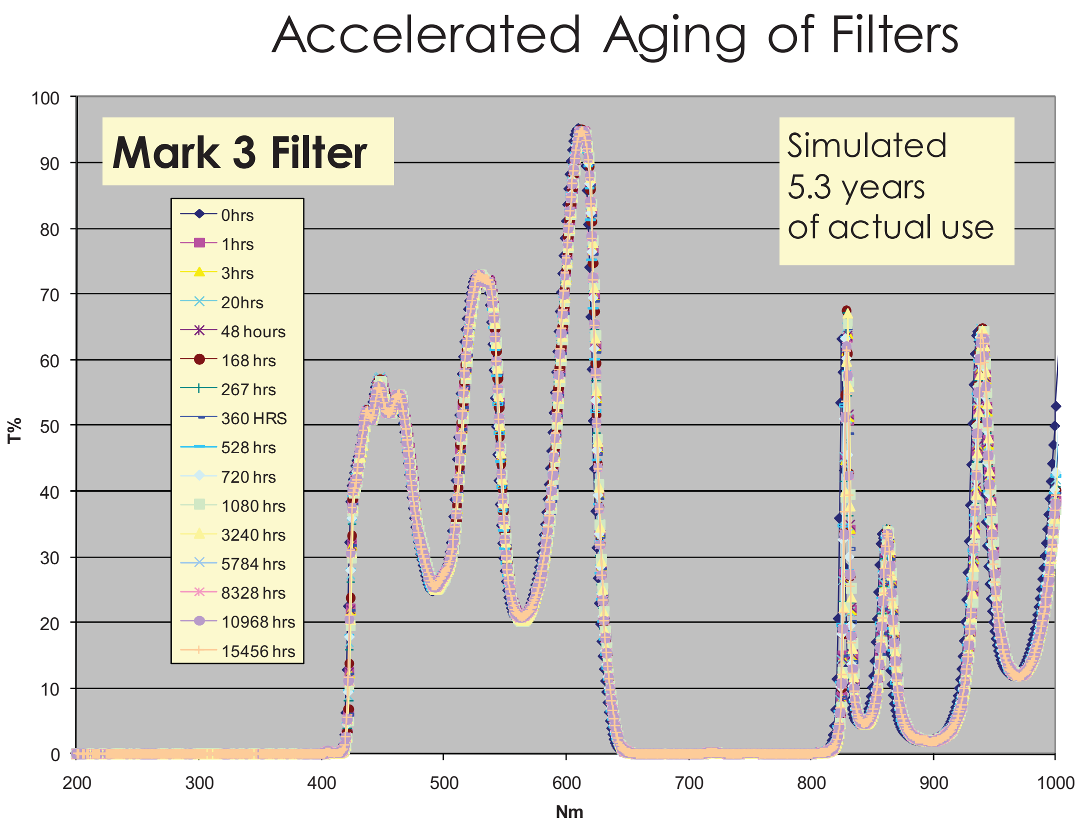

Accelerated Aging of Filters
Mark 3 Filter
Simulated 5.3 years of actual use
0hrs
1hrs
3hrs
20hrs
48 hours
168 hrs
267 hrs
360 HRS
528 hrs
720 hrs
1080 hrs
3240 hrs
5784 hrs
8328 hrs
10968 hrs
15456 hrs
T%
Nm
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
1000

Figure 6.16

Accelerated Thermo-Mechanical Stress Testing

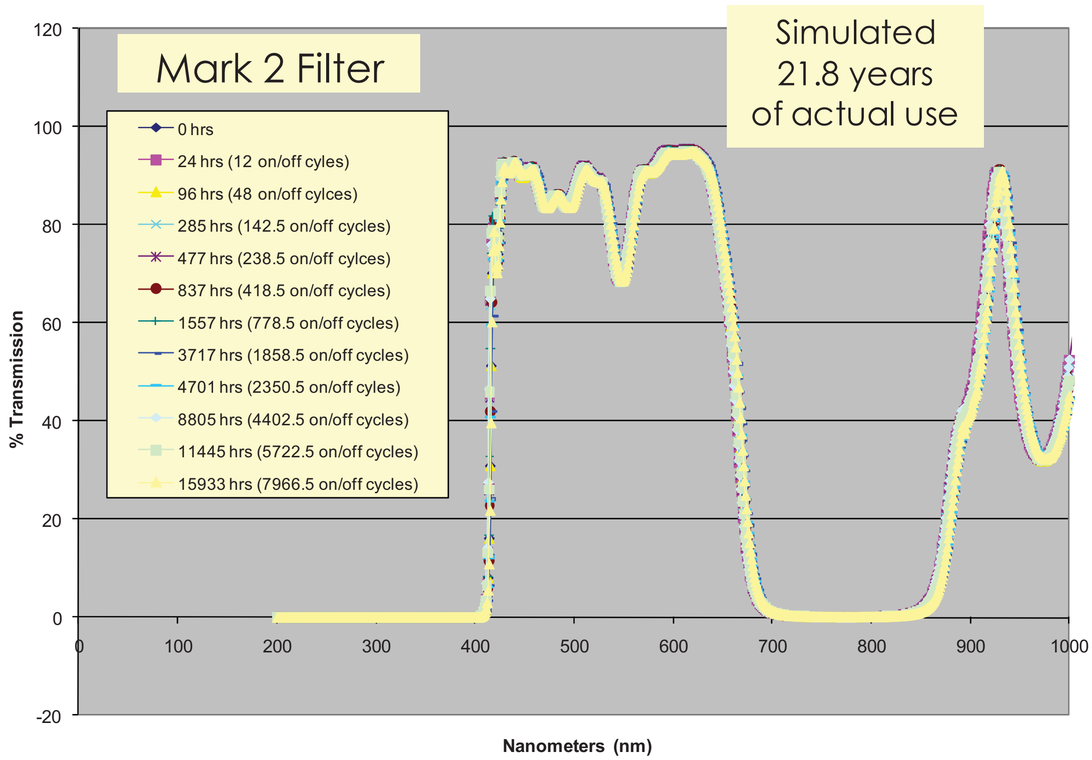


Figure 6.17

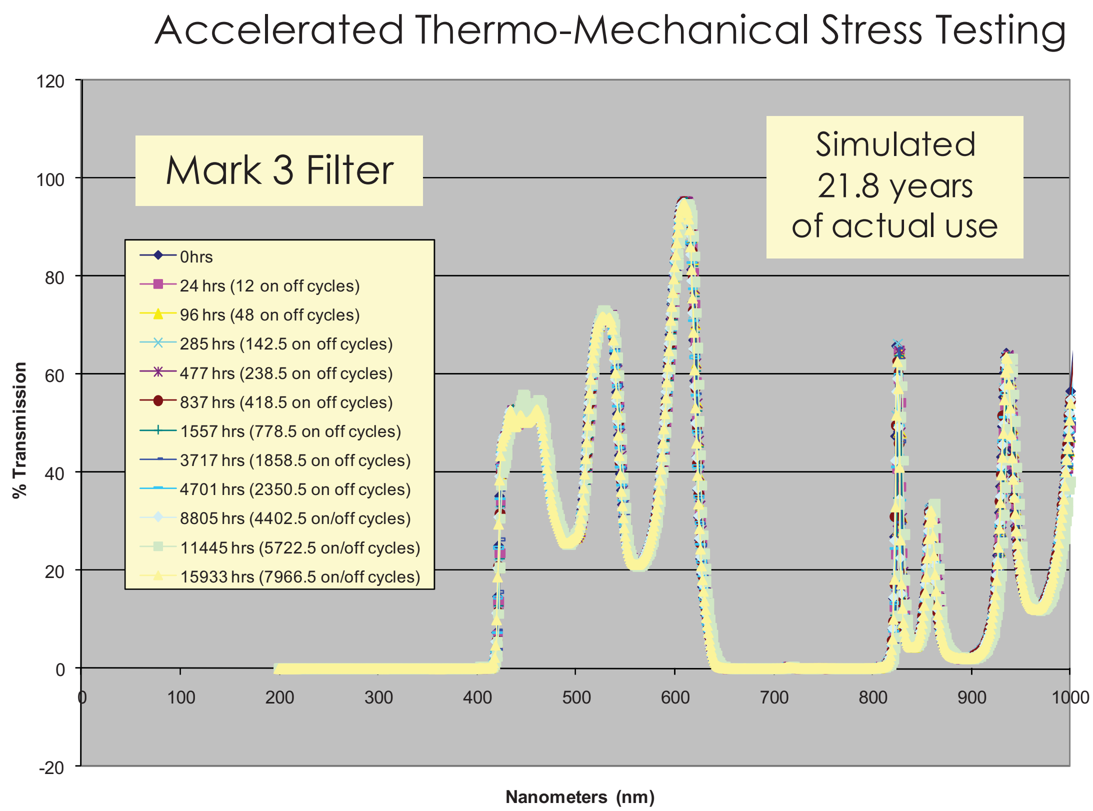


Figure 6.18

The accelerated aging results of the filter indicate significant long term stability. The filters can withstand extremely long periods of heating and light exposure of the lamp, as well as even longer periods of thermo-mechanical stress from switching lighting on and off. Changes over time are small, not detectable by its effects on human vision, and within experimental error for the transmission measurement. It is remarkable that these filters appear to not show significant changes for periods as long as decades and it would not be

apocryphal to claim that the filters might last longer than the people carrying out the installation.

6.6 Pigment fading testing

Ultimately, the utility of the filters are assessed by how well they attenuate changes in appearance of objects over periods of exposure to light. Studies on this were carried out both at the Getty Conservation Institute, and at UTEP. A summary of some of the pigment results from GCI, followed by an examination of the work carried out at UTEP.

GCI exposed a set of pigment samples to light from lamps which was either filtered by UTEP filters or Optivex® filters. The Optivex® filter is a complex control to implement. Work carried out first at UTEP and subsequently verified at GCI suggests the Optivex® filters display a variable instability which is best stated as a blue shift of the UV-visible cutoff after several days of exposure to the heat and light of a lamp. Individual filters vary to the degree that this shift is seen, but the average filter shifts an average of 7nm, but over eight different samples, the shift (measured at 50% transmission) ranged 0 to 13.5nm. Figure 6.19 provides the average of eight new filters which were ‘aged’ in front of a lamp for 272 hrs.

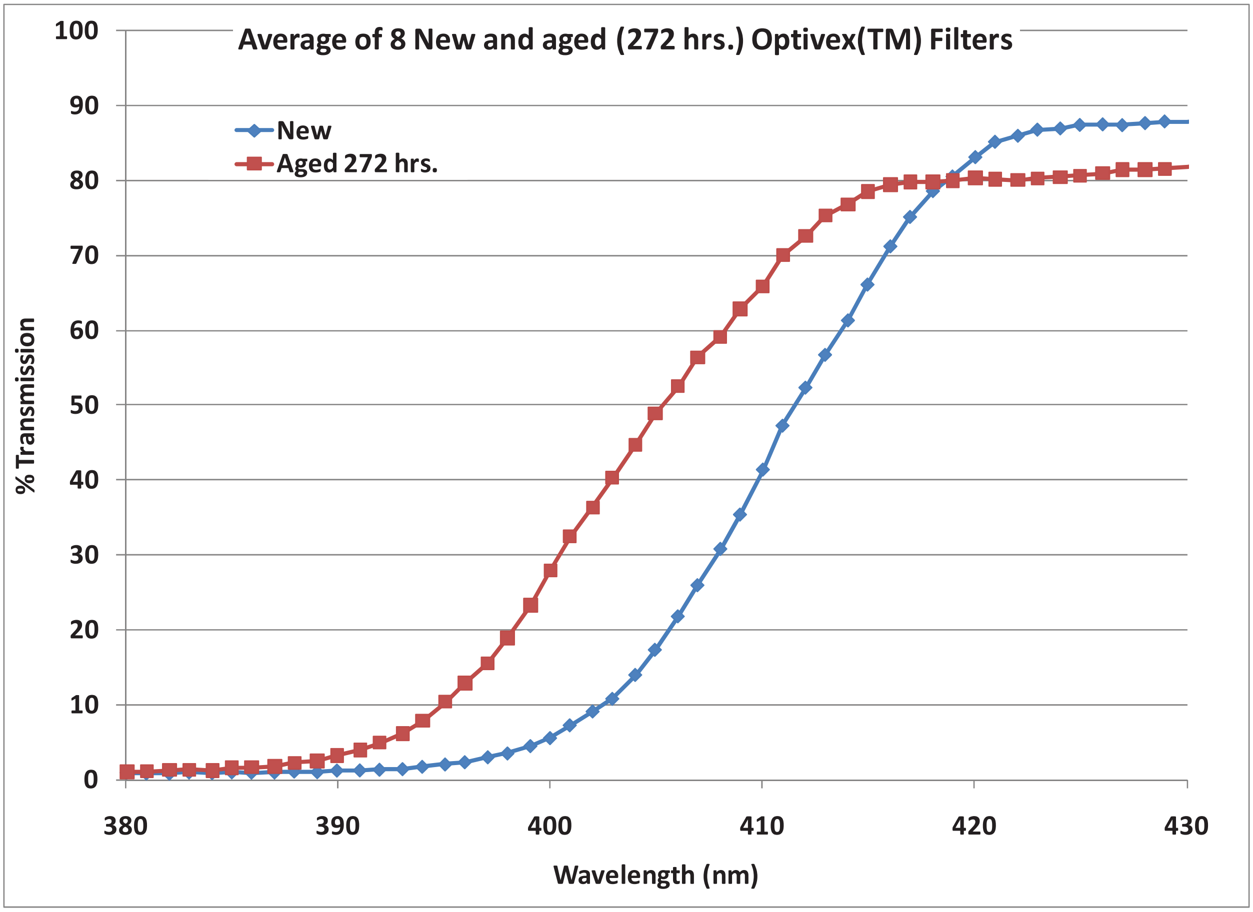


Figure 6.19

The pigment samples (listed in appendix P) measured at GCI were exposed in chambers of eight lamps each, equipped either with Optivex®, Mark 2 filters, or Unfiltered light. Luminosities of the chambers were within ±5% of each other. Reflection spectra were measured before irradiation and after irradiation of ≈18000lux at 838 hours. The color difference between before and after reflection spectra were calculated using the DE00 color difference equation.

This data can be found in Table 6.3, along with errors based on the noise of the reflection spectral data. One can gain an appreciation for the performance of one filter over another or the Mark 2 filter over Unfiltered light by plotting the differences in before and after color differences of the Mark 2 filter versus Optivex® . Figure 6.20 shows the Optivex® color difference subtracted by the Mark 2 color difference. One can see that within experimental error, pigments exposed to Mark 2 filtered light often display significantly less color change than for Optivex®. Some pigments are favored by Optivex® filtered light, but not within experimental error. A similar analysis can be done with Mark 2 versus Unfiltered light, and Mark 2 is even more favored in terms of reducing color change.

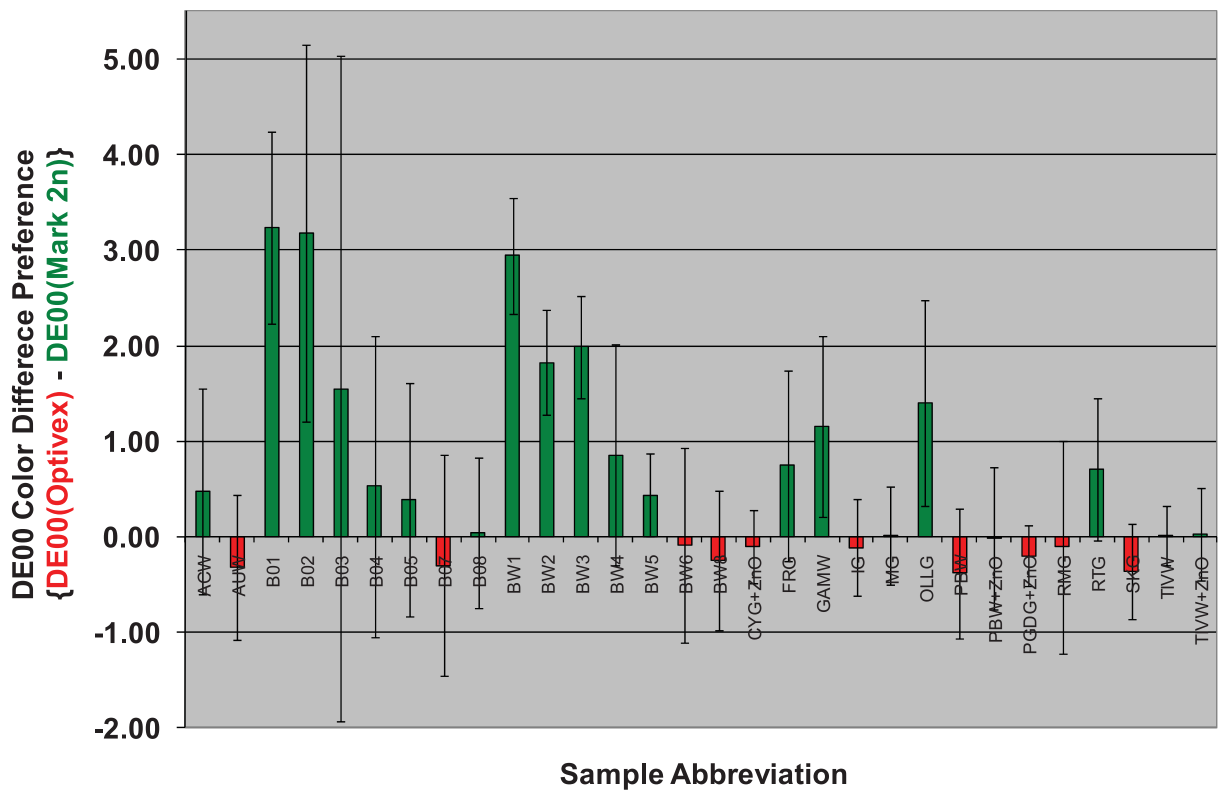


Figure 6.20

Table 6.3

	Mark 2n			Unfiltered			Optivex®		
	DE00	**+ error**	**- error**	**DE00**	**+ error**	**- error**	**DE00**	**+ error**	**- error**
ACW	5.17	0.32	0.32	5.43	0.25	0.25	5.65	0.51	0.51
AUW	5.96	0.47	0.47	6.93	0.39	0.39	5.64	0.04	0.04
B01_1	38.61	0.24	0.24	42.14	0.81	0.81	41.85	0.51	0.51
B02_1	28.38	0.79	0.79	31.49	0.72	0.72	31.56	0.93	0.93
B03_1	17.17	2.39	2.39	18.71	0.17	0.17	18.73	0.84	0.84
B04_1	1.98	0.75	0.75	2.55	0.61	0.61	2.52	0.58	0.57
B05_1	3.43	0.20	0.20	4.00	0.34	0.34	3.83	0.77	0.77
B07_1	0.93	0.40	0.40	0.97	0.48	0.48	0.63	0.51	0.51
B08_1	1.02	0.21	0.21	0.98	0.41	0.41	1.06	0.33	0.33
BW1	35.92	0.17	0.17	40.10	0.18	0.18	38.87	0.19	0.18
BW2	27.88	0.15	0.15	30.75	0.16	0.16	29.71	0.15	0.15
BW3	12.66	0.14	0.13	16.06	0.15	0.14	14.65	0.14	0.13

BW4	1.75	0.55	0.35	2.48	0.56	0.53	2.61	0.56	0.44
BW5	2.97	0.13	0.05	2.86	0.18	0.10	3.41	0.14	0.06
BW6	4.00	0.40	0.30	4.14	0.33	0.23	3.91	0.45	0.37
BW8	1.12	0.23	0.00	1.01	0.23	0.00	0.87	0.52	0.25
CYG+ZnO	0.95	0.12	0.12	1.27	0.12	0.12	0.85	0.02	0.02
FRG	4.97	0.30	0.30	5.42	0.38	0.38	5.72	0.45	0.45
GAMW	4.76	0.21	0.21	5.77	0.19	0.19	5.92	0.48	0.48
IG	1.66	0.16	0.16	1.63	0.25	0.25	1.55	0.10	0.10
MG	30.54	0.09	0.09	30.91	0.66	0.66	30.55	0.17	0.17
OLLG	12.39	0.53	0.53	12.99	0.07	0.07	13.79	0.30	0.30
PBW	2.47	0.30	0.30	2.52	0.19	0.19	2.09	0.13	0.13
PBW+ZnO	1.81	0.28	0.28	2.23	0.38	0.38	1.80	0.22	0.22
PGDG+ZnO	1.31	0.04	0.04	1.39	0.16	0.16	1.12	0.03	0.03
RMG	28.69	0.64	0.64	30.24	0.51	0.51	28.58	0.23	0.23
RTG	37.15	0.16	0.16	38.27	0.44	0.44	37.86	0.34	0.34
SKG	1.29	0.15	0.15	1.40	0.43	0.43	0.93	0.09	0.09
TIVW	1.66	0.03	0.03	1.85	0.08	0.08	1.68	0.03	0.03
TIVW+ZnO	1.67	0.09	0.09	1.86	0.09	0.09	1.70	0.15	0.15

The fading study outlined above involved irradiation for a fixed period. This is not the most useful fading information because some pigments could have been near the end of their possible color change, near infinite time for color change, while some which change more slowly would have displayed much less color change. A more useful study is to monitor color change as a function of time. One might anticipate that at different time periods, color change will be faster or slower depending on the pigment.

1) Stability of the lamps
    a. You only need one of the lamps to go bad
    b. Many of the measurements would go to near the anticipated end of the lamp lifetime

2) Contamination of the spectrometer

3) Further changes in Optivex®?

4) Fluctuations in MR16 power supplies

6.6.1 Summary of Fading test Observations and Results

The fading testing work is difficult to carry out. A number of issues have been identified:

1) Instabilities in power supplies and uncertainties in lamp performance are a problem. Earlier work in a study could possibly be better trusted than later work when the same lamps are used because of possibly non-uniform aging of the lamps.
2) Sample uniformity is difficult to achieve. Different methods where develop to prepare the samples. The best methods were chosen, those which achieved a uniformity of 90-95% to prepare the samples, but the samples were never a 100% uniform.
3) Sample change with time needs to be adequate in order to have a significant change relative to potential sources of error. Materials which undergo slower changes upon irradiation are less likely to display changes which are sufficiently significant with regard to potential sources of error. Coupled with instability in lighting, this means that the practicality of significantly measuring any given material depends on the intensity of

light within the chamber, and sensitivity of the material. Too little light means only the most sensitive materials can be accurately measured.

4) Irradiation chambers vary significantly in intensity with location within the chamber. This means that the gradient in light intensity across samples can be high. It is also difficult to match locations between boxes that have the same (within 1%) luminosity to achieve the constant luminosity condition. This meant that relatively few matched samples could be achieved with any run. The relative uniformity of lighting within boxes can be seen from the following three Figures (6.21, 6.22, and 6.23) each of which represents the box lighting distributions at the beginning of Fading Study C. As can be seen in the 3/7/08 snapshot of the Mark 2 (figure 6.21), Optivex® (figure6.22), and Unfiltered (figure 6.23) boxes, uniformity across the platforms is poor, and varies significantly between the boxes.

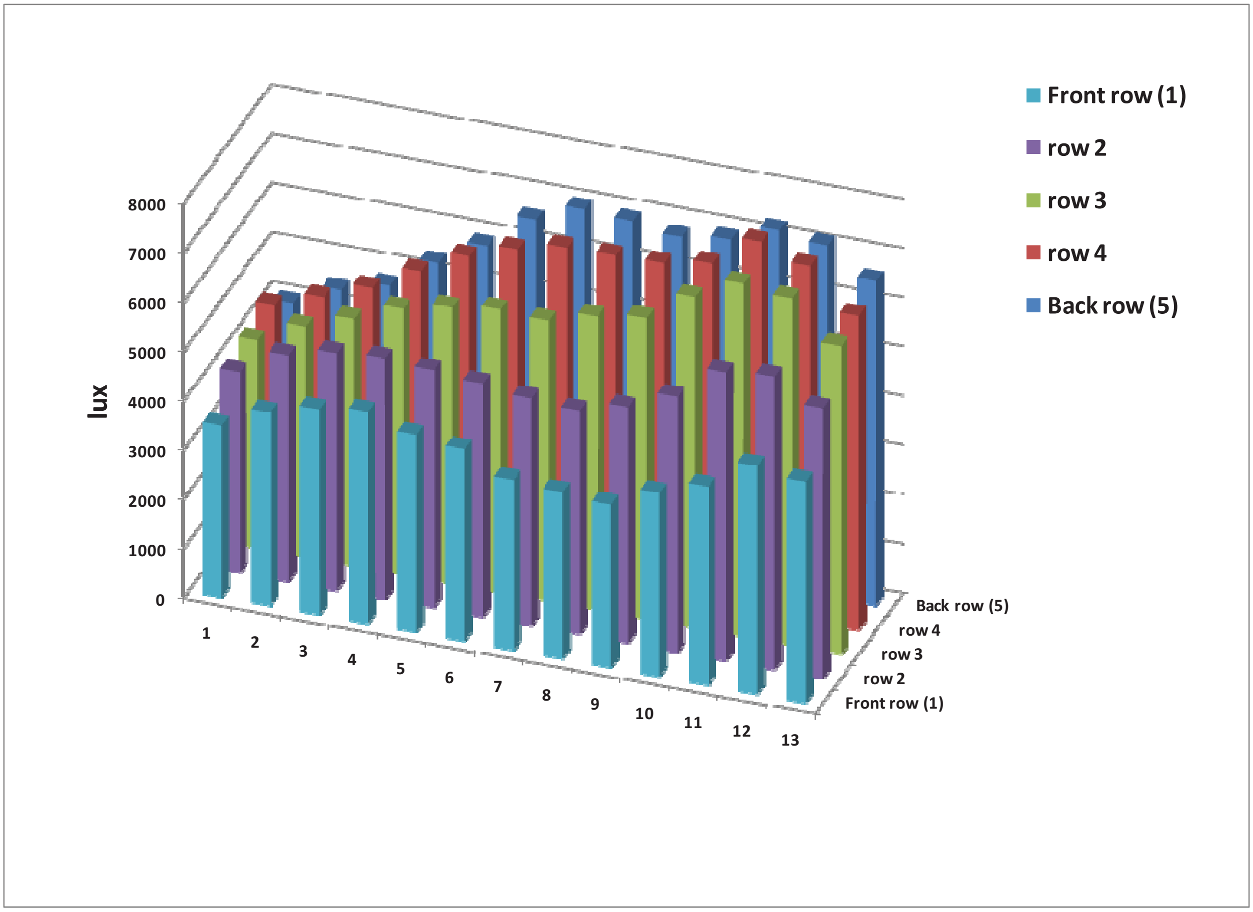
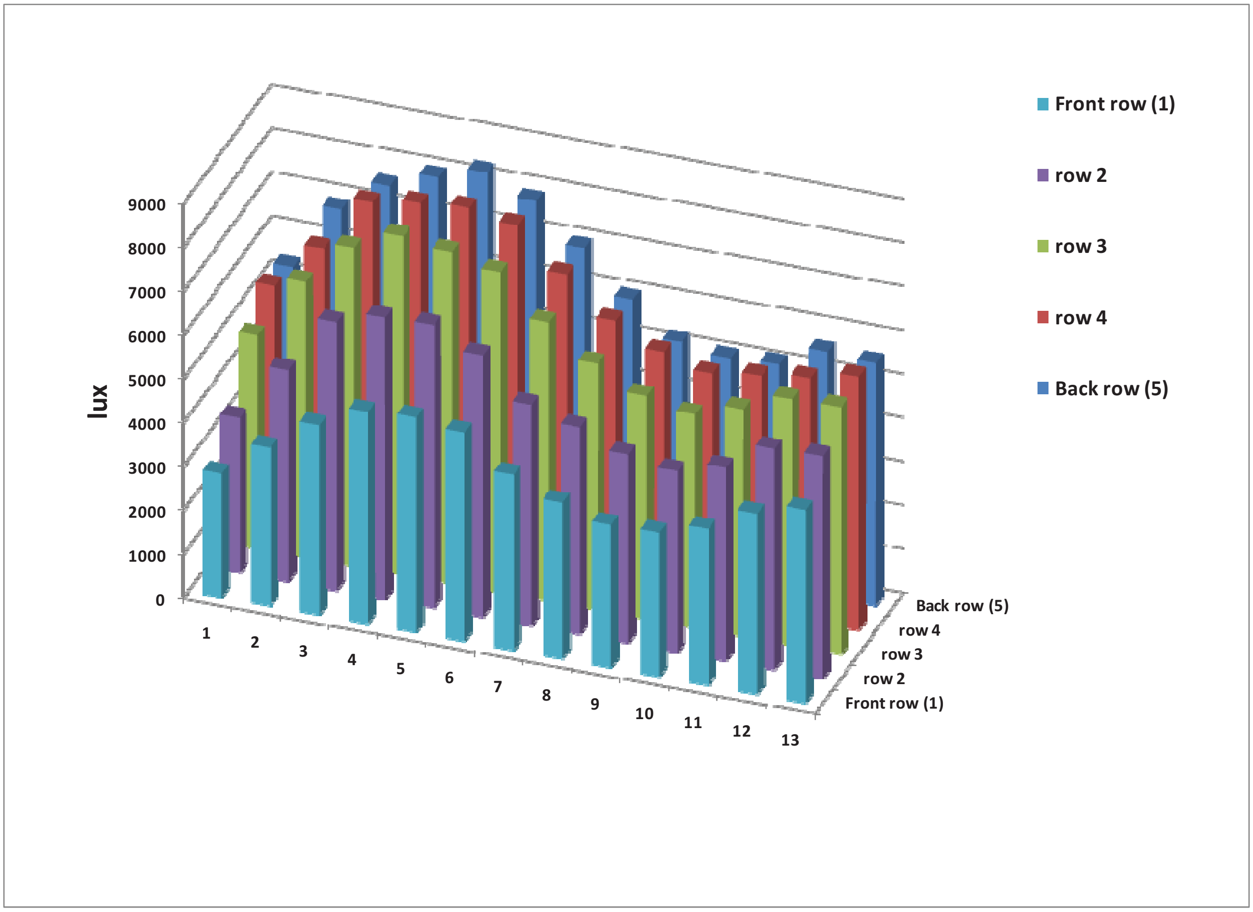

Front row (1)
row 2
row 3
row 4
Back row (5)
lux
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Back row (5)
row 4
row 3
row 2
Front row (1)

Figure 6.21



Front row (1)
row 2
row 3
row 4
Back row (5)
lux
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Back row (5)
row 4
row 3
row 2
Front row (1)

Figure 6.22

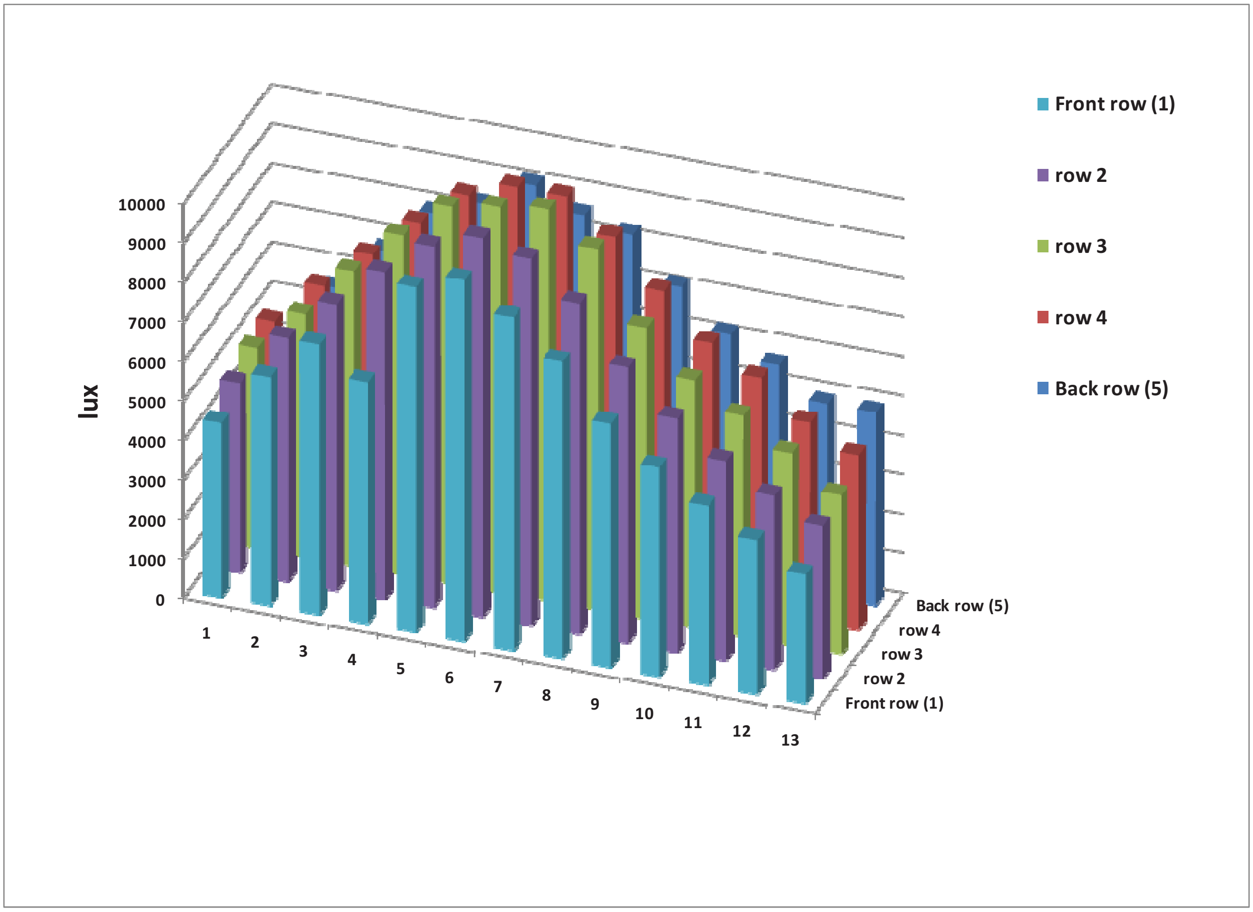


Figure 6.23

Figures 6.21, 6.22, 6.23 show both the variation in distribution of light within and between the boxes, and indicate why spots must be matched selectively to meet the equal luminosity condition.

In order to have some sort of statistical average over a sample, the protocol of measurement involved measuring a sample at its center point and at points from the center to the diagonal of the square sample. The center points for each measurement near each corner were centered

≈1.8 cm along the diagonal from the center of the sample. Four such measurements are made. Subsequent time series measurements involve subtractions from identical locations, and then averaged. The issue is whether the gradient of luminosity from the center point of the sample to the center point of the diagonal measurements might affect the error? As an example, the Blue Wool 1, 2, &3 gradient results for the Mark 2 testing (Fading Study C below) are supplied in table 6.4:

Table 6.4

	Average of Luminosity Gradients Along diagonal from sample center		
	Mark 2	Optivex®	Unfiltered
BW1	-1.49%	-1.91%	-0.32%
Position in box	16	29	29
BW2	7.7%	-1.60%	-0.41%
Position in box	58	38	38
BW3	-0.71%	-1.02%	2.19%
Position in box	22	19	34

Table 6.4 shows the average of the luminosity gradients for the Mark 2 Blue Wool 1-3 measurements. While the center points of Mark 2, Optivex®, and Unfiltered have been matched to within ≈1% luminosity, it can be seen

that the average gradient of luminosity is often higher than 1% when considering the additional four measurement sites along the diagonals. In some cases, these gradients can be quite significant. For instance, position 58 in the Mark 2 BW2 measurement displays an average gradient of +7.7%. This means that the diagonal measurements that are averaged with the center point reflect the effect of higher luminosity. One of the reasons that position 58 might display this higher gradient is because it is on the edge of the measurement platform.

It would be impossible to match luminosities, including gradients, and so gradients are neglected. They also are not included in the error analysis for the consideration of the error in lux-hour exposure. Consequently, the error bars along the lux-hour exposure axis for some measurements may be higher than estimated.

5) Error limits imposed by inherent noise in the reflection measurements are high.
6) Throughout the course of the study, the reflectance spectrometer was becoming contaminated by another research group's work.
7) Optivex® transmission cannot necessarily be taken as a constant. Comparison with Optivex® is complicated by changes which may be occurring in the Optivex® throughout the experiment.

8) The story with what goes on with any given sample can be complex. Samples may have both light and thermal reactions which are initiated by light. This can mean that light effects alone cannot necessarily be disentangled from the contributions of ongoing latent thermal effects, which may have first been set in motion by the light reaction.

The goal of the fading testing is to evaluate whether the UTEP designed filters (Mark 2 & Mark 3) slow pigment fading relative to no filter (often referred here to as "Unfiltered") or the Optivex® filter available from Applied Coatings Group, Inc. Comparison of the UTEP filters to no filter is logical since filtration often isn't used. On the other hand, Optivex® is a commonly used good filter useful for museum and archival lighting. It possesses a sharp cutoff near 400nm which very effectively blocks UV light. As reported here, Optivex® does have an issue with the blue shift of the wavelength of the cutoff. The blue shifting of the cutoff could be a concern, though it appears to not shift more than 7nm on average from its out–of-the-box condition. The variation in cutoff among Optivex® filters implies the comparison to Optivex® provides some additional uncertainty.

Fading results are presented as color change versus lux-hour. Color changes are relative to the original un-irradiated sample, and are calculated as CIE $DE00_{D65}$ values (hereafter referred to as DE00 for convenience). D65 refers to an illuminant reference white point for the L*a*b* coordinate system. The DE00

color difference is non-Euclidean in the L*a*b* coordinate system. Rather than plotting change in color versus time, it is more conveniently plotted in terms of lux-hour. This permits experiments to be done at different luminosity levels and yet plotted on a single common plot. The assumption of commutative reciprocity is usually made. In other words, if *a* lux x *b* hours = *c* lux-hours, and *d* lux x *e* hours = *c* lux-hours, then *a* lux x *b* hours = *d* lux x *e* hours, or less generally, *a* lux x *b* hours = *b* lux x *a* hours. One test for reciprocity was included in this fading analysis and will be presented and discussed below.

Significance of data is key to being able to interpret fading results. The method for determining error levels for the DE00 data is presented above in the section describing methods and procedures. These error levels are directly derived from the experimental data and are thus experimental in nature and should represent upper limits for the experimental error in determining DE00. Statistical confidence in the experimental error can only be determined by multiple identical experiments. However, assuring the same luminosity for multiple samples proved to be impossible given the variation in luminosity on the irradiated test platform. The experimental errors for DE00 that are presented here are a best effort without statistical verification. Luminosity is determined by spectrograph and is initially matched to within 1% for any given fixed luminosity fading test of Optivex® versus Unfiltered versus UTEP Filter (Mark 2 or Mark 3). In terms of time, the estimated error probably varies with the scale of the time

measurements. Measurements of periods early in a fade of less than one hour are probably accurate to ±1 minute, and subsequent measurements up to 10 hours are probably accurate to at least ±10 minutes; and longer periods accurate to perhaps ±15 minutes. Thus, errors in time could have been as large as 7-9% early in the fade, but would drop below 3% later in most fading tests. Errors in setting luminosity are limited by about a 3% error in the spectroscopic measurement, and the 1% uncertainty in matching luminosities between boxes (UTEP filter vs. Unfiltered, vs. Optivex®). Total luminosity error might be about 4%. Combining the error in time with that in luminosity implies that early in a fade, up to about 1-2 hours, the error in lux-hour could be as high as 10-12%, while later in the fade, the error in lux hour would be about 7%. Horizontal error bars are added to the data to represent the fixed error in luminosity and the varying error in time. Early in a fading experiment, the time and luminosity contributions to the horizontal error bars are about equal, while later, the error in time becomes insignificant, and the error in lux-hour is dominated by the 4% uncertainty in luminosity.

Presentation and discussion of fading results is complex. Outcomes require categorization in order for the discussion to be easily managed. The most meaningful categorization is by level of significance of the result. For instance, are the data for Optivex®, Unfiltered and UTEP filter well enough separated and of sufficient magnitude relative to the experimental error in DE00 and/or lux-

hour? A shorthand notation is delineated below to establish the universe of categories. For this notation, Optivex® is abbreviated " O", Unfiltered is abbreviated "U", and the UTEP filter (either Mark 2 or Mark 3) is abbreviated "M". The utility of this categorization and symbolism will become evident in the discussion of results which follows. The categorization is presented in the order of increasing significance from a fully non-significant result (type 1) to a fully significant result (type 4).

- **Type 1**
    - **O≈M≈U≈error** is the case where Optivex®, the UTEP filter, and Unfiltered are not significantly different and also display magnitudes of DE00 that are significantly above the level of experimental error. This is the special case where insufficient color change occurs in the data to make it meaningful. This is neither a negative or positive result. Basically, a much higher light level is required to render a meaningful result. This result is seen for a number of data sets.
        - While is it is possible to have a result where one or two sets of data are not of significant magnitude relative to error and at the same time the third set of data is of significant magnitude, this subset of this kind of result was not observed, and so symbolism is not developed for this kind of outcome.

- **Type 2**
  - **(O≈M≈U)>error** is an outcome where the magnitude of the color change is significant relative to error, but the three illuminants are not significantly different from one another. Several outcomes were observed of this type
- **Type 3**
  - **(O≈M)≠U**, as example. This is the case where, for the example notation, Optivex® and the UTEP filter are not significantly different, but Unfiltered is significantly different than both. There are six other analogous types and subtypes.
    - **(O≈M)>≠U**, implying that Optivex® and UTEP filters are not significantly different from each other, but are significantly different than Unfiltered, and both outperform (lower fading) Unfiltered.
    - **U>≠ (O≈M)** implying that Optivex® and UTEP filters are not significantly different from each other, but are significantly different than Unfiltered, and both outperform (lower fading) unfiltered.
    - **(U≈M)>≠O**

        - **O>≠ (U≈M)**

        - **(U≈O)>≠M**

        - **M>≠ (U≈O)**

- **Type 4**

    - **O≠M≠U** is the case where all three are significantly different from each other. These outcomes were uncommon and rarely or never seen throughout the entire lux-hour period of an experiment, though is seen in portions of data. There are six subtype outcomes of relative favorability:

        - **O≠>M≠>U** means Optivex® is more favorable (less fading) than the UTEP Filter which is more favorable than Unfiltered. The other sub-types of this kind of outcome are:

        - **M≠>O≠>U**

        - **M≠>U≠>O**

        - **O≠>U≠>M**

        - **U≠>M≠>O**

        - **U≠>O≠>M**

A number of pigments were investigated, including the Blue Wool 1-8 ISO test series. The Blue Wool tests used here were obtained from SDC Enterprises, Ltd.

Two of the three fading boxes were always Unfiltered light and Optivex® filtered light. With only one other box, the Mark 2 and Mark 3 filters could not be tested at the same time. This required splitting into at least two different sets of experiments. In addition, lamp failures or brownouts along the way required splitting the Mark 2 study into two different studies. Note that pigments were not necessarily entered into the boxes at the same time. This is noted below, and has some impact on subsequent analysis and discussion with regard to error.

The first fading study (Fading Study A) involved use of the Sylvania 58312 lamp and the Mark 3 filter being compared to Unfiltered and Optivex®, and consisted of the following pigments:

1) Methylene Blue (MB) (added four days after turning on lamps)
2) Dr. Ph. Martin's® watercolors
    a. Cyclamen (added 98 days after MB)
    b. Cherry red (added 15 days after MB)
    c. Violet (added 15 days after MB)
    d. Wild Rose (added 15 days after MB)
3) Winsor & Newton™ pigments
    a. Rose Bengal (added 131 days after MB)
    b. Rose Carthame (added 138 days after MB)

c. Rose Tyrien (added 97 days after MB)

d. Orange Lake (added 16 days after MB)

e. Linden Green (added 91 days after MB)

f. Fluorescent Yellow (added 138 days after MB)

Methylene Blue was chosen as the first pigment to study since, unlike commercial pigments and dyes, it could be obtained in pure form, it is a single molecular system, and its structure is known. Subsequent future chemical mechanistic studies can be done with such a well-defined material, though haven't yet been undertaken.

In addition to MB, for this first study, other pigments were chosen based on some anticipated sensitivity to light. The magnitude of useful light used in the fading boxes varies from about 4000 lux to 13000 lux. Normal office lighting could be as high as 500-700lux. Thus, the attainable 'high' light levels of the accelerated fading equipment varies from 6-25 times above ambient lighting. This is <u>not</u> an extremely accelerated test, and some sensitivity must exist in the pigments to see any measurable changes.

The second study (Fading Study B) involved the Mark 2 filter and use of the Philips 378083. The switch to the Philips lamp was an effort to save on cost since each study requires new lamps, and the Philips lamps could be purchased at a considerably lower cost. This fading study involved the following pigments:

1) Winsor & Newton™ pigments

    a. Linden Green (added 9 days after Rose Tyrien)

    b. Periwinkle Blue (added 16 days after Rose Tyrien)

    c. Orange Lake (added 9 days after Rose Tyrien)

    d. Rose Tyrien (added 4 days after turning on lamps)

    e. Spectrum Violet (added 16 days after Rose Tyrien)

2) Blue Wool 1 (BW1) (added 46 days after Rose Tyrien)

Fading Study B was halted shortly after the BW1sample was added due to a lamp failure. The BW1 data was discarded since it was collected over an insufficient period of time.

The third fading study (Fading Study C) involved the Mark 2 filter and a complete set of new Philips 378083 lamps. This study involved the following pigments:

1) Blue Wool standard samples

    a. Blue Wool 1 (added 18 days after BW7 &BW8, but ±1% luminosity matched 3 days prior to starting fade)

    b. Blue Wool 2 (added 18 days after BW7 &BW8, but ±1% luminosity matched 3 days prior to starting fade)

    c. Blue Wool 3 (added 18 days after BW7 &BW8, but ±1% luminosity matched 3 days prior to starting fade)

    d. Blue Wool 4 (added 18 days after BW7 &BW8)

e. Blue Wool 5 (added 1 day after BW7 & BW8)

f. Blue Wool 6 (added 1 day after BW7 & BW8)

g. Blue Wool 7 (added first to boxes; ≈96 hours after turning on lamps)

h. Blue Wool 8 (added first to boxes; ≈96 hours after turning on lamps)

One of the main reasons for concentrating solely on the standard Blue Wool samples in Fading Study C was because of the widely variable sensitivity of other pigment samples seen in the earlier studies for the magnitude of illumination possible in our equipment. Too little or too much sensitivity can tend to obscure differences in performance between the illuminations being tested. The Blue Wool standards provide a range of sensitivities so that the most significant data can readily be identified somewhere within the range. At this time, this sort of sensitivity calibration study has only been done at UTEP for Mark 2, though such is desirable also for Mark 3. We will introduce some Blue Wool data collected at The Getty Conservation Institute with regard to Mark 3.

6.6.1.1 The Equal Luminosity Condition

Under most practical circumstances, lighting will primarily be adjusted with regard to perceived brightness. It is the "bright enough" condition that will influence the engineering of lighting in museums, archives, and commercial and noncommercial locations. Besides "eyeball" adjustment, it is common now

within museums to adjust lighting using a lux meter. Lux meters measure luminosity, which is supposed to be a quantity related to perceived brightness. Lux meters would not necessarily be accurate in assessing the UTEP filtered lighting because they have been calibrated for common spectral distributions such as incandescent, fluorescent, and sunlight. The UTEP lighting spectral distributions differ significantly from these common lighting distributions. Thus, measuring luminosity must be done by spectrograph and applying the Photopic function, as discussed above.

Given the normal circumstance of requiring a particular luminosity for lighting, it makes sense to set the condition for testing fading of requiring all illuminants to have the same luminosity. Under these circumstances, the differences in overall power and spectral distribution should be expected to weigh differently to affect photochemistry and color or appearance change. Thus, the condition of equal luminosity was chosen among illuminants to test fading, by spectrographic measurement.

Requiring the equal luminosity condition and setting are two different things, entirely. It is extremely difficult to achieve either a given luminosity or uniformity in luminosity at a surface. For reliable results, illuminants must match within 1%. After much trial and error, it was decided to approximately match luminosities between the three illuminants: UTEP filter, Optivex® filtered, and Unfiltered, and by spectrographically measuring luminosities across the surfaces

of each irradiated platform within each box, identify positions at which luminosity could be matched to within 1% across all three boxes. This approach meant that the entire surface of a platform could never be used. Typically, if at least 12-15 matching points couldn't be identified, then boxes would undergo course lighting adjustments and a new assessment of matching positions undertaken.

Using the point matching approach meant that while a set of UTEP/Optivex®/Unfiltered samples could be matched within 1%, their luminosity value would usually differ from any other set. Comparing sets would require that lux-hour reciprocity could be applied. This has been discussed above, and will be discussed below.

Perceived brightness does not always track with luminosity. This is the basis of the Helmholtz-Kohlrausch effect discussed above. For common illuminant spectral distributions, this might not be expected to be an issue, especially if one is changing intensity, but not changing the spectral distribution. However, changing the distribution could mean that perceived brightness will not track with luminosity. Many of us had had the experience with the new compact fluorescent lighting in finding that the lumens rating on the box doesn't accurately describe the brightness sensation that is perceive in comparison with the older incandescent lighting. When modifying spectral distributions to optimize lighting to achieve better protection of art and archival documents,

this will likely also be a circumstance where perceived brightness doesn't track with measured luminosity.

There are two issues with the possible brightness-luminosity schism. One is that luminosity meters that do not spectrographically measure the light will not provide an accurate measure of luminosity/brightness. In fact, the failure of luminosity meters might be an issue regardless of whether brightness differs from luminosity because of the unusual spectral distributions of the light.

The other major issue with regard to the brightness-luminosity problem is that the equal luminosity condition for assessing fading may not apply. In reality, one would want to instead set an equal brightness condition. At this time, an equal brightness condition is almost impossible to set. Brightness (relative to luminosity), is determined by human assessment. To achieve a statistically reliable assessment of any illuminant would require many subjects and a very long testing period of months or years. In this study, it was decided to not do this since it would greatly slow the work to a scale of more than decade to complete, and to instead rely on the condition of equal luminosity, albeit with its uncertainties.

6.6.1.2 Assessing Perceived Brightness

While it was decided to not rely on perceived brightness as a condition for assessing fading, some work was undertaken here and at the Getty

Conservation Institute to assess brightness. There are two approaches to this. One is assessing the perceived brightness directly from an illuminant, and the other is to assessment perceived brightness reflected from an illuminated object. The direct from illuminant brightness work was done at UTEP, and the reflected brightness work done at GCI. These studies will be reported below in the section dealing with human trials.

6.6.1.3 Commutative Reciprocity

The very first pigment fading study involving methylene blue (MB) included an assessment of commutative reciprocity (hereafter referred to as "reciprocity") of the lux-hour unit of irradiation. This has been discussed above, but reciprocity is merely the statement that *a* lux * *b* hours = *b* lux * *a* hours. If reciprocity holds, then data collected at different luminosity levels can be plotted and compared together. This relieves the need to execute all measurements at the same luminosity. Since the irradiation boxes do not have uniform luminosity, reciprocity permits full use of the varying luminosity across the sample platform to allow for multiple samples.

Reciprocity was checked using three fading experiments for MB where each was a set of samples at different luminosities, in this case, 4460±45 lux, 5930±60 lux, and 7430±75 lux. Each of these experiments involved samples under Mark 3, Optivex®, and Unfiltered irradiation. Thus, apart from reciprocity, each of

these represents a comparison of fading for each of the three illuminants. The fading comparison will be dealt with separately below.

Judging reciprocity involves plotting all data of varying luminosity for a given illuminant (Mark 3 filtered, Optivex® filtered, or Unfiltered). This is shown in Figures 6.24, 6.25 and 6.26.

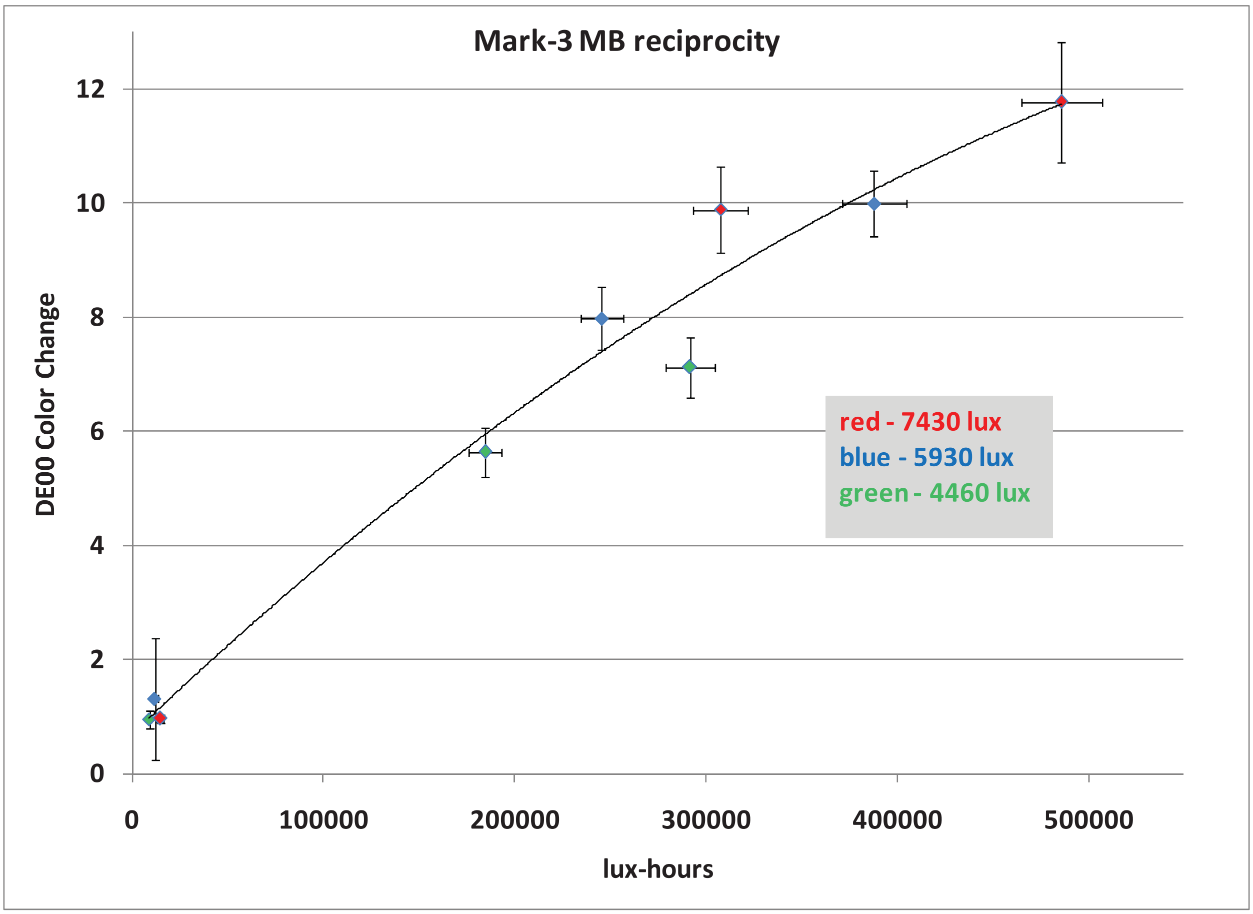


Figure 6.24

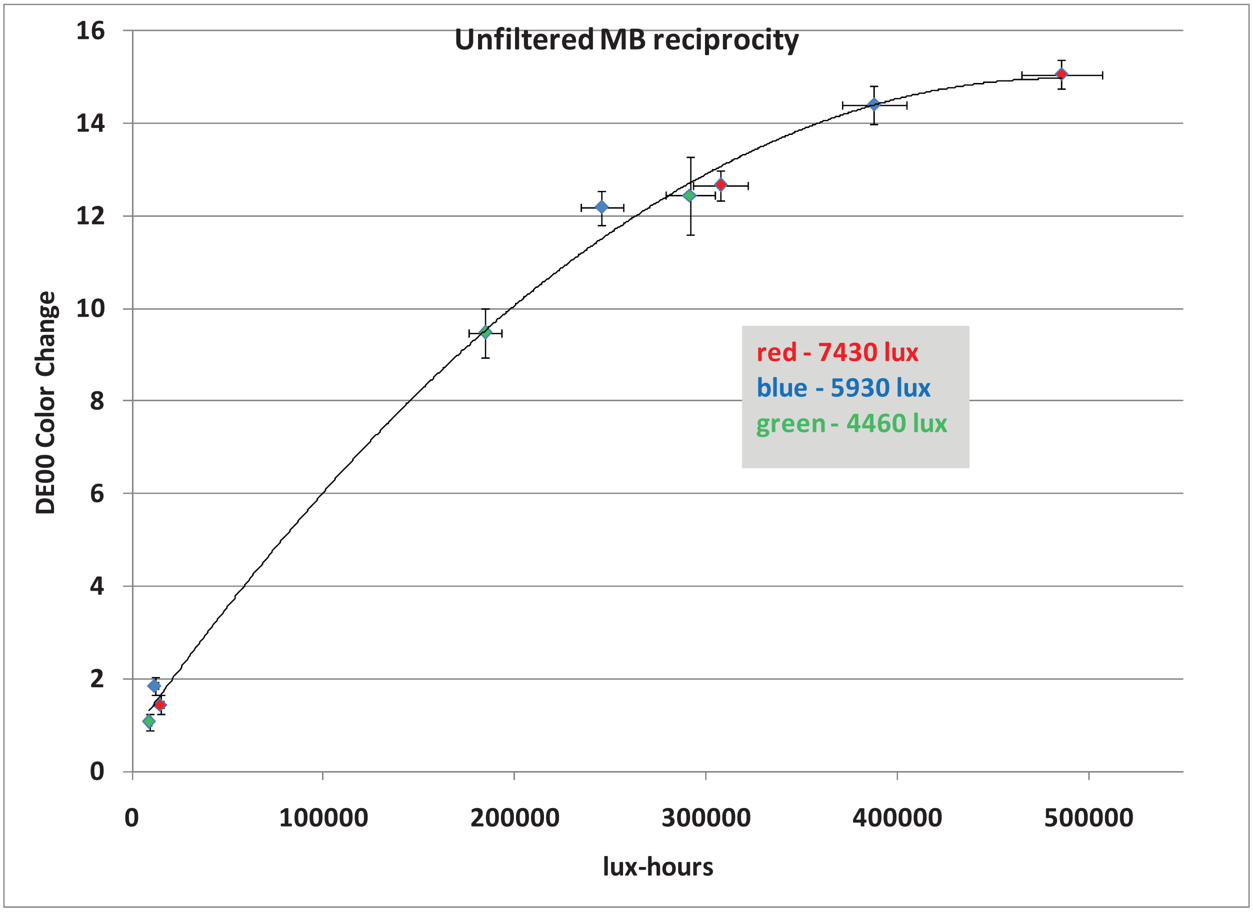

Unfiltered MB reciprocity
DE00 Color Change
16
14
12
10
8
6
4
2
0
0
100000
200000
300000
400000
500000
lux-hours
red - 7430 lux
blue - 5930 lux
green - 4460 lux

Figure 6.25

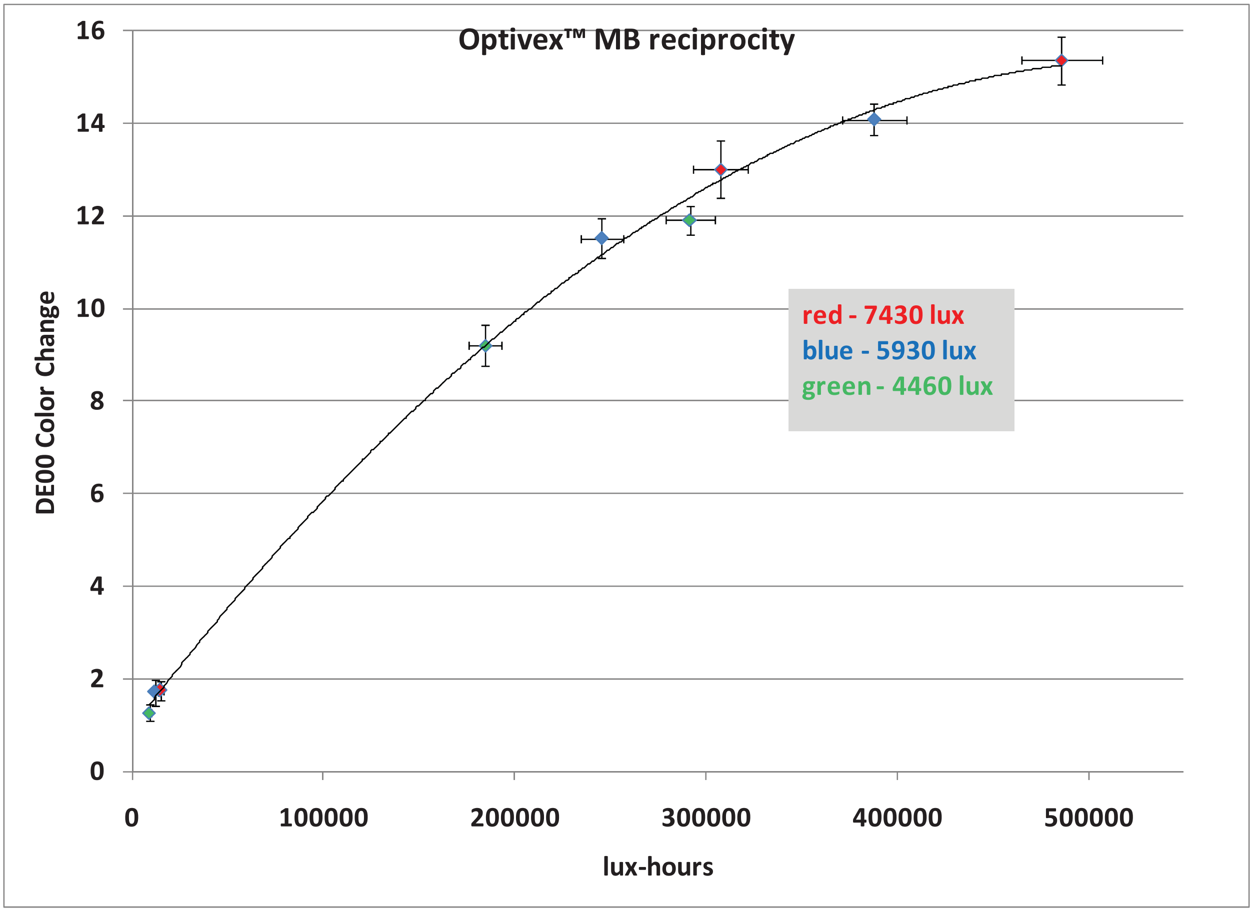


Figure 6.26

Note that in each of these figures, the line serves as a guide for the eye, but doesn't represent theory.

The judgment is subjective, but generally, reciprocity appears to be reasonably well held throughout the data, though apparently less well so for the Mark 3 filtered data. The range of luminosity is narrow, 4460-7430lux, though typical fading experiments in the equipment used for all fading studies will not range greatly above or below this range. Thus, this verification of approximate reciprocity suggests the data generated throughout this investigation can likely be compared with regard to fading rates by graphing on common plots.

Alternatively, assuming reciprocity is perfectly held, and then the deviations from a smooth trend suggest the normal experimental scatter that should commonly be expected in fading data. In other words, non-smooth color change trends are to be expected to some degree. This extra error could likely be due to the gradient of luminosity that exists within the boxes.

6.7 Fading Results

Note that in the measurements reported in this section, each data point is an average of five points on the sample. The center point is measured along with points approximately 1.79 cm diagonally from the center to each corner of the square 2" (5.08cm) sample. The measurement portal of the Shimadzu reflectance integrating sphere is approximately 1.7 cm in diameter. This means that the diagonal samplings overlap to some degree with the center sampling. This is shown in Illustration 6.1. When collecting data, differences are taken between the same points along a time series. In other words, the center point is always subtracted itself, and each of the other points are always subtracted from themselves. Data of the five points is then averaged.

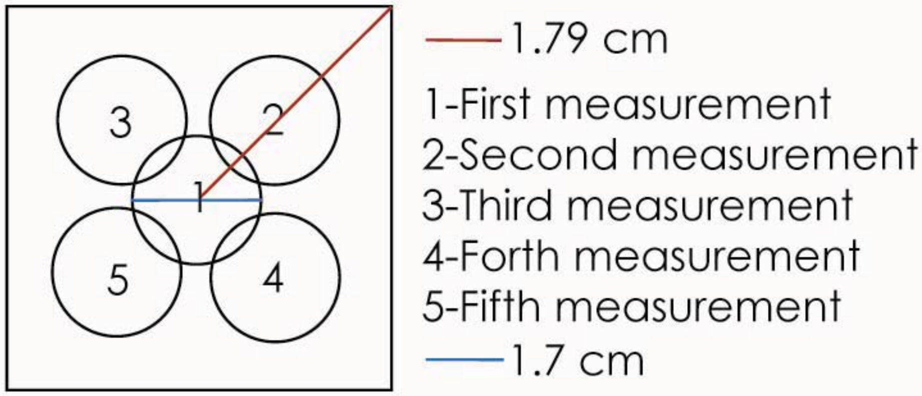


Illustration 6.1

Note that the effect of luminosity gradients in the boxes mean that while the center points are of equal luminosity when matched across boxes, the diagonal points might differ more than the condition of 1% equality. For some data, gradient information is calculated from the luminosity distributions, and may be discussed within the context of its possible contribution to error.

A number of fading experiments were Type 1 **O≈M≈U≈error**. This is the data for which the light induced change in color is smaller in magnitude or comparable to the experimental error. This data casts neither a negative or positive perspective on evaluation of the UTEP filters. It merely reflects inadequate intensity of illumination to produce a significant change. Data in this category includes:

A. Fading Study A (Mark 3)

    a. Rose Carthame (Figure 6.27) Note that this data is missing needed intermediate data points. However, this likely wouldn't change its categorization as being totally insignificant. Also note that this sample was added ≈142 days after turning on the lamps.

B. Fading Study B (Mark 2)

    a. Winsor & Newton Orange Lake (Figure 6.28)
    b. Winsor & Newton Linden Green (Figure 6.29)

C. Fading Study C (Mark 2)

    a. Blue Wool 4 (Figure 6.30)
    b. Blue Wool 5 (Figure 6.31)
    c. Blue Wool 6 (Figure 6.32)
    d. Blue Wool 7 (Figure 6.33)
    e. Blue Wool 8 (Figure 6.34)

Since this data provides no significant information, it will not be discussed further. Note that at the earliest stages of any fade, all data must be Type 1 significant.

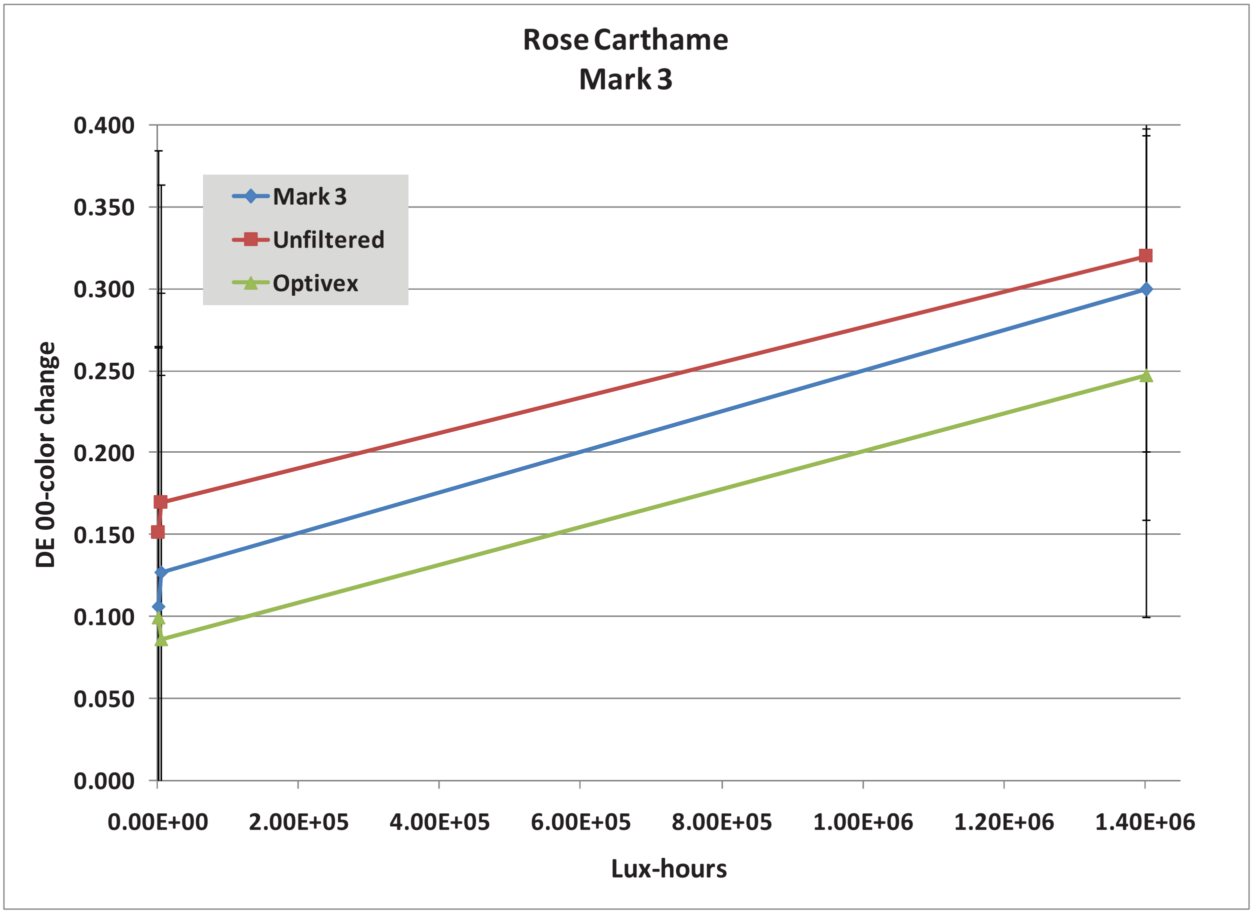

Rose Carthame
Mark 3
Mark 3
Unfiltered
Optivex
DE 00-color change
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0.00E+00
2.00E+05
4.00E+05
6.00E+05
8.00E+05
1.00E+06
1.20E+06
1.40E+06
Lux-hours

Figure 6.27

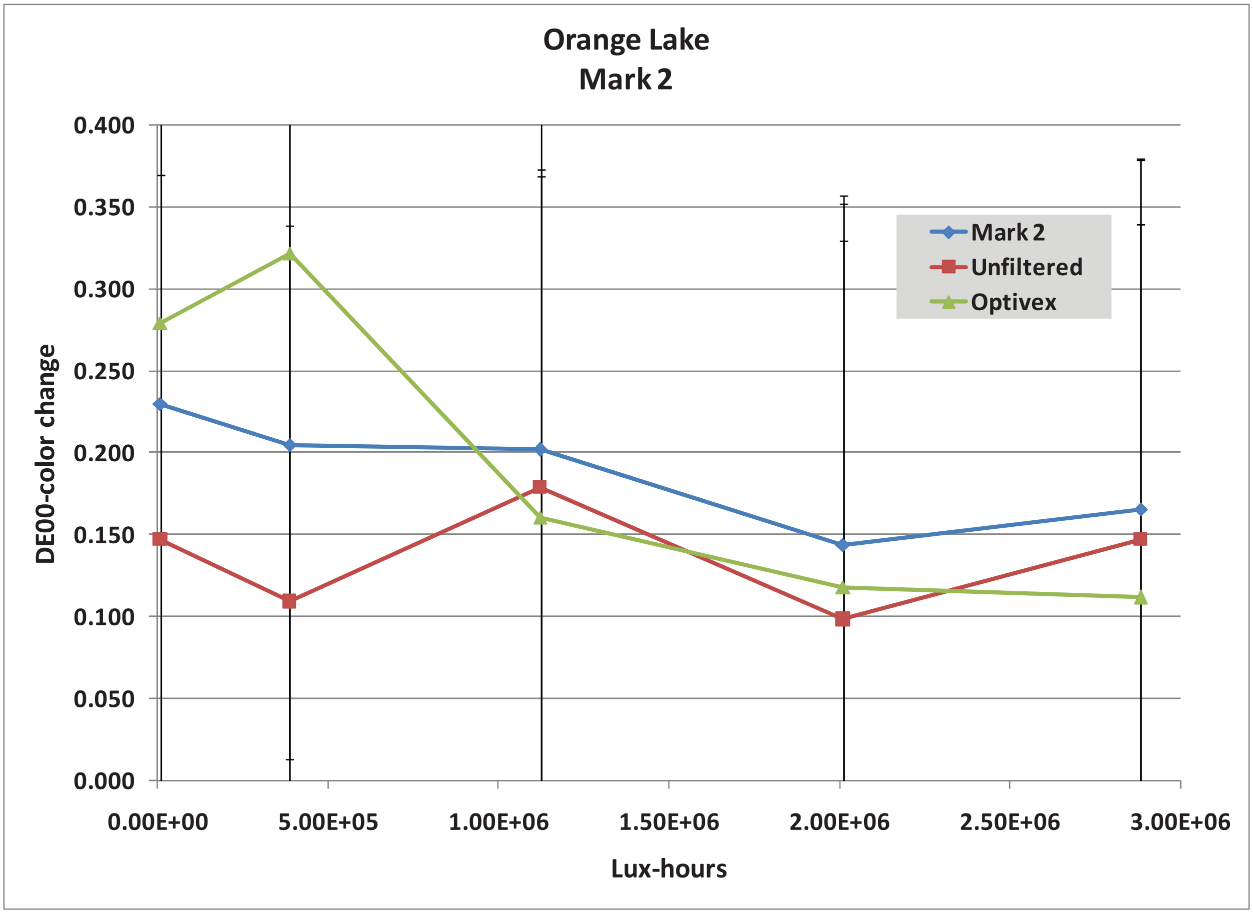

Orange Lake
Mark 2
DE00-color change
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0.00E+00
5.00E+05
1.00E+06
1.50E+06
2.00E+06
2.50E+06
3.00E+06
Lux-hours
Mark 2
Unfiltered
Optivex

Figure 6.28

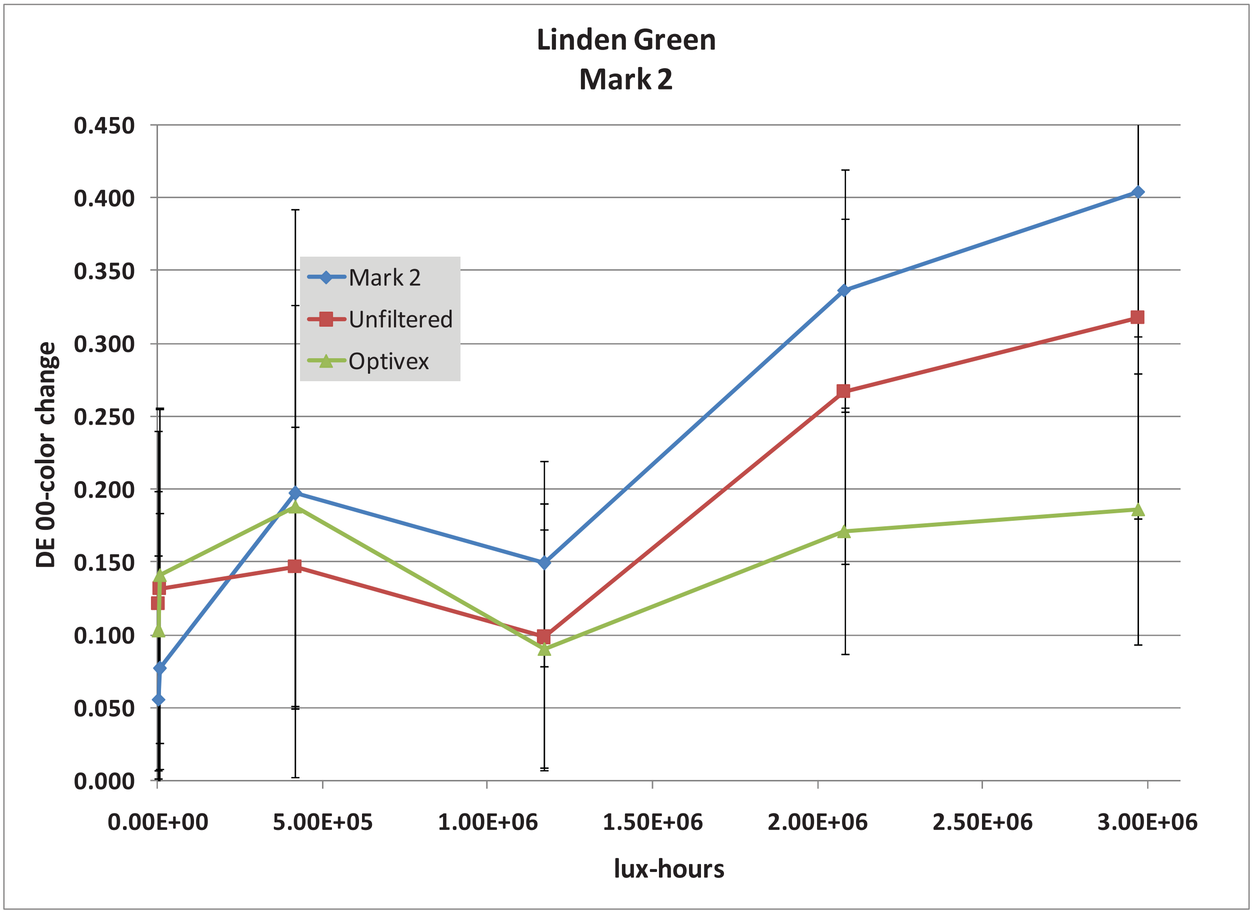

Linden Green
Mark 2
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
DE 00-color change
Mark 2
Unfiltered
Optivex
0.00E+00
5.00E+05
1.00E+06
1.50E+06
2.00E+06
2.50E+06
3.00E+06
lux-hours

Figure 6.29

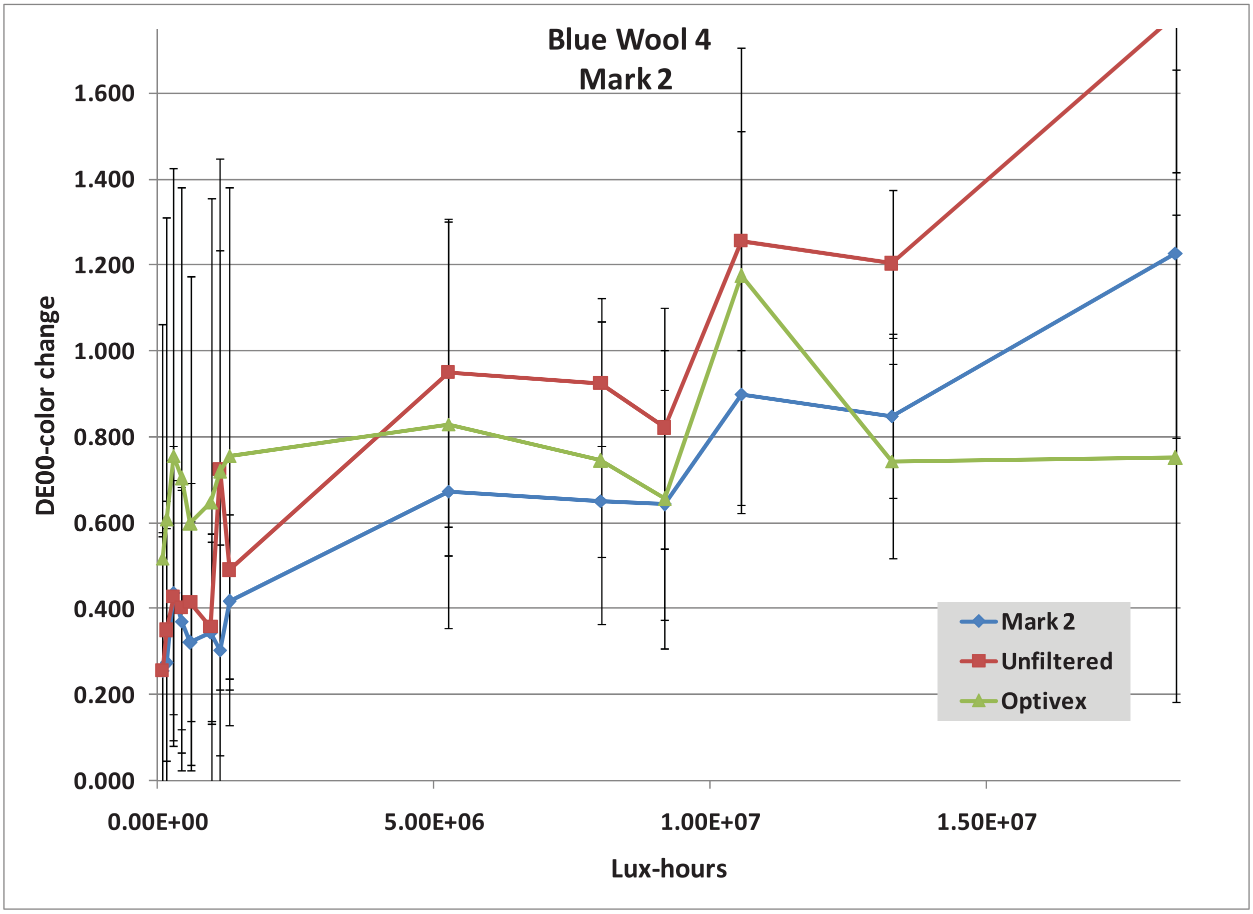

Blue Wool 4
Mark 2
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
DE00-color change
0.00E+00
5.00E+06
1.00E+07
1.50E+07
Lux-hours
Mark 2
Unfiltered
Optivex

Figure 6.30


Blue Wool 5
Mark 2
Mark 2
Unfiltered
Optivex
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
DE00-color change
0.00E+00
5.00E+04
1.00E+05
1.50E+05
2.00E+05
2.50E+05
3.00E+05
3.50E+05
4.00E+05
4.50E+05
5.00E+05
Lux-hours

Figure 6.31

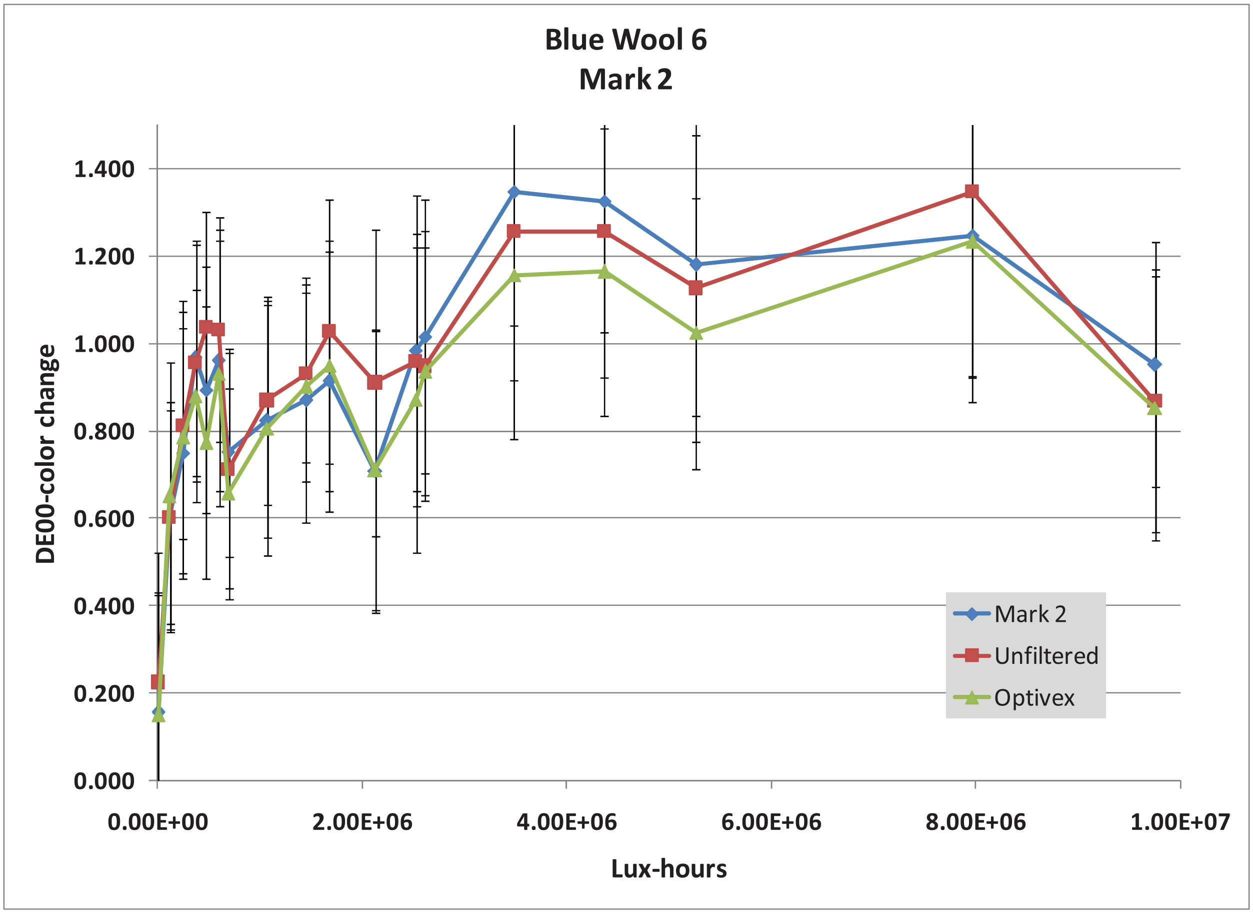

Blue Wool 6
Mark 2
DE00-color change
Lux-hours
Mark 2
Unfiltered
Optivex
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0.00E+00
2.00E+06
4.00E+06
6.00E+06
8.00E+06
1.00E+07

Figure 6.32

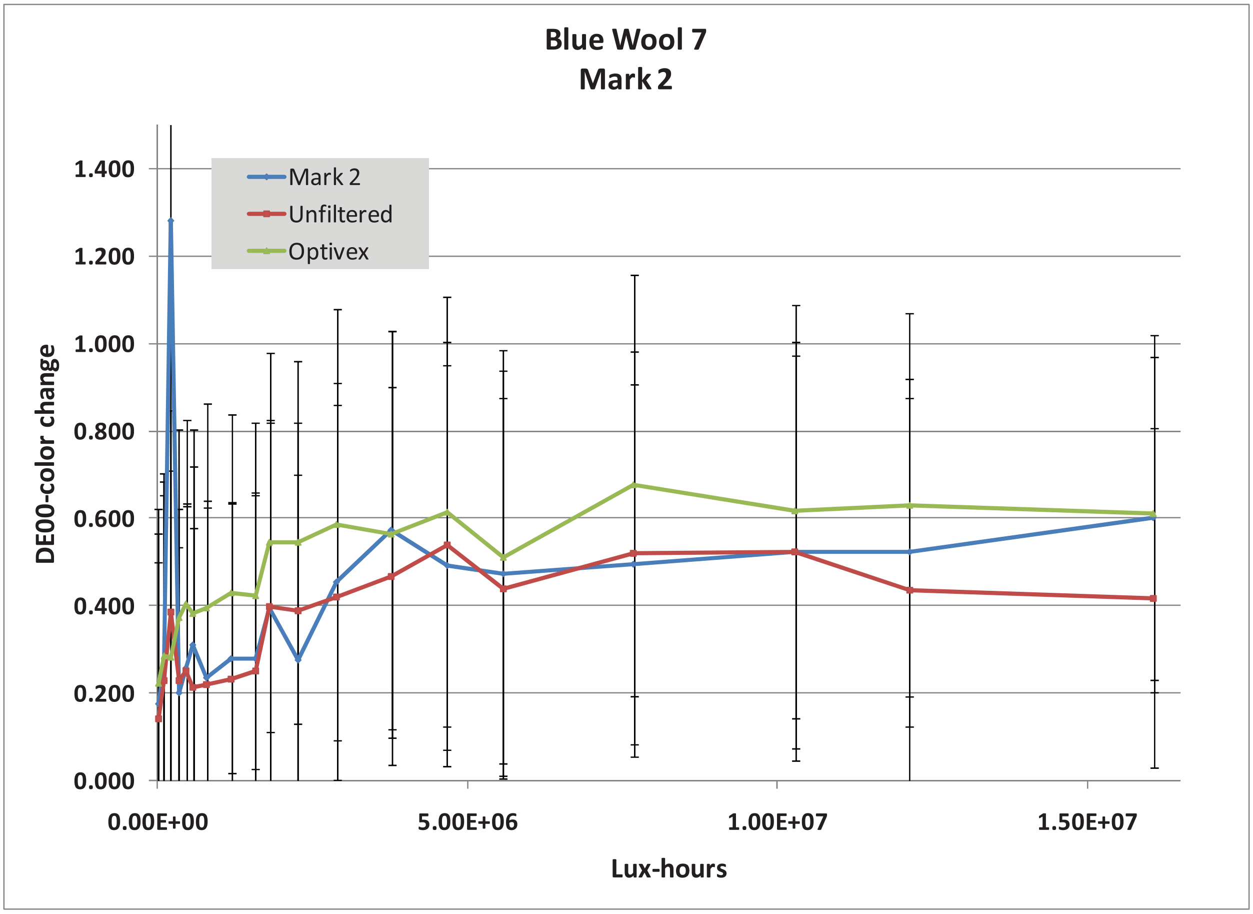

Blue Wool 7
Mark 2
Mark 2
Unfiltered
Optivex
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
DE00-color change
0.00E+00
5.00E+06
1.00E+07
1.50E+07
Lux-hours

Figure 6.33

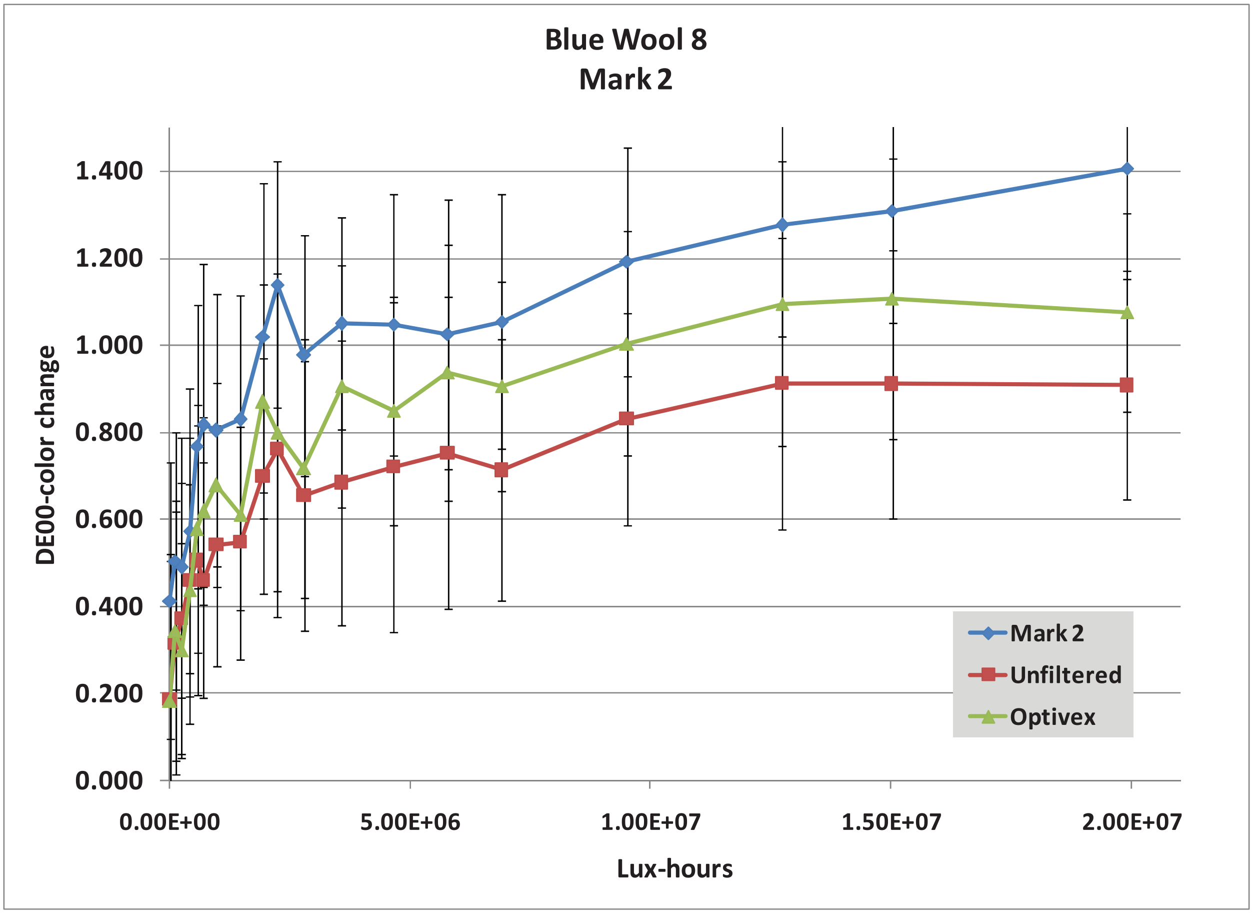


Figure 6.34

Data of Type 2 (**(O≈M≈U)>error**) significance is relatively less common across the period of an entire fade, but is seen early in many fades before the effects of the filters causes the data to separate significantly. As a reminder, this is data for which the error is relatively small compared to the magnitude of color change. Data for which the Type 2 significance characteristic applies across all of the data include:

A. Fading Study A (Mark3)

a. Winsor & Newton Linden Green (Figure 6.35). Optivex® and Unfiltered are favored, but not significantly over Mark 3. Note that the Linden Green samples were begun approximately 95 days (2280 hours) after turning on the lamps. This is ≈ 57% of the manufacturer specified lifetime for the lamps. Thus some additional uncertainty due to increased lamp instability should be weighed when considering this data.

b. Dr. Ph. Martins® Cherry Red (Figure 6.36). Note that at long exposure, Mark 3 is slightly favored over Optivex®, and both share a nearly significant benefit over Unfiltered. However, none of these differences are significant relative to experimental error.

c. Dr. Ph. Martin's® Cyclamen (Figure 6.37). Note that this data obviously is missing necessary intermediate measurements. Optivex® and Mark 3 are slightly favored over Unfiltered, but not significantly. Note that the Cyclamen samples were begun approximately 102 days (2448 hours) after turning on the lamps. This is ≈61% of the manufacturer specified lifetime for the lamps. Thus some additional uncertainty due to increased lamp instability should be weighed when considering this data.

d. Dr. Ph. Martin’s® Violet (Figure 6.38). Optivex® and Mark 3 are favored slightly over Unfiltered, but not significantly.

B. Fading Study B (Mark2)

a. Winsor & Newton Periwinkle Blue (Figure 6.39). Note that Mark 2 is favored, but error bars render the result insignificant.

b. Winsor & Newton Spectrum Violet (Figure 6.40). Note that Mark 2 is favored, but not significantly with regard to error bars.

Type 2 results require better signal to noise of data measurement and better controlled conditions to render unambiguous results.

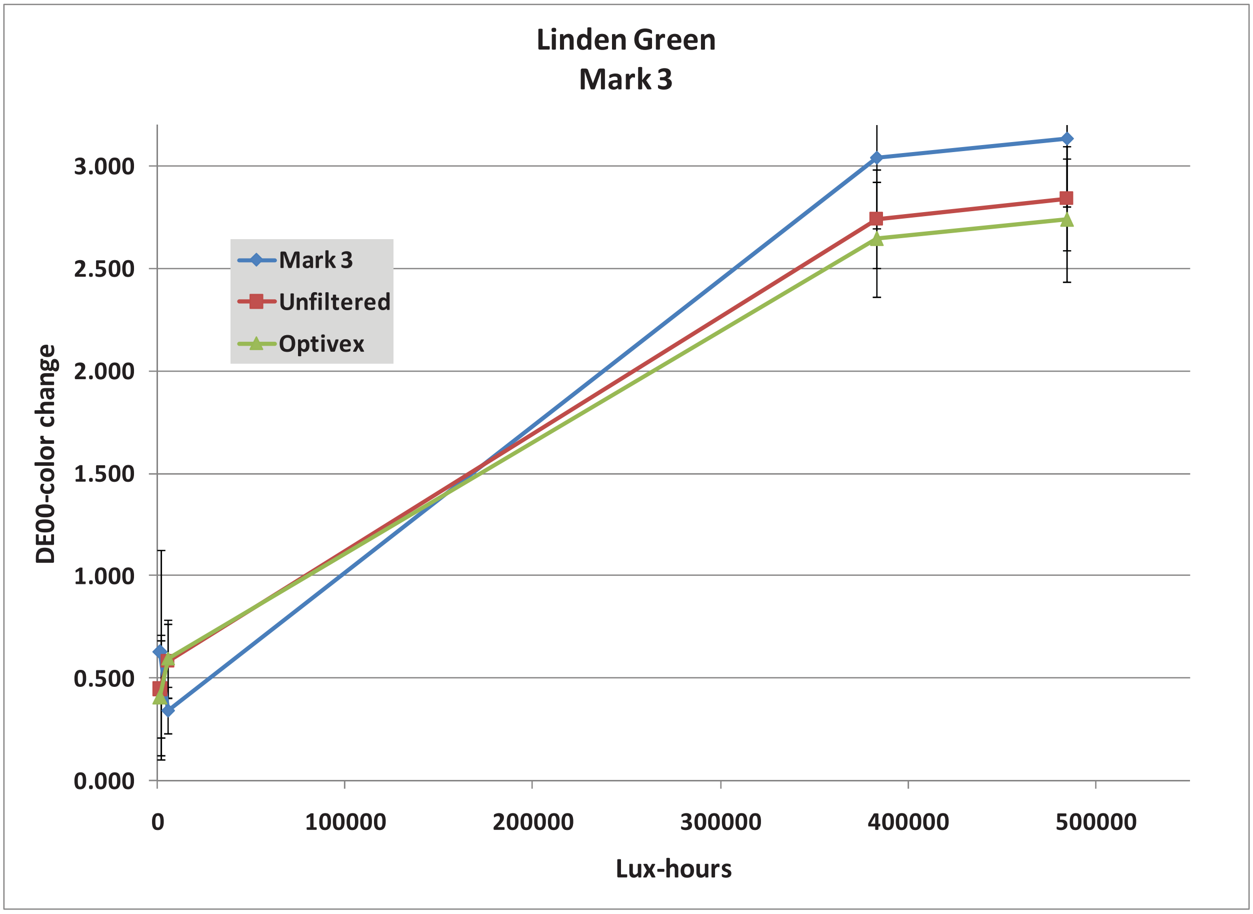
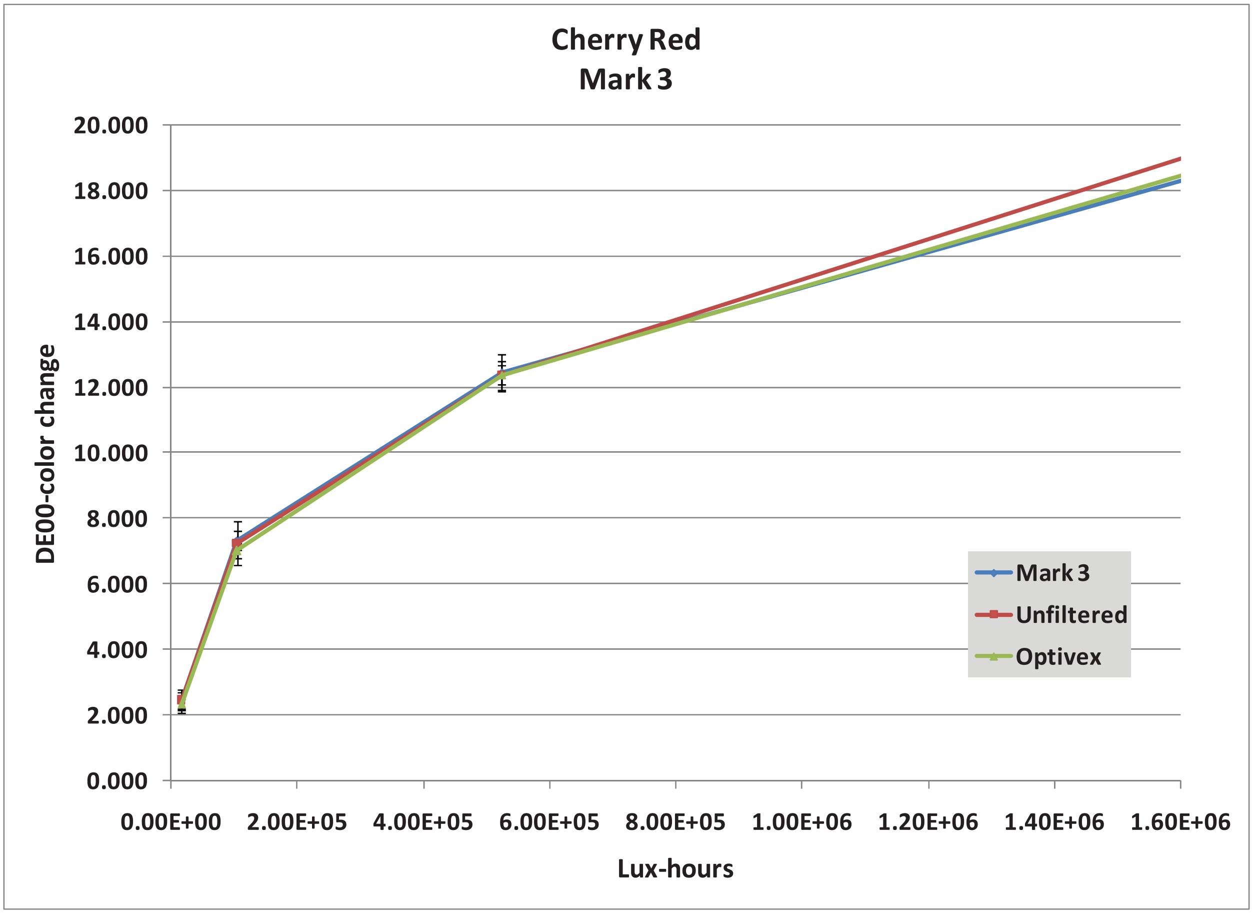

Linden Green
Mark 3
Mark 3
Unfiltered
Optivex
DE00-color change
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0
100000
200000
300000
400000
500000
Lux-hours

Figure 6.35



Cherry Red
Mark 3
20.000
18.000
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
DE00-color change
0.00E+00
2.00E+05
4.00E+05
6.00E+05
8.00E+05
1.00E+06
1.20E+06
1.40E+06
1.60E+06
Lux-hours
Mark 3
Unfiltered
Optivex

Figure 6.36

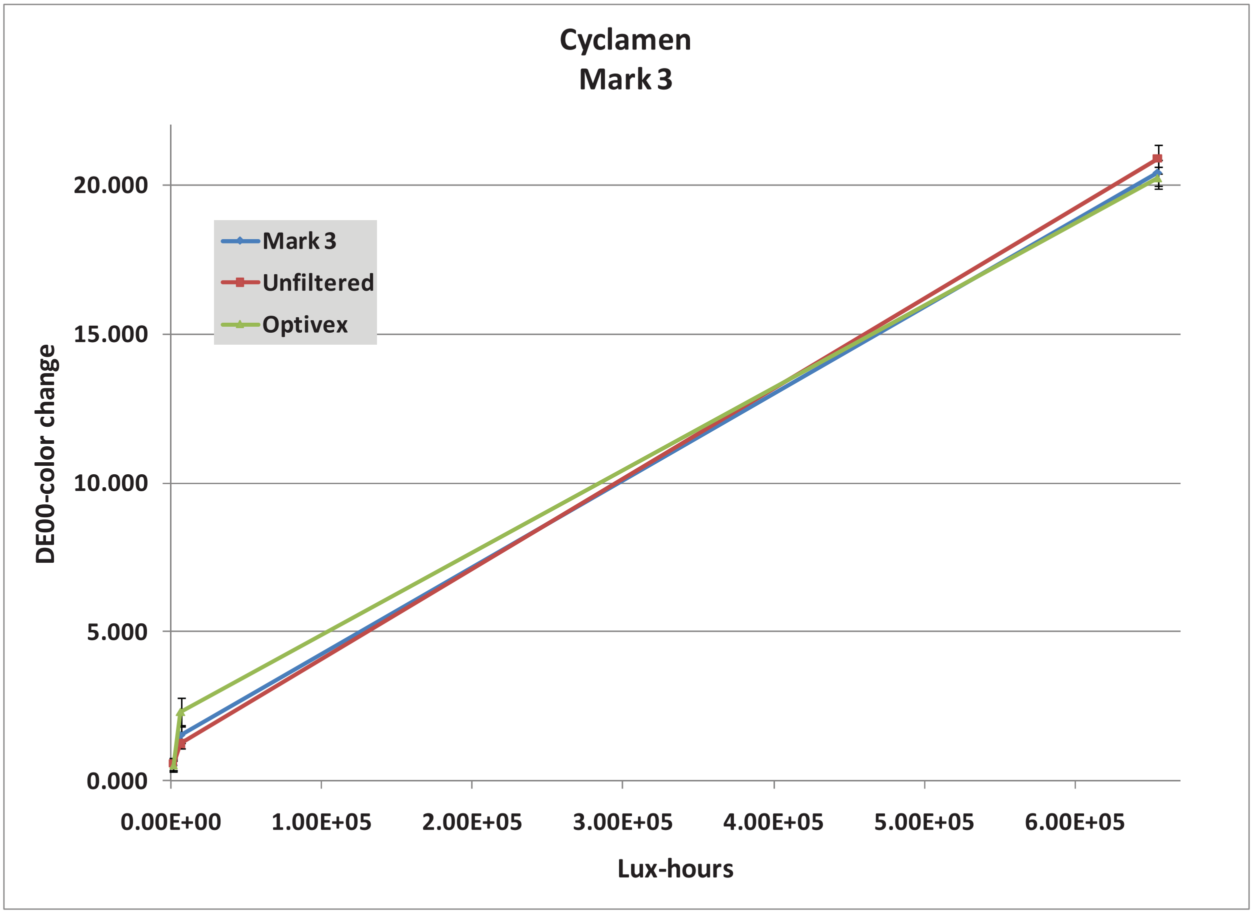

Cyclamen
Mark 3
Mark 3
Unfiltered
Optivex
DE00-color change
20.000
15.000
10.000
5.000
0.000
0.00E+00
1.00E+05
2.00E+05
3.00E+05
4.00E+05
5.00E+05
6.00E+05
Lux-hours

Figure 6.37

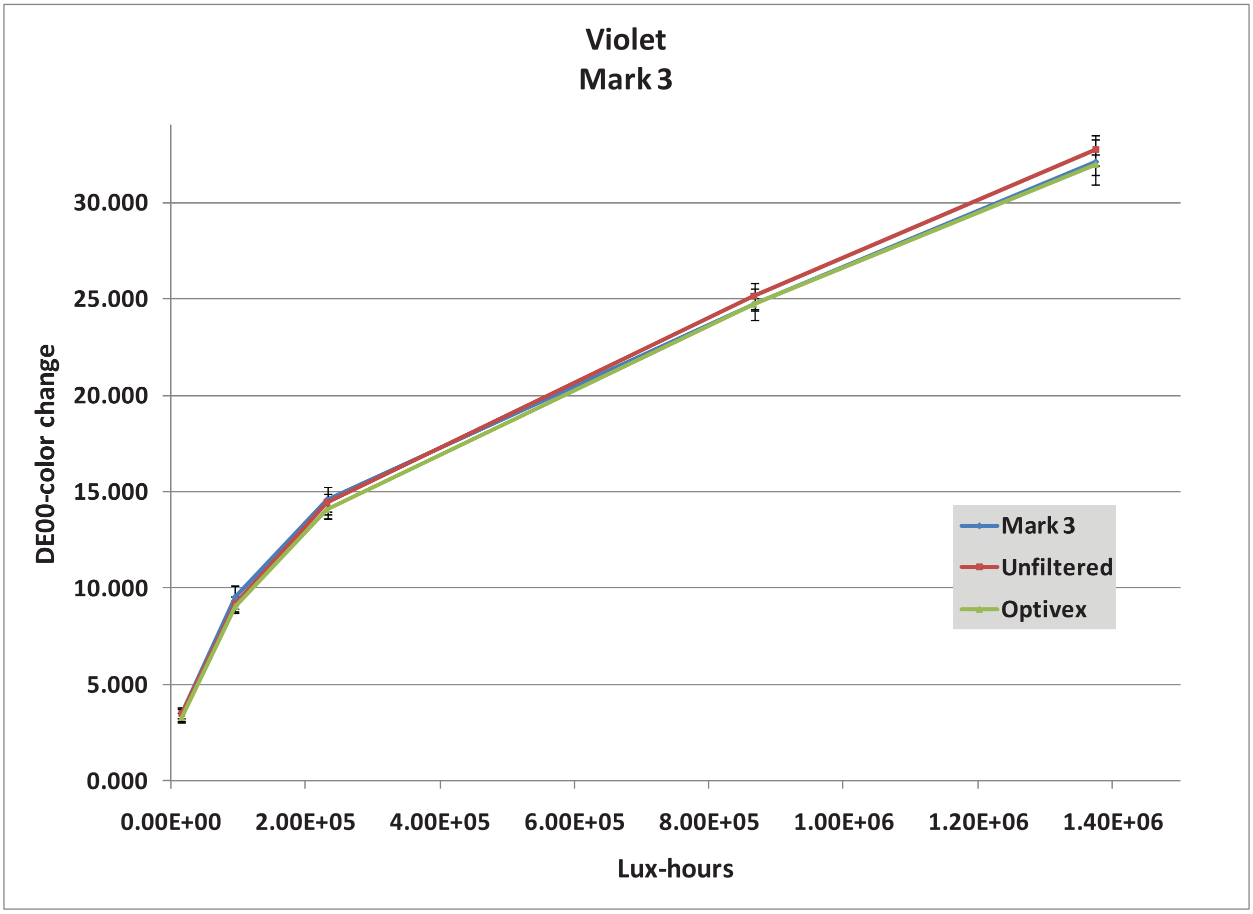
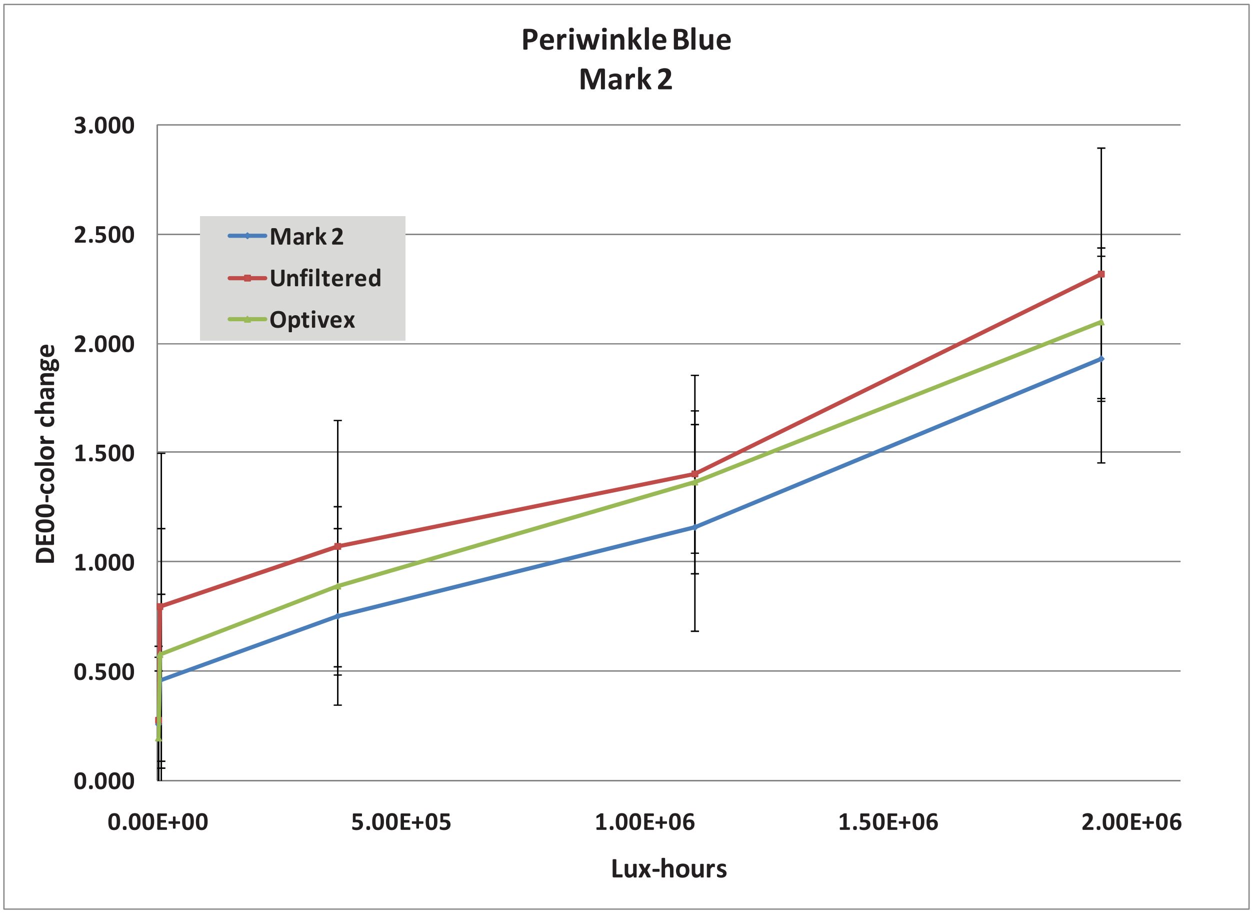

Violet
Mark 3
DE00-color change
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0.00E+00
2.00E+05
4.00E+05
6.00E+05
8.00E+05
1.00E+06
1.20E+06
1.40E+06
Lux-hours
Mark 3
Unfiltered
Optivex

Figure 6.38



Periwinkle Blue
Mark 2
3.000
2.500
2.000
1.500
1.000
0.500
0.000
DE00-color change
Mark 2
Unfiltered
Optivex
0.00E+00
5.00E+05
1.00E+06
1.50E+06
2.00E+06
Lux-hours

Figure 6.39

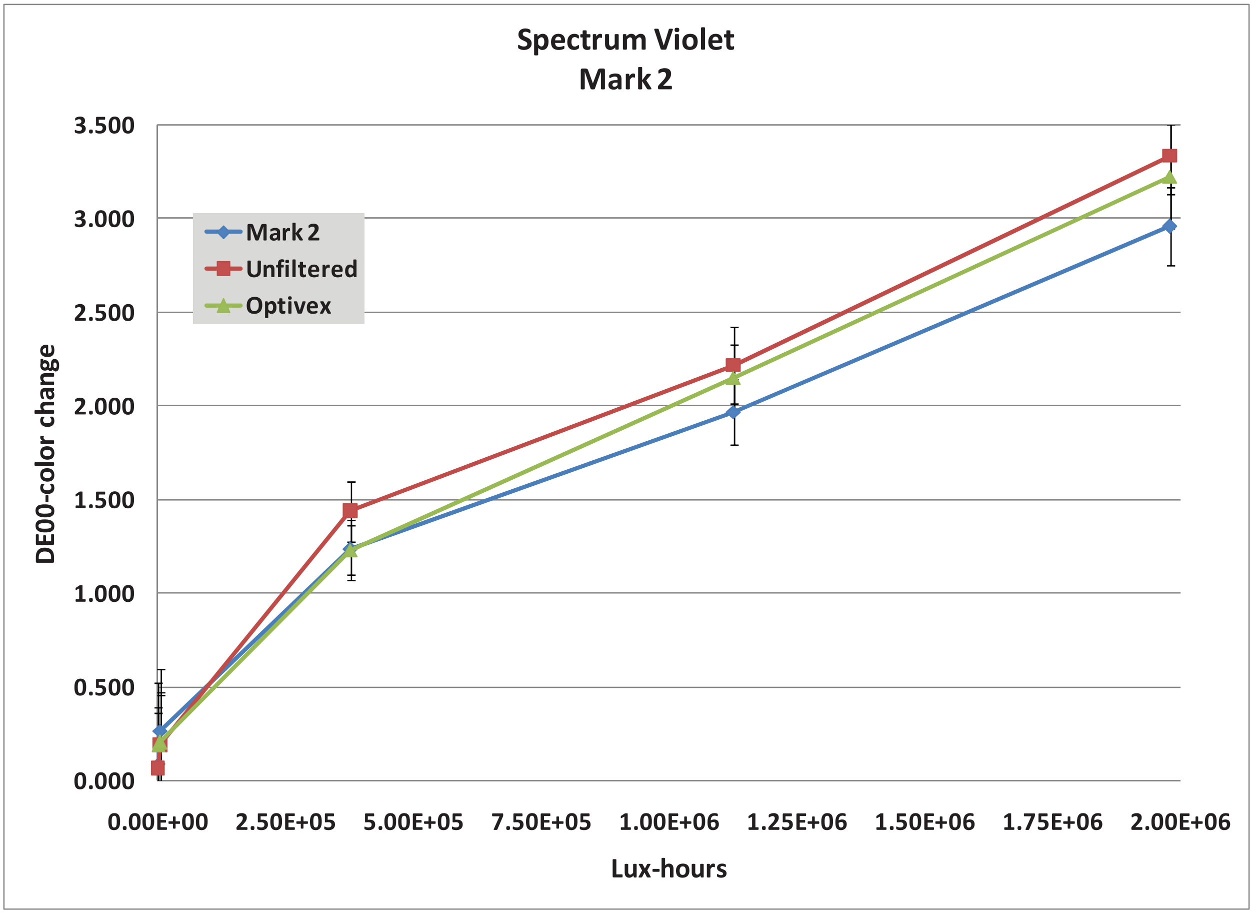


Figure 6.40

Results of Type 3 significance are those for which data for at least one illuminant are significantly different than the other two. Data which is Type 3 sometimes includes periods along the curve for which the data could be classified as Type 4 significance. Data of Type 4 significance is the circumstance that all of the illuminants are significantly different. Data of Type 3 and Type 4 significance are presented below:

A. Fading Study A (Mark 3)

   a. Methylene Blue (Figures 6.41, 6.42 and 6.43) Note that the data discussed here is the same data utilized in the reciprocity study discussed above. The figures presented here compare illuminants Mark 3 filtered, Optivex® filtered, and Unfiltered for three different luminosities. This data falls into the Type 3 significance category **M>≠ (U≈O)**, where Mark 3 significantly outperforms (lower fading) Unfiltered and Optivex® filtered light. In the 5930lux study (Figure 6.42) at 246000±11,000 lux-hours, there is a Type 4 significance (**M≠>O≠>U**). The results suggest an overwhelming benefit from Mark 3, and a likely much smaller, but possibly significant benefit for Optivex® over Unfiltered lighting.

   b. Winsor & Newton Rose Bengal. (Figure 6.44) This is a Type 3 significance case of **(M≈O)>≠U**. Basically Optivex® filtered and Mark 3 filtered are more beneficial than Unfiltered light. Mark 3 is slightly more beneficial than Optivex®, but not significantly. Note that the Rose Bengal samples were begun approximately 135 days (3240 hours) after turning on the lamps. This is ≈81% of the manufacturer specified lifetime for the lamps. Thus some additional uncertainty due to increased lamp instability should be weighed when considering this data.

c. Winsor & Newton Rose Tyrien. (Figure 6.45) This is a Type 3 significance case of **(M≈O)>≠U**. Basically Optivex® filtered and Mark 3 filtered are more beneficial than Unfiltered light. Optivex® is slightly more beneficial than Mark 3, but not significantly. This pigment has also been investigated at the Getty Conservation Institute, comparing Mark 3 and Optivex®, and Mark 3 is very slightly favored as shown in Figure 6.46. This discrepancy between two studies at two different sites suggests that a third better study would need to be done to resolve the issue. However, the GCI work displays relatively little scatter meaning that unaccounted measurement errors might have been smaller than in the UTEP work. The Rose Tyrien samples were begun approximately 101 days (2424 hours) after turning on the lamps. This is ≈ 60% of the manufacturer specified lifetime for the lamps. Thus some additional uncertainty due to increased lamp instability should be weighed when considering this data, and may be the cause of the discrepancy between the UTEP and GCI results.

d. Winsor & Newton Fluorescent Yellow. (Figure 6.47) This is a Type 3 significance case of **(U≈O)>≠M**. Unfiltered light and Optivex® filtered light are more beneficial than Mark 3. However, this case is almost Type 1 significance (no significance) since the magnitude of errors are nearly as large as the magnitude of color change. Additionally, this study required data to be collected at shorter intervening intervals. If the scatter of the data in the reciprocity study is indicative of the kind of data scatter not accounted for by anticipated experimental error, then the significance of these results might be questioned. The magnitude of the color change is about 2 DE00 units, and the magnitude of errors is about 0.25 DE00 units. Data points differ by less than 1.0 DE00 units. The scatter in the reciprocity study could be as high as 1-1.5 DE00 units. Thus, the significant differences reported in the data could be accounted for by the non-experimental error scatter possibly implied by the reciprocity results. This work would need to be repeated more carefully and perhaps at higher illumination to be sure. Note that the Fluorescent Yellow samples were begun approximately 142 days (3408 hours) after turning on the lamps. This is ≈ 85% of the manufacturer specified lifetime for the lamps. Thus some

additional uncertainty due to increased lamp instability should be weighed when considering this data.

B. Dr. Ph. Martin's® Wild Rose. (Figure 6.48). This is a Type 3 significance case of **O>≠(M≈U)**. The last data point might be Type 4 significance **O>≠M>≠U**. This is a case where Optivex® is significantly more beneficial than Mark 3 filtered or Unfiltered light.

C. Fading Study B (Mark 2)

    a. Winsor & Newton Rose Tyrien. (Figure 6.49) This is a Type 3 significance case in the category **(M≈O)>≠U**. Mark 2 filtered and Optivex® light are nearly identically significantly more beneficial than Unfiltered light.

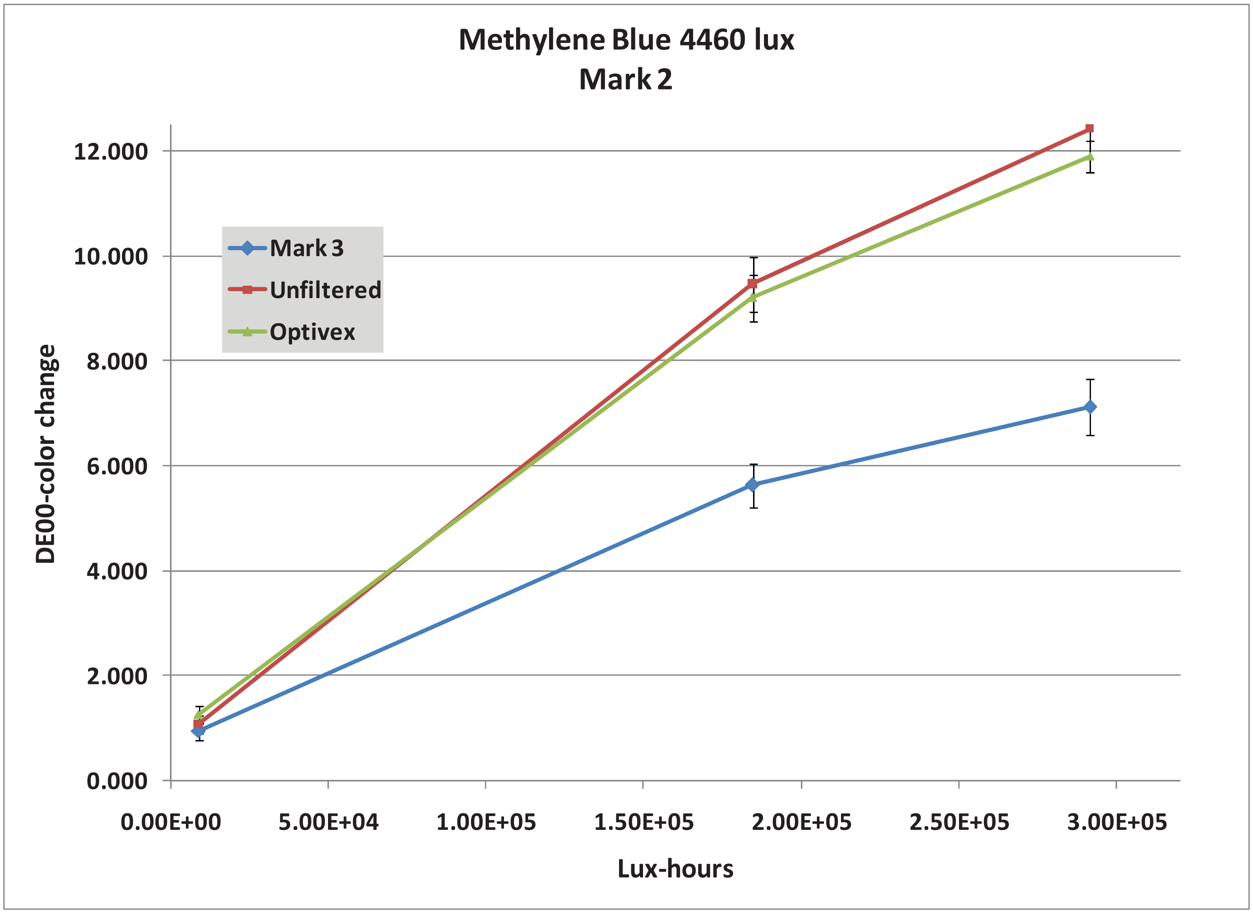

Methylene Blue 4460 lux
Mark 2
12.000
10.000
8.000
6.000
4.000
2.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
5.00E+04
1.00E+05
1.50E+05
2.00E+05
2.50E+05
3.00E+05
Lux-hours

Figure 6.41

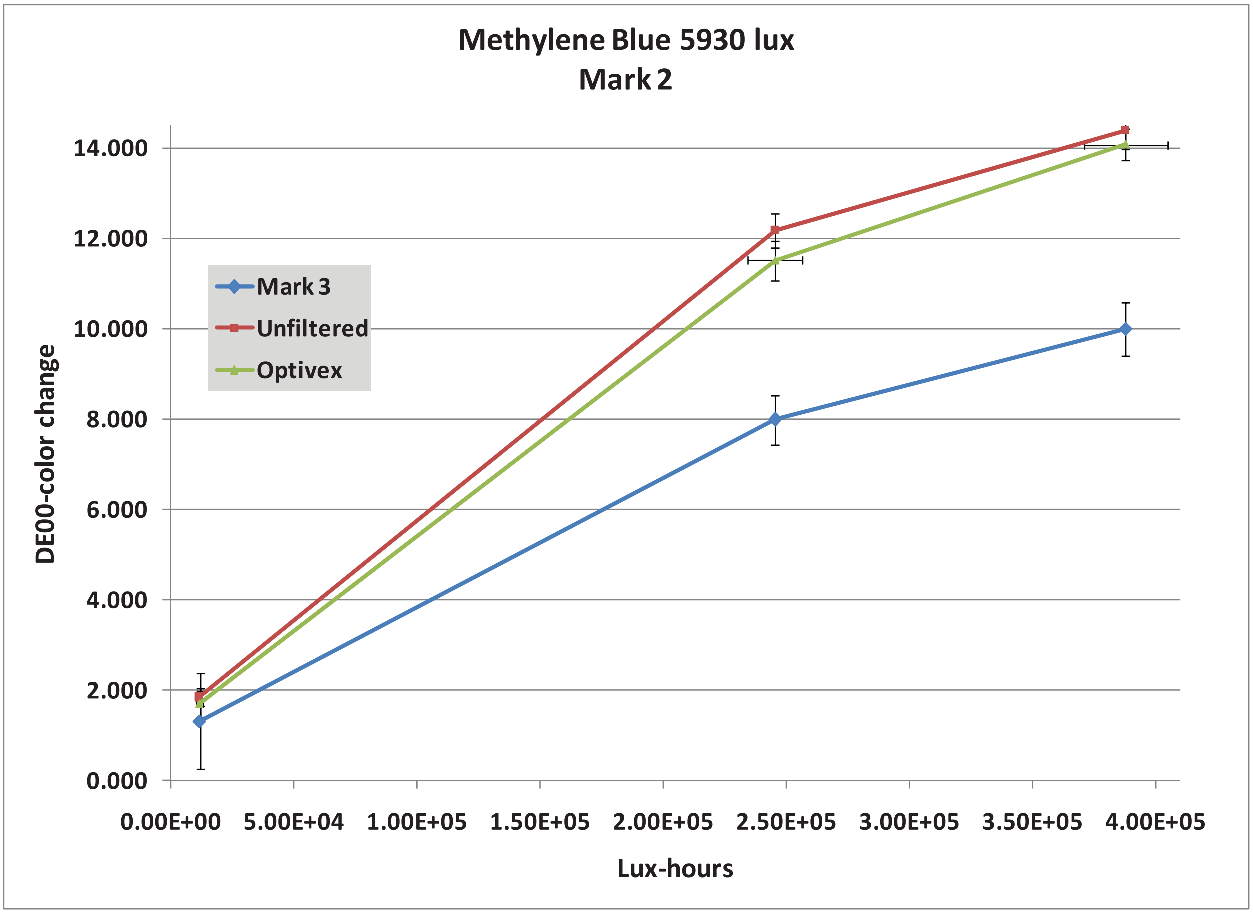
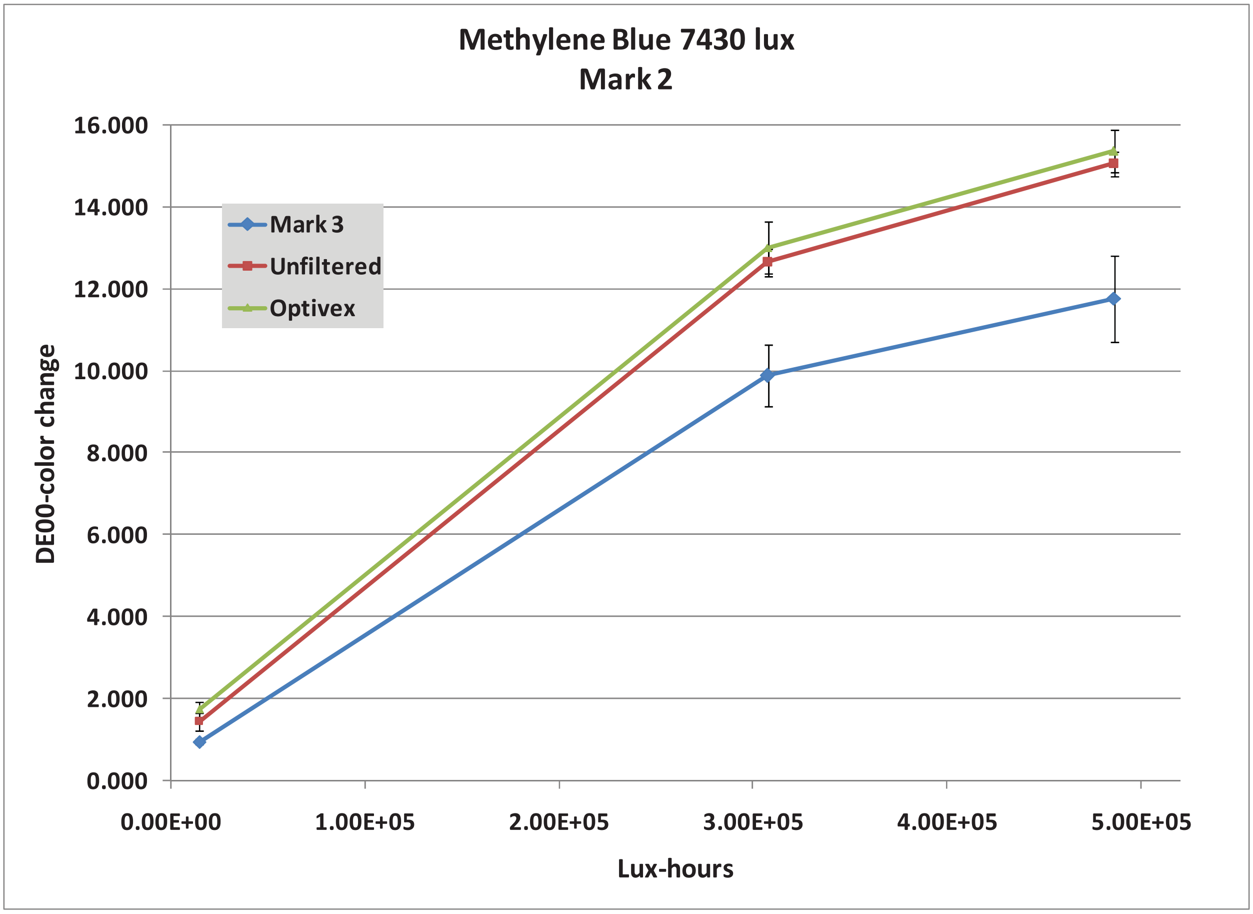

Methylene Blue 5930 lux
Mark 2
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
5.00E+04
1.00E+05
1.50E+05
2.00E+05
2.50E+05
3.00E+05
3.50E+05
4.00E+05
Lux-hours

Figure 6.42



Methylene Blue 7430 lux
Mark 2
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
1.00E+05
2.00E+05
3.00E+05
4.00E+05
5.00E+05
Lux-hours

Figure 6.43

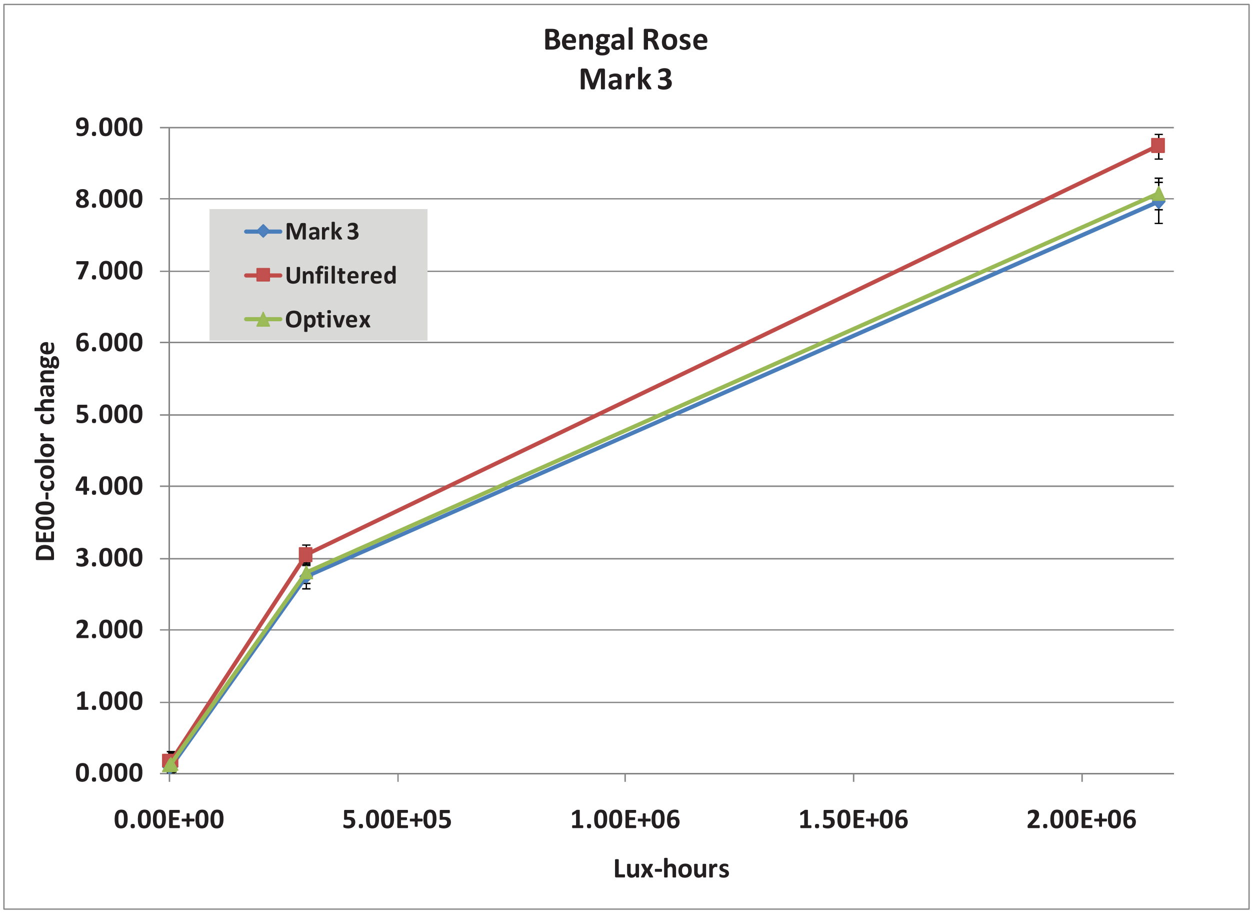

Bengal Rose
Mark 3
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
5.00E+05
1.00E+06
1.50E+06
2.00E+06
Lux-hours

Figure 6.44

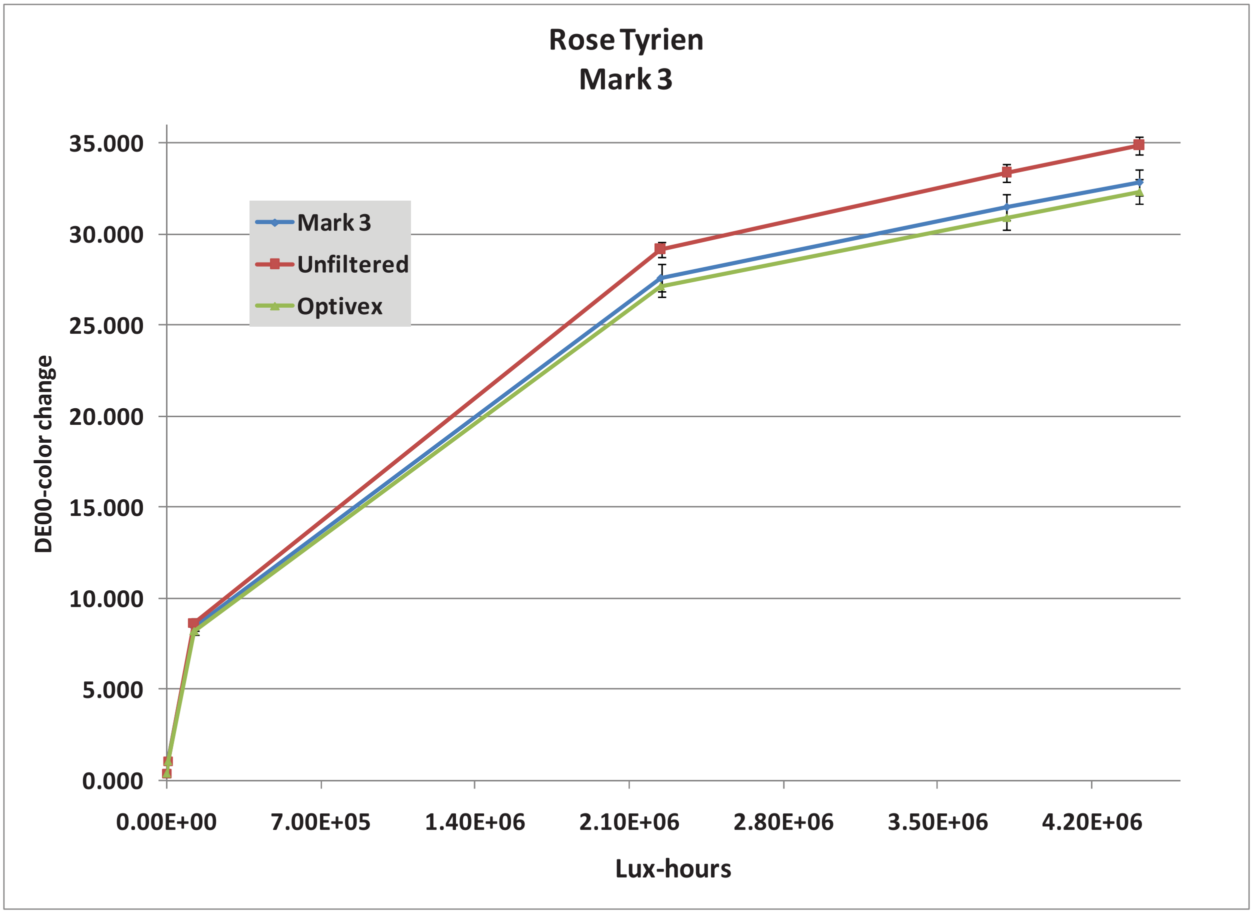
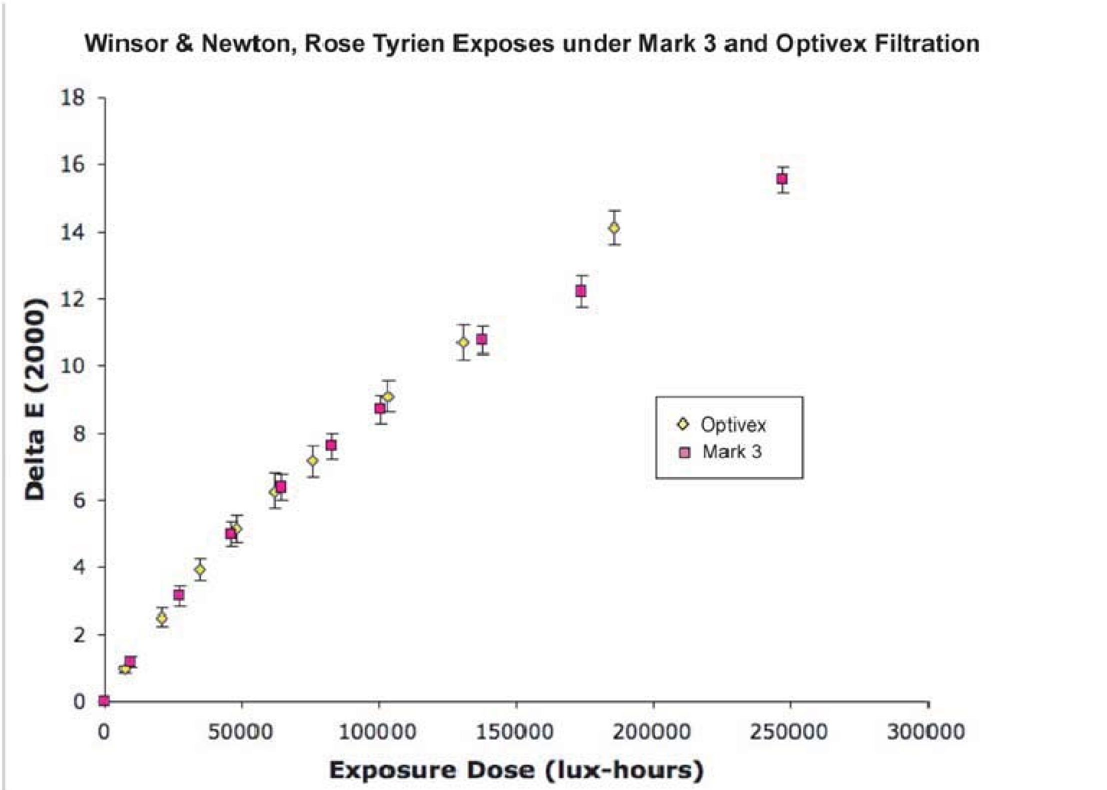

Rose Tyrien
Mark 3
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
7.00E+05
1.40E+06
2.10E+06
2.80E+06
3.50E+06
4.20E+06
Lux-hours

Figure 6.45



Winsor & Newton, Rose Tyrien Exposes under Mark 3 and Optivex Filtration
Delta E (2000)
Exposure Dose (lux-hours)
Optivex
Mark 3
0
2
4
6
8
10
12
14
16
18
0
50000
100000
150000
200000
250000
300000

Figure 6.46

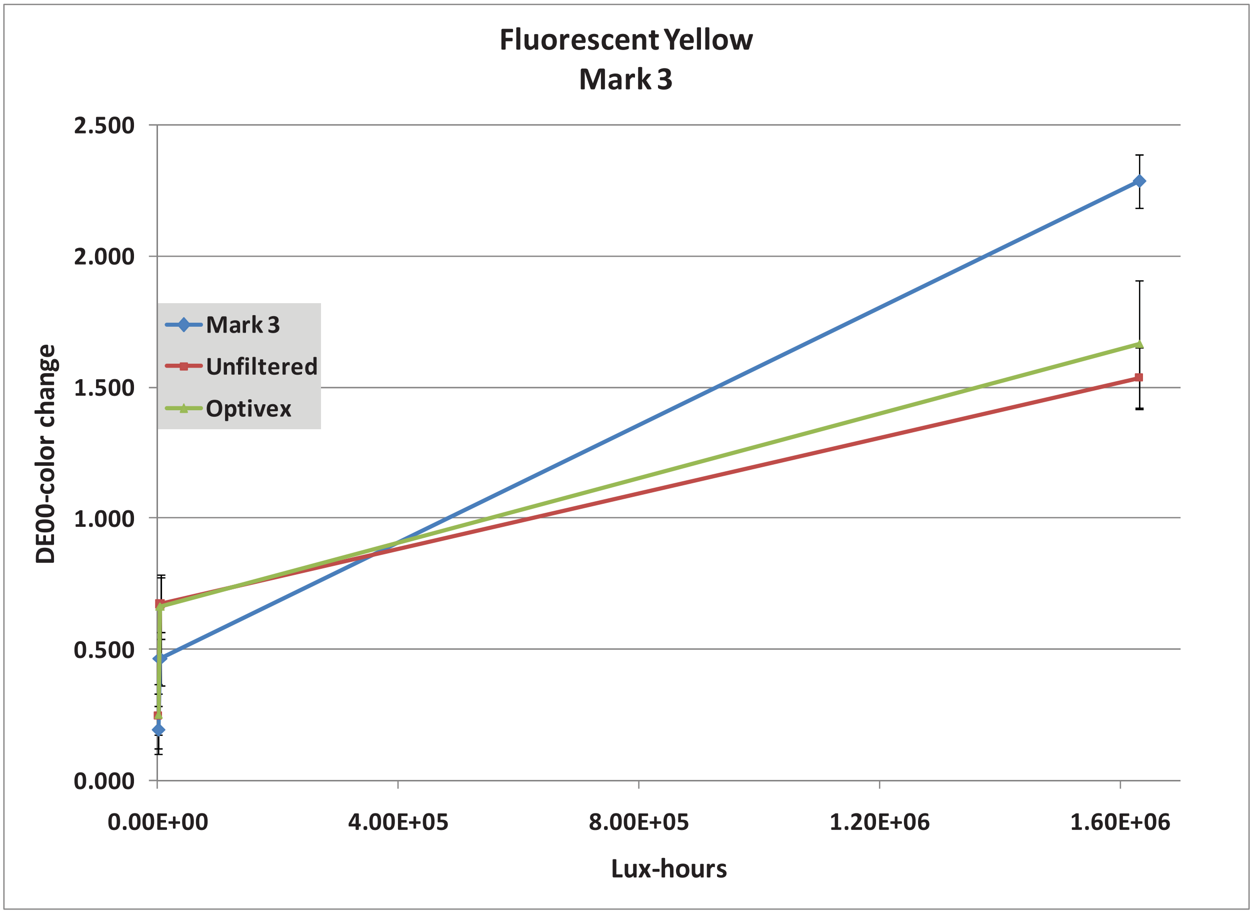
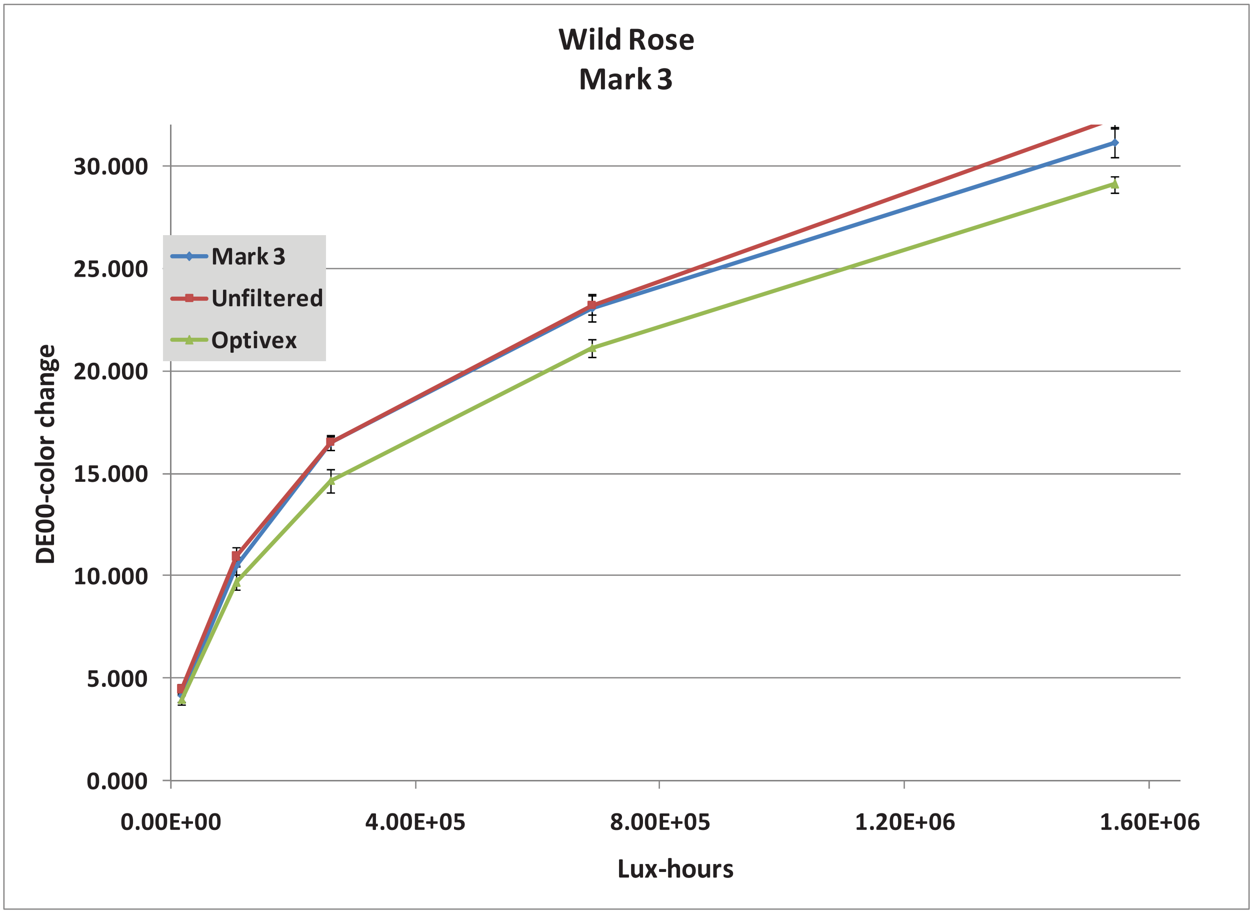

Fluorescent Yellow
Mark 3
2.500
2.000
1.500
1.000
0.500
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
4.00E+05
8.00E+05
1.20E+06
1.60E+06
Lux-hours

Figure 6.47



Wild Rose
Mark 3
30.000
25.000
20.000
15.000
10.000
5.000
0.000
DE00-color change
Mark 3
Unfiltered
Optivex
0.00E+00
4.00E+05
8.00E+05
1.20E+06
1.60E+06
Lux-hours

Figure 6.48

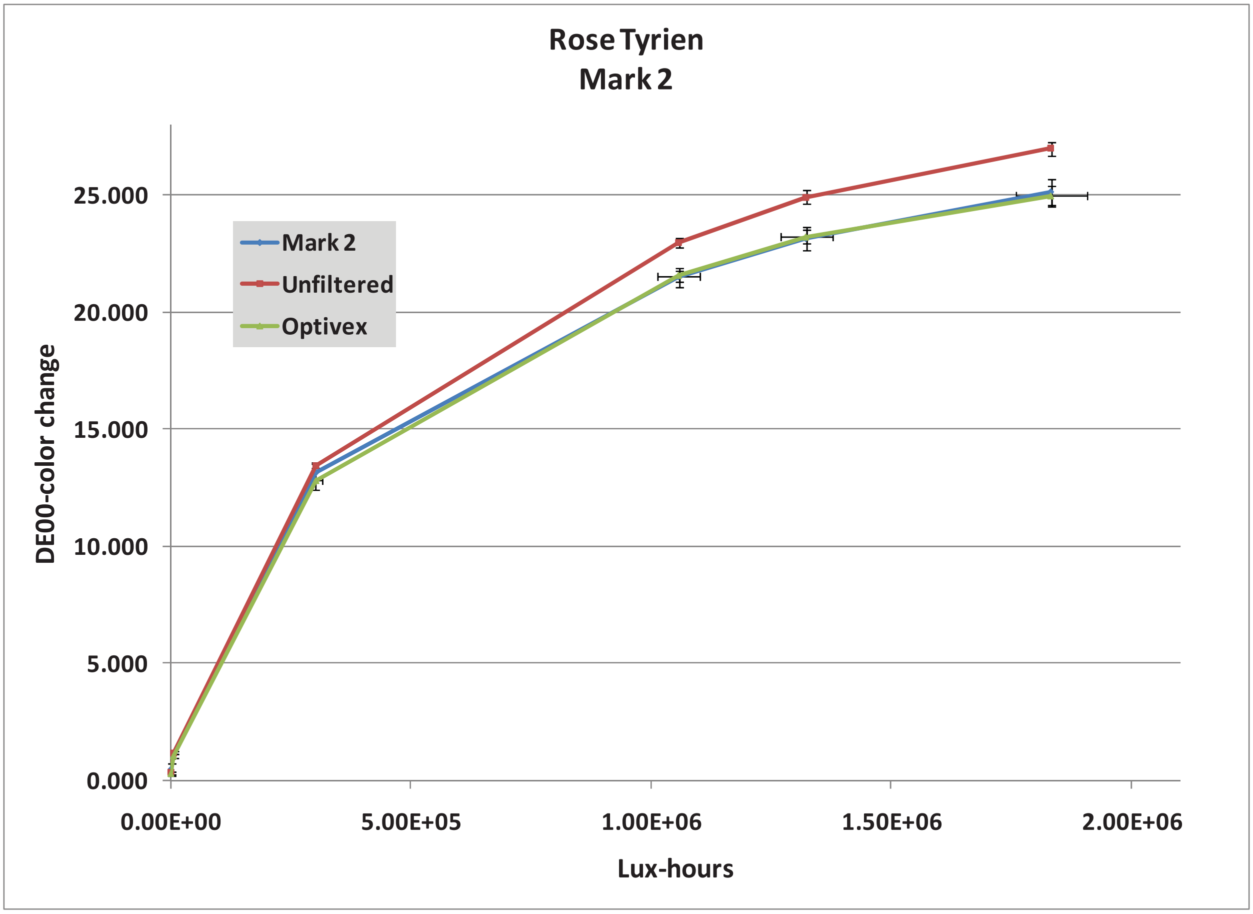


Figure 6.49

D. Fading Study C (Mark 2). The entries for this section are all Blue wool standards. For all three, the fade begins and evolves to a Type 3 significance favoring Mark 2 over Optivex® and Unfiltered. Some of this data becomes Type 4 significant with Mark 2 filtered, Optivex® filtered, and Unfiltered data significantly separated. All three Blue wool samples show a crossover of Optivex® with Mark 2 midway through the fades. For all three the crossover appears to set in at about 400-450 hours into

the fade. The composition of the Blue Wool samples is known to be different. It is not likely all three different materials would show this effect. Thus, it is more likely a lamp brownout has occurred in the Optivex® fading box. For fading study C, monitoring of the luminosity maintenance was not done. The BW1, BW2, and BW3 fades were begun approximately 22 days (≈528 hours) after turning on the lamps. Thus, if a brownout failure occurred in the Optivex® box, it was 900-1000 hours after turning on the lamps. Fading Study B experienced a lamp brownout failure after perhaps 800-1200 hours. Both lamps were the same Philips type. It is assumed that the latter (high lux-hour) data for the BW1, BW2, and BW3 are corrupted by this failure. This premise is well supported by the data presented in Figure 6.20 and Table 6.3 of the long term fading results completed at The Getty Conservation Institute. After 15 Mega-lux-hours (≈18000 lux for 838 hours), far beyond the exposure of the studies here, all of the ISO Blue Wools 1-3 and the AATCC (American Association of Textile Chemists and Colorists) Blue Wool 1-3 standards display significant benefit relative to Optivex® filtered lighting. Full results will be presented, though a truncation to exclude the exposure past the stage of the lamp failure results will be exercised for each, with analysis done on the results that are truncated to the shorter exposure periods.

a. Blue Wool 1(Figures 6.50-6.51)

Presented in Figure 6.50 is the whole fade of the Blue Wool 1 standard. As discussed above, a likely lamp failure in the Optivex® box requires the data to be truncated by no later than about 400 hours into the fade. The truncated data is shown in Figure 6.51. Up to this point, Mark 2 is clearly of more benefit than Unfiltered or Optivex®

b. Blue Wool 2 (Figures 6.52-6.53)

Presented in Figure 6.52 is the whole fade of the Blue Wool 2 standard. As discussed above, a likely lamp failure in the Optivex® box requires the data to be truncated by no later than about 400 hours into the fade. The truncated data is shown in Figure 6.53. Up to this point, Mark 2 is clearly of more benefit than Unfiltered or Optivex®

c. Blue Wool 3 (Figures 6.54-6.55)

Presented in Figure 6.54 is the whole fade of the Blue Wool 1 standard. As discussed above, a likely lamp failure in the Optivex® box requires the data to be truncated by no later than about 400 hours into the fade. The truncated data is shown in Figure 6.55. Up to this point, Mark 2 is clearly of more benefit than Unfiltered or Optivex®. The noise in the data and error bars

become progressively larger in the trend from BW1 to BW3 because the change in color is much smaller in the less sensitive BW3 standard.

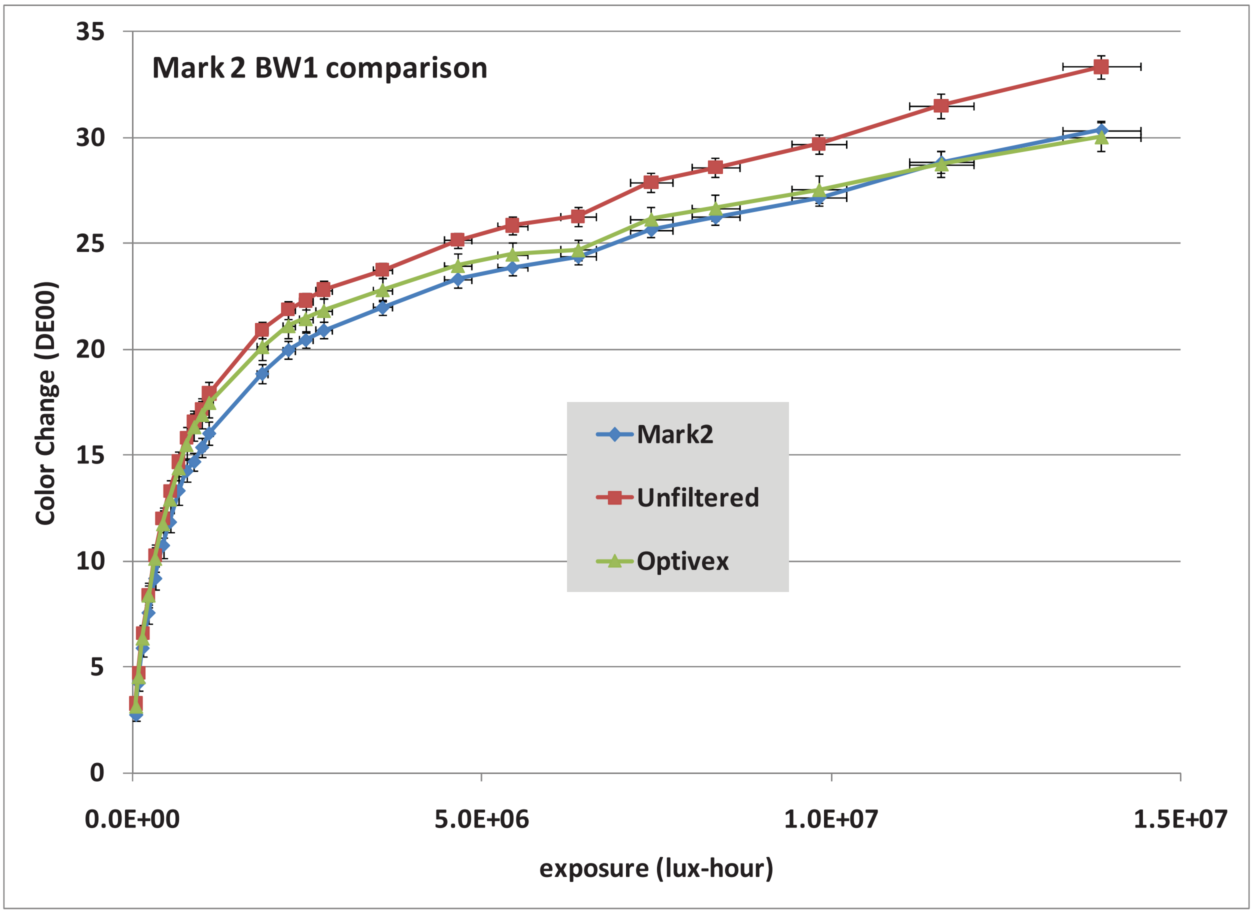


Figure 6.50

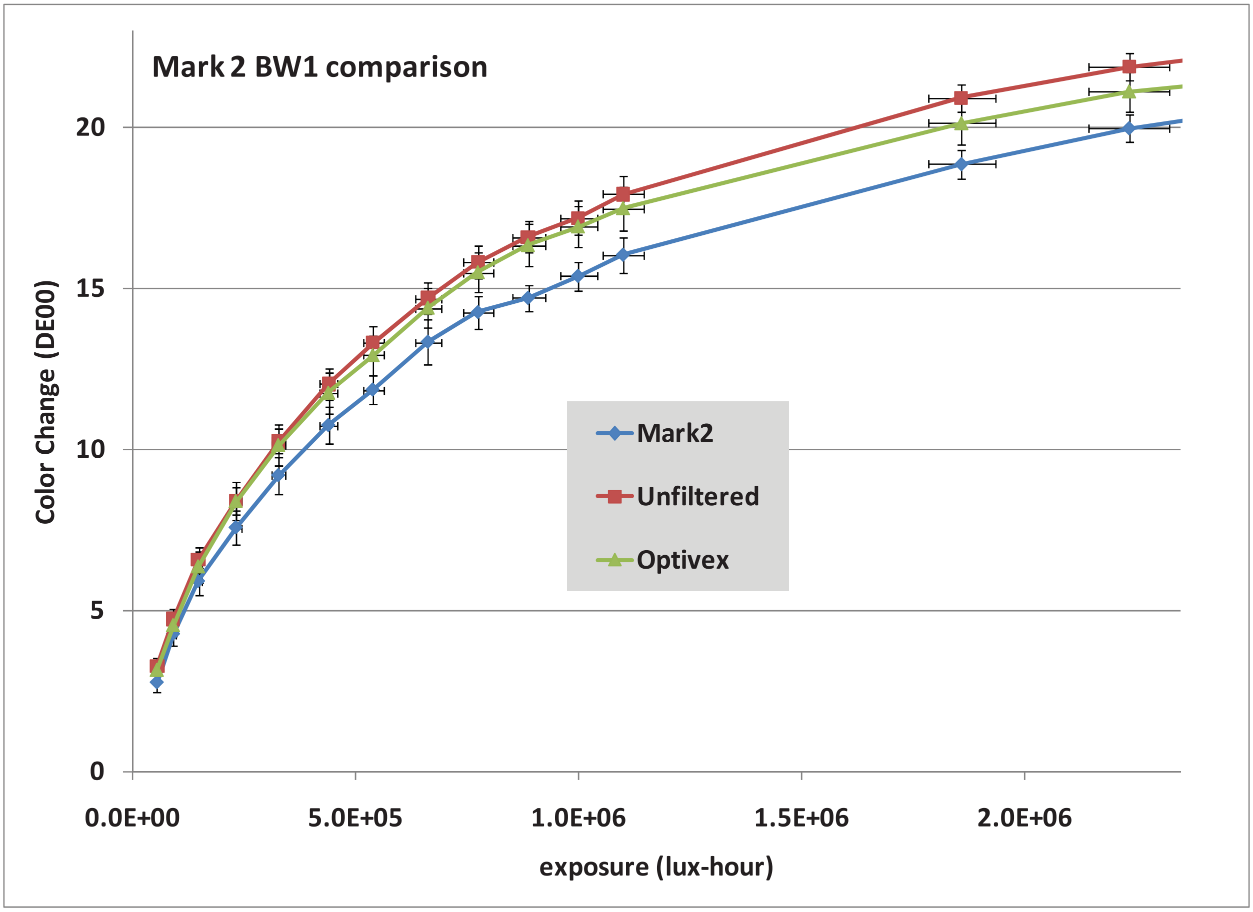

Mark 2 BW1 comparison
Color Change (DE00)
0
5
10
15
20
0.0E+00
5.0E+05
1.0E+06
1.5E+06
2.0E+06
exposure (lux-hour)
Mark2
Unfiltered
Optivex

Figure 6.51

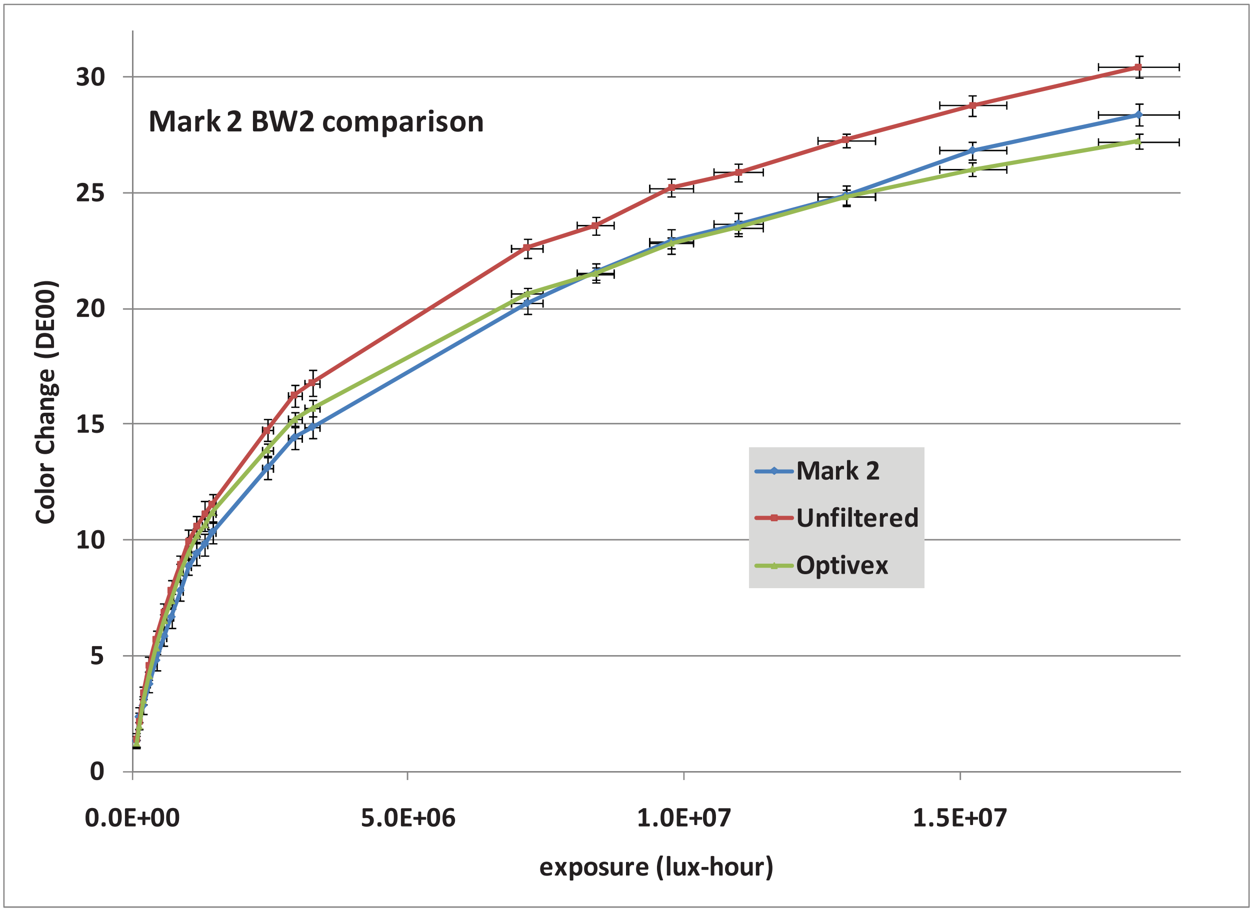
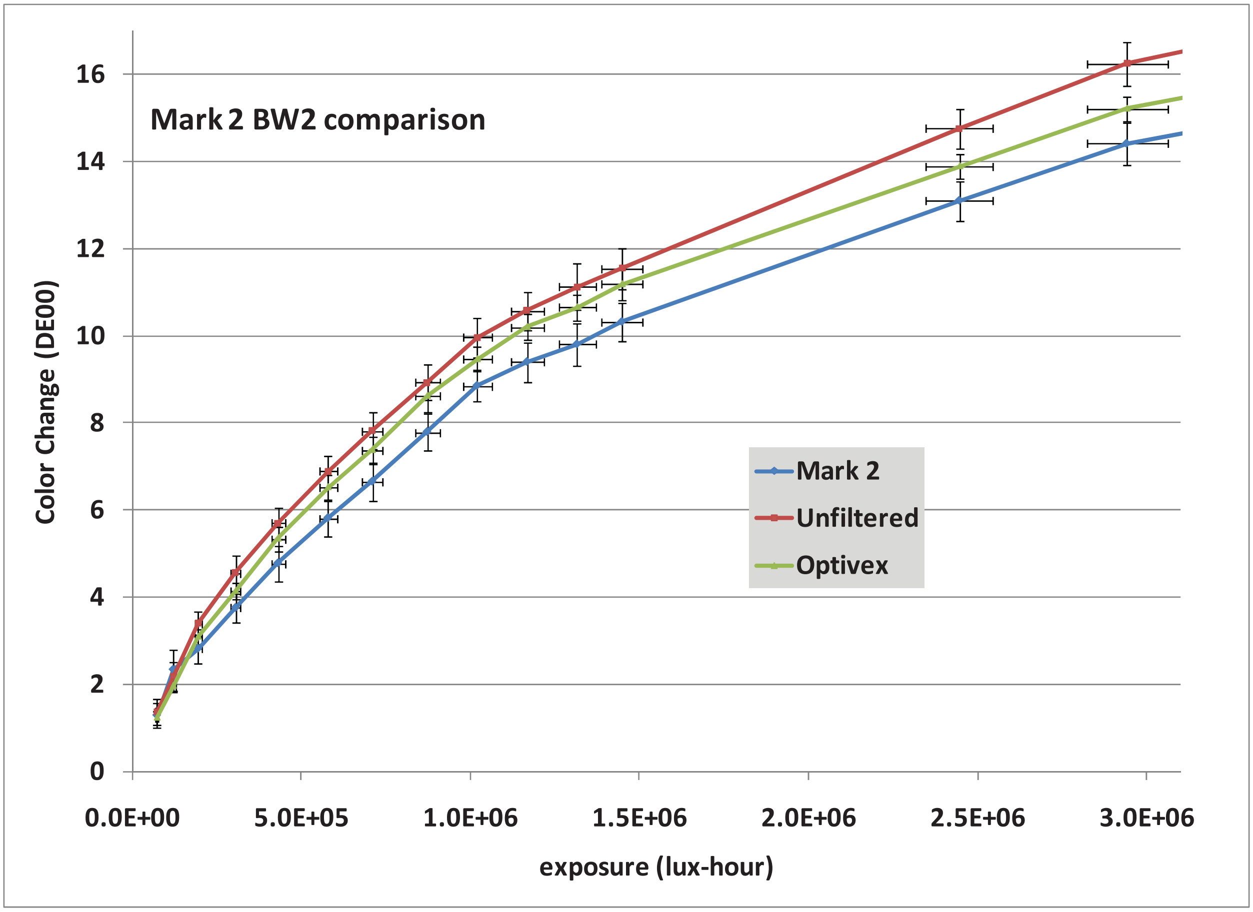
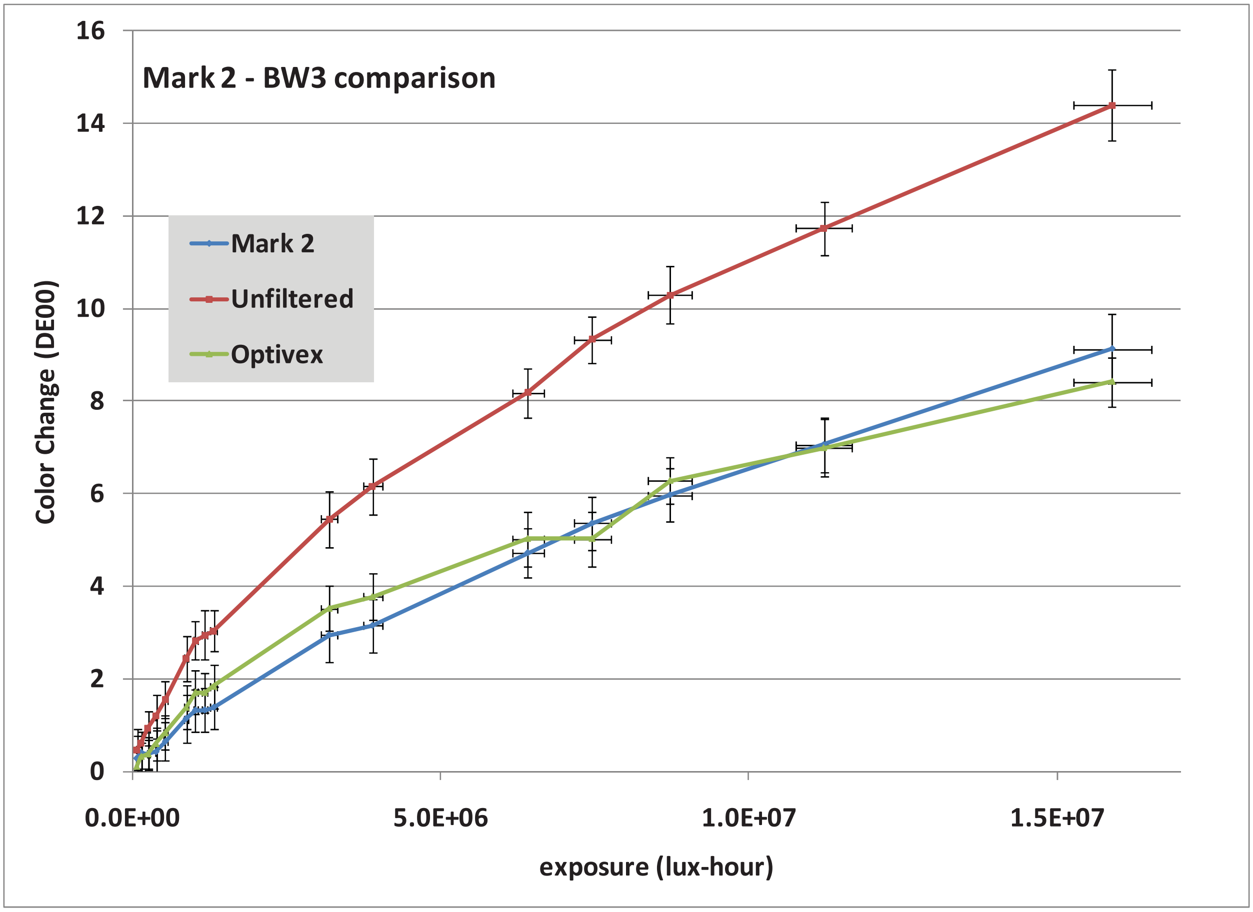

Mark 2 BW2 comparison
Color Change (DE00)
30
25
20
15
10
5
0
0.0E+00
5.0E+06
1.0E+07
1.5E+07
exposure (lux-hour)
Mark 2
Unfiltered
Optivex

Figure 6.52



Mark 2 BW2 comparison
Color Change (DE00)
0
2
4
6
8
10
12
14
16
0.0E+00
5.0E+05
1.0E+06
1.5E+06
2.0E+06
2.5E+06
3.0E+06
exposure (lux-hour)
Mark 2
Unfiltered
Optivex

Figure 6.53



Mark 2 - BW3 comparison
Mark 2
Unfiltered
Optivex
Color Change (DE00)
0
2
4
6
8
10
12
14
16
0.0E+00
5.0E+06
1.0E+07
1.5E+07
exposure (lux-hour)

Figure 6.54

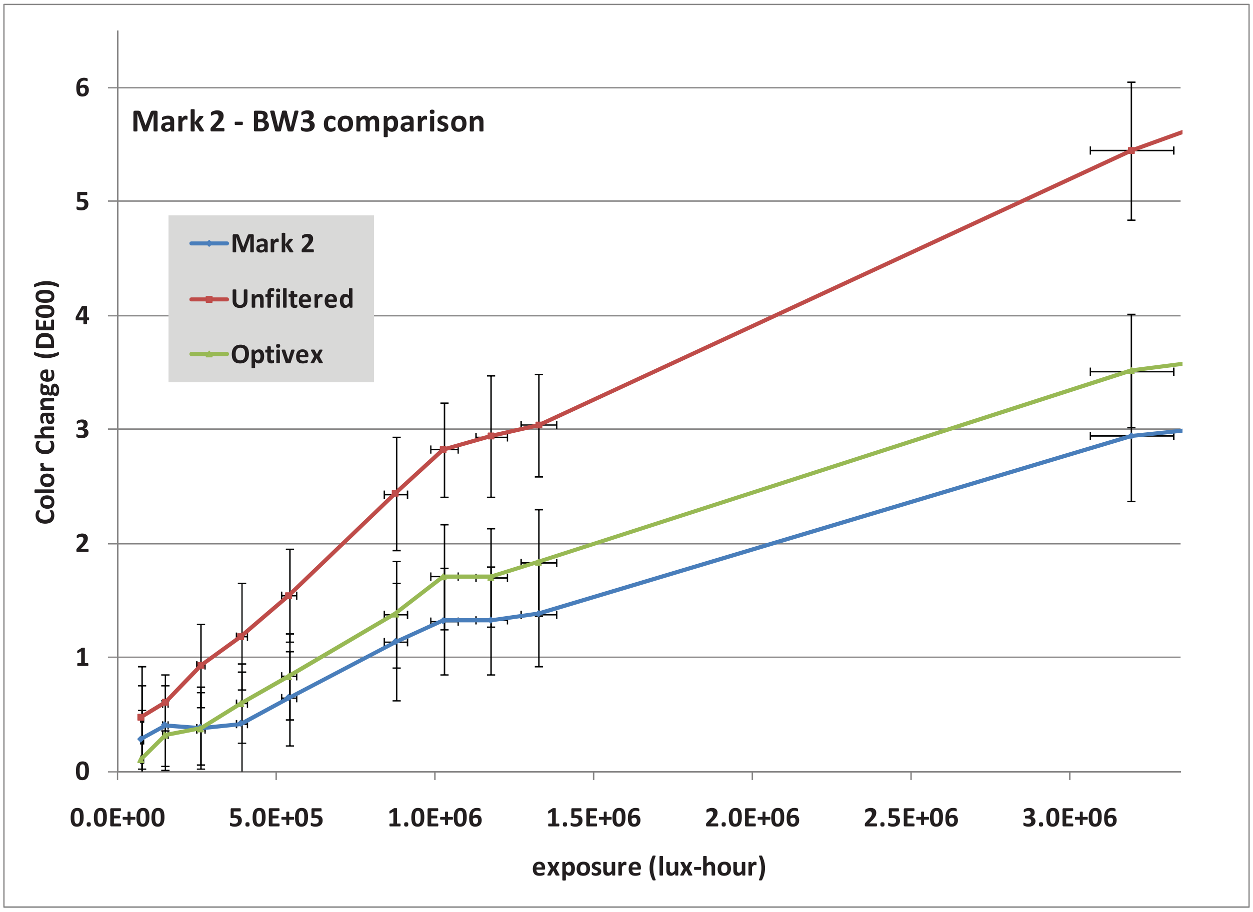


Figure 6.55

6.7.1 Delay in Fading

For all of the results presented above, the fading curves appear to show relatively small differences between the UTEP filter and the Unfiltered or the Optivex® filtration. This appearance is deceptive. The most useful way to approach the data is to assess the delay in fading that one illuminant may provide over another. This can be appreciated well by examination of Figure 6.56. This Figure is a zoomed section of the BW1 fading, just showing the Mark 2

and Unfiltered data. Added to this plot is a measurement of the temporal delay that occurs for Mark 2 to reach the same level of fading. One can see that Mark 2 slows fading by 21% relative to Optivex® in this temporal portion of the plot.

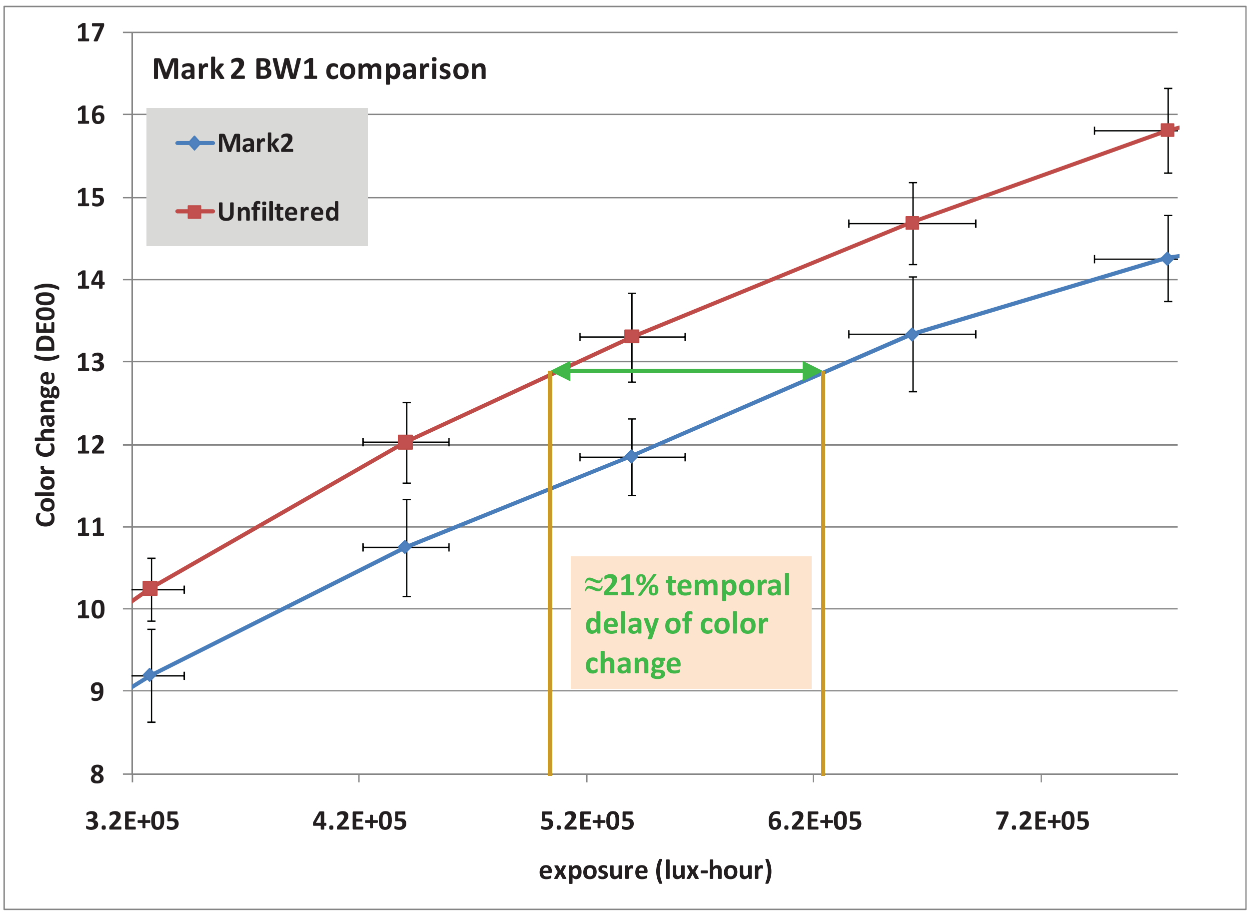


Figure 6.56

A similar analysis in the same temporal fading region of Optivex® versus Mark 2 is shown in Figure 6.57. One can see that the fading is delayed by ≈16%, a smaller value than for the comparison to Unfiltered, but still relatively large.

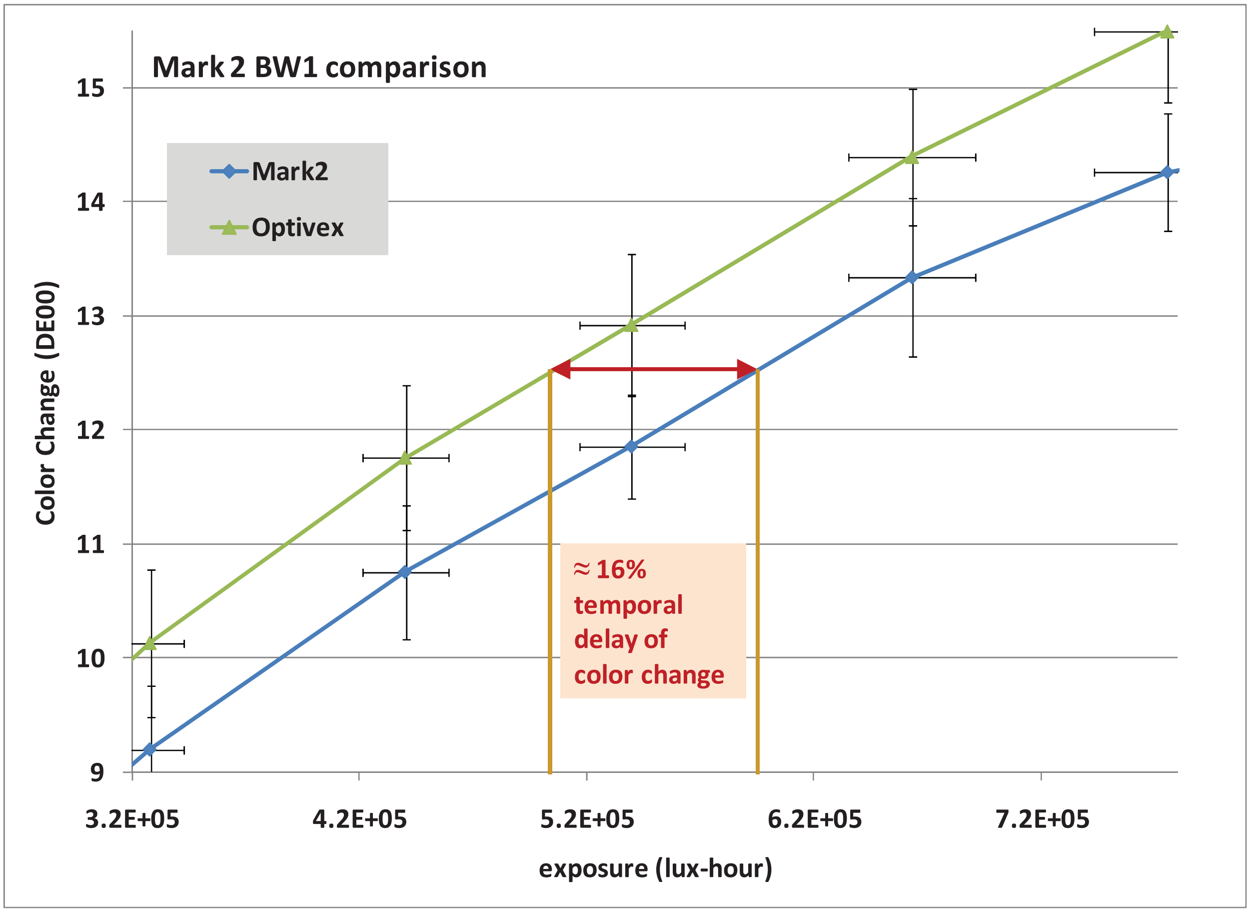


Figure 6.57

Examination of a more advanced portion of the fading data in Figures 6.58 and 6.59 indicate that the delay in fading is increased substantially as the fade proceeds. The 31% delay of this later data is nearly 1.5 times the 21% for the comparison of Unfiltered with Mark 2. Mark 2 is delayed by an extra 5%, 21% (Figure 5.59) versus 16% (Figure 6.57) earlier in the fade relative to Optivex®.

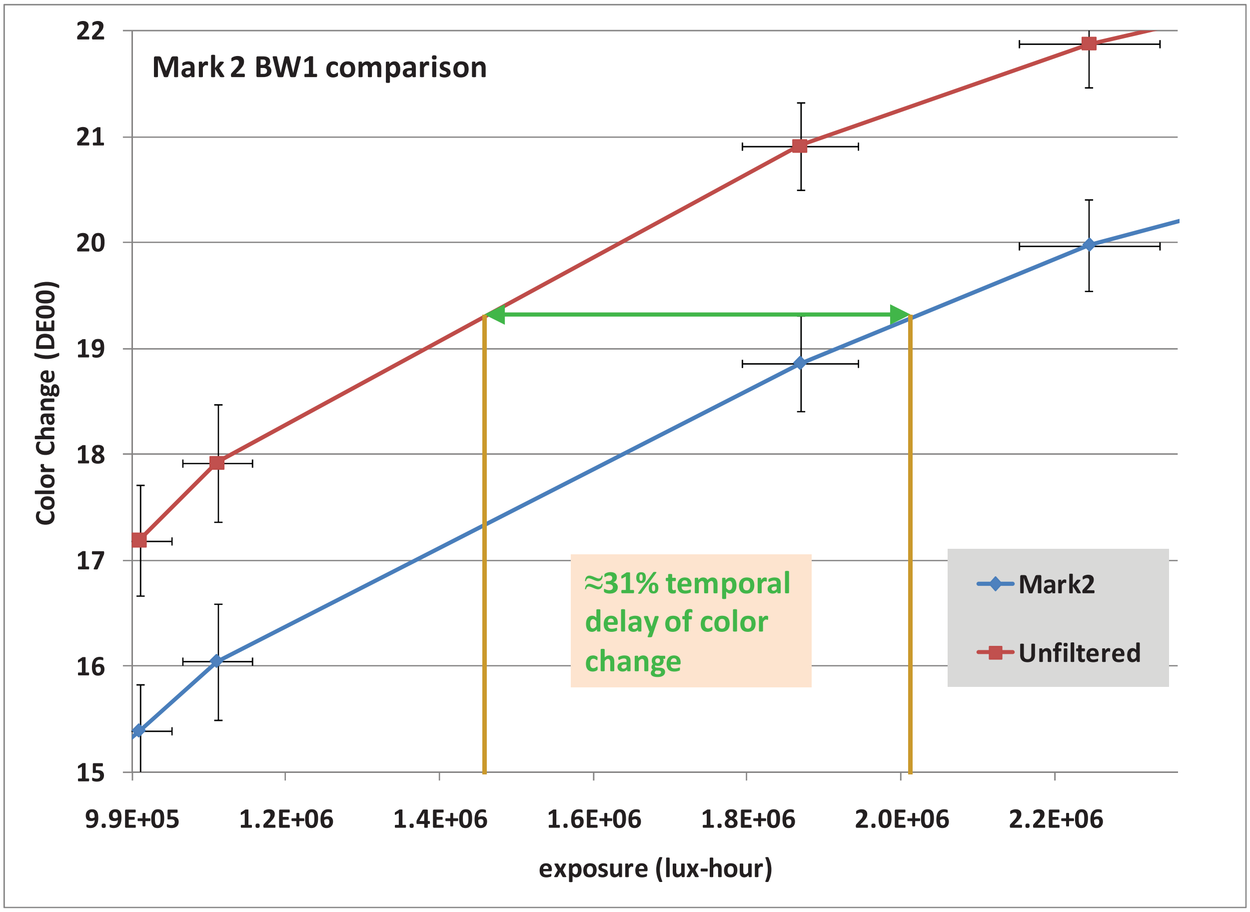

Mark 2 BW1 comparison
Color Change (DE00)
22
21
20
19
18
17
16
15
9.9E+05
1.2E+06
1.4E+06
1.6E+06
1.8E+06
2.0E+06
2.2E+06
exposure (lux-hour)
≈31% temporal delay of color change
Mark2
Unfiltered

Figure 6.58

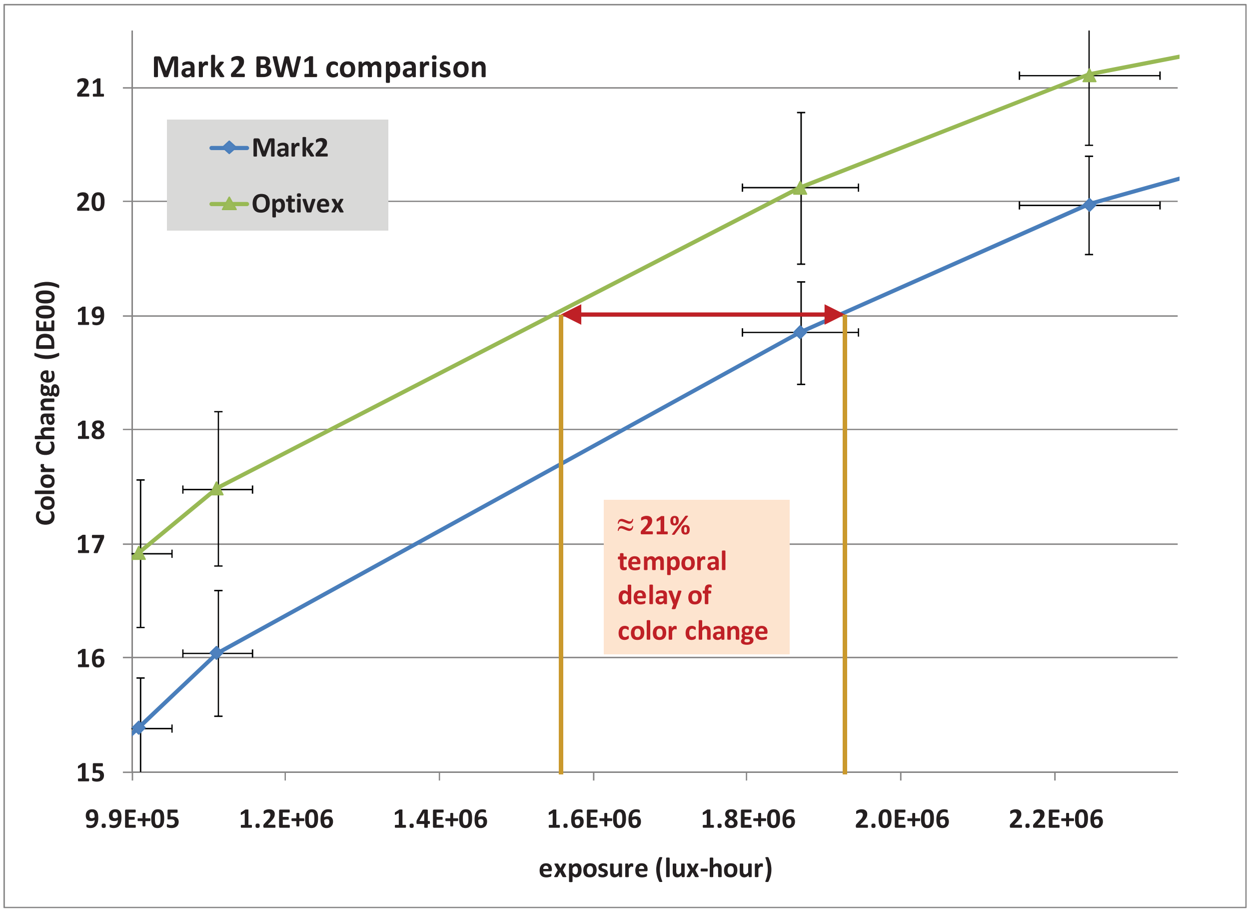


Figure 6.59

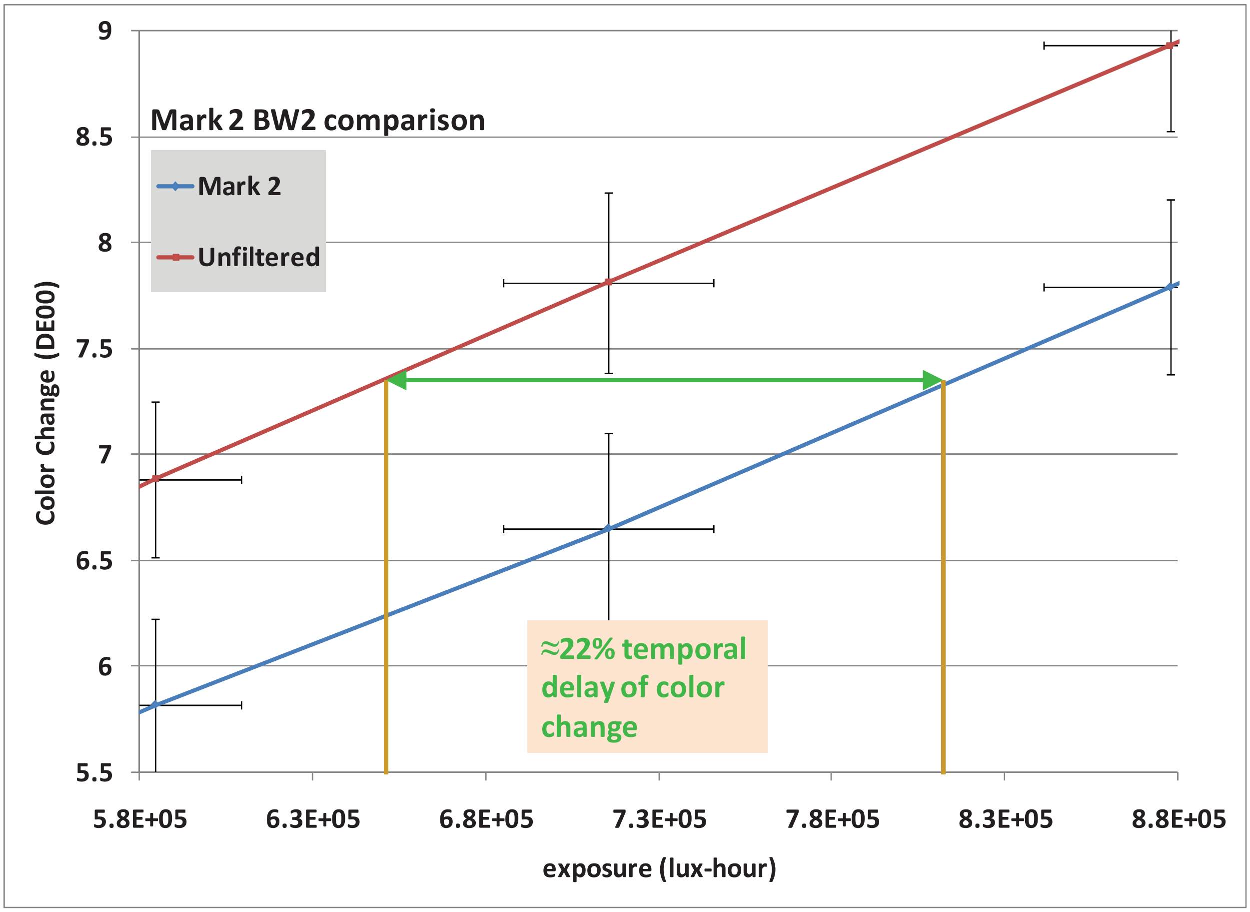
The earliest BW1 delay data was determined at 5.6E5 lux-hours, the second set was determined at 1.7E6 lux-hours. Data was also collected for 2.5E6 lux-hours.

This data is supplied in Table 6.5

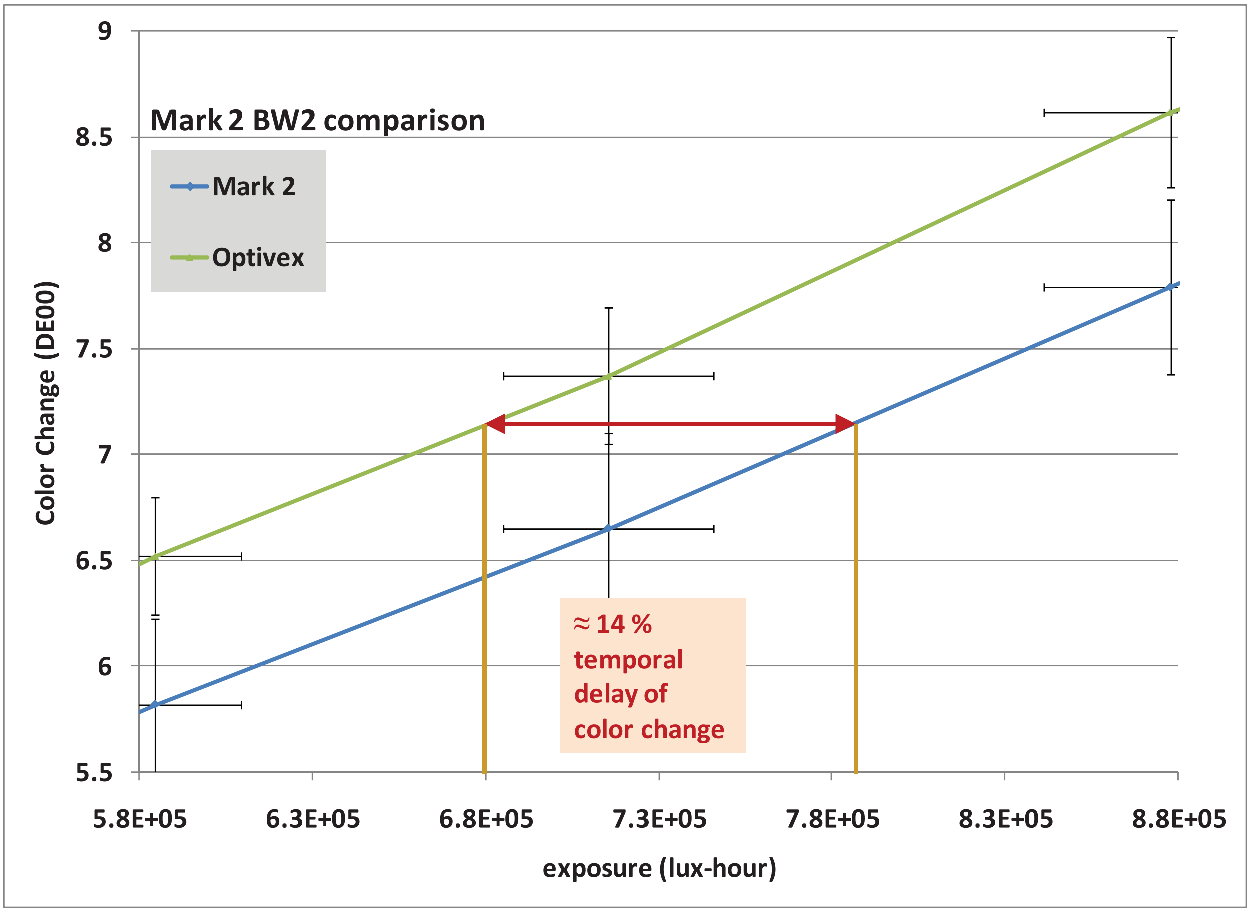
Table 6.5

BW1	lux hours	delay Mark2 Unfiltered	delay Mark2 Optivex®
	560000	21%	16%
	1.70E+06	31%	21%
	2.50E+06	41%	25%

A similar analysis of BW2 is shown in Figures 6.60-6.63, and same type of increase in temporal delay in fading is seen.


Mark 2 BW2 comparison
Mark 2
Unfiltered
Color Change (DE00)
9
8.5
8
7.5
7
6.5
6
5.5
5.8E+05
6.3E+05
6.8E+05
7.3E+05
7.8E+05
8.3E+05
8.8E+05
exposure (lux-hour)
≈22% temporal delay of color change

Figures 6.60


9
8.5
8
7.5
7
6.5
6
5.5
Mark 2 BW2 comparison
Mark 2
Optivex
Color Change (DE00)
≈ 14 %
temporal
delay of
color change
5.8E+05
6.3E+05
6.8E+05
7.3E+05
7.8E+05
8.3E+05
8.8E+05
exposure (lux-hour)

Figures 6.61

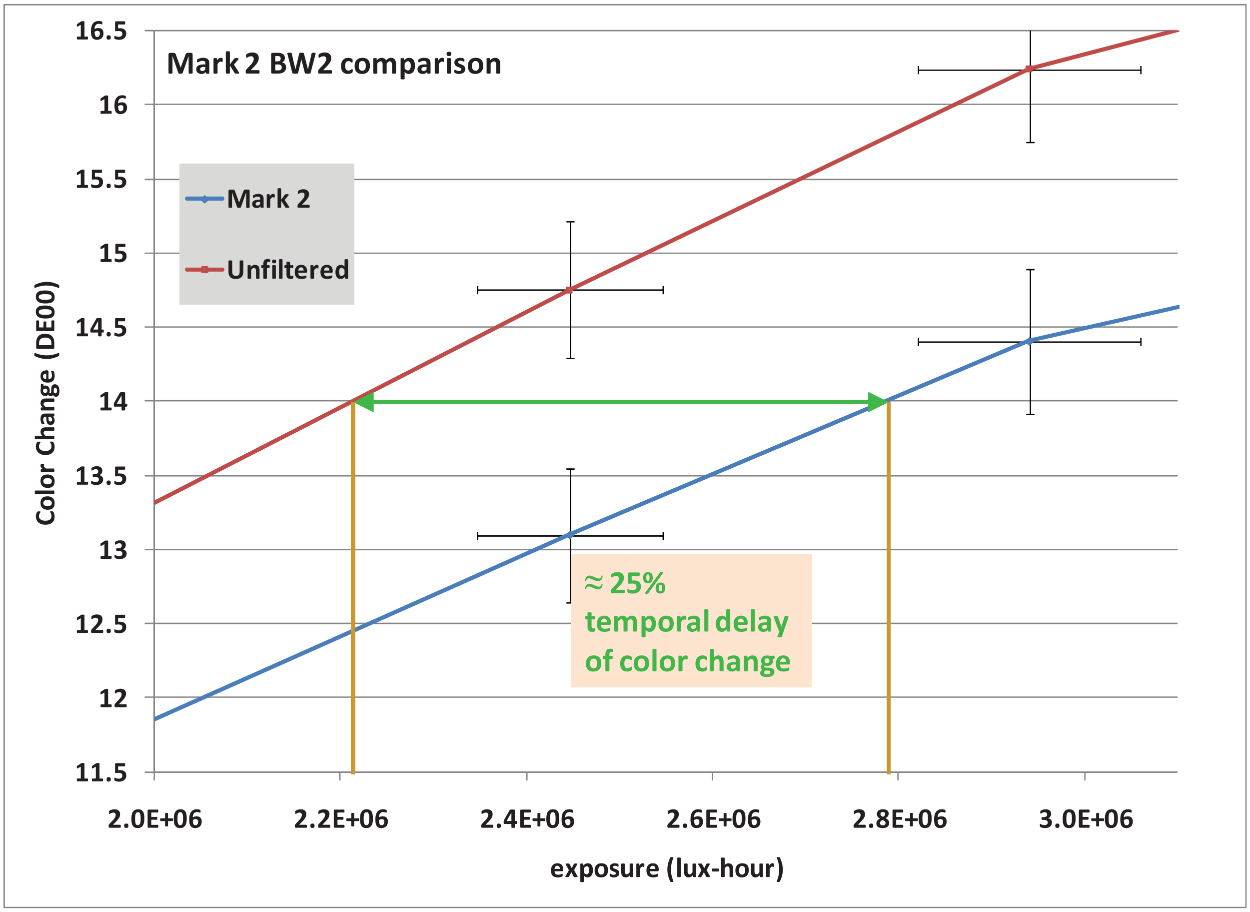

Mark 2 BW2 comparison
Mark 2
Unfiltered
≈ 25%
temporal delay
of color change
Color Change (DE00)
16.5
16
15.5
15
14.5
14
13.5
13
12.5
12
11.5
2.0E+06
2.2E+06
2.4E+06
2.6E+06
2.8E+06
3.0E+06
exposure (lux-hour)

Figure 6.62

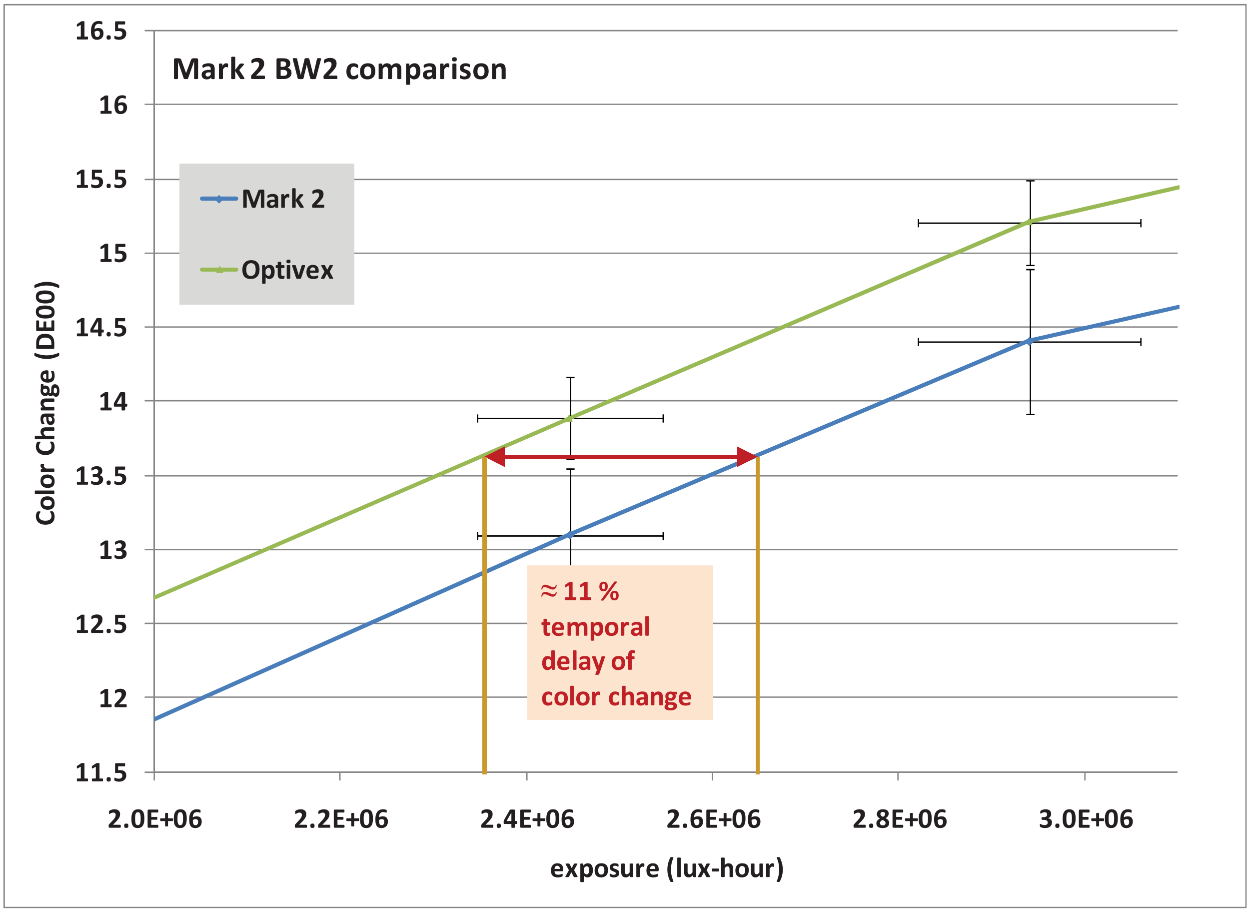


Figure 6.63

All fading data has the same apparent functional form, and it should be reasonable to generalize that fading curves which are significantly separated from each other will predict significant fading delays relative to one another. As can be seen in Table 6.6; the fading delay increases as one temporarily progresses through the fade. This is a thought provoking result, because it implies:

1) The effect of filtration improves as the object ages.

2) Older, already heavily faded works of art would profit by engineered light filtration.

Table 6.6

BW2	lux hours	delay Mark2 Unfiltered	delay Mark2 Optivex®
	560000	22%	14%
	1.70E+06	25%	11%

It can be understood, at least for the data presented here, that the Mark 2 filter is outperforming the Optivex® filter.

A plot of the data from Table 6.6 is shown in Figure 6.64

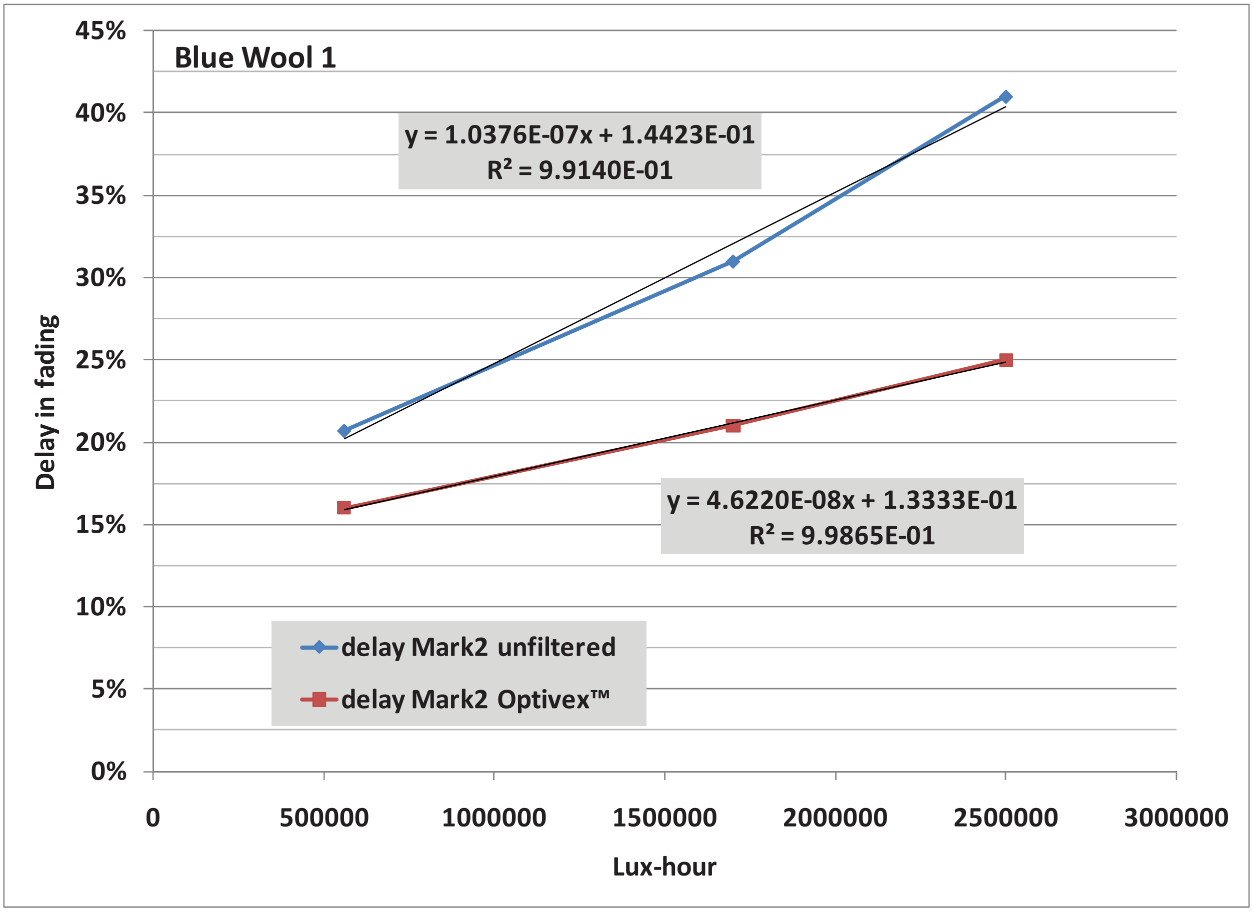


Figure 6.64

As can be seen in this Figure, the delay in fading is linearly related to the exposure in lux-hours. One can use this information to predict the delay that would be experienced in the future. For example, presuming that just the last 100 years, Da Vinci's *Mona Lisa* has had an 18M Lux-hour exposure (8 hours x 6 days x 52 weeks x 100 years x average of perhaps ≈75 lux). If it's fading curve followed BW1 (just for example), placing the Mark 2 filter instead of using Unfiltered light would now delay fading by at least 100%.

The linear plots in Figure 6.64 suggest another finding. Linear changes in rate imply exponential decays in color. If an exponential function is fitted to the Mark 2 BW1 data, the fit is reasonably good. The t-infinity color change is 20.45 DE00 units, and the exponential decay constant is 1.62E-6 $lux^{-1}hous^{-1}$.

ISO Blue Wool 1 is prepared from a single dye (Acid Blue 104[56]), and should exhibit a single exponential decay for fading, and the result in Figure 6.65 is indeed reasonably close to a single exponential fit. However, some of the fit is outside the experimental error bars. Therefore, it was decided to try a two-exponential fit. This is shown in Figure 6.66.

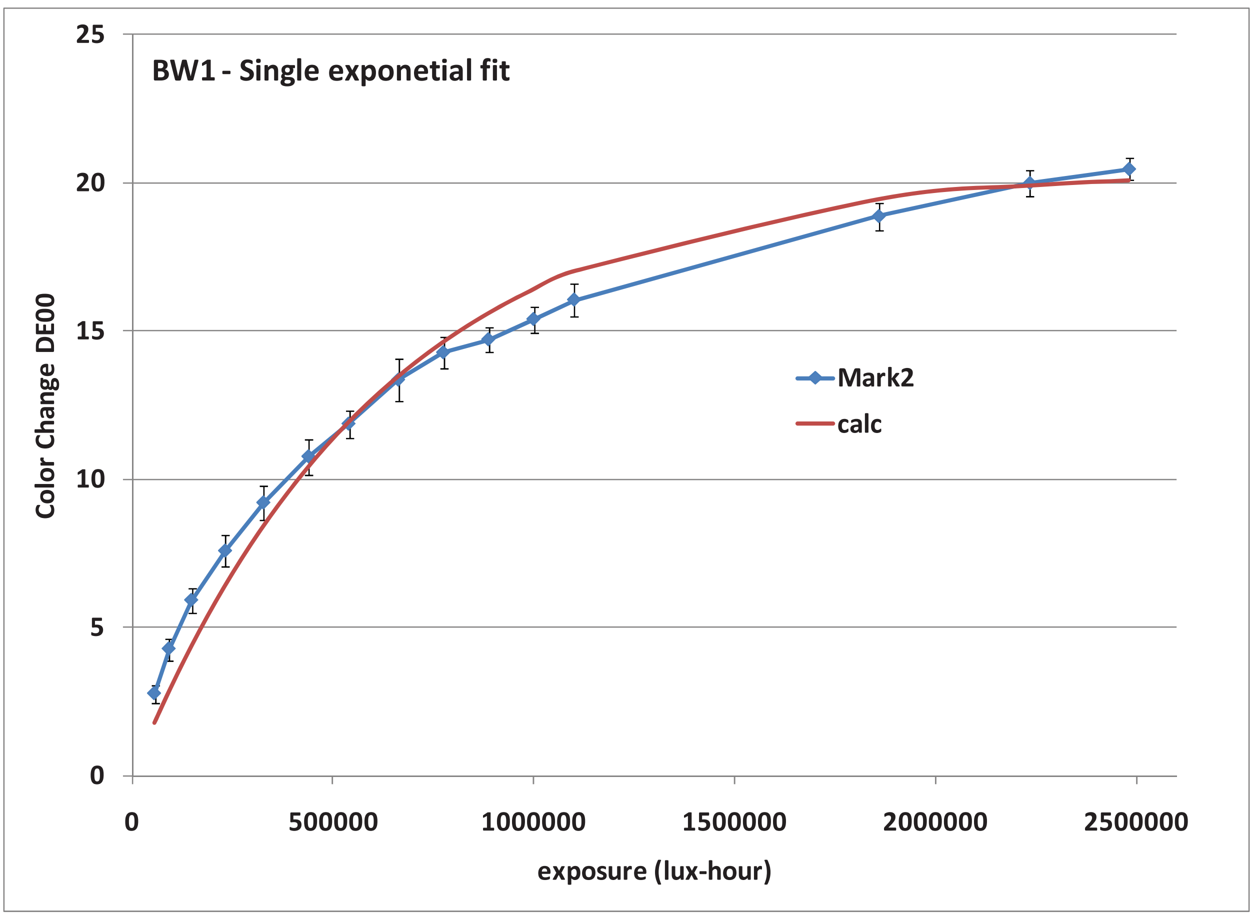


Figure 6.65

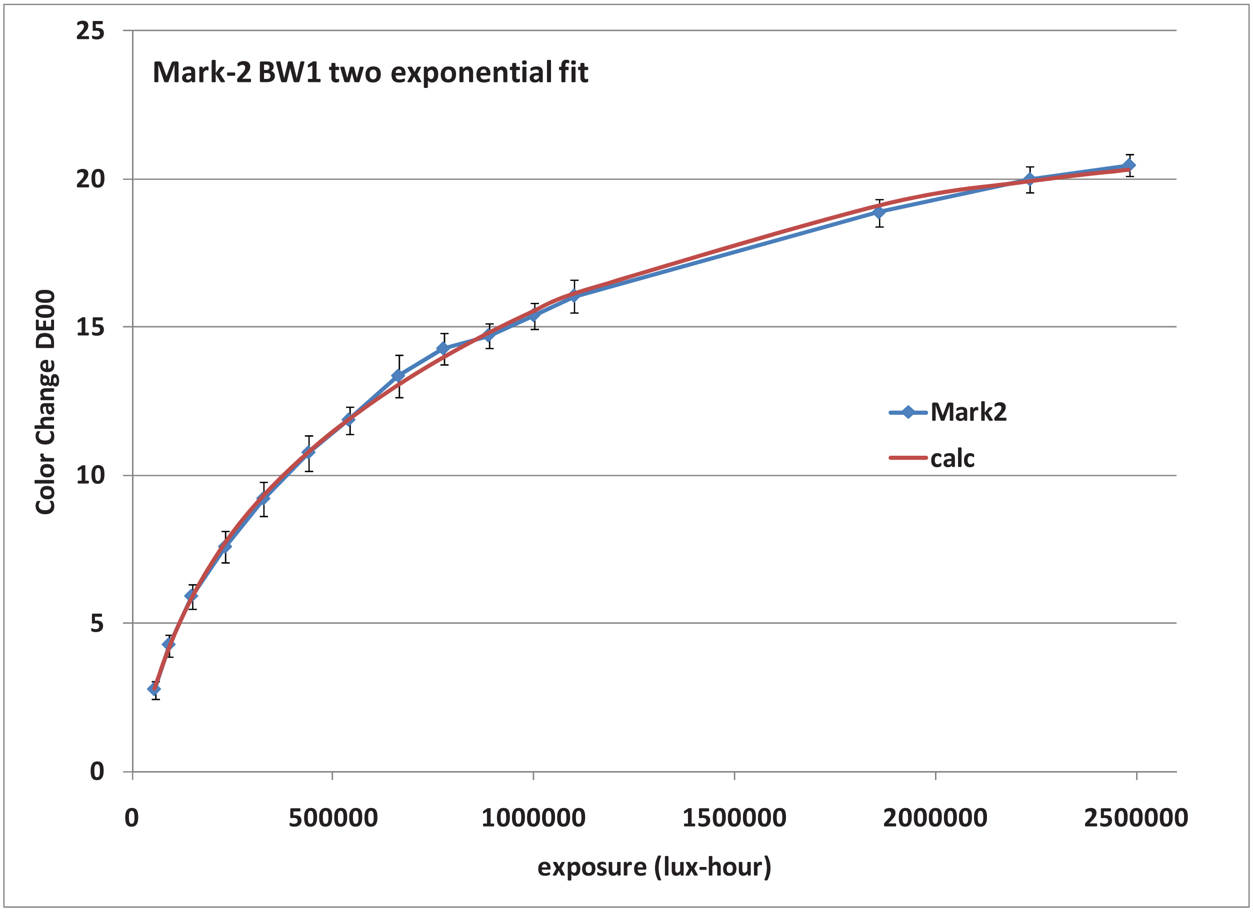


Figure 6.66

Similar fits for the Optivex® and Unfiltered fading are shown in Figures 6.67, 6.68. The general equation for the fit is given by:

$$DE00 = DE00_{\infty}(1 - A1\exp(k1 * l) - A2\exp(k2 * l))$$

where $DE00_{\infty}$ is the color change at infinite exposure, l is the exposure in lux hours, $A1$ and $A2$ are the fraction of the respective components, and $k1$ and $k2$ are the exposure rate constants in $lux^{-1}hour^{-1}$. The parameters for each fit (along with fitting uncertainties in italics are given in Table 6.7. Fitting uncertainties were estimated by Monte Carlo simulation of the equations with the condition to

remain within the experimental DE00 error bars. Typically, 20,000 Monte Carlo cycles reached a point of no further significant change in uncertainties.

Table 6.7

	Mark2	Unfiltered	Optivex®
$DE00_\infty$	21.72(+0.98,-0.86)	23.25(+1.22,-0.76	22.98(+0.29,-1.42)
A1	22.6(+9.4,-10.6)%	19.9(+9.5,-8.8)%	28.4(+6.3,-17.8)%
A2	77.4(+10.6,-9.4)	80.1(+8.8,-9.5)%	71.6(+17.8,-6.3)%
k1	0.85(+1.1,-0.03)E-6	1.0(+1.6,-0.35)E-5	0.6(+1.7,-0.08)E-5
k2	1,0(+0.28,-0.2)E-7	1.2(+0.3,-0.2)E-7	9.9(+5.1,-1.0)E-7

As can be seen from Table 6.7, the error bars for *k1*or *k2* overlap throughout. The set of Mark 2, Unfiltered, and Optivex®, which verifies that the fading rate constants are indistinguishable across the set. The error bars for *k1*are much larger than for *k2*. However, the error bars for the two rate constants do not overlap, suggesting that there may be two component contributions to the ISO BW1 fading in this study. The error bars for the % contribution of these two rate constant components are narrow enough to support the inference of two fading components. These results are inconsistent with this system as being known to be a single component dye. It is possible that other contributions, such as the gradual attenuation of the lamp output with time might be contributing to this, but this hypothesis would remain to be proven.

The $DE00_\infty$ differ between Mark 2, Unfiltered, and Optivex®. The Mark 2 value is the smallest and differs from Unfiltered by 1.53 DE00 units and from Optivex® by 1.26 DE00 units. The error bars for these parameters overlap, but not greatly. It is possible that the $DE00_\infty$ values differ significantly. This would be an important result, because it would suggest that the presence of a filter not only adjusts the rate of change of color change, but also the end point to which a material would change. Note that for older faded objects, the filter displays its greatest rate attenuation effect, while filtering new unaged objects are also benefited by adjusting the final end point to which the object might fade. Therefore, beneficial filtration of any kind would be highly recommended at any point in the life of the object. These results and this inference needs to be investigated with further research.

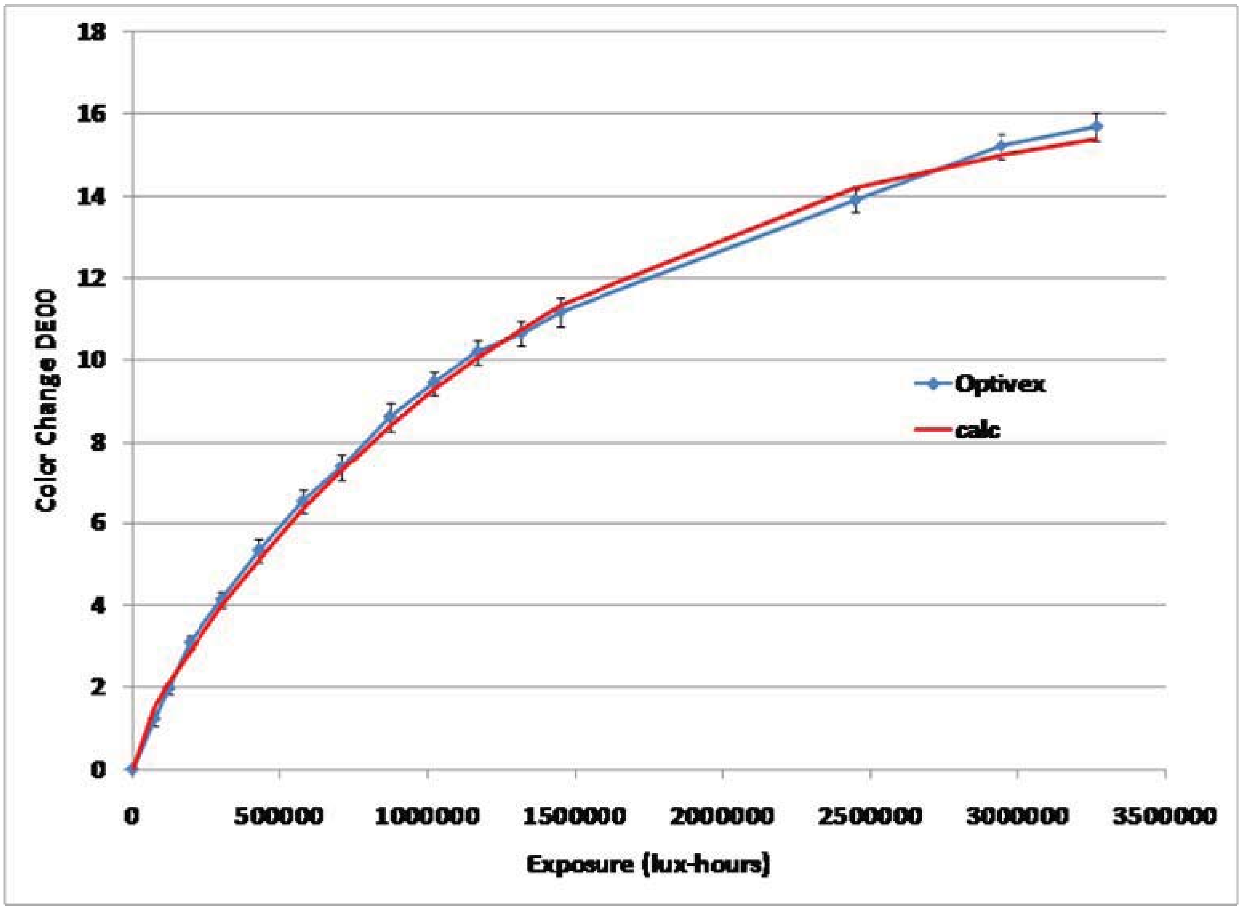
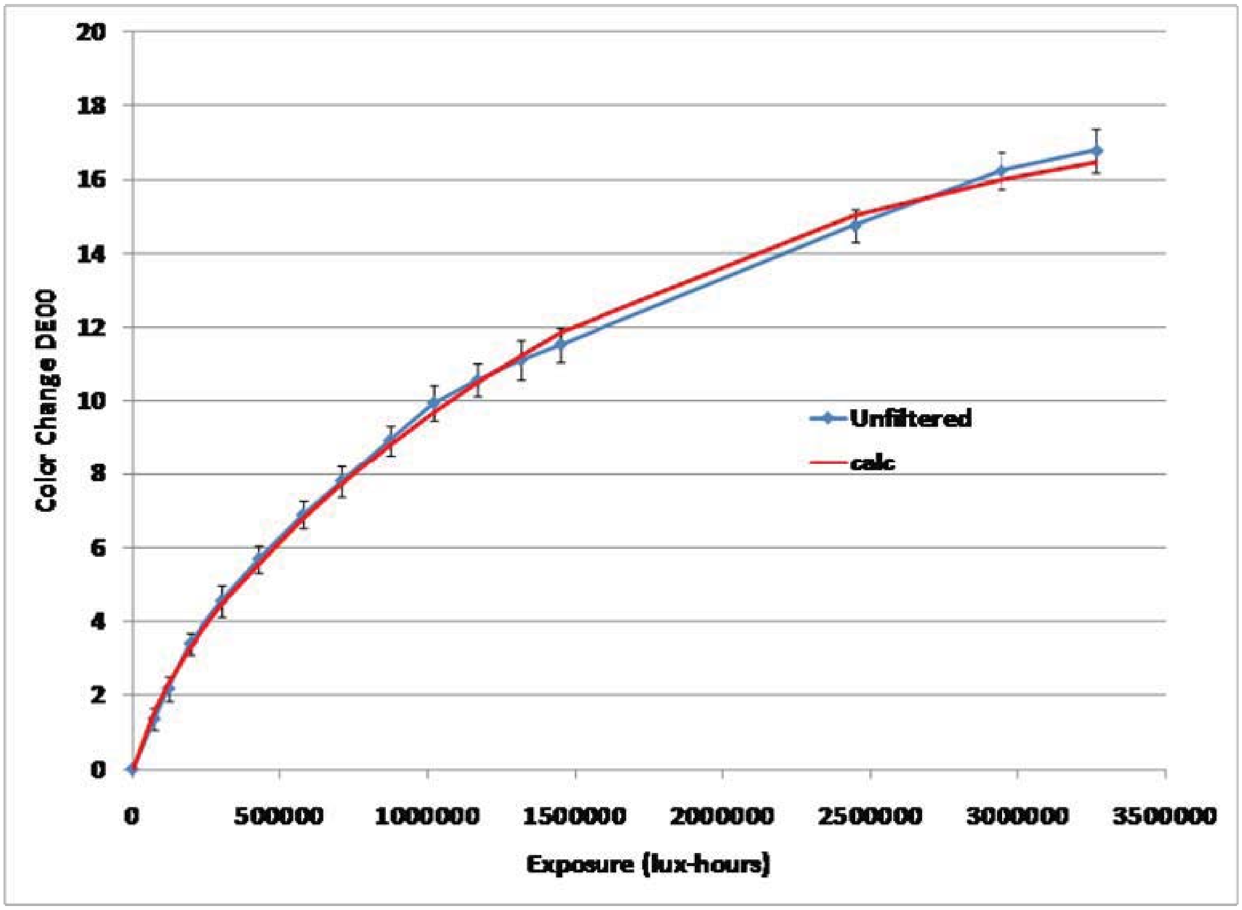

18
16
14
12
10
8
6
4
2
0
Color Change DE00
Optivex
calc
0
500000
1000000
1500000
2000000
2500000
3000000
3500000
Exposure (lux-hours)

Figure 6.67



20
18
16
14
12
10
8
6
4
2
0
Color Change DE00
Unfiltered
calc
0
500000
1000000
1500000
2000000
2500000
3000000
3500000
Exposure (lux-hours)

Figure 6.68

6.7.2 Some additional Fading Data

Fading experiments have been underway at the Getty Conservation Institute as well as at UTEP. Provided below there are a limited sample of some of these results for Alizarin Crimson Watercolor (ACW), Rose Tyrien, Tumeric, and ISO Blue Wool 1, Blue Wool 2 & Blue Wool 3. All of these results involve the testing of the Mark 3 filter versus Optivex®. This is illustrated in Figures 6.69 to 6.72.

Mark 3 is more beneficial than Optivex® for all of these results. In terms of significance, ACW, Rose Tyrien, and the early exposure data for Tumeric are Type 2 as defined above. There is not a significant difference between Optivex® and Mark 3. The latest part of the Tumeric data is of Type 3 significance, with Mark 3 significantly outperforming Optivex® by a small value.

Blue Wool data was not collected for Mark 3 in any UTEP study, but is reported here for work done at GCI. For all three, the Mark 3 filter is significantly more beneficial than Unfiltered. Note in Figure 6.69, that Mark 3 also shows the significant delay in fading relative to Optivex®.

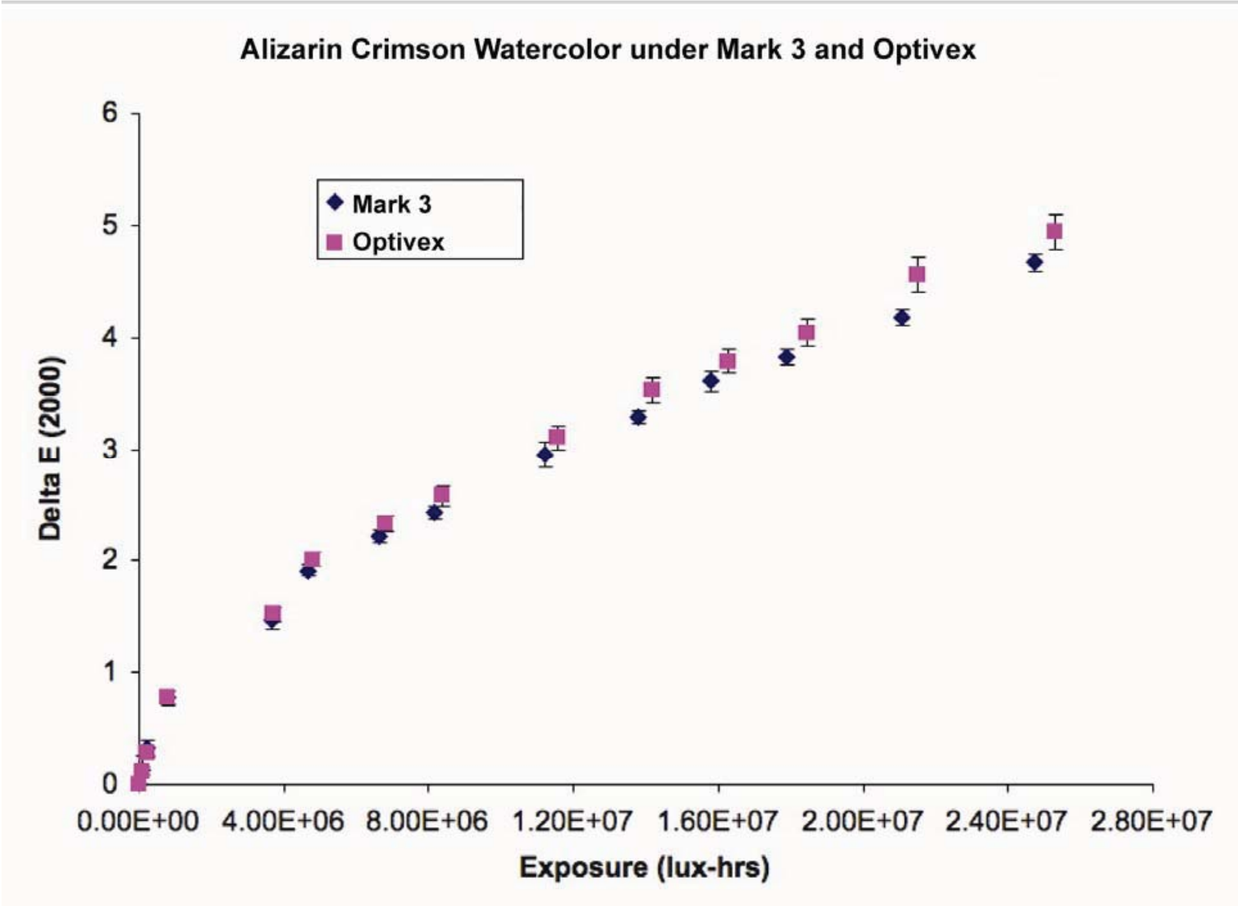

Alizarin Crimson Watercolor under Mark 3 and Optivex
Mark 3
Optivex
Delta E (2000)
0
1
2
3
4
5
6
0.00E+00
4.00E+06
8.00E+06
1.20E+07
1.60E+07
2.00E+07
2.40E+07
2.80E+07
Exposure (lux-hrs)

Figure 6.69

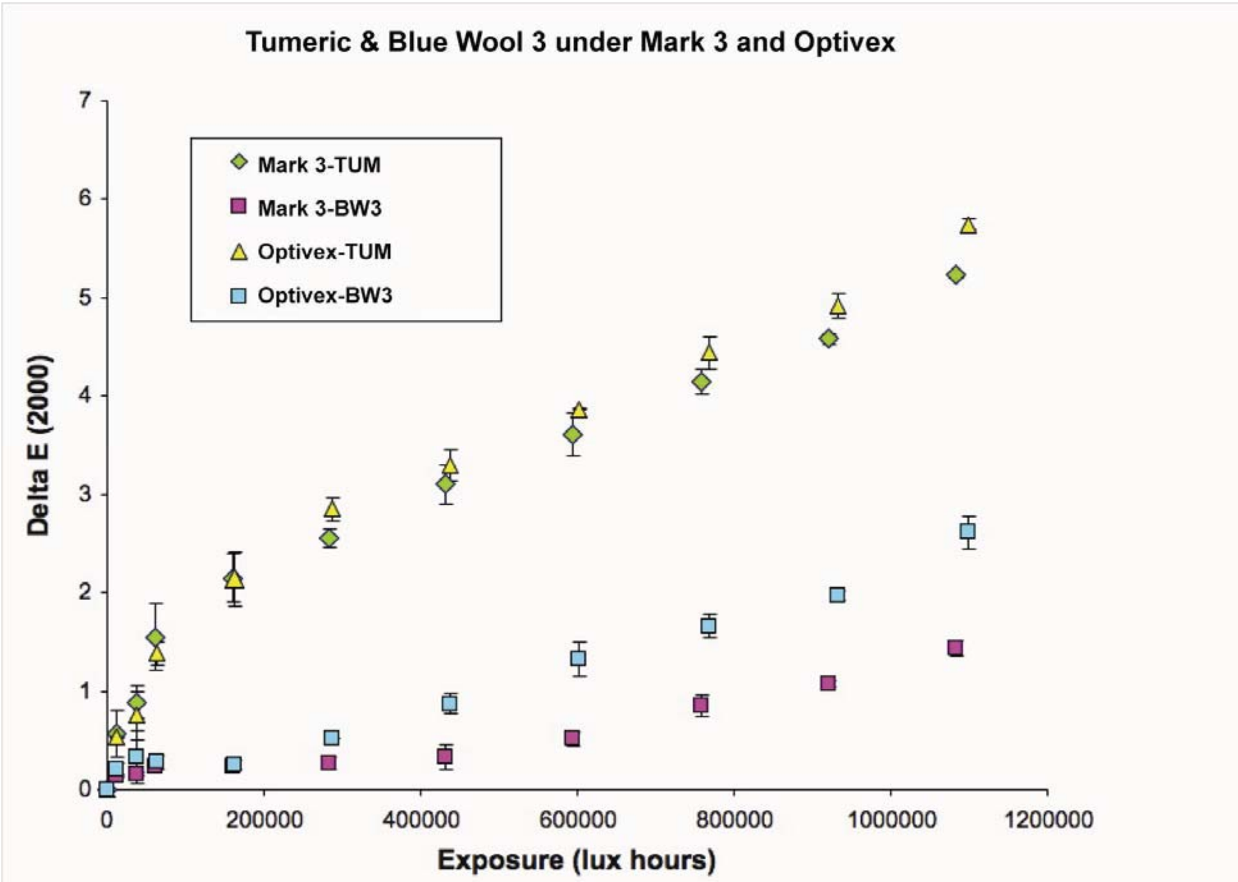
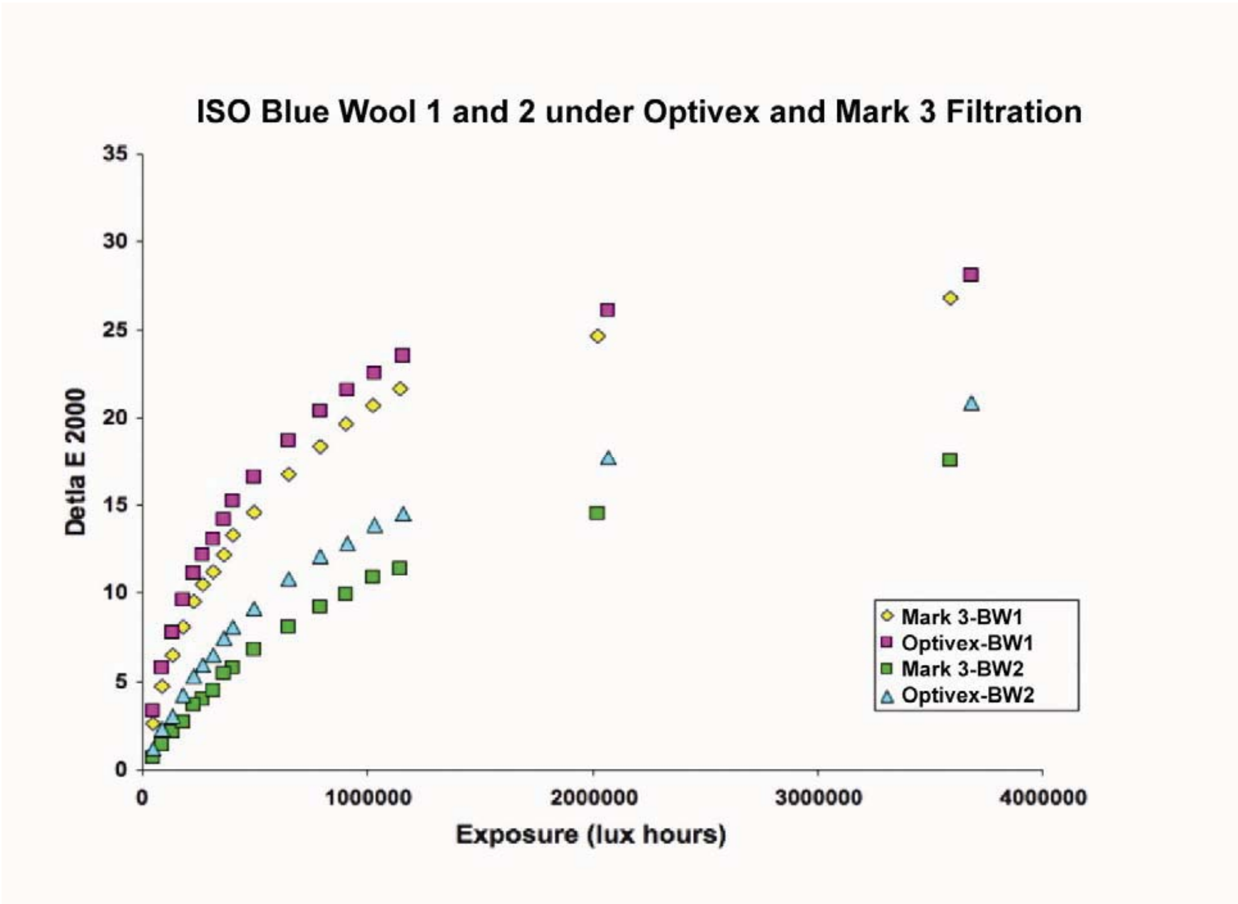

Tumeric & Blue Wool 3 under Mark 3 and Optivex
Mark 3-TUM
Mark 3-BW3
Optivex-TUM
Optivex-BW3
Delta E (2000)
Exposure (lux hours)
0
1
2
3
4
5
6
7
0
200000
400000
600000
800000
1000000
1200000

Figure 6.70



ISO Blue Wool 1 and 2 under Optivex and Mark 3 Filtration
Detla E 2000
Exposure (lux hours)
0
5
10
15
20
25
30
35
0
1000000
2000000
3000000
4000000
Mark 3-BW1
Optivex-BW1
Mark 3-BW2
Optivex-BW2

Figure 6.71

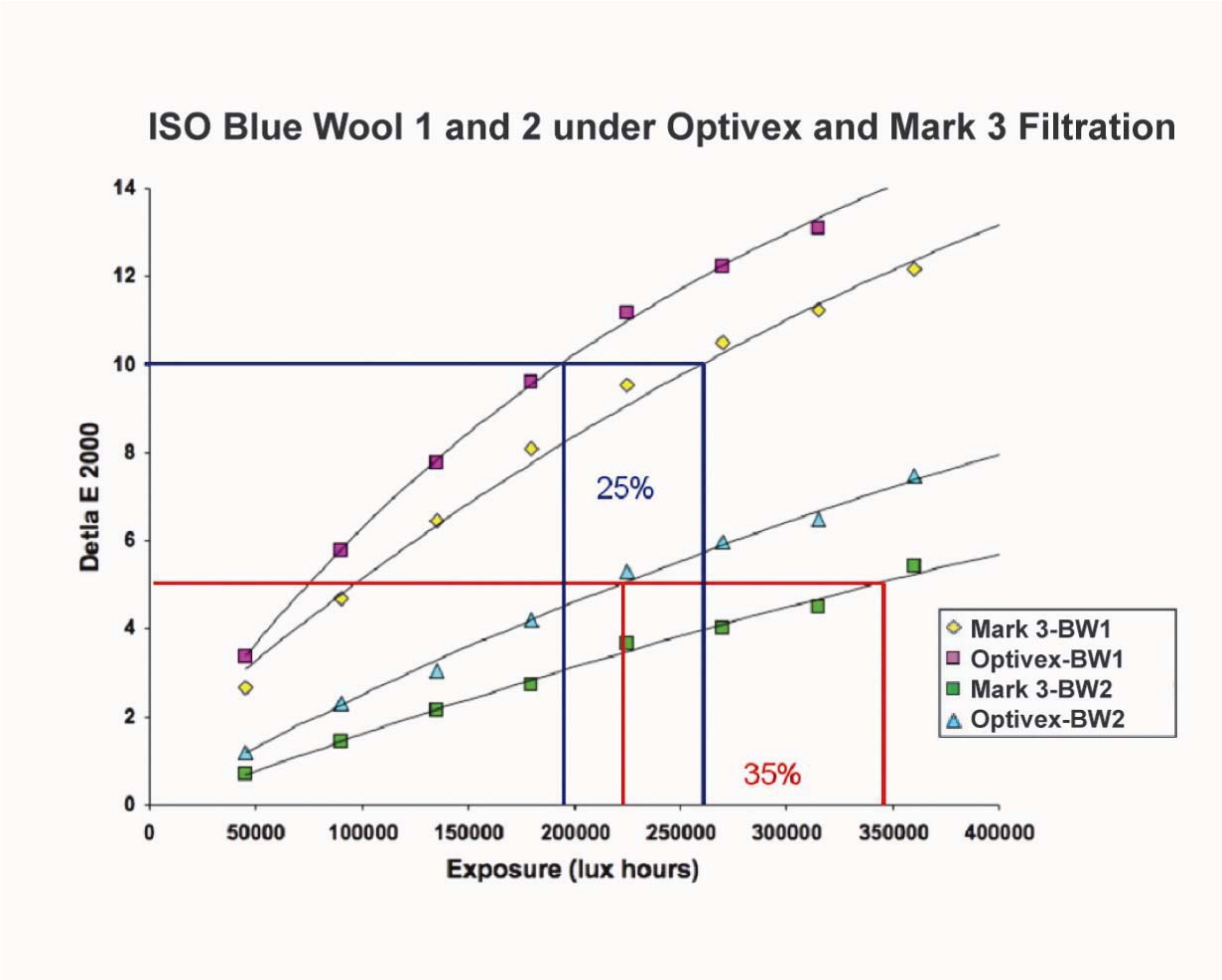

ISO Blue Wool 1 and 2 under Optivex and Mark 3 Filtration
Detla E 2000
Exposure (lux hours)
0
2
4
6
8
10
12
14
0
50000
100000
150000
200000
250000
300000
350000
400000
25%
35%
Mark 3-BW1
Optivex-BW1
Mark 3-BW2
Optivex-BW2

Figure 6.72

6.8 Human Trials

The filters designed and presented here are only so good as they provide lighting that is acceptable to human subjects. Consequently, human evaluation studies were initiated to under the efficacy of the filters for lighting. The initial work was begun using Mark 1, though this filter was a prototype to work out design and manufacturing methods, rather than as to provide aggressively beneficial lighting to halt photochemistry. Still the Mark 1 filter is probably as good as any other filter available prior to creation of the Mark 2 and Mark 3.

Mark 1, Mark 2, and Mark 3 differ not only in spectral profile of transmission, but also in angle dependence for color rendering. As shown above in Figure 6.8, Mark 1 has a beam angle dependence which is comparable to the Unfiltered lamps. Mark 2 may display some color aberrations with broad beam angle lamps, while Mark 3 could be the most problematic and may display color rendering aberrations with medium beam angle lamps. For this work, the SOURCE lamp used as lighting behind all of these filters was the Sylvania 58533 lamp with a beam angle of 40°. This is a medium beam angle lamp. For all three filters, no peripheral (along the outside perimeter of the beam) aberration was ever commented by observers at UTEP.

Filters were designed with a specific reference in mind primarily so that direct testing could be made of the efficacy of the design and manufacturing

protocol to simulate a given lighting. In other words, how precisely can one depend on the color and vision theory and filter design and manufacturing methods? For this reason, the basis of the data and discussion which follows is based on the premise that filters were designed to be perceived as not being significantly different than Unfiltered light. It is important to reiterate that the filtered lighting was designed to <u>exactly</u> match the characteristics of the reference Sylvania 58562 lighting. Comparisons are therefore relative to this reference.

All subjects were first tested with regard to their color vision. Results below include only those individuals who possessed adequate color vision. Color vision was tested using the HRR, Ishihara, L'anthony plate test, Farnsworth D15, and L'Anthony methods. In Table 6.8, are included the results for the HRR (plates 1-10), L'Anthony, and Ishihara (14 plate test) color vision tests. The HRR diagnostic plates (11-16) were also tested and these results are included in Appendix E but were not used to assess adequacy of color vision. The Farnsworth D15 and L'Anthony D15 disc test results are included in Table 6.9. Note that the HRR diagnostic tests were not fully implemented prior to subject #21 due to evolving changes in protocol. For subjects #1-23, the L'Anthony and Ishihara plate tests, and the Farnsworth and L'Anthony D15 disc tests were unavailable, though, however, some subjects who returned for testing on other filters were later tested

using some of these methods. Subjects 17 and 20 were children, and standard HRR protocol called for not testing with plates 12 and 13. However, plates 12 and 13 are part of the diagnostic component of the HRR test, and as stated above, are included in color vision assessment.

Table 6.8

Subject number	Age	HRR	Ishihara	L'Anthony
1	32	100	100	100
2	26	100	10	100
3	25	100		
5	24	100		
6	30	100		
7	37	100	100	80
8	58	100	100	20
9	66	100		
10	22	100		
11	42	100		
12	20	100		
13	19	100		
14	36	100		
15	26	100		
16	29	100		
17	13	100		
18	32	100		
19	27	100		
20	11	100		100
21	34	100		
22	47	100		
23	38	100		
24	19	100		100
25	50	100		100
27	46	100		80
28	54	100		100
29	22	100		100
30	48	90		100

31	64	100		80
32	28	100		100
33	24	100		100
34	38	90		100
35	22	100		100
36	35	100		100
37	32	100		100
38	35	100		100
39	20	100	100	100
40	24	100	100	100
41	42	100	100	100
42	23	100	100	100
43	28	100	100	100
44	24	100	100	100
45	58	100	100	100
46	41	100	100	100
47	40	100	100	100
50	21	100	100	100
51	48	100	100	100
52	22	100	92.85	100
53	31	100	100	100
54	22	100	100	100
55	33	100	100	100
56	22	100	92.85	100
57	34	100	100	100
58	26	100	100	100
59	24	100	92.85	100
60	23	100	100	100
61	26	100	92.85	100
62	38	100	100	100

Table 6.9

Subject Number	Farnsworth D15 (CCI)	Diagnosis	L'Anthony D15 (CCI)	Diagnosis
1	1	normal	1.157	normal
2	1	normal	1	normal
3				
5				
6				
7	1.305	normal	1	normal
8	1	normal	1	normal
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				

37				
38				
39	1.34	unclassified	1.088	normal
40	1	normal	1.071	normal
41	1	normal	1	normal
42	1	normal	1	normal
43	1	normal	1.071	normal
44	1	normal	1	normal
45	1	normal	1	normal
46	1	normal	1.088	normal
47	1	normal	1.209	normal
50	1	normal	1	normal
51	1	normal	1	normal
52	1	normal	1	normal
53	1	normal	1	normal
54	1	normal	1	normal
55	1	normal	1	normal
56	1	normal	1	normal
57	1	normal	1	normal
58	1	normal	1	normal
59	1	normal	1	normal
60	1	normal	1	normal
61	1	normal	1	normal
62	1	normal	1	normal

Of the 62 individuals tested in this study, four were found to have inadequate color vision. Inadequacy was based on the following criteria:

1) An HRR score lower than 70% of correct symbol identification within plates 1-10.
2) More than one plate incorrectly identified for the Ishihara test.
3) For Farnsworth D15, a color confusion index (CCI) greater than 1.5 for unclassified or diagnoses other than normal.

4) For L'Anthony D15, a color confusion index (CCI) greater than 1.75 for unclassified or diagnoses other than normal.
5) A L'Anthony plate test result of more than one incorrectly identified plate unless the subject scores perfectly on the Farnsworth and L'Anthony D15 tests. In this regard, the L'Anthony D15 test is a perhaps a more subtle measure of blue/yellow color discrimination than the L'Anthony plate test. In addition, passing the diagnostic disc test suggested the subject would be suitable to undertake the same test under varied lighting. Note that only one subject (#8) passed the vision test under this exception.

Test results for filters (Mark 1, 2 &3) include the subject number. All subjects did not participate in the evaluation of all filters, though some subjects did participate in evaluating more than one filter.

Human evaluation testing fell into three topics or layers of testing:

1) Evaluating color rendering. This was based on the ability of the subject to arrange the discs of the Farnsworth and L'Anthony D15 tests under reference and filtered lighting.
2) Evaluating relative brightness. This was based on the subject's efforts to equalize the perceived brightness of two illuminants placed side by side. This evaluation was done using the brightness box equipment that is described in Appendix Q.

3) Subjective evaluation based on a questionnaire explained in Appendix I. The subjective analysis consisted of a series of evaluations questions. Note that one set of these questions were not included until subject #19.
    a. Evaluation of primary tristimulus color prevalence, red, green, blue
        i. This portion of the subjective evaluation was added with subject #19
    b. Evaluation consistent with Opponent color theory
        i. Either too blue to too yellow
        ii. Either too red or too green
    c. Brightness
    d. Detail
    e. Color rendering
    f. Overall satisfaction

Subjective testing was not comparative of the lighting, but evaluated individually with each lighting, and then results compared. In other words, side by side comparison of filtered and Unfiltered lighting was not done, but were each done separately.

6.8.1 Evaluation of Color Rendering by Color Confusion Index

Tables 6.10, 6.11 and 6.12 provide the color confusion index results for Mark 1, Mark 2, and Mark 3, respectively, for the Farnsworth and L'Anthony D15

tests. In each Table the results are included for filtered and reference lighting. Recall that a CCI=1 means perfect ordering of the colored discs, and that the L'Anthony test is a much more sensitive diagnosis than the Farnsworth test.

For all three filters, with either Unfiltered or filtered illumination, and for either the Farnsworth or L'Anthony disc tests, color confusion indices do not differ significantly from CCI=1. Thus, neither filtered nor Unfiltered lighting caused confusion in the perception of color rendering sufficient to significant disarrangement of discs. The L'Anthony results reflect somewhat more uncertainty in disc ordering than the Farnsworth results, but this is to be expected with the much more sensitive L'Anthony D15 test.

For most results, the filtered lighting gave a somewhat better (lower) CCI than the Unfiltered reference illumination. The only exception was for Mark 3 lighting where the very small insignificant difference is based on one subject (#1). For all results, however, this 'preference' for the filtered lighting based on CCI is an insignificant result. This, in terms of color rendering as interpreted through the use of color confusion, the filtered lighting of all three filters can be considered as not being different than the reference illumination.

Table 6.10

Subject Number	Farnsworth D15 Mark 1	Farnsworth D15 Reference	L'Anthony D15	L'Anthony D15 Reference
20	1	1	1	1
24	1	1	1	1
25	1	1		
27	1	1.09		
28	1	1	1.17	1.17
29	1	1.17	1.04	1.04
30	1	1	1.07	1.07
31	1	1.1	1.17	1.17
32	1	1	1.37	1.37
33	1	1	1	1
34	1	1.74	1.74	1.74
35	1	1	1	1
36	1	1	1.104	1.104
37	1	1	1	1
38	1	1	1.099	1.099

Table 6.11

Subject Number	Farnsworth D15 Mark 2	Farnsworth D15 Reference	L'Anthony D15	L'Anthony D15 Reference
1	1	1	1.297	2.13
2	1	1	1.097	1
7	1	1.271	1	1.192
8	1.209	1.097	1	1
39	1	1.123	1.071	1.192
40	1	1	1.104	1
41	1	1.08	1	1
42	1	1	1	1
43	1	1	1	1
44	1	1	1	1.071
45	1	1	1	1

Table 6.12

Subject Number	Farnsworth D15 Mark 3	Farnsworth D15 Reference	L'Anthony D15	L'Anthony D15 Reference
1	1.112	1.087	1.225	1.349
2	1	1	1.225	1.282
46	1	1	1	1.282
47	1	1	1.621	1.534
50	1	1	1	1
51	1	1	1	1
52	1	1	1	1
53	1	1	1	1
54	1	1	1	1
55	1	1	1	1
56	1	1	1	1
57	1	1	1	1
58	1	1	1	1
59	1	1	1	1
60	1	1	1	1.74
61	1	1	1	1
62	1	1	1	1

6.8.2 Brightness Evaluation

As discussed above, variation in the spectral distribution may cause a change in perceived brightness. A higher perceived brightness may imply that an illuminant is more efficient in its use of light as the human eye perceives it. A higher perceived brightness would imply that possibly less light could be used for illumination, which could contribute to lowering photochemical change. Each of the three filters was evaluated against the Sylvania 58562 reference illumination with regard to perceived brightness. Note that there are two

methods that one could consider:

1) Assessment of the brightness of the illuminant.
2) Assessment of the brightness of an object under illumination of the illuminant.

The second method is potentially a much more useful result, since it applies to how the illuminant actually influences the brightness of an illuminated object. However, this method is much more complex to implement. Measuring the reflected light off an object is subject to many errors of location of measurement probe, and variation in the color of the object can influence the result. For this reason, brightness evaluation at UTEP was confined solely to considering the first method. The second method was undertaken at the GCI ELF and that work remains to be completed.

The brightness discrimination apparatus and its operation are described in Appendix Q. The results for Mark 1, Mark 2, and Mark 3 are provided in Tables 6.13, 6.14 and 6.15, respectively. For all results, the first column is the set point of the reference and filtered lighting in lux before the subject attempts to adjust the filtered lighting. The second column is the result of the adjustment by the subject to match the perceived brightness. A higher value than the initial reference value would suggest the subject initially perceived the Unfiltered lighting as being brighter. For all three filters, on average, the subjects evaluated the filtered lighting as being fainter.

Table 6.13

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	150	179.3
2	26	150	204
3	25	150	210
5	24	150	179.2
6	30	150	202.9
7	37	150	149
8	58	150	172.1
9	66	150	175
10	22	150	217
11	42	150	198.7
12	20	150	200
13	19	150	140.9
14	36	150	146.7
15	26	150	184
16	29	150	137.8
17	13	150	192.7
18	32	150	152.8
19	27	150	155
20	11	150	207.8
21	34	150	201.3
22	47	150	205.4
23	38	150	250.3
24	19	150	192.5
25	50	150	200.5
27	46	150	195.6
28	54	150	173
29	22	150	191.3
30	48	150	225.3
31	64	150	157.4
32	28	150	213.4
33	24	150	208.5
34	38	150	231.8
35	22	150	194.3
36	35	150	158.6
37	32	150	172.3
38	35	150	157.4

Table 6.14

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	168	175
2	26	168	176
7	37	168	179.7
8	58	168	178.4
39	20	168	182
40	24	168	185.2
41	42	168	172.5
42	23	168	180.1
43	28	168	174
44	24	168	183
45	58	168	180

Table 6.15

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	168	181.3
2	26	168	175
46	41	168	186
47	40	168	171.5
48	80	168	179
49	77	168	152
50	21	168	183.8
51	48	168	175
52	22	168	180
53	31	168	177
54	22	168	183.5
55	33	168	181.7
56	22	168	173
57	34	168	153
58	26	168	163
59	24	168	172
60	23	168	165
61	26	168	168.5
62	38	168	170

The standard deviation, relative to the difference between the average set point and the reference point is high for the Mark 3 filter, offering a confidence limit of 52% that the set point is significant. For Mark 1, the relative standard deviation is again relatively high, with a confidence limit of 83%. The Mark 2 result has the highest confidence of 99%.

The experimental error in measurement of lux using the Oriel™ Goldilux™ meter is about 3-5%. For any of the filter brightness tests, three measurements are necessary, one to set the luminosity of the reference illuminant, one to match the filtered illuminant to the reference, and one to measure the outcome of the adjustment by the subject. Therefore, there is possibly as much as a 9-15% experimental error in this test. Including a 5% uncertainty in setting the reference and a 10% uncertainty in setting and then measuring the filtered light as adjusted by the subject, the confidence limits for distinguishable differences in brightness are reduced appreciably from those discussed in the previous paragraph. Including experimental uncertainty, the confidence limits for the Mark 1, Mark 2, and Mark 3 are 51%, 28% and 12%, respectively, for the Unfiltered light to be perceived brighter than the filtered light. With the possible exception of the Mark 1, this brightness analysis of the filtered light relative to an unfiltered reference can probably be assessed as inconclusive.

Future work on this question probably requires more accurate measurements, and probably should be done spectrographically, rather than with light meters. This is because the light meters have been designed with specific likely spectral distributions in mind, such as incandescent, sunlight, and fluorescent, while the filtered light can significantly depart from these distributions.

6.8.3 Subjective assessment of lighting

Subjects were asked to assess the lighting as to its affects on OMD print artwork. These findings were subjective, and as described above were not directly comparative between the Unfiltered and filtered lighting but an assessment for each of the lighting circumstances as a whole.

6.8.4 Evaluation of primary tristimulus color prevalence, red, green, blue

These results are provided in Tables 6.16, 6.17, 6.18 and 6.19 for the reference Mark 1, Mark 2, and Mark 3 filters respectively. In Table 6.20, are summarized the averages and standard deviations of the data from these tables.

Table 6.16

Subject Number	Red	Green	Blue
1			
1	4.1	2.1	1.8
1	3.1	2.7	3.1
2	0.7	1	1
2			
3			
4			
5			
6			
7			
7	2.3	3.4	2.56
8			
8	5.34	3.1	3.1
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19	3.1	1.75	1.73
20	4.21	3.23	4.11
21	3.27	2.57	2.72
22	2.78	0.1	0.1
23	2.87	2.8	3.35
24	2.91	2.78	2.75
25	4.2	2.68	2.65
26	4.44	0.2	0.17
27	3.05	3.4	3.12
28	0.1	0.1	0.1
29	2.57	2.5	2.48
30	2.62	0.05	0.05
31	2.85	2.8	2.8
32	1.08	0.05	0.05

33	2.9	3.2	2.9
34	2.57	0.39	0.39
35	2	0.05	4.3
36	4.15	0.57	1.1
37	4.15	1.1	0.27
38	3.12	0.62	0.48
39	2.45	0.22	0.5
40	3.8	2.1	2.75
41	4.5	2.75	2.75
42	3.25	2.85	2.94
43	3.74	0	0
44	2.75	0	0
45	3.3	1.5	2.75
46	3.12	2.65	2.77
47	2.4	1.55	0.2
48	3.35	2.15	2.15
49	1.25	1.25	3.2
50	3.57	0.95	0.25
51	3.8	0.25	1
52	2.8	3	2.8
53	2.75	2.75	2.75
54	2.65	0.45	2.35
55	3	0.5	5.2
56	4.4	0	1.82
57	2	4.25	3.6
58	2.7	0.45	0.45
59	1.7	1.6	1.83
60	2.45	1.3	0.3
61	3.52	3.1	1.92
62	0.1	0.1	0.1

Table 6.17

Subject Number	Red	Green	Blue
19	1.49	3.76	3.99
20	3.6	2.79	3.83
21	3.14	2.7	2.68
22	2.75	0.1	0.1
23	2.85	2.86	2.79

24	4.68	0.48	0.43
25	2.52	2.68	2.62
27	4.44	0.2	0.17
28	4.2	4.17	3.77
29	0.1	0.1	0.1
30	2.57	2.5	2.48
31	2.08	0.05	0.05
32	4.77	2.8	2.8
33	4.4	0.05	0.05
34	2.9	3.2	2.9
35	2.57	0.39	0.39
36	4	0.05	1.2
37	4.42	0.72	1.3
38	3.15	1.85	0.42

Table 6.18

Subject Number	Red	Green	Blue
1	2.9	2.5	1.8
7	3.5	0.65	2.4
8	2.75	2.75	2.75
39	1.9	0.75	1.1
40	3.8	2.75	2.75
41	5.35	2.75	2.75
42	1	3.9	0
43	0.84	0	0
44	5.5	0	0
45	4.34	1.2	1.15

Table 6.19

Subject Number	Red	Green	Blue
1	3.54	2.94	2.7
2	4	1	1
46	2.77	2.85	2.55
47	3.2	2	0.2
48	3.35	2.75	3.3

49	2.87	2.87	2.87
50	3.1	2.25	0.25
51	2.75	1	0.1
52	2.8	2.8	2.8
53	5.2	2.75	2.75
54	5	2.5	3.77
55	2.5	0.15	5.5
56	2.8	0	2.3
57	4.64	1.65	3.62
58	5.15	0.35	2.75
59	3.1	2.75	2.75
60	3.8	1	1.2
61	3.8	3.1	2.4
62	2.85	0.1	0.1

Table 6.20

		Red	**Green**	**Blue**
Reference	**average**	**2.92**	**1.62**	**1.86**
	STDEV	1.06	1.28	1.39
Mark1	**average**	**3.18**	**1.67**	**1.71**
	STDEV	1.20	1.45	1.45
Mark 2	**average**	**3.19**	**1.73**	**1.47**
	STDEV	1.63	1.37	1.18
Mark 3	**average**	**3.59**	**1.72**	**2.16**
	STDEV	0.91	1.13	1.50

Note that standard deviations are large enough that much of the data cannot be considered significantly different. In the discussion that follows, this must be kept in mind. Confidence limits for data comparisons will be presented with the subsequent discussion.

For all three filters, and the Unfiltered reference, the sensation of red is ranked higher than that of green or blue. The confidence limits for these comparisons are given in Table 6.21. The confidence limits for the ranking of the red sensation over the blue or green sensation is higher than for blue or green over each other.

Table 6.21

	Red – Green difference confidence	Red – Blue difference confidence	Green – Blue difference confidence
Reference	42%	33%	7%
Mark 1	43%	42%	1%
Mark 2	37%	46%	8%
Mark 3	64%	45%	13%

However, the OMDs chosen for this study predominantly included red pigmentation to a dominant extent, and so the predominance of the red sensation might be expected.

In Table 6.22, the confidence limits for the comparison of red, green, and blue sensations of the filter compared to that of the reference are presented.

Table 6.22

	Confidence limits of red difference between reference and filter	Confidence limits of green difference between reference and filter	Confidence limits of blue difference between reference and filter
Mark 1	9%	1%	4%
Mark 2	8%	3%	12%
Mark 3	27%	3%	8%

The confidence level is low that the reference and filters are different in perception of predominance of colors. However, note that for the comparison of Mark 3 and the reference, the confidence is perhaps much higher that they could be perceived as being different with regard to the perception of red. Still, the confidence values are so low, even for the value of 27%; one could state that all filters are perceived as being indistinguishable from Unfiltered reference light.

6.8.5 Subjective evaluation results 3b-3f

The individual, average and standard deviations of the raw results for the subjective evaluation, parts 3b-3f are presented in tables 6.23, 6.24, 6.25 and

6.26 for the reference, Mark1, Mark 2, and Mark 3, respectively. Prior to delving deeply into the analysis of this data with respect to confidence of differences between the reference and filtered illuminants, we need to address what may be a systematic error within the results.

The subjective evaluation questionnaire instrument was set up to evaluate Blue/yellow and red/green opponent preference, darkness/brightness preference, good or bad color rendering preference, low or high perception of detail preference, and overall satisfaction or dissatisfaction with the lighting was designed with each of these factors being at the extreme of a scale that was zero in the center. Perusal of the average values throughout Tables 6.23, 6.24, 6.25 and 6.26, reveal that all average values are positive. It seems unlikely that all of the factors, many of which are unrelated to each other would always provide an average positive result given the design of the scale presented to the subjects. It might be suspected that a systematic error is revealed by this, being that people may be more biased to check toward the right than the left on a continuous scale! If so, this was unexpected, and could represent a significant skew in interpreting the results. Without further work, perhaps by offering a questionnaire instrument with scales randomly arranged right to left or left to right for different subjects, it isn't possible at this time to assess whether this is truly a systematic skew in the results. Further analysis below should however keep in consideration the possibility of a systematic error.

For all illuminants:

1) Yellow is perceived over blue, and red is perceived over green with regard to the opponent color response.
2) Illuminants are perceived to be more bright than dark.
3) Color rendering is perceived to be more good than bad.
4) Perception of details are perceived to be more high than low.
5) All illuminants are perceived to be net more satisfactory than unsatisfactory.

Table 6.23

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	-0.3	-0.15	0	1.58	1.9	1.8
1	1.2	0.9	0.45	0.65	1.2	2.42
1	0	1.15	0	1.7	1.7	1.7
2	1.5	1.7	0	1.7	1.7	1.7
2	1.6	1.6	0	1.1	1.72	1.75
3	0.47	0.7	0.47	1.32	1.57	1.4
4	-0.1	0.55	-0.09	1.17	1.5	1.82
5	0.2	0.18	0	1.96	2	2
6	-0.18	0.73	-0.1	1.09	0.94	1.09
7	0	0.74	0.8	1.71	-0.17	1.25
7	-0.4	0.85	0	1.9	1.3	1.32
8	1.05	0	0	1.7	1.35	1.1
8	0	0	0	0.3	0.85	1.45
9	0.1	0.12	0.25	-0.45	-0.35	1
10	1.28	1.75	0.2	-0.52	0.33	0.18
11	-0.9	0.72	0.12	0.42	0.92	1.1
12	0	-0.12	1.1	1.42	1.39	1.02
13	-1.25	-0.74	-0.5	-0.2	-0.75	-0.95
14	1.9	-1.12	0.1	0.12	0.13	-0.7
15	-0.25	1	0.55	1.12	1.1	1

16	-0.5	-0.5	0	1.25	1.2	1.3
17	-0.35	-1.17	0.91	0.71	0.69	1.09
18	0.2	-0.35	1	1.7	1.8	1.8
19	-1	-0.87	0.23	0.75	1.82	2.43
20	-0.35	-0.77	0.85	-0.1	0.25	0.85
21	0	0	0	2.57	2.5	2.58
22	0	-1.7	0	2.4	2.4	2.4
23	-0.4	0	0	1.2	1.2	1.2
24	0.1	0.15	2.25	0	2.15	0.25
25	0.75	0	0	2.5	0	2.5
26	1.8	1.9	0.8	-1.3	2	2.05
27	1.15	1.2	0.95	0.95	1.15	1.68
28	1.05	1.35	0	0.3	1.87	1.7
29	-0.2	2.66	-0.2	2.6	2.65	2.73
30	-0.1	0	0	2.5	2.5	2.5
31	1.2	0.11	0.11	1.85	2.09	2.09
32	0	2.7	0	2.65	2.6	1.5
33	0	0.5	0.15	-2.5	2.73	2.73
34	2.3	2.3	2.3	-0.26	-2.2	2.3
35	-0.8	-0.3	-0.15	-1.6	0.2	0.35
36	1.3	1.55	1.85	-0.6	1.2	0.8
37	1.1	0.6	0.85	1.1	1.08	1.55
38	-2	1.72	-1.7	1.3	1.35	1.35
39	0.6	1.7	1	1.12	0.9	0.6
40	1.12	1.12	1.12	1.75	1.75	2.2
41	1.33	0.87	0	2.5	2.5	2.54
42	0	-0.6	1.7	1.7	2.25	2.25
43	2	-1.5	2.5	2.5	2.5	2.5
44	2.37	0	2.3	2.3	0	2.25
45	0	0	0.6	0	1.15	1.7
46	0.4	-0.4	0.4	0	-0.88	2
47	0.9	1.4	0.27	1.48	1.4	1.44
48	0	0.6	1.15	1.15	-0.6	2.25
49	0.38	0.38	0.38	2	2	2
50	0.85	-0.8	0.9	2	1.4	2
51	-1.4	0.9		0.9	0.7	0.9
52	2.25	2.25	0.6	2.25	2.25	2.25
53	0	2.65	0	2.5	2.55	2.55
54	-0.25	-0.7	1.6	-0.8	1.5	1
55	1	-0.4	-0.4	1.4	1.4	2
56	0	0	1.1	0	0.6	1.7

57	1.15	-0.6	1.1	-2.25	-0.6	1.15
58	0	-0.12	1.15	1.7	1.7	2.25
59	0	0.6	-0.6	1.12	0	0.6
60	0	-1.2	0	-0.6	-1.2	0.6
61	1.7	1.15	1.15	1.7	1.7	1.7
62	0	0	0	0	2.3	0

Table 6.24

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.25	-0.32	0	1	1.5	0.25
2	0.3	0.3	0.18	2	1.72	0.3
3	1.4	-0.2	0.7	0.05	0.4	1.4
5	0.64	0.7	0	0.65	1	0.64
6	1.31	-0.2	-0.4	-0.95	-0.13	1.31
7	1.24	-0.43	0.43	-0.2	-0.08	1.24
8	1.45	0.78	0	1.2	1.55	1.45
9	0.35	0.45	0.4	1.05	1	0.35
10	-0.52	-1.09	-0.2	1.8	1.25	-0.52
11	1.08	0.25	-0.65	0.15	-0.47	1.08
12	1.1	1.1	1.75	-0.15	-0.6	1.1
13	0.92	1.2	0.92	0.27	1.3	0.92
14	0	1.5	0	1.3	1.4	0
15	0.8	-1.12	0.54	-0.8	-1.1	0.8
16	0.22	-0.05	-0.05	1.17	1.3	0.22
17	0.85	0.1	-0.4	-0.7	-0.6	0.85
18	0.94	1.42	1.5	-0.84	-1.24	0.94
19	1.35	2	-0.85	0.2	-0.5	1.35
20	1.12	1.15	-0.2	-0.2	0.75	1.12
21	0	0	0	2.57	2.5	0
22	1.45	2.45	0	0	0	1.45
23	0.1	0	0	0.85	1.2	0.1
24	2.1	0.15	2.25	0	0.25	2.1
25	0	0	0	2.5	2.5	0
27	1.8	1.82	1.42	0.95	1.45	1.8
28	0.5	-1	-0.2	0.1	1.7	0.5
29	-0.2	-0.2	-0.2	2.6	-0.15	-0.2

30	-1.4	-2.3	2.5	0.15	0.15	-1.4
31	0.11	1.7	1.35	0	0	0.11
32	1.3	-0.9	2.68	-2.6	-1.8	1.3
33	-0.3	-0.15	-0.15	-0.15	2.73	-0.3
34	2.3	2.3	2.3	-0.26	-0.15	2.3
35	2.6	0.2	-0.7	-2.3	-0.1	2.6
36	1.7	2.1	2.52	-1.19	1.2	1.7
37	2	1.2	1.45	1.7	1.8	2
38	-2.12	-0.42	-1.9	-1.6	-1.92	-2.12

Table 6.25

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.8	-0.8	0.45	-0.95	0.3	1.4
7	0.3	-0.4	0.27	1.4	-0.92	0.8
8	1.4	0	1.4	0	0.85	0
39	0	0	0.6	1.12	0.6	0
40	0	1.12	1.12	1.75	1.75	1.75
41	2.5	0	0	2.5	2.5	1.95
42	1.12	1.7	0.6	1.12	1.7	1.7
43	2	0	2.5	2	1.45	2
44	2.37	2.3	2.3	0	0	0
45	1.13	0	1.2	1.2	0	1.2

Table 6.26

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.6	-0.6	1.15	-0.3	-0.3	-0.6
2	0.2	0	0.6	0.6	1.7	1.7
46	0	-0.4	0	0	-0.88	2
47	0.9	0.3	0.9	0.75	-0.4	0.8
48	0.6	0	0.6	1.15	0	1.15
49	-0.3	-0.3	-1.09	0.28	-0.38	-0.38
50	0.34	0.9	0.3	1.4	0.33	0.95

51	-0.4	0	1.4	0	-1	1.4
52	2.25	1.7	0	2.27	1.7	1.7
53	-1.2	1.7	1.35	0	0	1.15
54	0.6	2	1.35	0.25	1.7	0.2
55	-0.15	1	0	0	0	1.4
56	-1.2	-2.3	0	-0.6	-0.6	-0.6
57	-1.2	1.15	0	-0.98	1.15	0
58	1.4	0	2.25	0.6	0.6	1.15
59	0.2	-0.6	0.6	0	0.6	0
60	0	-0.6	1.7	0	-0.6	-0.6
61	1.7	0.6	1.7	1.7	1.15	1.15
62	0	1.15	0.6	-0.6	2.25	0.6

6.8.6 Evaluation consistent with Opponent color theory

Presented in Table 6.27 are the results for the confidence limits for the comparison of the reference illuminant and the filters with regard to the Yellow-Blue **b*** scale of opponent color theory and Red-Green **a*** scale of opponent color theory. Colors are perceived along **b*** as being either more yellow or more blue and colors are perceived along **a*** as being either more red or more green.

Table 6.27

	Confidence of a difference of Blue/Yellow perception between reference and filter	Confidence of a difference of Red/Green perception between reference and filter
Mark 1	6%	8%
Mark 2	19%	21%
Mark 3	5%	16%

Keeping in mind the possible systematic error discussed above, the confidence is not high that the filtered light is perceived as being different than the Unfiltered light with regard to opponent color perception.

6.8.7 Evaluation of Brightness, Detail, Color rendering, and Overall Satisfaction

Presented in Table 6.28 are the results for the confidence limits for the comparison of the reference illuminant and the filtered illuminants with regard to the Brightness, Detail, Color Rendering, and Overall Satisfaction. The results are presented in terms of the confidence of a filter and Unfiltered as being *distinguishable*. Alternatively, if one wanted to state the data as being in terms of being indistinguishable, one would subtract the values provided from 100%.

Table 6.28

	Confidence of a distinguishable difference between reference and filter			
	Brightness /Darkness	Color Rendering	Perception of details	Overall satisfaction
Mark 1	3%	3%	1%	3%
Mark 2	2%	19%	10%	22%
Mark 3	1%	25%	28%	35%

Table 6.29

	Related to Table 6.28, the preference for a filter over unfiltered is stated; preference for Unfiltered reference = "U"; for filter ="M"			
	More bright	Better Color Rendering	Higher Perception of details	Overall satisfaction
Mark 1	M	U	M	U
Mark 2	U	M	M	M
Mark 3	U	U	U	U

The results suggest that confidence is low that the filtered illuminants can be distinguished from the Unfiltered reference with regard to brightness, color rendering, perception of details, and overall satisfaction. Notice however, that confidence limits increase somewhat for the case of Mark 2 and somewhat more for the case of Mark 3 with regard to color rendering, perception of details, and overall satisfaction. In terms of brightness, there seems to be no difference among the filters relative to Unfiltered; essentially zero confidence in being distinguishable. This is potentially a good internal control of the data, because the lighting for the subjective gallery testing is set to be of equivalent luminosity, within ±5%. Earlier brightness work discussed above suggests that perceived brightness would not depart significantly from this equal luminosity setting. This equivalent luminosity setting would beg a result of complete

undistinguishability between filtered and Unfiltered light, and this is what is observed.

Table 6.29 states the preference relative to the confidence limits of Table 6.28. Mark 2 has the highest preference among the filters. Keeping in mind the potential for a systematic error (discussed earlier) contributing to the uncertainty, there is a possibility that some preference for the Unfiltered light may be arising in the data relative to Mark 3, though the levels are well below significant confidence. Much larger sampling of the population would be required to obtain data with significant confidence.

Conclusions

Filters have been designed and manufactured with optimized color rendering and enhanced Lumens per Watt efficiency. Extensive testing has been done on all three filters. The fading studies have demonstrated that the UTEP filters reduce pigment photochemical degradation more than any existing filter technology. Human evaluation suggests a high confidence that the filtered light is indistinguishable from Unfiltered reference illumination.

The lifetime studies have proven that the filters have a long life. For the always-on testing, no failure has been observed up to the 10.4 simulated years of accelerated aging for Mark 1 and Mark 2. No failure has been observed up to the 5.3 simulated years of accelerated aging for Mark 3. No failure has been observed up to the 21.8 simulated year of thermo-mechanical stress for Mark2 and Mark 3.

Results suggest enhanced benefit for objects that have already faded. The fading delay increases as one temporally progresses through the fade. The effect of filtration improves as the object ages. Older, already heavily faded works of art would profit by engineered light filtration.

From data analyzed in section 6.7.1 it was concluded that the presence of a filter not only adjusts the rate of change of color change, but also the end point to which a material would change. For older faded objects, the filter displays its greatest rate attenuation effect, while filtering new unaged objects

are also benefited by adjusting the final end point to which the object might fade. Therefore, beneficial filtration of any kind would be highly recommended at any point in the life of the object. These results and this inference needs to be investigated with further research.

Specific conclusions about methods and results are discussed below.

7.1 Methods-Human Testing

The Testing Gallery Facility can be improved by eliminating the black curtains, using separate rooms for testing and painting everything gray. The ASTM guidelines (American Society for Testing and Materials, E1808-96, "Standard Guide for Conducting Visual Experiments") can be used to set the surround and ambient field. The surround is defined as the area immediately surrounding the specimen and it states that it should have a color similar to the specimen. For art, this of often a white or cream colored mat. However, the mat cannot be included in the spectral design of a filter, since it could vary, and it was thought that a more neutral level of gray should be used for testing purposes[35]. For the ambient field, the ASTM standard recommends that the field of view when the observer glances away from the specimen should have a neutral color that is Munsell Chroma less than 0.2 and a Munsell value of N6 or N7 with a luminous reflectance of 29-42.

As discussed above, variation in the spectral distribution may cause a change in perceived brightness. A higher perceived brightness may imply that an illuminant is more efficient in its use of light as the human eye perceives it. A higher perceived brightness would imply that possibly less light could be used for illumination, which could contribute to lowering photochemical change. There are two methods that one could consider:

3) Assessment of the brightness of the illuminant.
4) Assessment of the brightness of an object under illumination of the illuminant.

The second method is much more useful result, since it applies to how the illuminant actually influences the brightness of an illuminated object. The first method was the one used in this study. The second method can be implemented in order to improve this part of the human evaluation of the filters.

The brightness measurement methods can be improved by utilizing a spectrograph to make the measurements instead of the light meter. This will ensure that the measurements are more accurate. And instead of setting the two lamps (Unfiltered and filtered) at equal or equivalent luminosity, the filtered lamp can be set either at a lower luminosity than the Unfiltered or at a higher luminosity. This will ensure that neither the Unfiltered nor filtered are biased.

It is believed that the subjective evaluation of the filters via the questionnaire has a systematic error. This error is believed to have appeared due

to the visual design of the questionnaire. People may be more biased to check toward the right than the left on a continuous scale!. This can be prevented perhaps by offering a questionnaire instrument with scales randomly arranged right to left or left to right for different subjects.

The replicas of the OMDs chosen for this study predominantly included red pigmentation to a dominant extent, and so the predominance of the red sensation might have been expected. Other replicas of OMD's or other replicas of works of art can be chosen to prevent this problem in the future.

7.2 Methods-Fading

Procedures to assess fading of pigments need to be addressed. Lamps displayed relatively short periods of adequate stability for properly controlled experiments. Fading slower than the equivalent of Blue Wool 3 could not be reliably completed with the equipment used in this study, and some data needed to be truncated at longer time intervals to provide a meaningfully interpretable result.

Lamps in this study were powered with very inexpensive commercial power supplies. Lower voltages and better voltage control would be desirable as a first step to achieve more stable lighting for fading measurements. No diffusion of light was used in this work because of inadequate intensity. More lamps should be used, as well as adequate light diffusion would reduce the

dependency on any one lamp failing. Diffusion would also reduce the gradient of lighting across the sample.

Fading work may also require real time monitoring of the light level to assure when a lamp failure might have occurred, and to possibly correct the data so that even with a lamp failure, useful data could be reaped from the entire fading time period.

Some fading samples did not have enough measurements in between points. A specific number of measurements and specific time intervals of when these measurements are made need to be determined for each pigment.

7.3 Methods – Light measurement

Monitoring and incidental measurement and setting of light levels was occasionally done with a hand held meter. The meters often departed from the result obtained spectrographically, possibly more than can be explained by the anticipated error in either instrument. As optimized spectral profiles depart from the profiles for which meters are commonly calibrated, one will need to depend more on spectrographic measurement of photometric properties.

It was determined that an instrument for storing and determining climatological data is needed to be included in the fading boxes. The instrument needs to have at least the following features.

1) Data that is acquired needs to be reported with the fading results.

2) The instrument needs to record black body temperature
3) Needs to record total radiant energy.
4) Needs to record ultraviolet radiant energy.
5) The instrument needs to have the same angle as the fading boxes.
6) Ambient temperature recording, daily, minimum and maximum.

7.4 Physical Evaluation of filters

There were two types of lifetime study tests that were conducted; the constant exposure and the cyclical exposure. A variation and improvement of these two lifetimes' studies is to push the stress of the filters by including other factors such as humidity, vibration, air pollutants, and noise. This would be to simulate closer the environment of a gallery or museum.

References

1. a) Bansa, Dr. Helmut. Selecting for Conservation-Selecting for Conversion: Some Practical Recommendations for Policy. Munich: Bavarian State Library (1985. b) Buchanan, Sally. "Conservation Needs, Priorities, and Options at Stanford University" in Merrill-Oldham The Library Preservation Program. c) Thornton, W. A. 1972. Three-color visual response. Journal of the Optical Society of America. Volume 62 Issue 3 Pages 457-459.

2. Thomson, Garry. The museum environment / Garry Thomson. London ; Boston : Butterworths, 1978.

3. Schaeffer Terry T. Effects of Light on Materials in Collections Data on Photoflash and Related Sources. Research in Conservation. The Getty Conservation Institute. The J. Paul Getty Trust 2001.

4. DeCusatis, Casimer. Handbook of Applied Photometry. Sponsored by the Optical Society of America. IBM Corporation Poughkeepsie, New York.

5. Matija, Strlic and Jana, Kolar. Ageing and stabilisation of paper. Published by the National and University Library. Ljubljana, Slovenia, 2005.

6. Oyster, Clyde W. The human eye : structure and function / Clyde W. Oyster. Sunderland, Mass. Sinauer Associates, c1999.

7. Hecht, Eugene. Optics. Reading, Mass. : Addison-Wesley, c2002.

8. a) Wyszecki, G., & Stiles, W. S. (1982). Color Science: concepts and methods, quantitative data and formulae. (2nd Ed.). New York: Wiley. b) Wyszecki, G. & Stiles, W. S. Color science: concepts and methods, quantitative data, and formulae. Wiley classics library edn(John Wiley & Sons, 2000).

9. Crawford (1949). The scotopic visibility function. Proceedings of the Physical Society, B62, 321-334.

10. a) CIE (1926). Commission Internationale de l'Eclairage. Proceedings, 1924. Cambridge: Cambridge University Press. b) CIE. (1932). Commission Internationale de l'Eclairage. Proceedings, 1931. Cambridge: Cambridge University Press. c) Stiles, W. S. & Burch, J. M. (1955). Interim report to the Commission Internationale de l'Eclairage Zurich, 1955, on the National

Physical Laboratory's investigation of colour-matching. Optica Acta, 2, 168-181.

11. Fairchild, Mark D. Color appearance models. Hoboken, NJ : J. Wiley, 2005.

12. a) CIE Proceedings (1964) Vienna Session, 1963, Vol. B, pp. 209-220 (Committee Report E-1.4.1), Bureau Central de la CIE, Paris. b) Stiles, W. S., & Burch, J. M. (1959). NPL colour-matching investigation: Final report. Optica Acta, 6, 1-26.

13. a) Rowe, Michael H. "Trichromatic color vision in primates." News Physiol Sci. 2002 Jun; 17:93-8. b) Rowe, Michael H (2002). "Trichromatic color vision in primates." News in Physiological Sciences. 17(3), 93-98. c) Kandel ER, Schwartz JH, Jessell TM (2000). Principles of Neural Science (4th ed.). New York: McGraw-Hill. p. 182-185. ISBN 0-8385-7701-6. d) Eysenck, M. W.; Keane, M. T. (2005). Cognitive Psychology: A Student's Handbook (Fifth ed.). East Sussex: Psychology Press.

14. a) Wright, William David (1928). "A re-determination of the trichromatic coefficients of the spectral colours". Transactions of the Optical Society 30: 141–164. b) Smith, Thomas; Guild, John (1931-32). "The C.I.E. colorimetric standards and their use". Transactions of the Optical Society 33 (3): 73–134. c) Guild, John (1931). "The colorimetric properties of the spectrum". Philosophical Transactions of the Royal Society of London A230: 149–187.

15. a) Troland, L. T. (1922). "Report of Committee on Colorimetry for 1920-21". Journal of Optical Society of America 6 (6): 527–596. b) Jones, L. A. (1943). "Historical background and evolution of the colorimetry report". Journal of the Optical Society of America 33 (10): 534–543. c) Judd, Deane B. (January 1940). "Hue saturation and lightness of surface colors with chromatic illumination" Journal of the Optical Society of America 30 (1): 2–32.

16. a) Wyszecki, Günther (November 1963). Proposal for a New Color-Difference Formula. 53. pp. 1318–1319. b) Glasser, L.G.; A.H. McKinney, C.D. Reilly, and P.D. Schnelle (October 1958). "Cube-root color coordinate system". Journal of the Optical Society of America 48 (10): 736–740. c) Hunt R.W.G. The reproduction of colour. Wiley. 2004 Sussex England.

17. Pauli, H., 1976. Proposed extension of the CI E recommendation on "Uniform color spaces, color difference equations, and metric color terms". Journal of the Optical Society of America 66, 866-867, 1976.

18. a) Nickerson, Dorothy (1976). "History of the Munsell color system, company, and foundation". Color Research and Application 1 (1)): 7–10. b) Munsell, Albert H. (January 1912). "A Pigment Color System and Notation". The American Journal of Psychology 23: 236–244.

19. a) Turner, R S (1993), "Vision studies in Germany: Helmholtz versus Hering." Osiris 8: 80–103. b) Turner, R. M. (1994). In the eye's mind: vision and the Helmholtz-Hering controversy. Princeton, N.J: Princeton University Press. ISBN 0-691-03397-8. c) G. A. Agoston Color Theory and Its Application in Art and Design, Heidelberg 1979 d) Hering, Ewald. (1890). Zur Diagnostik der Farbenblinheit, Arch. F. Ophthalm. 36: 217-233.

20. Anders Hård and Lars Sivik (1981). NCS - Natural Color System: A Swedish Standard for Coloer Notation vol 6 number 3 pages 129-138. Copyright © 1981 Wiley Periodicals, Inc., A Wiley Company.

21. Roy S. Berns, "Billmeyer and Saltzman's Principles of Color Technology," 3rd Edition, John Wiley & Sons, New York, 2000.

22. Wyszecki, Günter. Color science : concepts and methods, quantitative data and formulae. New York : Wiley, c1982.

23. a) Johannes Adolf von Kries. Ueber eine Art polyrhythmischer Herzthätigkeit", Archiv für Physiologie, no. 5/6: 477-491 (1902). b) Ueber die im Netzhautcentrum fehlende Nachbilderscheinung und über die diesen Gegenstand betreffenden Arbeiten von C. Hess", Zeitschrift für Psychologie und Physiologie der Sinnesorgane 29: 81-98 (1902).

24. CIE. A Method of Predicting Corresponding Colours Under Different Chromatic and Illuminance Adaptations (CIE 109.1-1995 Revision 1) (CIE 109.2-1995 Revision 2) (E) Technical Report.

25. Wee Kheng Leow. Color Spaces and Color Difference Equations. Department of Computer Science. National University of Singapore. 3 Science Drive 2, Singapore 117543. February 19th 2002.

26. Sharma, G., Wu, W., and Dalal, E.N. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Research and Application 30, 21-30 (2005).

27. Commission Internationale de l'Éclairage: Method of measurnig and specifying colour rendering properties of light sources. CIE Central Bureau CIE 13.2-1974.

28. a) CIE (1995), Method of Measuring and Specifying Colour Rendering Properties of Light Sources, Publication 13.3, Vienna: Commission Internationale de l'Eclairage. b) CIE (1999), Colour rendering (TC 1-33 closing remarks), Publication 135/2, Vienna: CIE Central Bureau. c) CIE (2007), Colour rendering of white LED light sources, Publication 177:2007, Vienna: CIE Central Bureau.

30. CIE 13.3-1995 Method of Measuring and Specifying Colour Rendering Properties of Light Sources (E) Technical Report.

31. a) Nayatani, Y., Hashimoto, K., Takahama, K. & Sobagaki, H. A nonlinear color appearance model using Estevez-Hunt-Pointer primaries. Color Research and Application 12, 231-242 (1987). b) Nayatani, Y. Development of Chromatic Adaptation Transforms and Concept for Their Classification. Color Research and Application 31, 205-217 (2006).

32. a) Ngai Peter. The relationship between luminance uniformity and brightness perception. Journal of the Illuminating Engineering Society. Winter 2000. b) Kaiser P.K 1971 Luminance and brightness. Applied Optics 10:2768-70. c)Guth, S.L. Donely, N.V. and Marroco, R.T. 1969. On Luminance additivity and related topics. Vision Research 9:537-575.

33. Nayatani Yoshinobu. A colorimetric explanation of the Helmholtz-Kohlrausch effect. Color Research & Application Volume 23 Issue 6, Pages 374 – 378. 1998.

34. a) Thornton, W. A. Fluorescent lamps with high color discrimination capability. J. Illum. Eng. Soc. 3, 61-64 (1973). b) Thornton, W. A. Lamps for assessing metamerism. J. Illum. Eng. Soc. 4, 11-18 (1974). c) Davis, Raymond; Gibson, Kasson S. (January 21 1931). "Filters for the reproduction of sunlight and daylight and the determination of color temperature". Precision Measurement and Calibration (National Bureau of Standards) 10: 641–805. d) Judd, Deane B.; MacAdam, David L.; Wyszecki, Günter (August 1964). "Spectral Distribution of Typical Daylight as a Function of Correlated Color Temperature". Journal of the Optical Society of America 54 (8): 1031–1040. d) Commission Internationale de l'Eclairage (1964). "Proceedings of the 15th Session, Vienna" e) Hernández-Andrés, Javier; Javier Romero, Antonio García-Beltrán, and Juan L. Nieves (February 20

1998). "Testing Linear Models on Spectral Daylight Measurements". Applied Optics 37 (6): 971–977

35. Personal Communication with. Jim Druzik, Senior Scientist at the Getty Conservation Institute. 1200 Getty Center Drive, Suite 700 Los Angeles, CA 90049-1684.

36. Janos Schanda "3. CIE Colorimetry. Colorimetry: Understanding the CIE System, Wiley Interscience (2007). ISBN 978-0-470-04904-4.

37. Dirk Carl, Delgado Monica F., Olgin Marco and Druzik James. A Prism-Grating-Prisim Spectral Imaging Approach. Studies in Conservation 54 (2009) 77-89.

38. a) Glover, F., Kelly, J. & Laguna, M. Genetic algorithms and tabu search. (Graduate School of Business, University of Colorado, 1992.) b) Glover, F. & Laguna, M. Tabu search. (Kluwer Academic, 1997). c) Hwang, C. L., Williams, J. L.& Fan, L. T. Introduction to the generalized reduced gradient method. (Institute for Systems Design and Optimization, Kansas State University, 1972). d) Laguna, M. & Martí, R. Scatter search : methodology and implementations in C. (Kluwer Academic Publishers, 2003).

39. New products. New Waggoner HRR for Color Vision Testing American. Academy of Optometry. Optometry and Vision Science: March 2003 - Volume 80 - Issue 3 - pp 193-194.

40. a) S. Ishihara, Tests for colour-blindness (Handaya, Tokyo, Hongo Harukicho, 1917).Ishihara Pseudoisochromatic Charts for Color Blindness. Tokyo, Kanehara & Co, 1925. This 5th edition is the first international edition b) S. Ishihara, Tests for Colour-Blindness. Tokyo, Handaya Company, 1917. 15th edition, 1960.

41. a) Lawrenson J.G, Kelly C, and Birch J. Acquired colour vision deficiency in patients receiving digoxin maintenance therapy. British Journal of Ophthalmology. 2002 November; 86(11): 1259–1261. b) Heron Gordon, Erskine Niall, Farquharson Elaine, Moore Ann and White Helen. Colour vision screening in glaucoma: the Tritan Album and other simple tests. Ophthalmic and Physiological Optics. Volume 14 Issue 3, Pages 233 – 238.

42. a) Farnsworth, D. (1943). The Farnsworth-Munsell 100-hue and dichotomous tests for color vision. Journal of the Optical Society of America, 33, 568-578.

43. Bassi Carl, Galamis John, and Hoffman John. Comparison of the Farnsworth-Munsell 100 Hue, the Farnsworth D-15, and the L'Anthony D-15 Desaturated Color Tests. Archives of Ophthalmology Vol 111, May 1993.

44. Mäntyjärvi, M. Normal values for the Pelli-Robson contrast sensitivity test Journal of Cataract & Refractive Surgery, Volume 27, Issue 2, Pages 261-266.

45.a) Vingrys, A.J. and King-Smith, P.E. (1988). A quantitative scoring technique for panel tests of color vision. Investigative Ophthalmology and Visual Science, 29, 50-63. b)Rushton, W.A.H. (1975). Visual pigments and color blindness. Scientific American, 232, 64-74. c) Rushton, W.A.H. (1972). Pigments and signals in colour vision. Journal of Physiology, 220, 1-3.1 d) Baro, J.A. and Lemkuhle, S. (1991) InSight2 – InColor v1.01.

46. Lori A. Polette, George Meitznera, Miguel Jose Yacamanb and Russell R. Chianelli Maya blue: application of XAS and HRTEM to materials science in art and archaeology Microchemical Journal Volume 71, Issues 2-3, April 2002, Pages 167-174.

47. Product Information Bulletin TRU-AIM® MR11 & MR16 FAMILY Low Voltage Halogen Lamps, 2006 OSRAM SYLVANIA 11/06.

48. Philips product data sheet, Long Life EYF 75WGU5.3 12V MR16 10D CL 1CT, 5/22/2009.

49. Philips Halogen Long Life MR16 Lamps Long Life Low-Voltage Halogen Reflector Lamps, P-5757, July 2005, Philips Lighting Company 200 Franklin Square Drive P.O. Box 6800 Somerset, NJ 08875-6800.

50. Philips Long Life MR-16 product bulletin, 5/22/2009.

51. "Product Information Bulletin TRU-AIM® MR11 & MR16 FAMILY Low Voltage Halogen Lamps", 2006 OSRAM SYLVANIA 11/06.

52. Philips Halogen Lamps Product Information, 3222 635 36621, Provisional 12/02 Printed in the Netherlands

53. a) ISO 105-B01:1994(E) Fifth Edition 1994-11-15. b) ISO 105-B08:1995(E) First Edition 1995-06-01

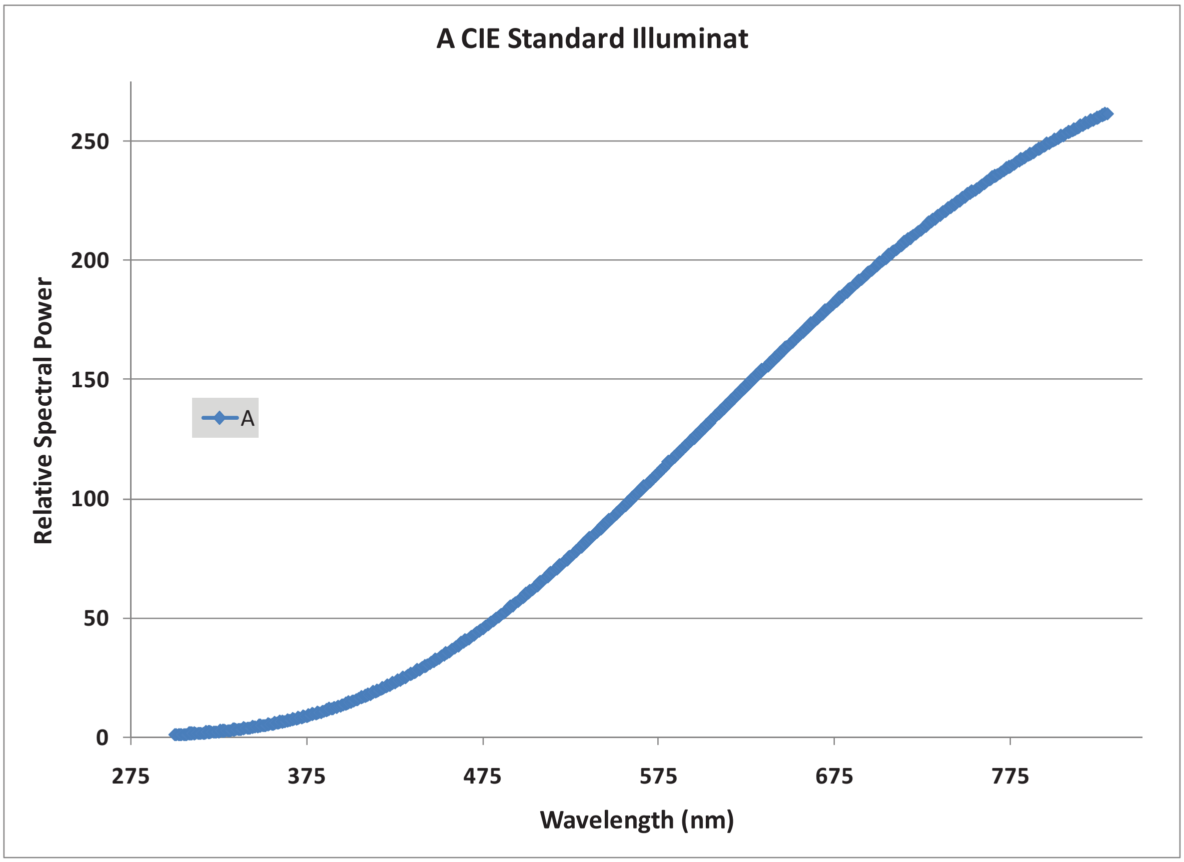
54. a) Francois Cardarelli (2008) Materials Handbook Springer London. b) Wells A.F. (1984) Structural Inorganic Chemistry 5th edition Oxford Science Publications. c) The crystal structure of the high temperature form of niobium pentoxide B. M. Gatehouse and A. D. Wadsley Acta Cryst. (1964). 17, 1545-1554. d) D.A. Bayot and M.M. Devillers, Precursors routes for the preparation of Nb based multimetallic oxides in Progress in Solid State Chemistry Research, Arte M. Newman, Ronald W. Buckley, (2007),Nova Publishers. e) Electrical properties of NbO_2 and Nb_2O_5 at elevated temperature in air and flowing argon, G. C. Vezzoli Phys. Rev. B 26, 3954 - 3957 (1982). f) Studies on the hydrothermal synthesis of niobium oxides, I.C. M. S. Santos, L. H. Loureiro, M. F. P. Silva and Ana M. V. Cavaleiro, Polyhedron, 21, 20, (2002), 2009-2015.

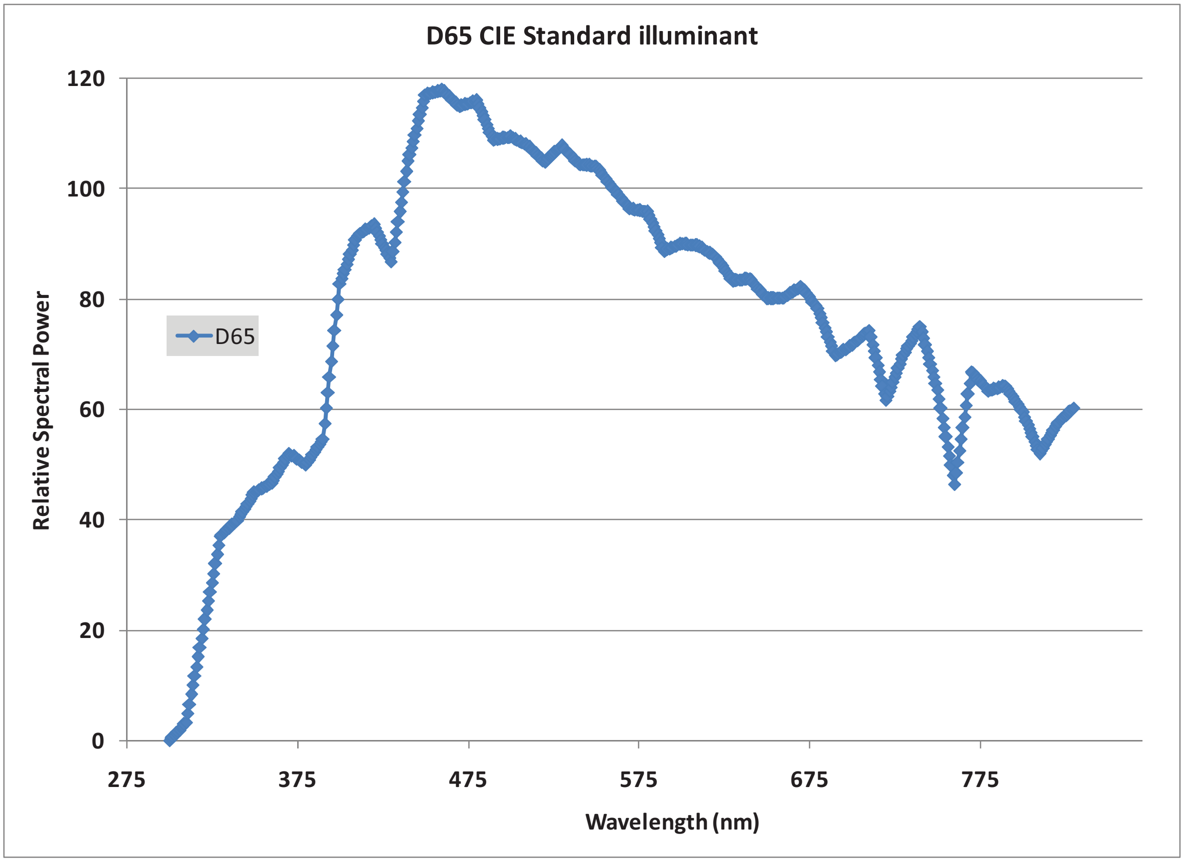
55. a) J. Scherzer (1978). "Dealuminated faujasite-type structures with SiO2/Al2O3 ratios over 100". Journal of Catalysis 54: 285. b) Robert Doering, Yoshio Nishi (2007), Handbook of Semiconductor Manufacturing Technology, CRC Press, ISBN 1574446754. c) Holleman, A. F.; Wiberg, E. (2001), Inorganic Chemistry, San Diego: Academic Press, ISBN 0-12-352651-5.

56. a) Reference ISO 105-B01:1994(E) b) The Color Index (third edition). Society of Dyers and Colourists. P.O. Box 244, Perkin House. 82 Grattan Rd, Bradford BD1 2JB, West Yorks., UK, and by the American Association of Textile Chemists and Colorists, P.O. Box 12215, Research Triangle, NC 27709 USA.

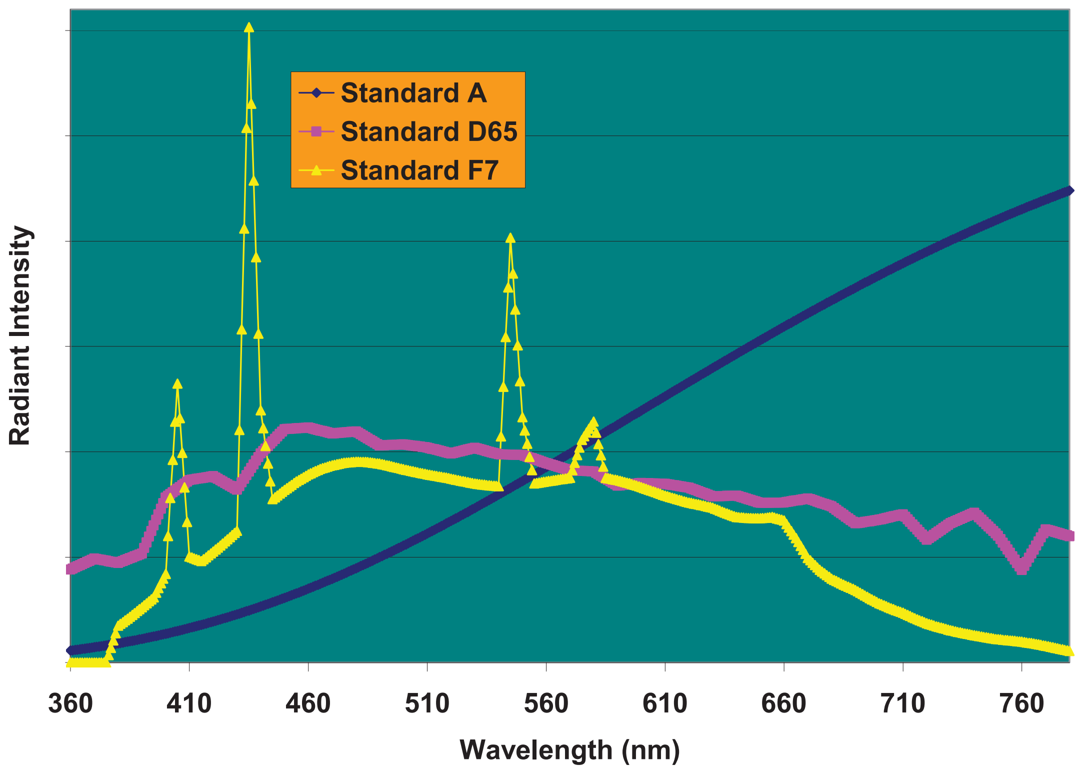
APPENDIX A

The following figures are related to section 3.1 in the document. These are the CIE theoretical illuminants that are known as standard illuminants. The F7[8, 34, 36] is a CIE fluorescent standard. The A[8, 34, 36] is a CIE incandescent standard. The D65[8, 34, 36] is a sunlight standard.



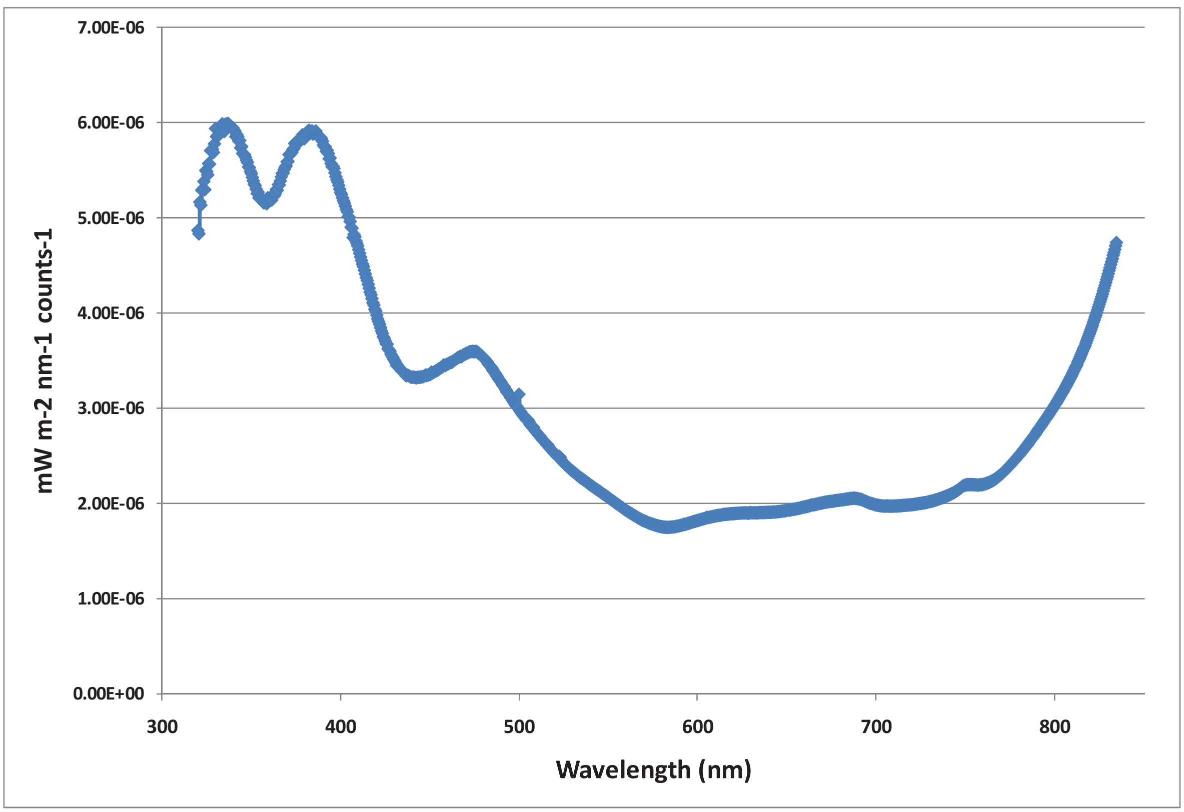


D65 CIE Standard illuminant
120
100
80
60
40
20
0
Relative Spectral Power
D65
275
375
475
575
675
775
Wavelength (nm)


Standard A
Standard D65
Standard F7
Radiant Intensity
360
410
460
510
560
610
660
710
760
Wavelength (nm)

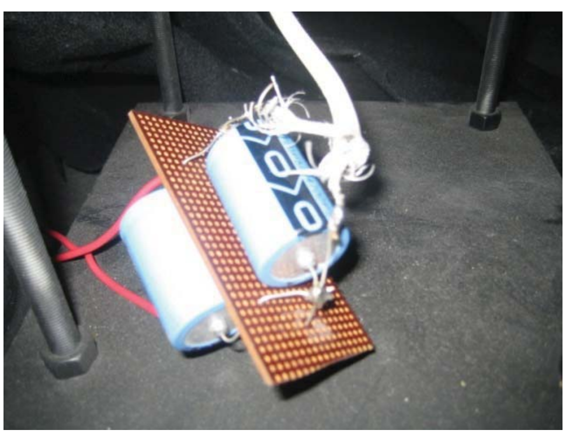
APPENDIX B

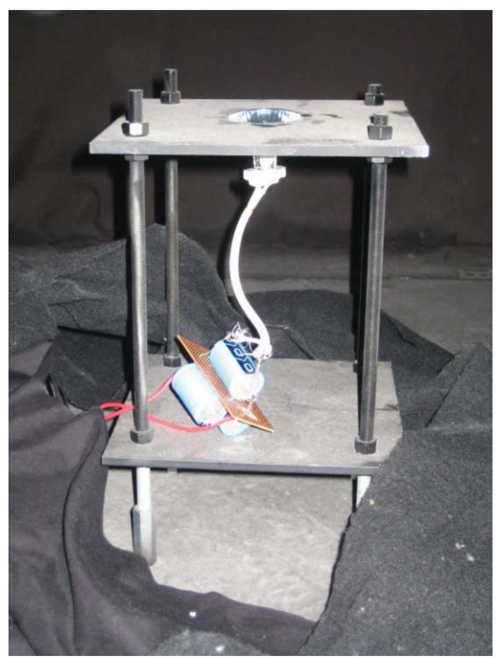
This image is related to section 3.3.1 Calibration in the document. The Oriel InstaSpec software for Windows, version 1.1 was wavelength calibrated. This wavelength calibration was retained within the InstaSpec software to be applied to subsequent measurements. The figure shown here is the calibration curve used in this work.



APPENDIX C

The figures shown in this appendix are related to section 3.3.2 Lamp measurement methods. Two lamp fixtures were used to mount the lamps to be tested. One of these fixtures ("A") involved a standard commercial "12V" power supply commonly used for MR16 lamps. In order to better understand the voltage and current characteristics, a device was wired in a way to have both current measuring and voltage measuring capability across the lamp filament circuit. So fixture "B" was created. This was constructed by the research group to have more control over either the applied voltage or current, to have greater geometric control for aiming the lamp, and to have a controlled level surface for placing and testing filters on a lamp.



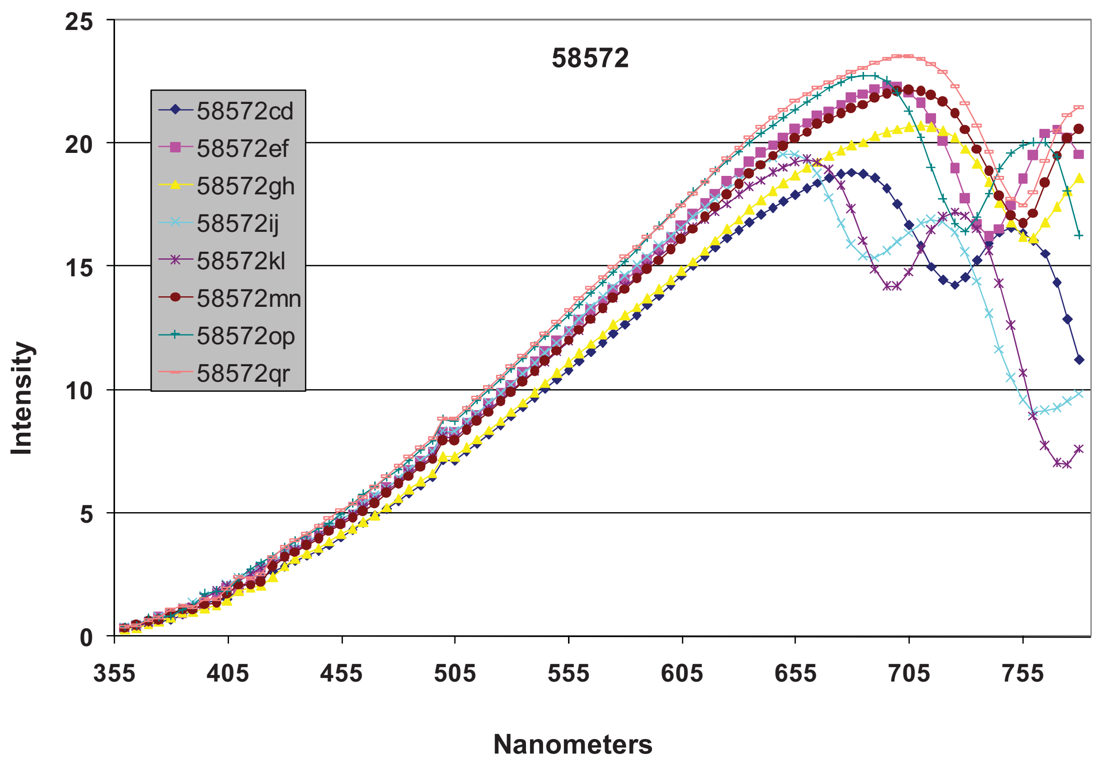


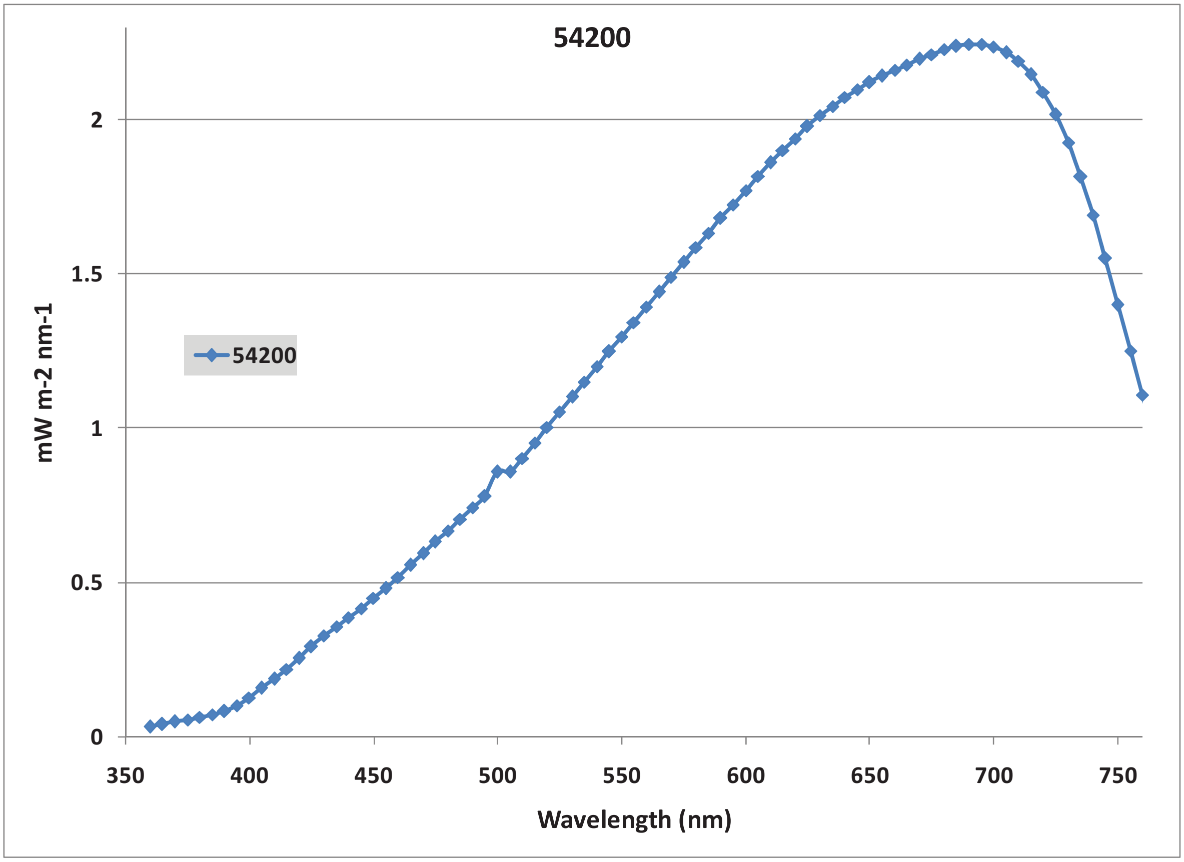
APPENDIX D

The figures shown in this section are related to section 3.3.4 Results of lamp measurements, in this document.

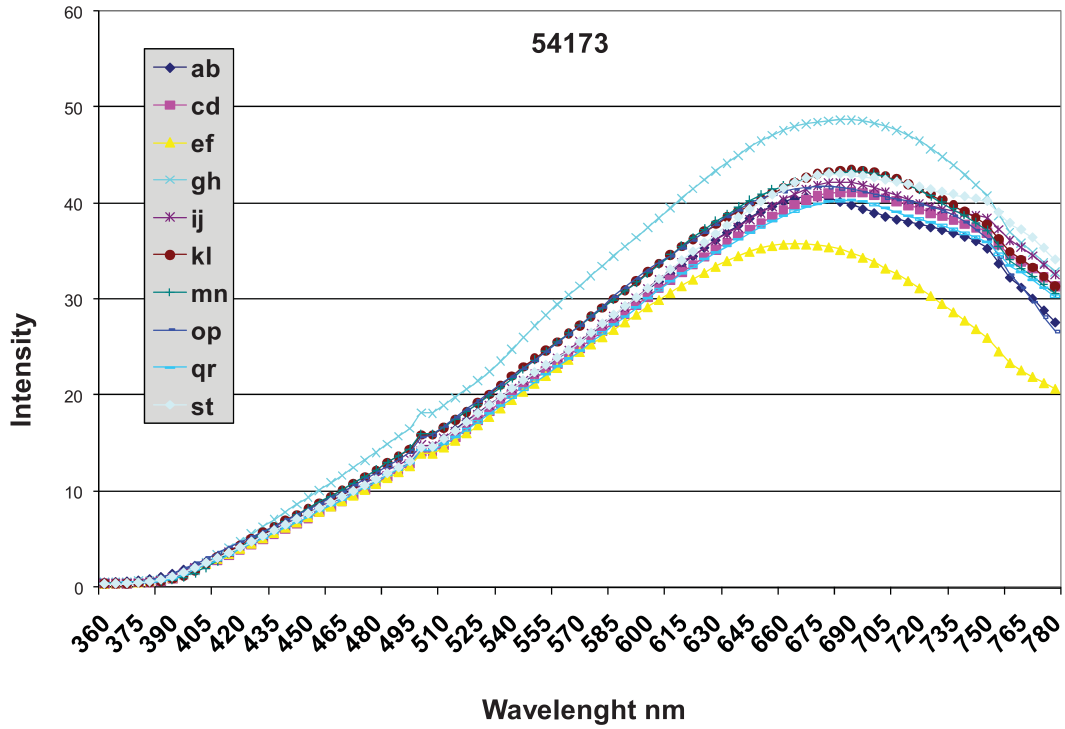
The objective of these lamp measurements was to select a source (illuminant to be filtered) and a reference lamp (is that to which filtered light would be compared), and to obtain the necessary data for spectral profile optimization. Typically, 6-20 lamps of a given product number where measured, and the results averaged.

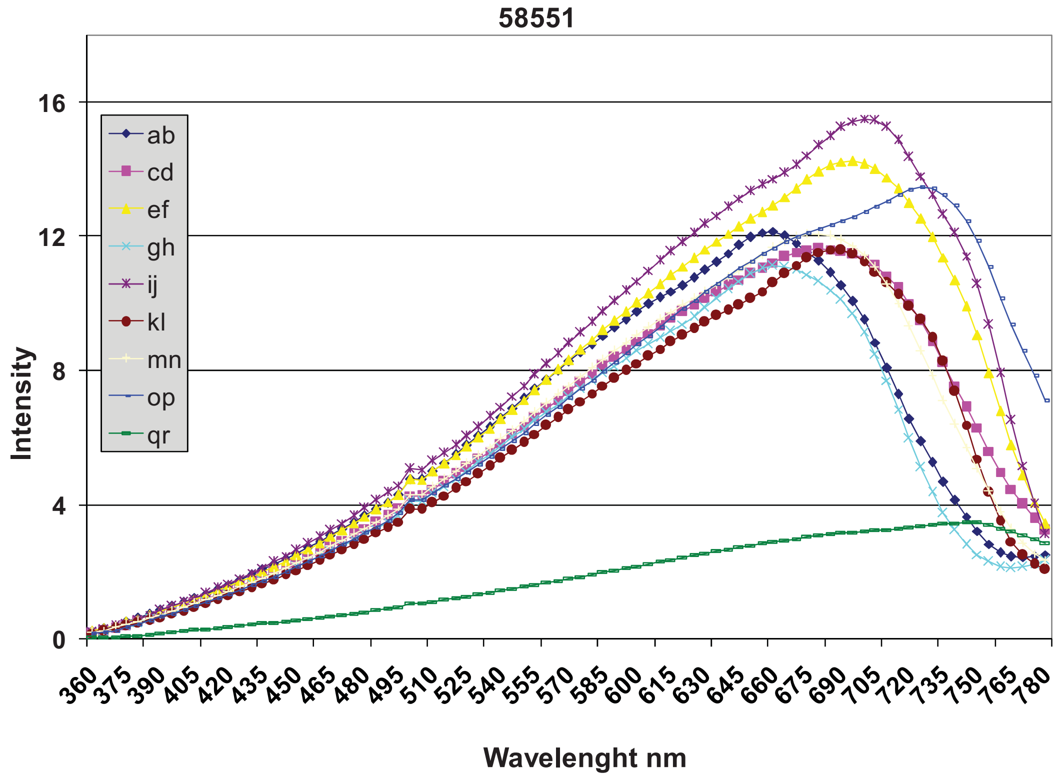
The lamps that were measured were found to vary widely in performance. A wide range of Sylvania MR16 products were measured. The following figures are of the lamps measured.



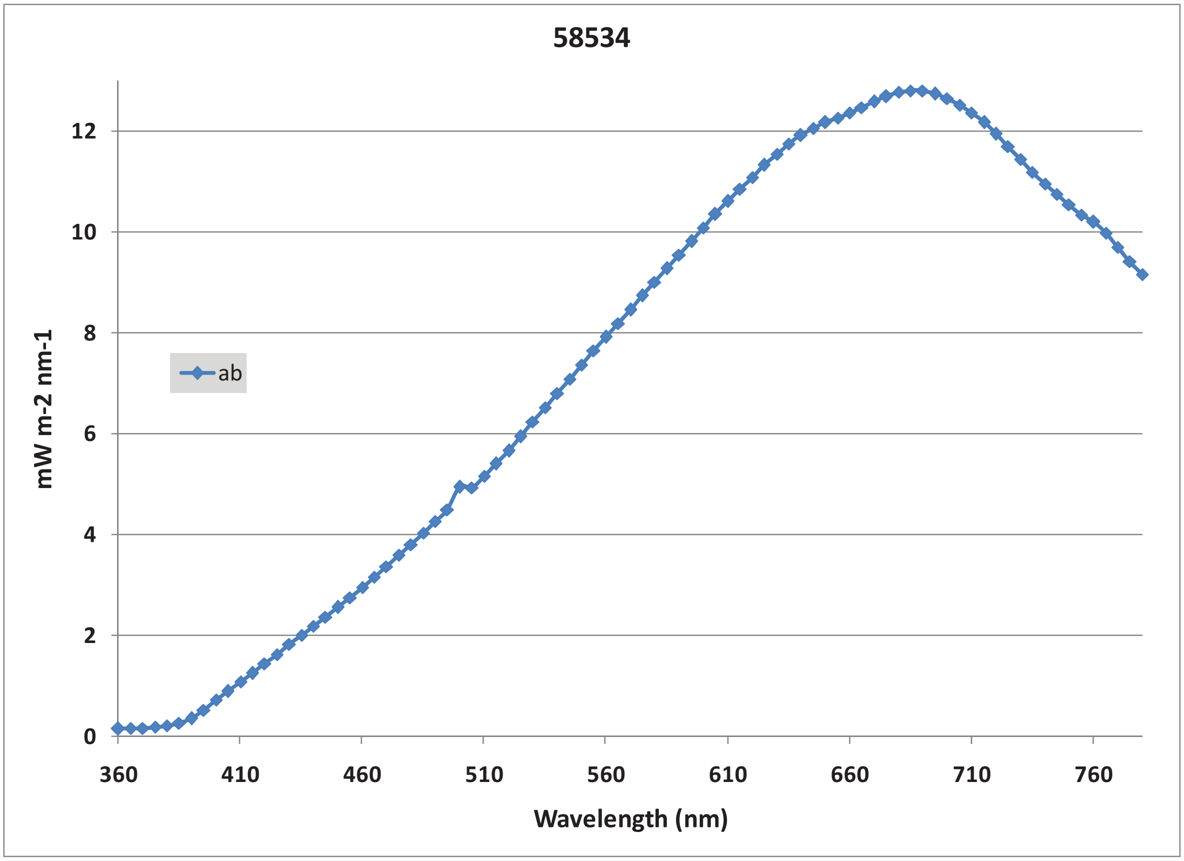


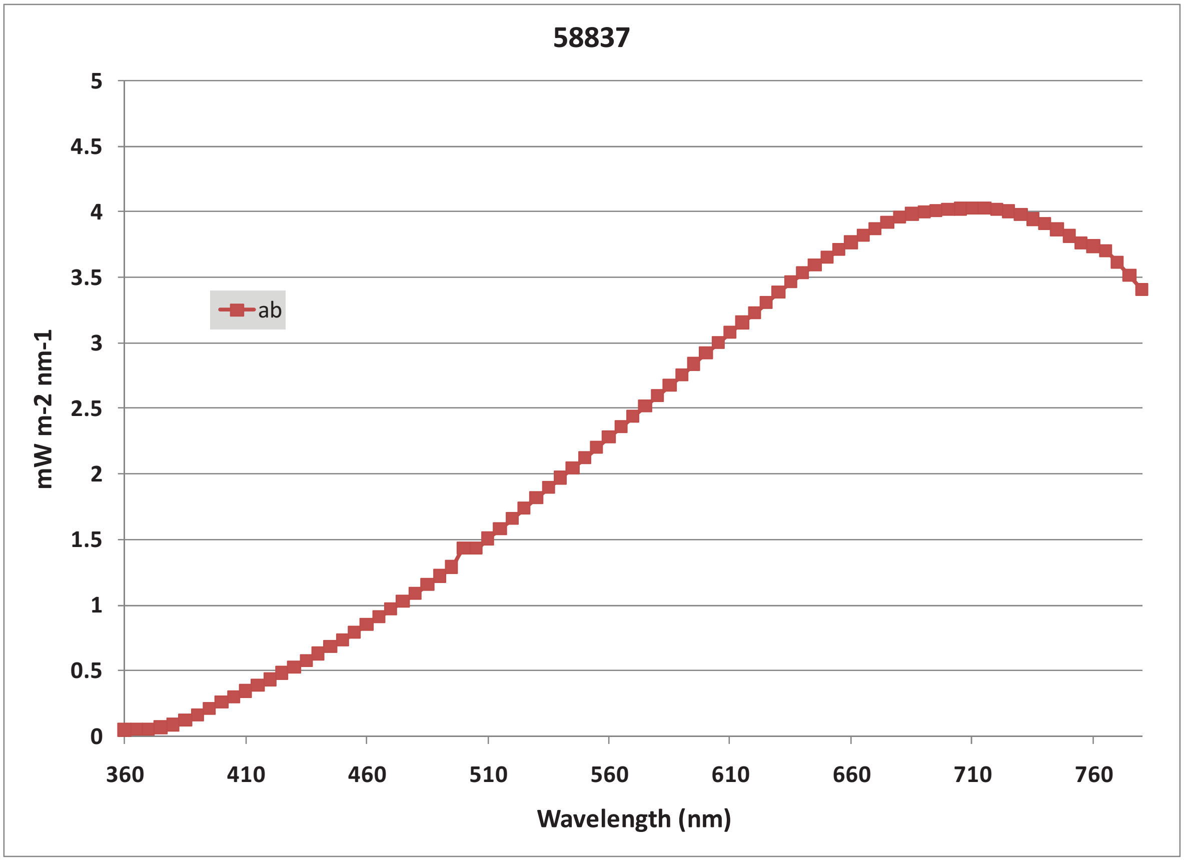
54200
54200
mW m-2 nm-1
0
0.5
1
1.5
2
350
400
450
500
550
600
650
700
750
Wavelength (nm)

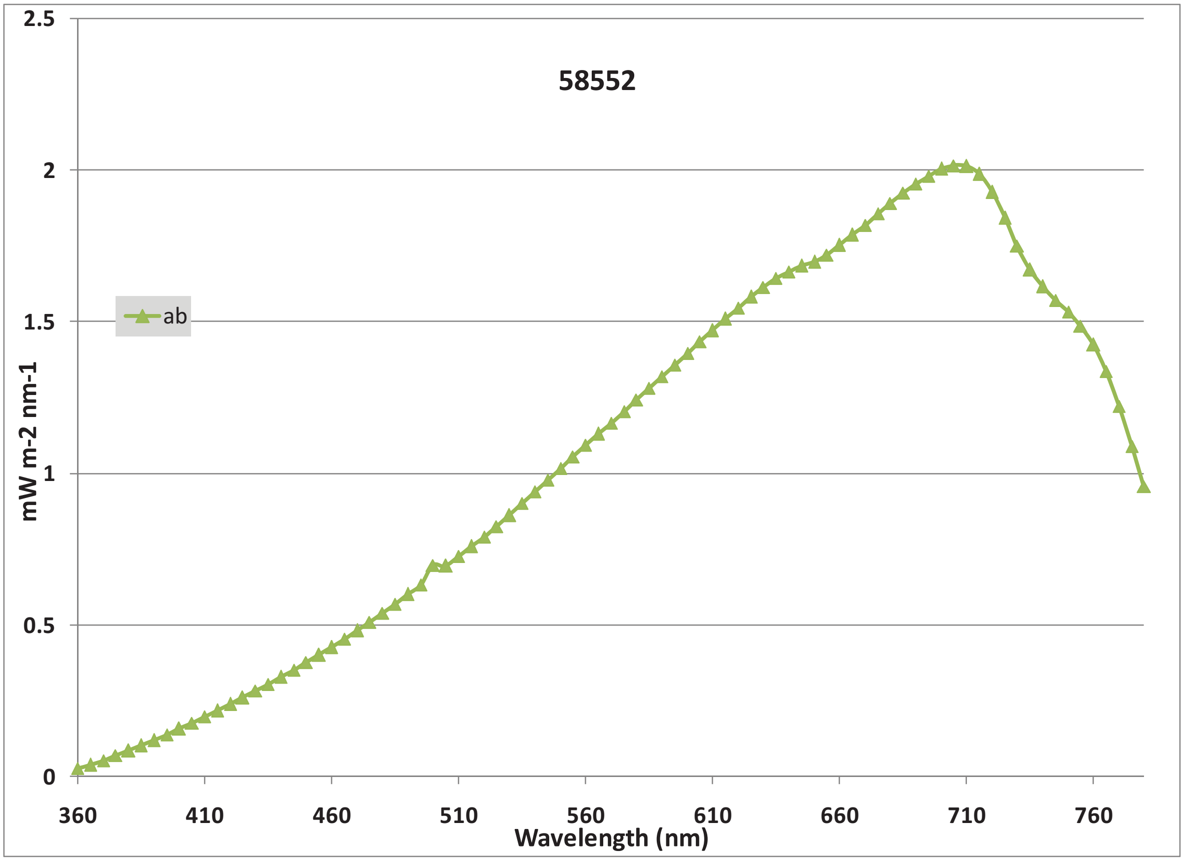

54173
Intensity
Wavelenght nm
ab
cd
ef
gh
ij
kl
mn
op
qr
st
0
10
20
30
40
50
60
360
375
390
405
420
435
450
465
480
495
510
525
540
555
570
585
600
615
630
645
660
675
690
705
720
735
750
765
780

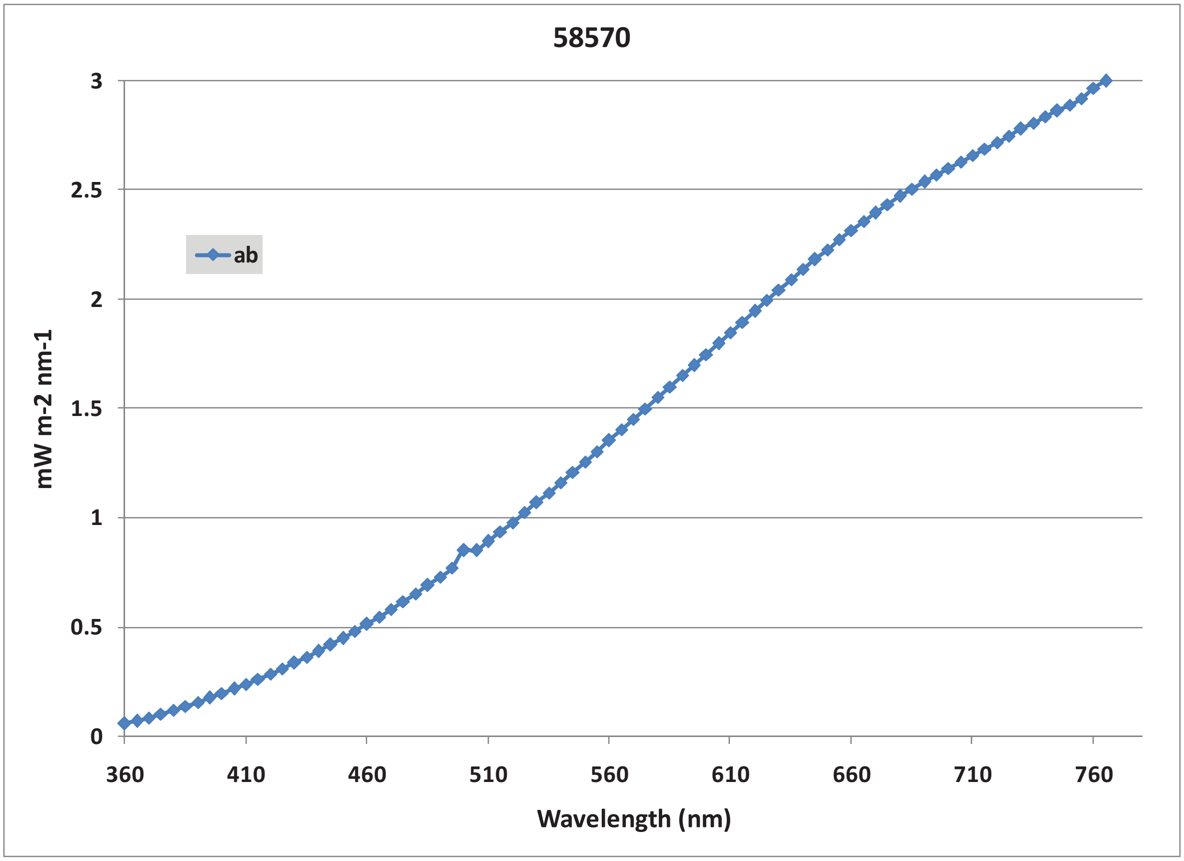


58551
16
12
8
4
0
ab
cd
ef
gh
ij
kl
mn
op
qr
Intensity
360 375 390 405 420 435 450 465 480 495 510 525 540 555 570 585 600 615 630 645 660 675 690 705 720 735 750 765 780
Wavelenght nm

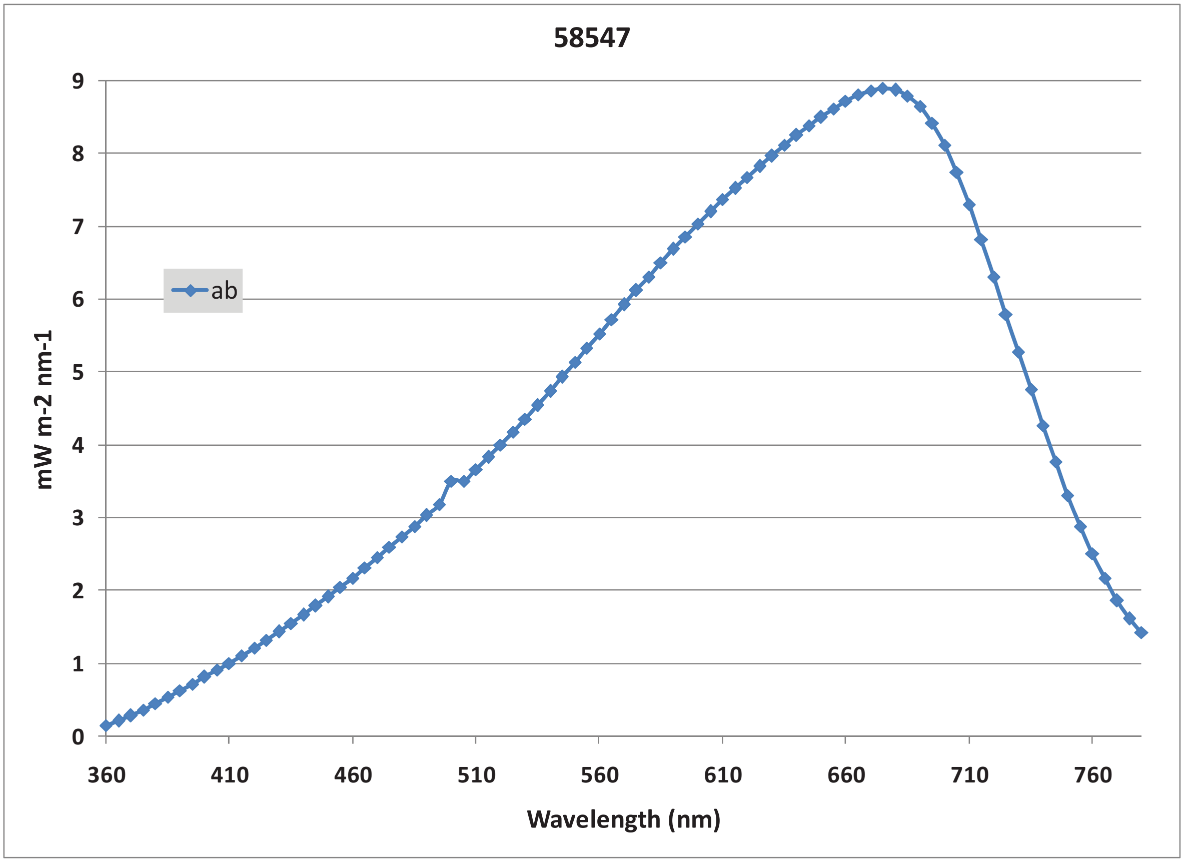

58534
12
10
8
6
4
2
0
mW m-2 nm-1
ab
360
410
460
510
560
610
660
710
760
Wavelength (nm)

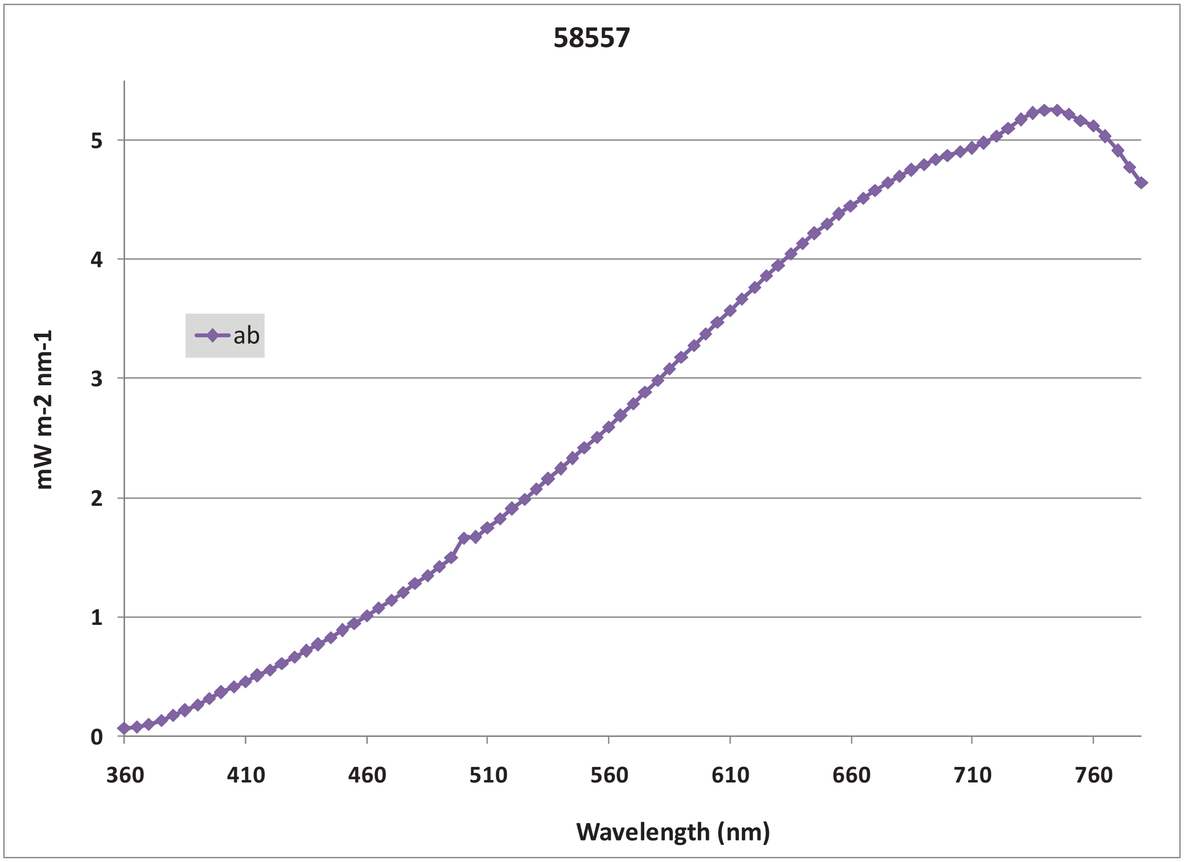

58837
mW m-2 nm-1
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ab
360
410
460
510
560
610
660
710
760
Wavelength (nm)


58552
ab
2.5
2
1.5
1
0.5
0
mW m-2 nm-1
360
410
460
510
560
610
660
710
760
Wavelength (nm)

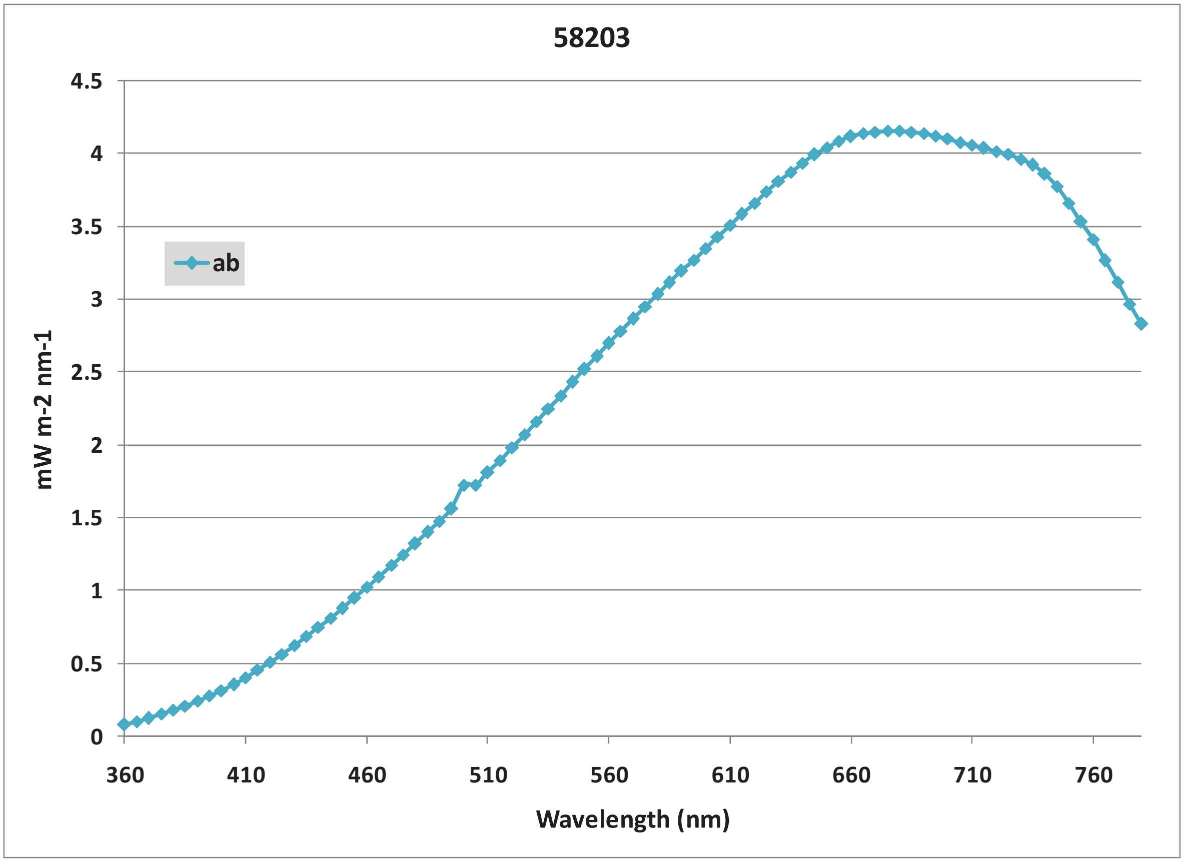


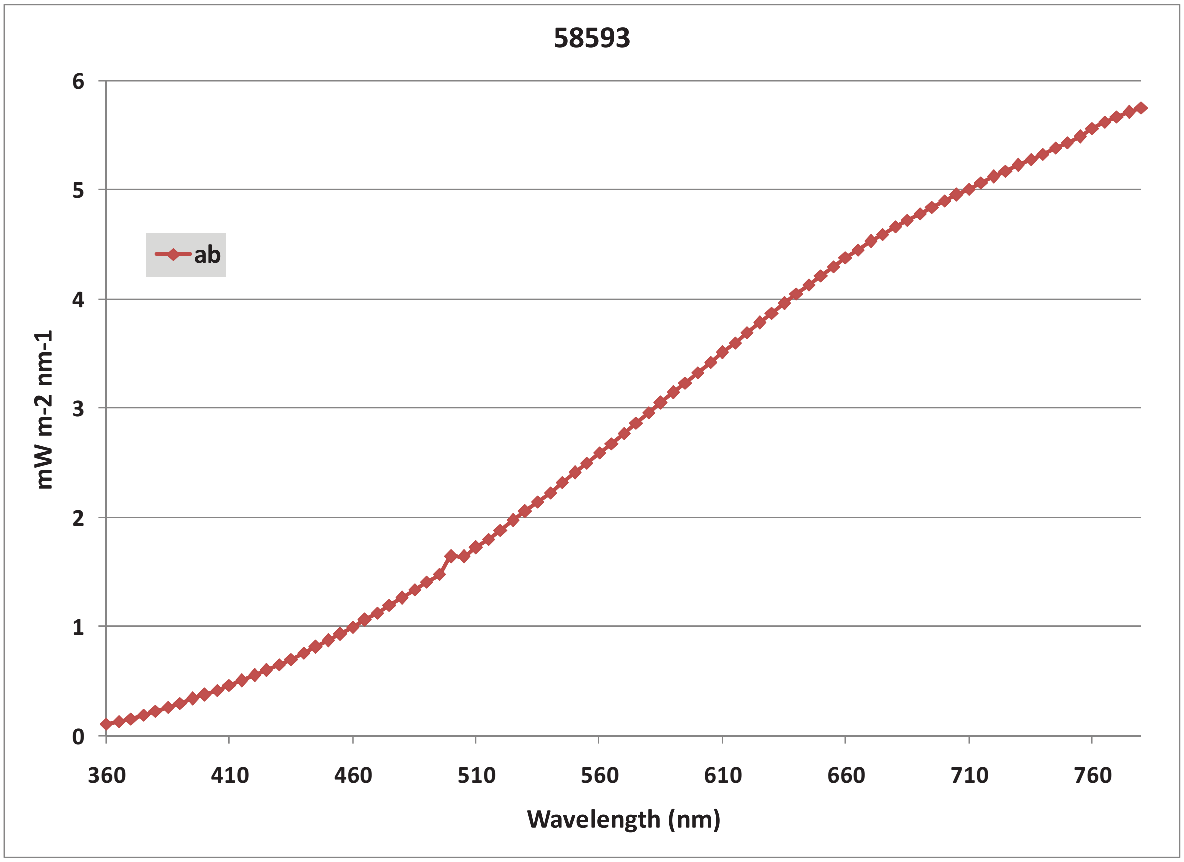
58570
3
2.5
2
1.5
1
0.5
0
ab
mW m-2 nm-1
360
410
460
510
560
610
660
710
760
Wavelength (nm)

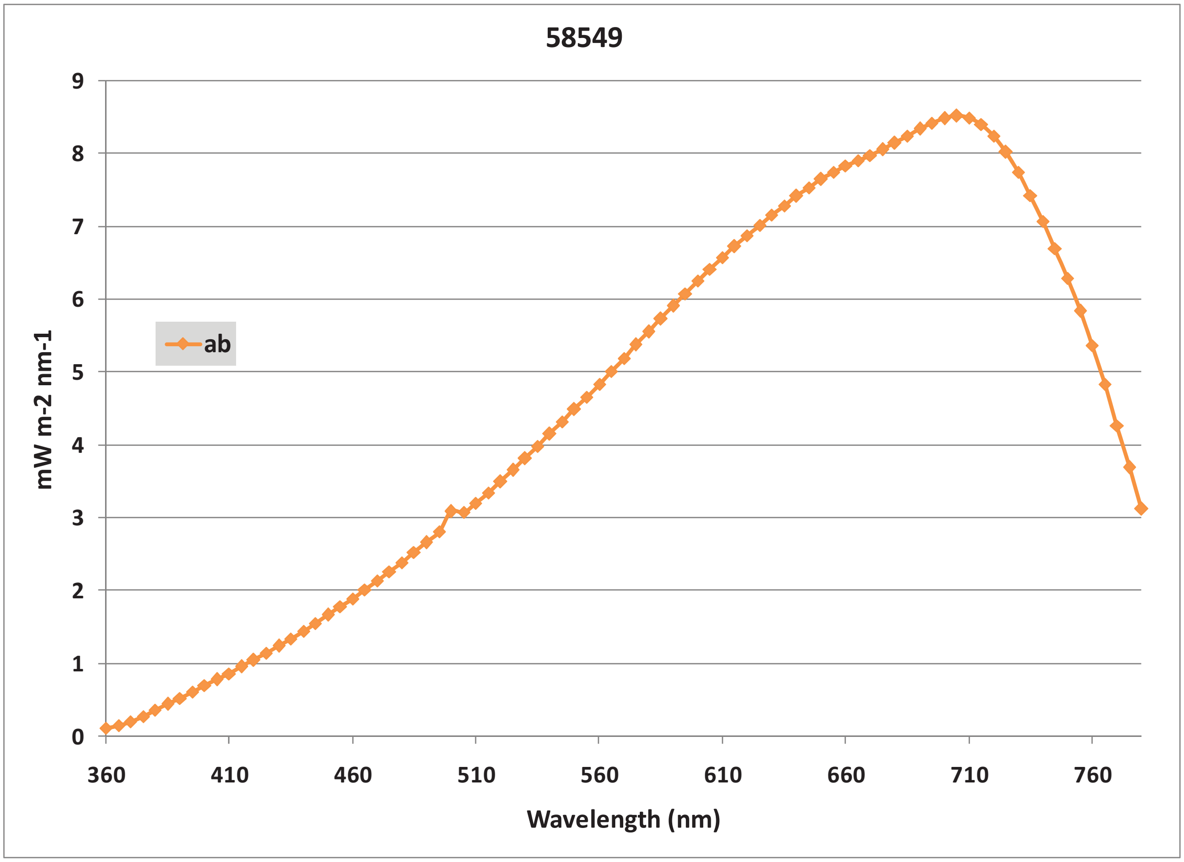

58547
9
8
7
6
5
4
3
2
1
0
ab
mW m-2 nm-1
360
410
460
510
560
610
660
710
760
Wavelength (nm)



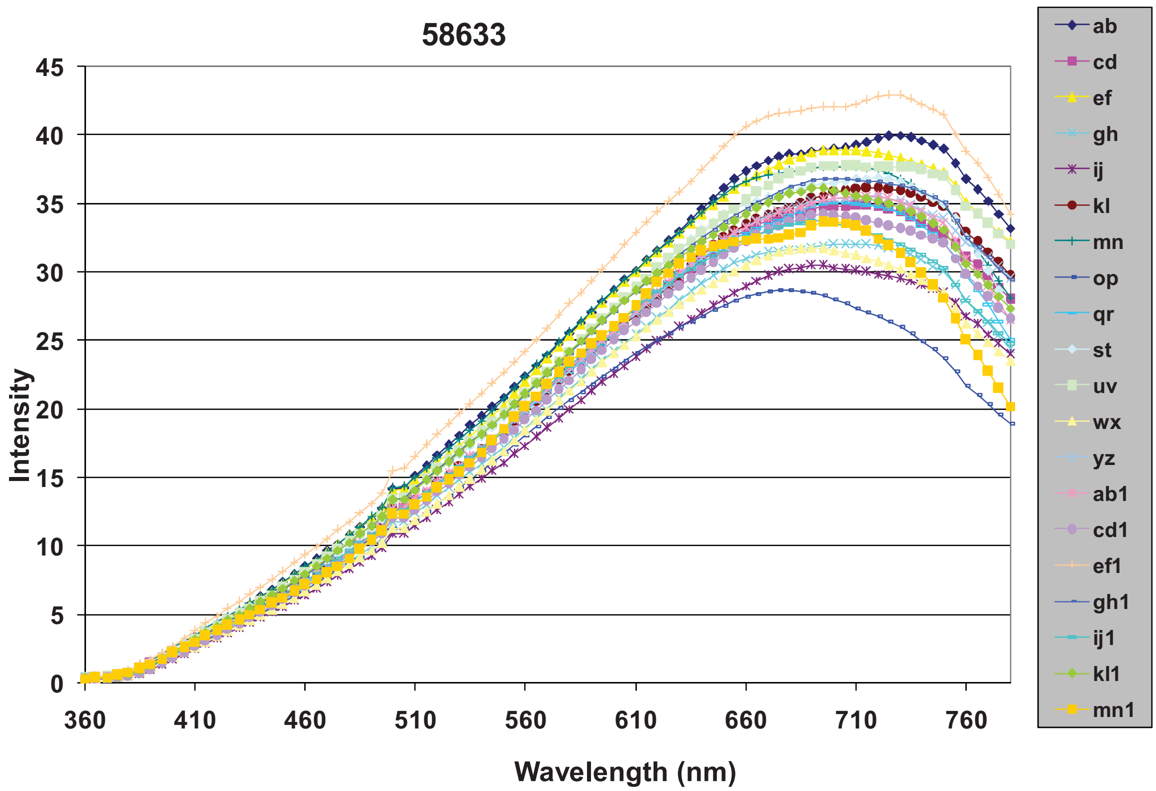
58557
mW m-2 nm-1
ab
0
1
2
3
4
5
360
410
460
510
560
610
660
710
760
Wavelength (nm)


58203
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
mW m-2 nm-1
ab
360
410
460
510
560
610
660
710
760
Wavelength (nm)

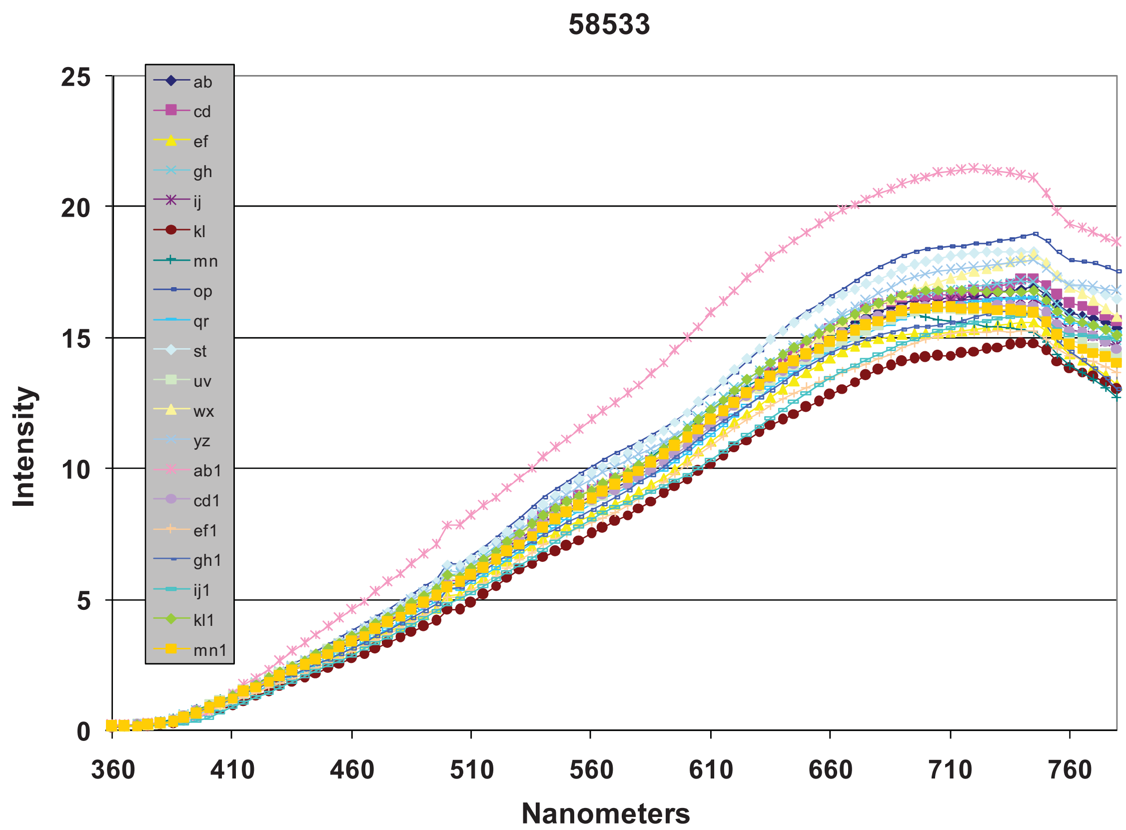

58593
6
5
4
3
2
1
0
ab
mW m-2 nm-1
360
410
460
510
560
610
660
710
760
Wavelength (nm)



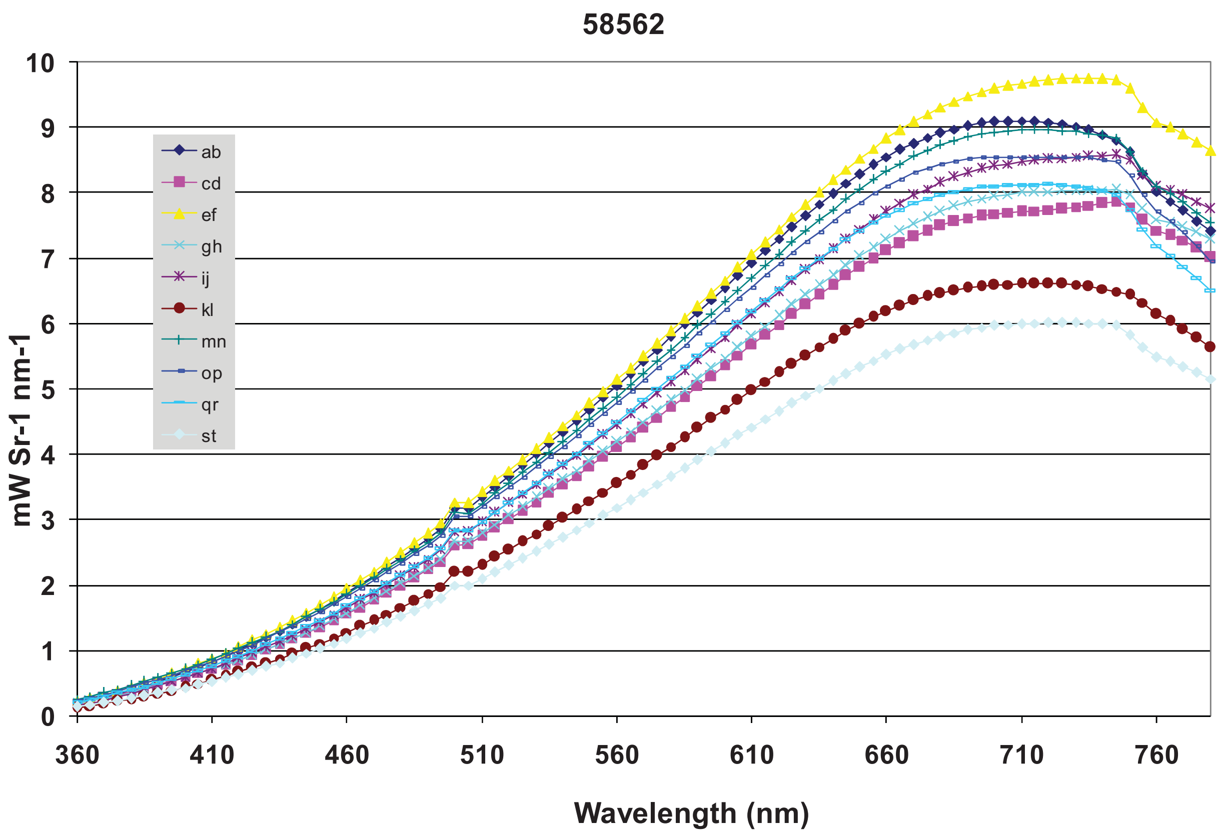
58549
9
8
7
6
5
4
3
2
1
0
mW m-2 nm-1
ab
360
410
460
510
560
610
660
710
760
Wavelength (nm)



58633
Intensity
Wavelength (nm)
0
5
10
15
20
25
30
35
40
45
360
410
460
510
560
610
660
710
760
ab
cd
ef
gh
ij
kl
mn
op
qr
st
uv
wx
yz
ab1
cd1
ef1
gh1
ij1
kl1
mn1



58533
25
20
15
10
5
0
Intensity
360
410
460
510
560
610
660
710
760
Nanometers
ab
cd
ef
gh
ij
kl
mn
op
qr
st
uv
wx
yz
ab1
cd1
ef1
gh1
ij1
kl1
mn1


58562
mW Sr-1 nm-1
Wavelength (nm)
0
1
2
3
4
5
6
7
8
9
10
360
410
460
510
560
610
660
710
760
ab
cd
ef
gh
ij
kl
mn
op
qr
st

APPENDIX E

The following figures are related to section 4.1Human Lighting Evaluation Methods, in this document.

When a participant comes into the testing facility he or she is given the following: a detailed explanation of the purpose of the project and a consent form to participate in the research. A copy of each of these forms is included in the following pages.

Dr. Carl Dirk (cdirk@utep.edu), Monica F. Delgado (gafiromon@aol.com) : The University Of Texas at El Paso

Evaluation of illuminants for museum lighting of Old Master Drawings

Thank you for participating in this evaluation. The purpose of the research is to design better lighting that will minimize long term photochemical degradation of Old Master Drawings and other light-sensitive works of art. Your answers will help define future museum lighting standards. This will contribute significantly toward preserving the great works of art of the world.

In order to fulfill its educational and exhibition mandates, a museum must have on display its major works of art, for long periods of time. This means the some works of art may be exposed to light for decades or centuries. Light exposure is a great environmental risk because it cannot be eliminated or readily stabilized. This light exposure is the transmission of energy to the piece. Photochemical degradation is inevitable. Most of this damage is irreversible, and the consequence is that works of art will lose their luster within decades or destroyed in centuries. Works of art on paper particularly watercolors, are among the most susceptible, and could be destroyed in years or months of exposure. Thus we are first concentrating on Old Master Drawings e.g. drawings earlier than the 18th century.

The most common methods of controlling the damage caused by light exposure has been to reduce the intensity of the light, limit the amount of light exposure and remove non-visible wavelengths from the illuminants. We have pioneered a method that removes unnecessary *visible* wavelength regions of light as well. Thin-film, dielectric, multi-coating technology is used to create filters that remove ultraviolet light, near infrared light, and significant unnecessary *visible* regions of light thus maximizing the reduction in photochemical degradation, while maintaining optimal color rendering.

We can measure reduction in damage quantitatively, but it will be determined by the participant's opinions whether this filter can do this without compromising the color rendering of the work of art. Your conscientious help is crucial in aiding the development of the best lighting, and your contributions will preserve the world's artistic cultural heritage for future generations.

Supported by The Getty Conservation Institute

Consent to Participate in Research

Project: **Evaluation of illuminants (lighting) for museum lighting of Old Master Drawings (OMDs)**
Principal Investigator: **Dr. Carl Dirk, Department of Chemistry, cdirk@utep.edu, x-7560**
Purpose of the Research: To optimize lighting which will minimize long term photochemical degradation of Old Master Drawings and/or other works of art

Value: Your participation will help define future museum lighting standards, AND contribute significantly toward preserving the great works of art of the world

Procedures:

1) **Participation is voluntary**
2) You will read this consent form and ask any questions.
3) You will sign this consent form, in duplicate, if you agree to participate
4) You will be provided with one of the signed copies of this form.
5) Your color vision will be tested
6) You will be asked to evaluate one or more prints of watercolors or OMDs, under two different lighting conditions
7) You will be asked to judge the brightness of the two lighting systems by adjusting a dial control to equivalent brightness
8) You may be asked to return to assess other lighting under development, though you can refuse at any time to continue further participation.

Duration (typical):
The Color Vision test needs to be administered once, 10 minutes.
The comparative lighting test may require 10-15 minutes.
The brightness assessment will require approximately 5 minutes.

Total time for the entire procedure: Less than 45 minutes (includes color vision check)
Less than 30 minutes for future assessments (procedures 5-7 only)

Risks and Discomfort:	None
Costs to you:	None beyond the time you contribute
Information we require from you:	your age in years and your gender
Compensation for participation:	None

Confidentiality: Neither your age, the results of your scientific color vision assessment nor your opinions on lighting or brightness will be disclosed to anyone other than the PI and test administrator (one of the students participating in the study). Upon completion of the study, the master list identifying participants will be destroyed and results will be linked only by anonymous subject numbers.
Voluntary participation: You may at any time during a testing session withdraw from that session or the entire study. You are not required to continue participation after having participated in an earlier assessment. You may skip participation in a session and continue in a future session.
Scheduling: The testing administrator (one of the students working on this study) will attempt to schedule you at times convenient for you. You will not be required to attend at a time that may be inconvenient.
Color Vision assessment: It is understood that the color vision test is a scientific assessment of your color vision, not a clinical assessment. It cannot be used as proof of adequacy or inadequacy

of color vision. You may choose to receive or not receive the result of this scientific assessment. If you choose to receive this result, it will be sent to you, in writing, after the first lighting assessment is complete. You do not need to fully complete the entire session in order to receive the color vision assessment. It is understood that no follow-up vision care or testing will be supplied. If the subject has questions or concerns about the Color Vision test, they may consult with a physician at their expense. It is understood that this scientific assessment of color vision may not agree with a clinical assessment for color vision administered by your doctor. The PI, student testing administrators, and The University of Texas at El Paso assume no liability for the consequences of divulging or not divulging the results of the color vision test to you.

Additional questions: Any concerns or questions about this study can be directed to Karen Hoover, Institutional Coordinator for Research Review, 915-747-7939

Do you wish the results of the color vision test disclosed to you? ____yes ______no

If you do wish the results of the color vision test disclosed, please provide an address (this can be a campus address).
Name____

Address____

Address____

City ____________________ State______ Zip________

I ______________________________have read and understand this document, and by signing, agree to volunteer for this study. I understand I may withdraw at any time.

Age________________________ Gender: Male_____ Female_____

Signature____________________________date______________

Signature of parent or Guardian______________________

Signature of PI or designated representative____________________

Please provide an e-mail address or phone number to be used solely to schedule you for future sessions: ____

To be filled in by test administrator ____________________________
Subject number ____________________

APPENDIX F

Administration of Color Vision Tests

Waggoner HRR Color Vision Test

The information for the Waggoner HRR Color Vision Test was obtained directly from the instructions included in the test plates. The test book was obtained from the Color Vision Store (806 Idaho Ave. Ames, IA 50014). The Waggoner HRR Color Vision Test is made up of 26 plates. This test identifies, classifies, and assesses the degree of the defective color vision in the general population, from infants to senior citizens. The plates from 1-10 and 12-13 examine for red/green (protan/deutan) color deficiency. Plate number 11 tests for blue/yellow (tritan) color deficiency. The plates 11 and 14-16 examine the severity of the tritan color deficiency. And plates 18-26 assess the severity and type of the red/green color deficiency.

The test should be administered in the following manner. The administrator or assessor of the test should hold the plates about 24-30 inches away from the subject. The plates should be held at right angles directly to the subjects' line of sight. The examiner should ask: Tell me what figures you see on each plate, and where the figures are located. You don't have to tell me the colors of the figure that you see. The answers should be given by the subject within 3-4 seconds. The response should be immediate the subject is not allowed to change his or her initial response. On the score sheet a check should be placed next to the

symbol or symbols identified. The normal area on the score should be check only if all the symbols are correctly identified.

The test was designed employing the light source classified as "C" by the CIE. This test should be administered under this light source or another very close light source. The Waggoner HRR Color Vision Test manual recommends the MacBeth Solsource for the testing. The other alternate light sources that can be used for this test are color corrected fluorescent tubes. If fluorescent tubes are going to be used, these have to have a color temperature of 6500° Kelvin, a balanced spectral distribution and a color rendering index of ≥ 90. Incandescent light sources should not be employed under any circumstances. The utilization of any other light source not mentioned here will reduce the validity of this test. The fluorescent tubes that were used in this test are from Sylvania product number 21718. The brand name is the Octron®) 800 XP® ecologic®. The length of the lamp is 23.78 inches and is 1.10 inches in diameter. The average life of this lamp is 36000 hours. The color rendering index is 85 (reference illuminant unknown). The color temperature is 6500 K and the wattage is 17.

Before the test is administered two demonstration plates should be shown to the subject. The purpose of these plates is to have the subject become familiar with the plates. There is no time limit for the use of these plates. These plates should not be scored. After the subject has become familiar with the

testing, the screening plates should be shown. As it was mentioned before plates 1-10 and 12-13 screen for protan/deutan color deficiency. If the subject is an adult all plates from 1-10 and 12-13 should be identified correctly in order to pass. If all, 13 plates are passed then normal vision should be recorded on the score sheet. For the purposes of the museum lighting test the youngest subjects that are accepted are of 13 years of age. From 13-16 years of ages is still considered pediatric. For the pediatric age group only the plates from 1-10 and 11 should be employed. Pediatric subjects should only identify 9 plates correctly out of the 1-10 and 11 in order to pass and receive a normal test score.

The Waggoner HRR Color Vision Test as it was mentioned before has 26 plates, for the purposes of this work, only plates 1-16 are used. The classification of the subject for plates 11 and 14-16 is done as follows: if the subject scores deficient only on plate 11, he or she is classified as mild tritan, if the subject score deficient on plate 14 he or she is classified as medium tritan and if the subject scored deficient on plates 15 and 16 he or she is classified as strong tritan. In the following illustration the score sheet for the Waggoner HRR Color Vision Test can be appreciated.

Waggoner HRR® Score Sheet Date ________ Age ___

Name ______________________ ID______________ Sex __

Do not score the two demo plates

R/G (Protan/Deutan) Screening

	Normal		Deficient	
1.	O Δ	___	Δ	___
2.	☆O	___	O	___
3.	X O	___	X	___
4.	Δ O	___	O	___
5.	Δ O	___	Δ	___
6.	O X	___	O	___
7.	O □	___	□	___
8.	X O	___	X	___
9.	□ O	___	Error	___
10.	Δ OX	___	Error	___
Total R/G		___		___

B/Y (tritan) Screening

M 11. O Δ ___ Error___

R/G Screening *(adults only)*

12. Δ O ___ Error___

13. OX ___ Error___

Diagnostic Analysis Starts Here

Degree of B/Y (Tritan)

	Normal		Deficient
Med. 14.	XΔ	___	Error___
S 15.	O	___	Error___
S 16.	X	___	Error___
17.	No symbols do not count		

Type and Degree of R/G

	Protan		Deutan	
M 18.	Δ	___	X	___
M 19.	O	___	X	___
M 20.	X	___	O	___
M 21.	Δ	___	O	___
Med. 22.	O	___	Δ	___
Med. 23.	Δ	___	X	___
S 24.	X	___	O	___
S 25.	O	___	Δ	___
S 26.	Δ	___	□	___
Total		___		___

Screening Analysis

Normal ___

Defective:

R/G ___

B/Y ___

Questionable ___

Diagnostic Analysis

Type

Deutan ___

Protan ___

Tritan ___

Unclassified___

Degree

M=Mild ___

Med.= Medium ___

S=Strong ___

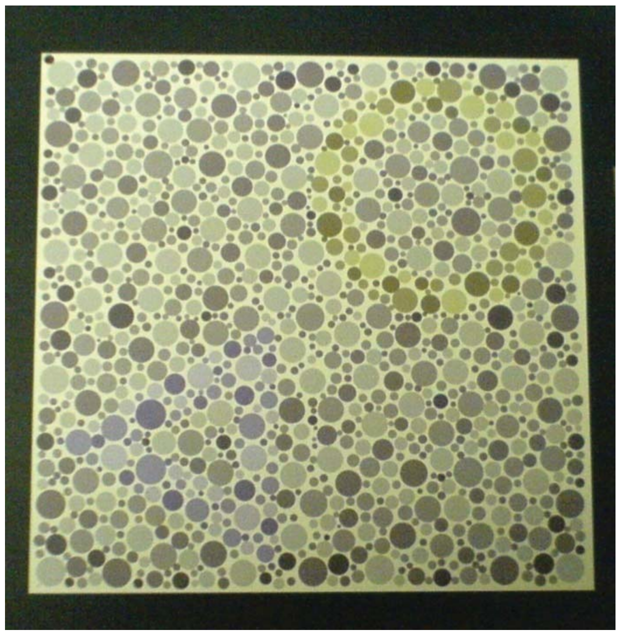
For this work, scores in percentages are given. These scores are calculated as follows: plates 1-9 have two symbols if both symbols in each plate are identified by the subject correctly the subject will receive a score of a 100, if only one of the two symbols is identified correctly the score will be 50 for that plate. For plate 10 there are three symbols. If the subject identifies all of these symbols correctly the subject will receive a score of 100, if only 2 are identified correctly a score of 66 will be given if only one symbol is identified correctly a score of 33 will be assigned. Plates 11-14 have also two symbols each. If the subject identifies correctly the two symbols on each plate the subject will receive a score of a 100 for each plate. If only one symbol is identified correctly on each plate then a score of 50 is assigned to that plate where only one symbol was identified.

The correct answers for this test are identified in the following chart.

Plate No.1 O Δ	Plate No.5 Δ O	Plate No.9 □ O	Plate No.13 O X
Plate No.2 ☆ O	Plate No.6 O X	Plate No.10 Δ O X	Plate No.14 X Δ
Plate No.3 X O	Plate No.7 O □	Plate No.11 O Δ	Plate No.15 O
Plate No.4 Δ O	Plate No.8 X O	Plate No.12 Δ O	Plate No.16 X

In order to keep the plates pristine for a long period of time, they should not be exposed to sunlight and should be kept in the dark when not in use.

When administering the test, it is recommended that the assessor wears gloves and that he or she should never come into contact with the color in the plates without gloves. The next image shows one of the plates used to screen tritan deficiency. The following image is a photograph taken by Monica F. Delgado from the Waggoner HRR Color Vision Test book.



The next image shows one of the plates used to screen protan/deutan deficiency. The following image is a photograph taken by Monica F. Delgado from the Waggoner HRR Color Vision Test book.

Ishihara's Tests[40] for Colour Deficiency by Shinobu Ishihara MD

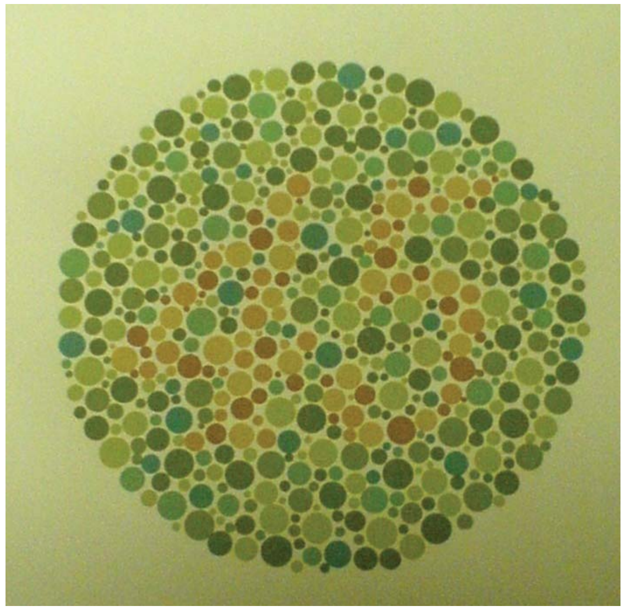
This color test was designed by an ophthalmologist by the name of Shinobu Ishihara, who created this test to detect color blindness. His research in ophthalmology started in the early 1900's while working in the Military Medical School. His research consisted of selecting superior soldiers based on their eyesight capabilities. This research was called "battlefield ophthalmology". He was asked by the Military Medical School to create or design a test that could screen military recruits for aberration in their color vision. He designed some color plates with the help of his assistant who happened to be color blind. The original plates designed by Dr. Ishihara were hand painted by him using watercolors and

hiragana symbols. The Ishihara color vision charts were officially established in 1918.

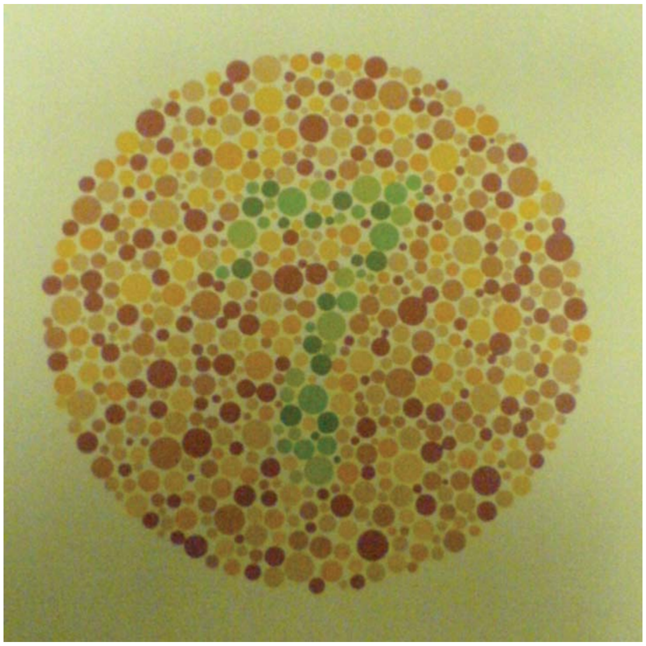
This color test is a specific test for red-green color deficiencies. This test is composed of thirty-eight color plates, each plate has a circle that contains numerous, and different size dots, each dot are of somewhat dissimilar color. These dots inside the central circle of each plate are spread in an apparent random manner. Inside the dot pattern mentioned above, a number is located right at the center.

The patient or subject may see nothing, something, or a number on each plate. What the subject sees is what is going to determine whether the subject has a color vision deficiency and what kind. Even though the complete test needs to be administered, if the subject has a deficiency it often can be determined by the forth plate.

There are mainly two types of color plates. The first kind is to determine protanopia. These kinds of plates have a circle of dots in two colors green and light blues. The number in the middle of this pattern of dots is in a brown color. This type of plate is shown in the following image. The image is a photograph taken by Monica F. Delgado from the Ishihara book.



The second category of plates is to determine deuteranopia. In these plates, the colored dots are in shades of red, orange and yellow, the number in the middle being in green. This type of plate is shown in the following image. The image is a photograph taken by Monica F. Delgado from the Ishihara book.



The illumination for this test should be conducted in a room where the illumination is least 500 lux and having a light source with a color temperature of 6000° K.

This test is still considered to this date to be the first choice for identifying and determining color blindness around the world.

The correct answers are as follows:

Plate No.1 12	Plate No.5 74	Plate No.9 -	Plate No.13 96
Plate No.2 8	Plate No.6 7	Plate No.10 16	Plate No.14 wavy line
Plate No.3 5	Plate No.7 45	Plate No.11 wavy line	
Plate No.4 29	Plate No.8 2	Plate No.12 35	

For the purposes of this work, the scoring is as follows: If the subject correctly identifies the number or symbol on each plate a check is placed next to the correctly identified plate number or a cross if not identified correctly. At the end the number of the total plates identified correctly is divided by the total number of plates, this number is multiplied by a 100 to get a number in percentage. For example if the subject identified correctly plates from 1-12 and incorrectly 13 and 14 the total score will be 12/14 giving a score of 85.71%. The score sheet made up for this Museum Lighting Test is shown in the following image.

12 ___
8 ___
5 ___
29 ___
74 ___
7 ___
45 ___
2 ___
- ___
16 ___
~ ___
35 ___
96 ___
ی ___

Tritan Album

The Tritan Album was created by Dr. Philippe L'anthony[41]. This album was created to identify, diagnose, and evaluate the blue-yellow dyschromatopsia. This type of color blindness is almost never inherited and is very commonly

acquired due to other problems of the eye and the optic pathways. This test is manly applied in clinical ophthalmology.

This tritan album is made up 6 plates that are numbered from 0 to 5. These plates are called pseudoisochromatic plates. Pseudoisochromatic means[40] of or relating to a plate or image of two or more colours that appears isochromatic (uniform in colour) to a person with a particular form of colour-blindness and is included in a set of plates such as the Ishihara test or the Stilling test used to test colour vision. Each plate has an equilateral rhombus that is made up of multiple small circles these circles are very closely packed together. The circles are arranged so that they form a background of different shades of grey. The different grays' that make up the background are very close to the Munsell chrome from 10 to 2. Within these grey small circles another smaller rhombus is located. This smaller rhombus is of a different color that becomes less noticeable from plate number one to plate number 5.

Each plate is shown to the subject, starting with plate number 0. The assessor or person administrator of the test gives the following instruction to the subject: There is a figure that is different in color from the figure that contains it. You need to tell me where this figure of different color is located, whether is top, bottom, left or right. Only one answer is allowed per plate.

The correct answers are as follows:

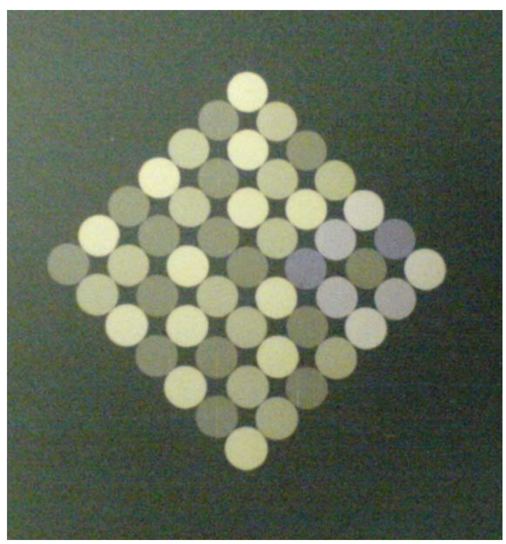
Plate No.0	Top	Plate No.3	Bottom
Plate No.1	Right	Plate No.4	Top
Plate No.2	Top	Plate No.5	Bottom

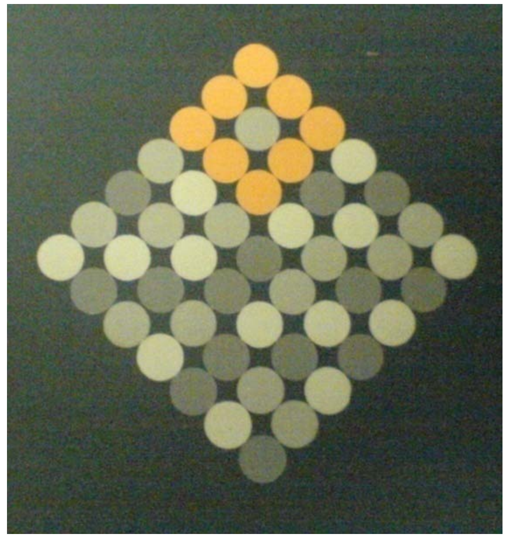
The explanation of the calculation of the score for this test is only to be used for the Museum Lighting Test. The score for this test depends on the number of plates correctly read by the subject. Plate number 0 should be read correctly in order to get a score. In other words if the subject did not identify plate number 0 correctly a score cannot be given. If plate 0 is read correctly then a score can be assigned based on the number of plates read correctly. The score is calculated as follows: the total number of correctly identified plates divided by the total number of plates, this number is then multiplied by a 100. The score will therefore be a percentage. For example plates 0 and 1 have been read correctly but 2, 3, 4, and 5 are not then the score is 1/5. Then this is multiplied by a 100 and it gives 20%. If plates 0, 1, 2, 3 are read correctly but 4 and 5 are not the score could be 3/5 giving a 60%. Again this score is calculated only for the Museum Lighting Test.

The number 0 plate is only an example or demonstration plate. This plate can be read by all normal subjects and people that have inherited color deficiencies. If the number 0 plate cannot be read by the subject it usually

means that the subject has a problem related to poor visual acuity and it has no significance in color discrimination.

This test should be conducted in a room where the illumination is at least 500 lux and the light source having a color temperature of 6000° K. In order to keep the plates pristine for a long period of time, they should not be exposed to sunlight and should be kept in the dark when not in use. When administering the test it is recommended that the assessor wears gloves and that he or she should never come into contact with the color in the plates. In the following image the number 1 plate from the tritan album is shown. The following images are photographs taken by Monica F. Delgado from the L'Anthony book.





On the following chart the colors for plates number 1 thru 5 are identified. The information for this chart was obtained from Laboratoire de la Vision des Couleurs, located at Centre National D'Ophtalmologie des Quinze Vingts in Paris, France.

Plate Number	Munsell
0	2,5 YR 5/12
1	10PB 4/10 5/10 6/10
2	10PB 4/8 5/8 6/8
3	10PB 4/6 5/6 6/6
4	10PB 4/4 5/4 6/4
5	10PB 4/2 5/2 6/2

The following tables show all the results for the color vision tests that were used in this study.

Subject number	Age	HRR 1-10	HRR 11	HRR 12	HRR 13	HRR 14	HRR 15	HRR 16
1	32	100	100					
2	26	100	100					
3	25	100	50					
5	24	100	100					
6	30	100	50					
7	37	100	0					
8	58	100	0					
9	66	100	50					
10	22	100	50					
11	42	100	50					
12	20	100	50					
13	19	100	100					
14	36	100	50					
15	26	100	0					
16	29	100	100					
17	13	100	50					
18	32	100	100					
19	27	100	100					
20	11	100	100					
21	34	100	50	100	100	100	100	100
22	47	100	100	100	100	100	100	100
23	38	100	0	50	100	100	50	100
24	19	100	100	100	100	100	100	100
25	50	100	100	100	100	100	100	100
27	46	100	100	100	100	100	100	100
28	54	100	100	50	100	100	50	100
29	22	100	100	100	100	100	100	100
30	48	90	100	100	100	100	100	100
31	64	100	50	50	100	100	50	100
32	28	100	50	100	100	100	100	100
33	24	100	100	100	100	100	100	100
34	38	90	100	50	100	100	50	100
35	22	100	50	100	100	100	100	100
36	35	100	100	100	100	100	100	100
37	32	100	100	100	100	100	100	100
38	35	100	100	100	100	100	100	100
39	20	100	100	100	100	100	100	100
40	24	100	100	100	100	100	100	100
41	42	100	100	100	100	100	100	100

42	23	100	100	50	100	100	100	100
43	28	100	100	100	100	100	100	100
44	24	100	100	100	100	100	100	100
45	58	100	100	50	100	100	100	100
46	41	100	100	100	100	100	100	100
47	40	100	100	100	100	100	100	100
50	21	100	100	100	100	100	100	100
51	48	100	100	100	100	100	100	100
52	22	100	100	100	100	100	100	10
53	31	100	100	100	100	100	100	100
54	22	100	100	100	100	100	100	100
55	33	100	100	100	100	100	100	100
56	22	100	100	100	100	100	100	100
57	34	100	100	100	100	100	100	10
58	26	100	100	100	100	100	100	100
59	24	100	100	100	100	100	100	100
60	23	100	100	100	100	100	100	100
61	26	100	100	100	100	100	100	100
62	38	100	100	100	100	100	100	100

Subject number	Age	Ishihara	L'Anthony
1	32	100	100
2	26	10	100
3	25		
5	24		
6	30		
7	37	100	80
8	58	100	20
9	66		
10	22		
11	42		
12	20		
13	19		
14	36		
15	26		
16	29		
17	13		
18	32		
19	27		

20	11		100
21	34		
22	47		
23	38		
24	19		100
25	50		100
27	46		80
28	54		100
29	22		100
30	48		100
31	64		80
32	28		100
33	24		100
34	38		100
35	22		100
36	35		100
37	32		100
38	35		100
39	20	100	100
40	24	100	100
41	42	100	100
42	23	100	100
43	28	100	100
44	24	100	100
45	58	100	100
46	41	100	100
47	40	100	100
50	21	100	100
51	48	100	100
52	22	92.85	100
53	31	100	100
54	22	100	100
55	33	100	100
56	22	92.85	100
57	34	100	100
58	26	100	100
59	24	92.85	100
60	23	100	100
61	26	92.85	100
62	38	100	100

APPENDIX G

Administration of the Farnsworth D-15 Test[42, 43]

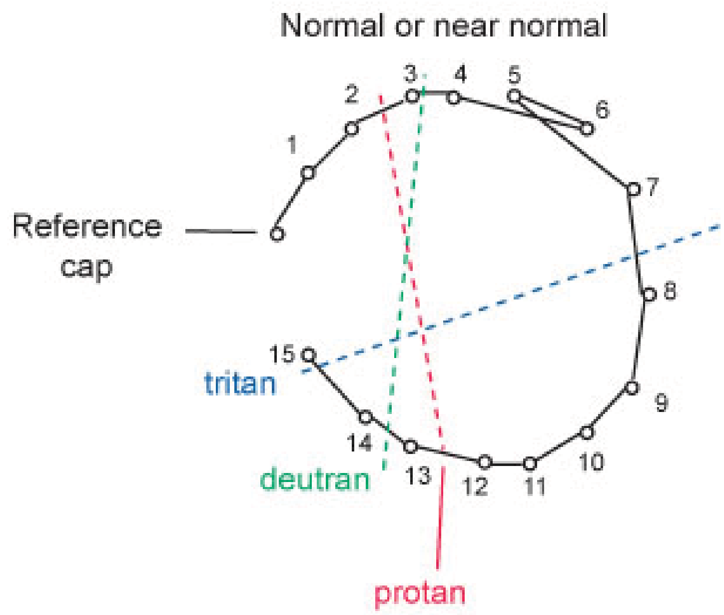
The test is administered in the following manner. It should be conducted in a room where the illumination is at least 500 lux and the light source having a color temperature of 6000° K. The subject and the examiner should be wearing gloves at all times to prevent damage to the discs. The discs are shuffled or mixed up by the examiner the numbers are facing down; this means that the color of each disc is facing up always. These discs are spread out on a table preferably the table should be of neutral color or black color. If a table of neutral or black color is not available a table cloth of neutral color or black color can be used. The subject should not flip the discs before during or after the testing otherwise the results will be invalidated. The subject has to arrange the discs in order or similarities in color starting from the reference color. People or subjects with normal color vision will arrange the colored discs from the reference blue through green, then yellow then orange and then finally red. The people or subjects arranging these discs do not need to know any color theory in order to take this test. In other words people who do not know color theory will not affect their results. Subjects with an acute deficiency will have severe problems arranging the discs in the right order.

This is how the D-15 test works. This Farnsworth test is designated as dichotomous. Dichotomous means diving into two parts. The D-15 test is

classified as dichotomous because subjects based on their results are classified into two categories. The first category is strongly deficient. The second category is normal. This test comes with a computer program that calculates the score for each subject based on each subject's answers. This computer program is used for the Museum Lighting Study.

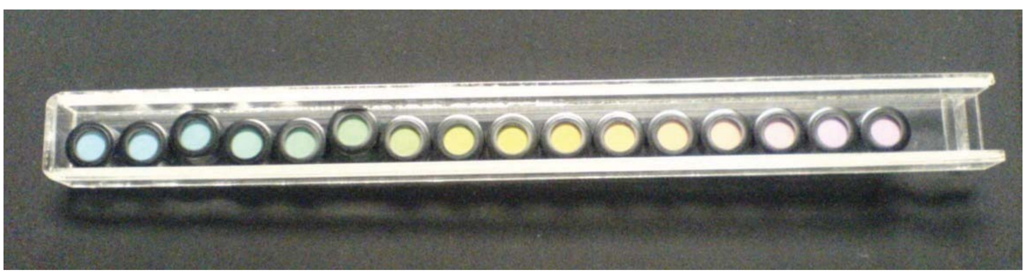
Information of who created this program and what computer code is not provided by the company who makes or distributes this test. In simple terms, the computer program works in the following manner. The computer program creates a graphical representation where each color chip is shown as a dot in a CIE color diagram. These dots are connected with lines according to the order of the arrangement of the subject. The lines that connect these dots have different angles. These different angles produce what are called color difference vectors, according to Vingrys and King-Smith[45]. These color difference vectors are used to produce a score. This score is made up of three significant values. These three significant values are the angle, the color confusion index, and the scatter index. The angle indicates the type of color deficiency. The confusion index measures de severity of the color deficiency. The scatter index asses the degree of the scatter. For the purposes of the Museum Lighting Study only the color confusion index is used. The following illustration shows the diagram that the computer program creates as graphical representation where each color chip is shown as a dot in a CIE color diagram.

As it was mentioned in the above paragraphs, these dots are connected with lines according to the order of the arrangement of the subject. The lines that connect these dots have different angles. These different angles produce what are called color difference vectors. The image that illustrates what it mentioned above was made by Monica F. Delgado adapted from Color Confusion Index Sheet[42, 45].



In order to keep the discs pristine for a long period of time, the discs should not be exposed to sunlight and should be kept in the dark when not in use. When administering the test it is recommended that the assessor and the subject wear gloves at all times. Neither the assessor not the subject should ever come into contact with the color discs without gloves.

For the purposes of the Museum Lighting Study the D-15 test is administered three times to each subject. The first time the test is administered under the specified illumination of 500 lux. The fluorescent tubes that were used in this test are from Sylvania product number 21718. The brand name is the Octron®) 800 XP® ecologic®. The second time is given under the Unfiltered light using the 58562 Sylvania lamps. The third time is given under the filtered light using the 58533 Sylvania lamps. It should be clear that the subject does not know before during or after the test which light is the filtered light and which one is the Unfiltered light. The following image is a photograph taken by Monica F. Delgado of the set that is used in the Gallery Testing Facility.



The D-15 is a subset of the Farnsworth Munsell 100 Hue Test. The D-15 is what is called a color arrangement test. These types of tests can identify if someone is color blind. These color arrangement tests are made up of a specific number of color discs. In this case for the D-15, the number of colored discs is 16. The D-15 is numbered at the back of the discs from 0 to 15 the 0 disc being just a reference point.

The volunteer is instructed to come into the testing gallery. The lights for the daylight testing are on. Inside the gallery a black table is placed and a chair for the subject to sit down. The table and chair are placed in an exact location marked on the floor. This exact location was determined by using a lux meter. The lux meter determined that that specific area is where the optimum level of light of at least 500 lux was met. Once the subject is in place gloves are given to him or her to wear. The instructions are given to the subject. The discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the discs are removed from the area by the administrator of the test. The results of the test are recorded by the test administrator; the subject does not see the results or scores of the test.

Once this 1st part of the testing is completed the subject is asked to stand while the table and chair are moved to another location within the gallery. The subject is instructed to keep the gloves. This new area is also marked on the floor. The area was determined by using a lux meter. The lux meter determined that that specific area is where the optimum level of light of at least 150 lux was met. Once the table and chair are in the specified area the subject is asked to sit down. All the lights are turned off for 15 seconds so that the eyes can “forget” the other light source and adapt to the “new” light source. After the 15 seconds have elapsed the Unfiltered light is turned on. The instructions are given to the

subject. The discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the discs are removed from the area by the administrator of the test. The results of the test are recorded by the test administrator; the subject does not see the results or scores of the test.

Once this 2nd part of the testing is completed the subject is asked to stand while the table and chair are moved to another location within the gallery. The subject is instructed to keep the gloves. This new area is also marked on the floor. The area was determined by using a lux meter. The lux meter determined that that specific area is where the optimum level of light of at least 150 lux was met. Once the table and chair are in the specified area the subject is asked to sit down. All the lights are turned off for 15 seconds so that the eyes can "forget" the other light source and adapt to the "new" light source. After the 15 seconds have elapsed the filtered light is turned on. The instructions are given to the subject. The discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the discs are removed from the area by the administrator of the test. The results of the test are recorded by the test administrator; the subject does not see the results or scores of the test. The subject is asked to keep the gloves and asked to step out of the testing gallery while the administrator prepared the gallery for the L'Anthony's Desaturated 15-Hue Test.

The following tables show the results for the Farnsworth D15 of all the subjects, for daylight, for the reference, Mark 1, Mark 2 and Mark 3.

Subject Number	Farnsworth D15 Daylight (CCI)	Diagnosis	Farnsworth D15 Mark1 (CCI)	Farnsworth D15 Reference
1	1	normal		
2	1	normal		
3				
5				
6				
7	1.305	normal		
8	1	normal		
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23			1	1
24			1	1
25			1	1
27			1	1.09
28			1	1
29			1	1.17
30			1	1
31			1	1.1
32			1	1

33			1	1
34			1	1.74
35			1	1
36			1	1
37			1	1
38			1	1
39	1.34	unclassified		
40	1	normal		
41	1	normal		
42	1	normal		
43	1	normal		
44	1	normal		
45	1	normal		
46	1	normal		
47	1	normal		
50	1	normal		
51	1	normal		
52	1	normal		
53	1	normal		
54	1	normal		
55	1	normal		
56	1	normal		
57	1	normal		
58	1	normal		
59	1	normal		
60	1	normal		
61	1	normal		
62	1	normal		

Subject Number	Farnsworth D15 Mark 2 (CCI)	Farnsworth D15 Reference	Farnsworth D15 Mark3 (CCI)	Farnsworth D15 Reference
1	1	1	1.112	1.087
2	1	1	1	1
3				
5				
6				
7	1	1.271		
8	1.209	1.097		

9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				
37				
38				
39	1	1.123		
40	1	1		
41	1	1.08		
42	1	1		
43	1	1		
44	1	1		
45	1	1		
46			1	1
47			1	1
50			1	1
51			1	1
52			1	1

53			1	1
54			1	1
55			1	1
56			1	1
57			1	1
58			1	1
59			1	1
60			1	1
61			1	1
62			1	1

APPENDIX H

Administration of the L'anthony Desaturated 15-Hue Test[42, 43]

These types of tests can identify if someone is color blind. These color arrangement tests are made up of a specific number of color discs. In this case for the L'Anthony, the number of colored discs is 16. The L'Anthony test is numbered at the back of each disc from 0 to 15 the disc labeled 0 is just a reference point. The front part of the disc is where the color is located at. The colored paper has a diameter of 1.2 centimeters. The total diameter of each disc is of 2 centimeters. The color of each cap is a Munsell color from the Munsell color system.

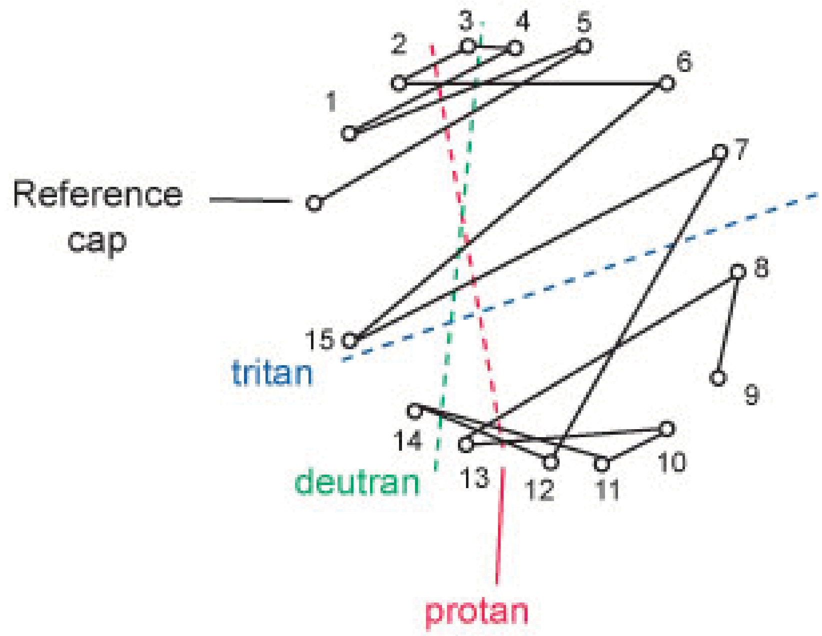
The L'Anthony test is administered in the following manner. This de-saturated test should be conducted in a room where the illumination is at least 500 lux and the light source has a color temperature of 6000° K. The subject and the examiner should be wearing gloves at all times. The de-saturated discs are shuffled or mixed up by the examiner with the numbers are facing down; this means that the color of each disc is facing up always. These unsaturated discs are spread out on a table preferably the table should be of neutral color or black color. If a table of neutral or black color is not available a table cloth of neutral color or black color can be used. The subject should not flip the unsaturated colored discs before during or after the testing otherwise the results will be invalidated. The subject has to arrange the unsaturated colored discs in

order or similarities in color starting from the reference color. Subjects with normal color vision will arrange the unsaturated colored discs from the reference unsaturated blue through unsaturated the green, then unsaturated yellow, then the unsaturated orange and then finally the unsaturated red. The subjects arranging these unsaturated colored discs do not need to know any color theory in order to take this test. In other words people who do not know color theory will not affect their results. Subjects with an acute deficiency will have severe problems arranging these unsaturated colored discs in the right order.

This is how the L'anthony unsaturated test works. This unsaturated test is designated as dichotomous. Dichotomous means diving into two parts. The L'anthony test is classified as dichotomous because subjects based on their results are classified into two categories. The first category is strongly deficient. The second category is normal.

This test comes with a computer program that calculates the score for each subject based on each subject's answers. This computer program is used for the Museum Lighting Study. In extremely straightforward terms the computer program works in the following manner. The computer program for the L'anthony unsaturated test creates a graphical representation where each unsaturated color chip is shown as a dot in a CIE color diagram. These dots are connected with lines according to the order of the arrangement of the subject.

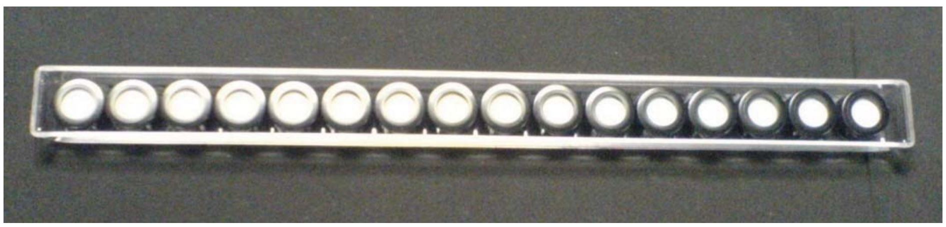
The lines that connect these dots have different angles. These different angles produce what are called color difference vectors, according to Vingrys and King-Smith[45]. These color difference vectors are used to produce a score. This score is made up of three significant values. These three significant values are the angle, the color confusion index, and the scatter index. The angle indicates the type of color deficiency. The color confusion index measures de severity of the color deficiency. The scatter index asses the degree of the scatter. For the purposes of the Museum Lighting Study only the color confusion index is used. The following illustration shows the diagram that the computer program creates as graphical representation where each unsaturated color chip is shown as a dot in a CIE color diagram. As it was mentioned in the above paragraphs, these dots are connected with lines according to the order of the arrangement of the subject. The lines that connect these dots have different angles. These different angles produce what are called color difference vectors. The image that illustrates what it mentioned above was made by Monica F. Delgado adapted from Color Confusion Index Sheet[42, 45].



In order to keep the unsaturated colored discs pristine for a long period of time, the unsaturated colored discs should not be exposed to sunlight and should be kept in the dark when not in use. When administering the test it is recommended that the assessor and the subject wear gloves at all times. Neither the assessor not the subject should ever come into contact with the unsaturated colored discs without gloves.

For the purposes of the Museum Lighting Study the L'anthony test is administered three times to each subject. The first time the test is administered under the specified illumination of 500 lux. The fluorescent tubes that were used in this test are from Sylvania product number 21718. The brand name is the Octron®) 800 XP® ecologic®. The second time is given under the Unfiltered light using the 58562 Sylvania lamps. The third time is given under the filtered light

using the 58533 Sylvania lamps. It should be clear that the subject does not know before during or after the test which light is the filtered light and which one is the Unfiltered light. The following image shows what the L'anthony unsaturated colored discs look like. The image is a photograph taken by Monica F. Delgado of the set that is used in the Gallery Testing Facility.



L'Anthony's Desaturated 15-Hue Test is designed to screen for congenital and acquired color defects. The color discs are less saturated than that of the Farnsworth D-15. These color discs because they are less saturated can help detect more subtle color vision deficiencies. These color arrangement tests are made up of a specific number of color discs. In this case for the L'anthony, the number of colored discs is 16. The L'anthony test is numbered at the back of each disc from 0 to 15 the disc labeled 0 is just a reference point.

The volunteer is instructed to come into the testing gallery. The lights for the daylight testing are on. Inside the gallery a black table is placed and a chair for the subject to sit down. The table and chair are placed in an exact location marked on the floor. This exact location was determined by using a lux meter.

The lux meter determined that that specific area is where the optimum level of light of at least 500 lux was met. Once the subject is in place gloves are given to him or her to wear. The instructions are given to the subject. The L'anthony discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the L'anthony discs are removed from the area by the administrator of the test. The results of the test are recorded by the test administrator; the subject does not see the results or scores of the test.

Once this 1st part of the testing is completed the subject is asked to stand while the table and chair are moved to another location within the gallery. The subject is instructed to keep the gloves. This new area is also marked on the floor. The area was determined by using a lux meter. The lux meter determined that that specific area is where the optimum level of light of at least 150 lux was met. Once the table and chair are in the specified area the subject is asked to sit down. All the lights are turned off for 15 seconds so that the eyes can "forget" the other light source and adapt to the "new" light source. After the 15 seconds have elapsed the Unfiltered light is turned on. The instructions are given to the subject. The L'anthony discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the L'anthony discs are removed from the area by the administrator of the test. The results of the test are recorded by

the test administrator; the subject does not see the results or scores of the test.

Once this 2nd part of the testing is completed the subject is asked to stand while the table and chair are moved to another location within the gallery. The subject is instructed to keep the gloves. This new area is also marked on the floor. The area was determined by using a lux meter. The lux meter determined that that specific area is where the optimum level of light of at least 150 lux was met. Once the table and chair are in the specified area the subject is asked to sit down. All the lights are turned off for 15 seconds so that the eyes can "forget" the other light source and adapt to the "new" light source. After the 15 seconds have elapsed the filtered light is turned on. The instructions are given to the subject. The L'anthony discs are scrambled by the test administrator. The subject is now ready to begin the test. The subject has two minutes to complete the test. When the volunteer has finished the test the L'anthony discs are removed from the area by the administrator of the test. The results of the test are recorded by the test administrator; the subject does not see the results or scores of the test.

This completes the end of the color rendering studies for a single subject. The following tables show the results for the L'Anthony D15 of all the subjects, for daylight, for the reference, Mark 1, Mark 2 and Mark 3.

Subject Number	L'Anthony D15 Daylight (CCI)	Diagnosis	L'Anthony D15 Mark1 (CCI)	L'Anthony D15 Reference
1	1.157	normal		
2	1	normal		
3				
5				
6				
7	1	normal		
8	1	normal		
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20			1	1
21				
22				
23				
24			1	1
25				
27				
28			1.17	1.17
29			1.04	1.04
30			1.07	1.07
31			1.17	1.17
32			1.37	1.37
33			1	1
34			1.74	1.74
35			1	1
36			1.104	1.104
37			1	1
38			1.099	1.099

39	1.088	normal		
40	1.071	normal		
41	1	normal		
42	1	normal		
43	1.071	normal		
44	1	normal		
45	1	normal		
46	1.088	normal		
47	1.209	normal		
50	1	normal		
51	1	normal		
52	1	normal		
53	1	normal		
54	1	normal		
55	1	normal		
56	1	normal		
57	1	normal		
58	1	normal		
59	1	normal		
60	1	normal		
61	1	normal		
62	1	normal		

Subject Number	L'Anthony D15 Mark 2 (CCI)	L'Anthony D15 Reference	L'Anthony D15 Mark 3 (CCI)	L'Anthony D15 Reference
1	1.297	2.13	1.225	1.349
2	1.097	1	1.225	1.282
3				
5				
6				
7	1	1.192		
8	1	1		
9				
10				
11				

12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				
37				
38				
39	1.071	1.192		
40	1.104	1		
41	1	1		
42	1	1		
43	1	1		
44	1	1.071		
45	1	1		
46			1	1.282
47			1.621	1.534
50			1	1
51			1	1
52			1	1
53			1	1
54			1	1
55			1	1

56			1	1
57			1	1
58			1	1
59			1	1
60			1	1.74
61			1	1
62			1	1

APPENDIX I

Subjective Evaluation of Lighting

The subject provides the answers; the answers to the questions in the survey are based solely on the subjects' opinion and perception. The subject is asked to come back into the testing gallery where there are three replicas of three Old Master Drawings. The questions in the survey are solely based on these replicas. There is no time limit to answer the questions, the decision on how much time should be spent on this section and on each answer is left to the subject to decide. The questionnaire was designed by the Museum Lighting Research Study Team (Dirk's Research Team).

There are 9 questions on this written survey. On each question the volunteer is asked to compare two sets of illuminants; illuminant 1 and illuminant 2. Illuminant number 1 is the filtered lighting and the Illuminant number 2 is the Unfiltered lighting. The volunteer does not know before, during or after the test which illuminant is the filtered and which one is the Unfiltered. This is what the examiner says to the volunteer: Please answer the following questions below, place an X along the line shown. Each question is the average of how you perceive the three drawings under each illuminant. The stronger your perception, the closer you should place the X to one side or the other. For example if the three drawings look to red under illuminant 1 you will place an X on the extreme right of the line. If the three drawings look not too red or too little red under illuminant 1 then the X will be place in the middle. If the three

drawings do not look red at all under illuminant 1 then you will place an X on the extreme left of the line.

The first question of the survey asks the volunteer if the three drawings look too red, not too red, or not red at all under the two different illuminants. The volunteer should answer the questions as it was instructed previously. The second question of the survey asks the volunteer if the three drawings look to green under the two different illuminants. The volunteer should answer the question as it was instructed previously. The third question of the survey asks the volunteer if the three drawings look blue under the two different illuminants. The volunteer should answer the question as it was instructed previously.

The remaining six questions deal with comparisons. On the 4th question the subject is asked to compare if the three drawings look blue (on the extreme left of the line) or yellow (on the extreme right of the line) under a particular illuminant. The volunteer should answer the question as it was instructed previously.

On the 5th question the subject is asked to compare if the three drawings look darker (on the extreme left of the line) or brighter (on the extreme right of the line) under a particular illuminant. The volunteer should answer the question as it was instructed previously.

On the 6th question the subject is asked to compare if the three drawings look green (on the extreme left of the line) or red (on the extreme right of the

line) under a particular illuminant. The volunteer should answer the questions as it was instructed previously. The 7th question is regarding color rendering where the subject is asked to compare if the three drawings have bad color rendering (on the extreme left of the line) or good color rendering (on the extreme right of the line) under a particular illuminant. The volunteer should answer the questions as it was instructed previously.

The 8th question is regarding the perception of details where the subject is asked to compare if the three drawings have a low perception of details (on the extreme left of the line) or high perception of details (on the extreme right of the line) under a particular illuminant. The volunteer should answer the questions as it was instructed previously.

The last question is regarding the overall perception of the art with the illumination provided. The subject is asked to compare whether this overall illumination is unsatisfactory (on the extreme left of the line) under a particular illuminant or satisfactory (on the extreme left of the line) under a particular illuminant. The volunteer should answer the questions as it was instructed previously.

There are two methods from which the subject can choose from on how to answer this survey. The first method is to have the illuminant 1 on and answer all the questions regarding illuminant 1. Then switch to the illuminant 2 and answer all the questions regarding the illuminant 2. The second method is to

have illuminant 1 on and answer the 1st question regarding illuminant 1. Then switch to illuminant 2 and answer the 1st question regarding illuminant 2. Then proceeding in the same manner for the remaining questions, that is switching back and forth between each illuminant for each question until all the questions are answered. How this questionnaire is answered is completely up to the subject.

The statistical evaluation of the answers for the survey is handled in the following manner. A precision ruler is used to make all the measurements. Each subject places an X on the answer line based on their own opinion for each question. For the first three questions the measurements are made from the beginning of the line to where the X was placed by the subject. This number is recorded in a spread sheet where measurements for Illuminant 1 and Illuminant 2 are recorded and later compared to each other. For the last six questions the measurements are taken from the middle point of the answer line, and these numbers are recorded in the spread sheet. This means that if the subject placed the X on the far left the number will be a negative number. This number can be a positive number only if the subject's X was placed on the right side from that middle point of the answer line. Once all the measurements are made and recorded onto the spread sheet, the ratios for Illuminant 1 and Illuminant 2 for each measurement are calculated. The ratios are calculated for each question in the same manner, which is dividing the number recorded for Illuminant 1 by Illuminant 2.

The results are interpreted in the following manner depending on the question. For the 1st question if the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number this indicates that Illuminant 1 makes the drawings look redder. If the ratio is a small positive number this indicates that Illuminant 2 makes the drawings look redder.

For the 2nd question if the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number this indicates that Illuminant 1 makes the drawings look greener. If the ratio is a small positive number this indicates that Illuminant 2 makes the drawings look greener.

For the 3rd question if the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number this indicates that Illuminant 1 makes the drawings look bluer. If the ratio is a small positive number this indicates that Illuminant 2 makes the drawings look bluer.

For the 4th question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 makes the drawings look yellower. If the ratio is a small positive number it denotes that Illuminant 2

makes the drawings look yellower. If the ratio is a large negative number it denotes that Illuminant 1 makes the drawings look bluer. If the ratio is a small negative number it denotes that Illuminant 2 makes the drawings look bluer.

For the 5th question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 makes the drawings look brighter. If the ratio is a small positive number it indicates that Illuminant 2 makes the drawings look brighter. If the ratio is a large negative number it indicates that Illuminant 1 makes the drawings look darker. If the ratio is a small negative number it indicates that Illuminant 2 makes the drawings look darker.

For the 6th question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 makes the drawings look redder. If the ratio is a small positive number it indicates that Illuminant 2 makes the drawings look redder. If the ratio is a large negative number it indicates that Illuminant 1 makes the drawings look greener. If the ratio is a small negative number it indicates that Illuminant 2 makes the drawings look greener.

In the 7th question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference

according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 gives good color rendering to the drawings. If the ratio is a small positive number it indicates that Illuminant 2 gives good color rendering to the drawings. If the ratio is a large negative number it indicates that Illuminant 1 gives bad color rendering to the drawings. If the ratio is a small negative number it indicates that Illuminant 2 gives bad color rendering to the drawings.

In the 8th question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 offers high perception of details to the drawings. If the ratio is a small positive number it denotes that Illuminant 2 offers high perception of details to the drawings. If the ratio is a large negative number it signifies that Illuminant 1 gives low perception of details to the drawings. If the ratio is a small negative number it signifies that Illuminant 2 gives low perception of details to the drawings.

In the last question there are five possible outcomes depending on the subject's opinion. If the ratio is 0 this indicates that there is no difference according to the subject's opinion between Illuminant 1 and Illuminant 2. If the ratio is a large positive number it denotes that Illuminant 1 gives a satisfactory overall perception of the art. If the ratio is a small positive number it denotes that

Illuminant 2 offers a satisfactory overall perception of the art. If the ratio is a large negative number it signifies that Illuminant 1 offers an unsatisfactory overall perception of the art. If the ratio is a small negative number it signifies that Illuminant 2 offers an unsatisfactory overall perception of the art. A copy of the questionnaires that were used in this study is shown below. The first questionnaire was used only temporarily, for Mark 1 subjects 1-18 only. Then the second questionnaire was created and implemented thereafter.

Test number ________ Part number ________ Subject Number________

Dear volunteer,

Please answer the following questions below with an X along the line shown. For instance, if you perceive the lighting as being too yellow, place an X on the line closer to the word yellow. The stronger your perception, the closer you should place the X to one side or the other.

Please express your opinion on the artwork itself, not the surrounding environment.

blue ———————————— yellow

darkness ———————————— brightness

green ———————————— red

bad ———————————— good

Color rendering

low ———————————— high

Perception of details

unsatisfactory ———————————— satisfactory

Overall perception of the art with the illumination provided

Test number ________ Part number________ Subject number ________

Dear volunteer,

Please answer the following questions below with an X along the line shown. For instance, if you perceive the lighting as being too yellow, place an X on the line closer to the word yellow. The stronger your perception, the closer you should place the X to one side or the other.

Please express your opinion on the artwork itself, not the surrounding environment.

Illuminant One (1)
Illuminant Two (2)

1
RED
2

1
GREEN
2

1
BLUE
2

BLUE 1 YELLOW
2

DARKNESS 1 BRIGHTNESS
2

GREEN 1 RED
2

BAD 1 GOOD
2

Color Rendering

LOW 1 HIGH
2

Perception of Details

UNSATISFACTORY 1 SATISFACTORY
2

Overall Perception of the Art
with the illuminantion provided

APPENDIX J

Mark 1

The following table summarizes the results for the evaluation of primary tristimulus color prevalence, red, green, blue or Mark 1.

Subject Number	Red	Green	Blue
19	1.49	3.76	3.99
20	3.6	2.79	3.83
21	3.14	2.7	2.68
22	2.75	0.1	0.1
23	2.85	2.86	2.79
24	4.68	0.48	0.43
25	2.52	2.68	2.62
27	4.44	0.2	0.17
28	4.2	4.17	3.77
29	0.1	0.1	0.1
30	2.57	2.5	2.48
31	2.08	0.05	0.05
32	4.77	2.8	2.8
33	4.4	0.05	0.05
34	2.9	3.2	2.9
35	2.57	0.39	0.39
36	4	0.05	1.2
37	4.42	0.72	1.3
38	3.15	1.85	0.42

The following table summarizes the results for the subjective evaluation parts 3b-3f for Mark 1.

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.25	-0.32	0	1	1.5	0.25
2	0.3	0.3	0.18	2	1.72	0.3
3	1.4	-0.2	0.7	0.05	0.4	1.4
5	0.64	0.7	0	0.65	1	0.64
6	1.31	-0.2	-0.4	-0.95	-0.13	1.31
7	1.24	-0.43	0.43	-0.2	-0.08	1.24
8	1.45	0.78	0	1.2	1.55	1.45
9	0.35	0.45	0.4	1.05	1	0.35
10	-0.52	-1.09	-0.2	1.8	1.25	-0.52
11	1.08	0.25	-0.65	0.15	-0.47	1.08
12	1.1	1.1	1.75	-0.15	-0.6	1.1
13	0.92	1.2	0.92	0.27	1.3	0.92
14	0	1.5	0	1.3	1.4	0
15	0.8	-1.12	0.54	-0.8	-1.1	0.8
16	0.22	-0.05	-0.05	1.17	1.3	0.22
17	0.85	0.1	-0.4	-0.7	-0.6	0.85
18	0.94	1.42	1.5	-0.84	-1.24	0.94
19	1.35	2	-0.85	0.2	-0.5	1.35
20	1.12	1.15	-0.2	-0.2	0.75	1.12
21	0	0	0	2.57	2.5	0
22	1.45	2.45	0	0	0	1.45
23	0.1	0	0	0.85	1.2	0.1
24	2.1	0.15	2.25	0	0.25	2.1
25	0	0	0	2.5	2.5	0
27	1.8	1.82	1.42	0.95	1.45	1.8
28	0.5	-1	-0.2	0.1	1.7	0.5
29	-0.2	-0.2	-0.2	2.6	-0.15	-0.2
30	-1.4	-2.3	2.5	0.15	0.15	-1.4
31	0.11	1.7	1.35	0	0	0.11
32	1.3	-0.9	2.68	-2.6	-1.8	1.3
33	-0.3	-0.15	-0.15	-0.15	2.73	-0.3

34	2.3	2.3	2.3	-0.26	-0.15	2.3
35	2.6	0.2	-0.7	-2.3	-0.1	2.6
36	1.7	2.1	2.52	-1.19	1.2	1.7
37	2	1.2	1.45	1.7	1.8	2
38	-2.12	-0.42	-1.9	-1.6	-1.92	-2.12

The following table summarizes the results for brightness evaluation for Mark 1.

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	150	179.3
2	26	150	204
3	25	150	210
5	24	150	179.2
6	30	150	202.9
7	37	150	149
8	58	150	172.1
9	66	150	175
10	22	150	217
11	42	150	198.7
12	20	150	200
13	19	150	140.9
14	36	150	146.7
15	26	150	184
16	29	150	137.8
17	13	150	192.7
18	32	150	152.8
19	27	150	155
20	11	150	207.8
21	34	150	201.3
22	47	150	205.4
23	38	150	250.3
24	19	150	192.5
25	50	150	200.5
27	46	150	195.6
28	54	150	173
29	22	150	191.3
30	48	150	225.3

31	64	150	157.4
32	28	150	213.4
33	24	150	208.5
34	38	150	231.8
35	22	150	194.3
36	35	150	158.6
37	32	150	172.3
38	35	150	157.4

APPENDIX K

Mark 2

The following table summarizes the results for the evaluation of primary tristimulus color prevalence, red, green, blue for Mark2.

Subject Number	Red	Green	Blue
1	2.9	2.5	1.8
7	3.5	0.65	2.4
8	2.75	2.75	2.75
39	1.9	0.75	1.1
40	3.8	2.75	2.75
41	5.35	2.75	2.75
42	1	3.9	0
43	0.84	0	0
44	5.5	0	0
45	4.34	1.2	1.15

The following table summarizes the results for the subjective evaluation parts 3b-3f for Mark 2.

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.8	-0.8	0.45	-0.95	0.3	1.4
7	0.3	-0.4	0.27	1.4	-0.92	0.8
8	1.4	0	1.4	0	0.85	0
39	0	0	0.6	1.12	0.6	0
40	0	1.12	1.12	1.75	1.75	1.75
41	2.5	0	0	2.5	2.5	1.95
42	1.12	1.7	0.6	1.12	1.7	1.7
43	2	0	2.5	2	1.45	2
44	2.37	2.3	2.3	0	0	0
45	1.13	0	1.2	1.2	0	1.2

The following table summarizes the results for the brightness evaluation for Mark 2.

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	168	175
2	26	168	176
7	37	168	179.7
8	58	168	178.4
39	20	168	182
40	24	168	185.2
41	42	168	172.5
42	23	168	180.1
43	28	168	174
44	24	168	183
45	58	168	180

APPENDIX L

Mark 3

The following table summarizes the results for the evaluation of primary tristimulus color prevalence, red, green, blue for Mark 3.

Subject Number	Red	Green	Blue
1	3.54	2.94	2.7
2	4	1	1
46	2.77	2.85	2.55
47	3.2	2	0.2
48	3.35	2.75	3.3
49	2.87	2.87	2.87
50	3.1	2.25	0.25
51	2.75	1	0.1
52	2.8	2.8	2.8
53	5.2	2.75	2.75
54	5	2.5	3.77
55	2.5	0.15	5.5
56	2.8	0	2.3
57	4.64	1.65	3.62
58	5.15	0.35	2.75
59	3.1	2.75	2.75
60	3.8	1	1.2
61	3.8	3.1	2.4
62	2.85	0.1	0.1

The following table summarizes the results for the subjective evaluation for parts 3b-3f for the Mark 3.

Subject Number	Blue/ Yellow	Dark/ Bright	Green/ Red	Bad/ Good	Low/ High	Unsatisfactory/ Satisfactory
1	0.6	-0.6	1.15	-0.3	-0.3	-0.6
2	0.2	0	0.6	0.6	1.7	1.7
46	0	-0.4	0	0	-0.88	2
47	0.9	0.3	0.9	0.75	-0.4	0.8
48	0.6	0	0.6	1.15	0	1.15
49	-0.3	-0.3	-1.09	0.28	-0.38	-0.38

50	0.34	0.9	0.3	1.4	0.33	0.95
51	-0.4	0	1.4	0	-1	1.4
52	2.25	1.7	0	2.27	1.7	1.7
53	-1.2	1.7	1.35	0	0	1.15
54	0.6	2	1.35	0.25	1.7	0.2
55	-0.15	1	0	0	0	1.4
56	-1.2	-2.3	0	-0.6	-0.6	-0.6
57	-1.2	1.15	0	-0.98	1.15	0
58	1.4	0	2.25	0.6	0.6	1.15
59	0.2	-0.6	0.6	0	0.6	0
60	0	-0.6	1.7	0	-0.6	-0.6
61	1.7	0.6	1.7	1.7	1.15	1.15
62	0	1.15	0.6	-0.6	2.25	0.6

The following table summarizes the results for the brightness evaluation for the Mark 3.

Subject Number	Age	Starting point (lux)	Ending point (lux)
1	32	168	181.3
2	26	168	175
46	41	168	186
47	40	168	171.5
48	80	168	179
49	77	168	152
50	21	168	183.8
51	48	168	175
52	22	168	180
53	31	168	177
54	22	168	183.5
55	33	168	181.7
56	22	168	173
57	34	168	153
58	26	168	163
59	24	168	172
60	23	168	165
61	26	168	168.5
62	38	168	170

APPENDIX M

ISO Methodology

The color change is determined via comparison of the specimen being tested and the reference that is being utilized.

The dyes for the blue wools that are used as references are listed in the following table[56].

Reference	Dye-Color Index designation
1	CI Acid Blue 104
2	CI Acid Blue 109
3	CI Acid Blue 83
4	CI Acid Blue 121
5	CI Acid Blue 47
6	CI Acid Blue 23
7	CI Solubilized Vat Blue 5
8	CI Solubilized Vat Blue 8

The exposure system should be facing south if the investigators location is in the Northern hemisphere, and if in the Southern hemisphere then the system should face north. The slope of the system should form an angle that is very close to that of the latitude of the location. The system should be placed in areas that are neither residential nor industrial. The surrounding area of the

system should be free of objects that might cast a shadow on the samples. There should be adequate air circulation behind the samples. The samples need to be covered with glass; this is to protect the samples from environmental damage other than light.

The specifications for the glass cover are as follows:

1) Clear flat drawn sheet.
2) 5.00 to 1.00 mm in thickness.
3) Single strength.
4) Free of bubbles and other possible imperfections.
5) A transparency of 1% in the range 300nm-320nm.
6) Reaching a transparency to 90% in the range 380nm-750nm.
7) The mentioned measurements done with a light source that is comparable to CIE illuminant C.

The cover glass and the samples should have a distance of at least 50mm. This is to control the shadows that might form with the changing light of the sun.

A solid non transparent material is needed. This can be a sheet of aluminum, cardboard, construction paper, etc.

A grey scale is needed in order to evaluate color change and to assign a number to this change. This grey scale need to be in agreement with ISO 105-A02.

If it has been determined that an instrument for storing and determining climatological data is needed the guidelines are the following:

1) Data that is acquired needs to be reported with the fading results.
2) The instrument needs to record black body temperature sensed under glass.
3) Needs to record total radiant energy.
4) Needs to record ultraviolet radiant energy.
5) Needs to record relative humidity daily, the minimum and the maximum.
6) The instrument needs to have the same angle as the exposure system.
7) Ambient temperature recording, daily, minimum and maximum
8) Hours of precipitation.
9) The total hours of wetness, this includes rain and dew.

The samples should have a minimum area of 600 mm^2 for exposure method 1 and 1000 mm^2 for exposure method 2. This ensures that the minimum area exposed is at least 200 mm^2. The samples can be mounted as is shown in figure A and B.

The samples (the reference and the test samples) need to be exposed that the same time for 24 h each day following the guidelines described above.

Method 1 is the most widely used method. The investigator should arrange the samples as shown in figure A. The solid cover is placed along the middle one-third part of the samples. Continuous checks are required, and as soon as a change can be noticed that is equivalent to that of the grey scale 4-5. A check at this point for photochromism is required (ISO 105-B05). Exposure should continue. Once the difference between the sample and the reference is equivalent to the gray scale grade 4; the left portion of the samples should be covered with another solid sheet. This is shown in figure A. The exposure should continue. Then check at this point if the difference between the sample and the reference is equivalent to gray scale grade 3. Continue exposure until the reference 7 or L7 had faded to gray scale grade 4. At this point stop the exposure.

Method 2 is used for multiple samples that need to be tested at the same time. The samples to be tested can be ordered like it is shown in figure B. The covers should protect one-fifth of the total length of each sample along with the reference. The exposure should be done as described above. Lift the cover 11 (first cover) at regular intervals to check the samples against the reference and monitor the color changes. As soon as a change in color can be detected in reference 3 or L2 that is equivalent to grey scale grade 4-5, check the samples and compare them to references 1, 2 and 3 or to L1. This is used as an initial measurement. Put the cover back to its original place. The exposure should be

continued. If a change can be seen in reference 4 or L3 that is equal to grey scale grade 4-5, then put an additional cover 33 (second cover) as shown in figure B. The exposure should continue. Then if a change in reference 6 or L5 is equivalent to the grey scale grade 4-5, then put another cover 44 (third cover) as shown in figure B, the other covers should be left where originally placed. The exposure should continue until one of the following conditions is met:

1) Reference 7 of L7 has reached an equivalent color of the grey scale grade 4.
2) A color change has been reach by the slowest changing samples and is equivalent to that of the grey scale grade 4.

A numerical designation is given to the changes experienced by the samples. These assignments are based on the grey scale grade of 4 or grade 3 among the covered and uncovered parts of the samples being tested. All covers need to be removed at this point. There should be areas more faded than others an at least one area completely unexposed to the light. The number that will be assigned to the sample will be that of the reference that shows comparable change to the sample. In the case of a sample demonstrating a change that is in between two references an intermediate rating is given. In the case if getting different results from the repetition of the same sample the final number is taken as the arithmetic mean of these results then rounded up or down to the nearest whole number. For example 4.3 would be 4 and 5.7 would

be 6. In the case of the sample being faster than reference 1or L2 the number 1 or L2 is still assigned to it. When comparing the sample and the references a matboard or a surface with a neutral grey as background is recommended. In the case of the sample being photochromatic a P should be included in the result.

The test should be reported in the following manner:

1) The number and year of the publication that is being used, example ISO 105-B01:1994.
2) All the information pertaining the sample that was tested.
3) The numerical assignment should be only one number when using the blue wools reference 1-8.
4) The result should include a number and the letter L if using the blue wools reference L2 to L9.
5) When the final rating is higher than 4 or L3 and the preliminary assignment is equal to or lower than 3 or L2 the report should be written 6(3). And if its photochromatic 6(P3).

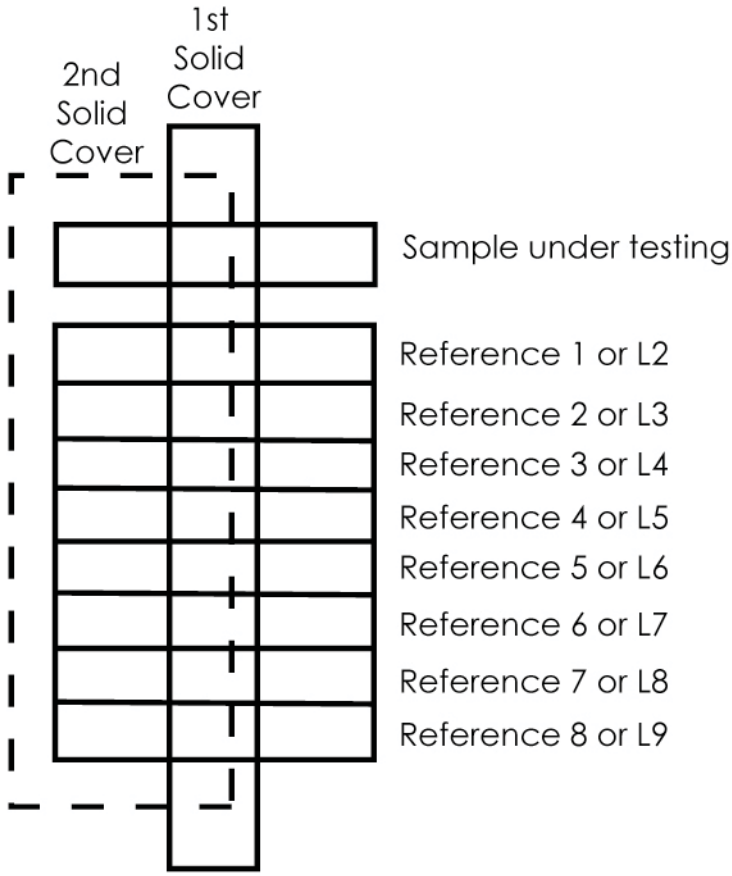


Figure A. Arrangement for exposure method 1.

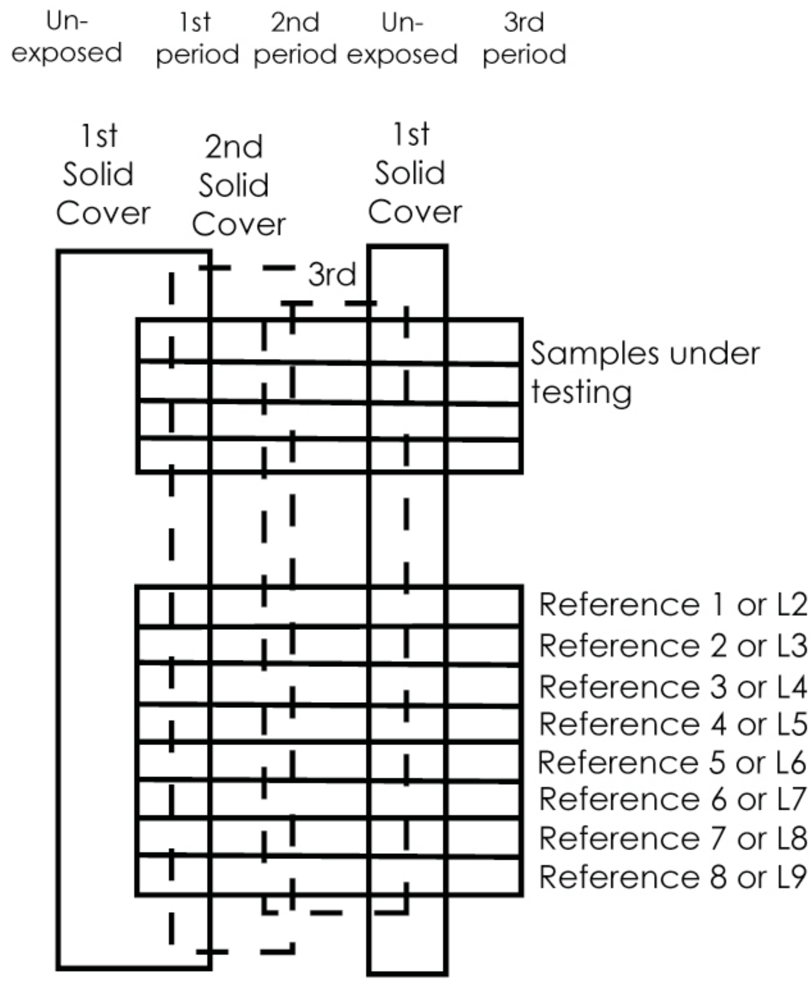
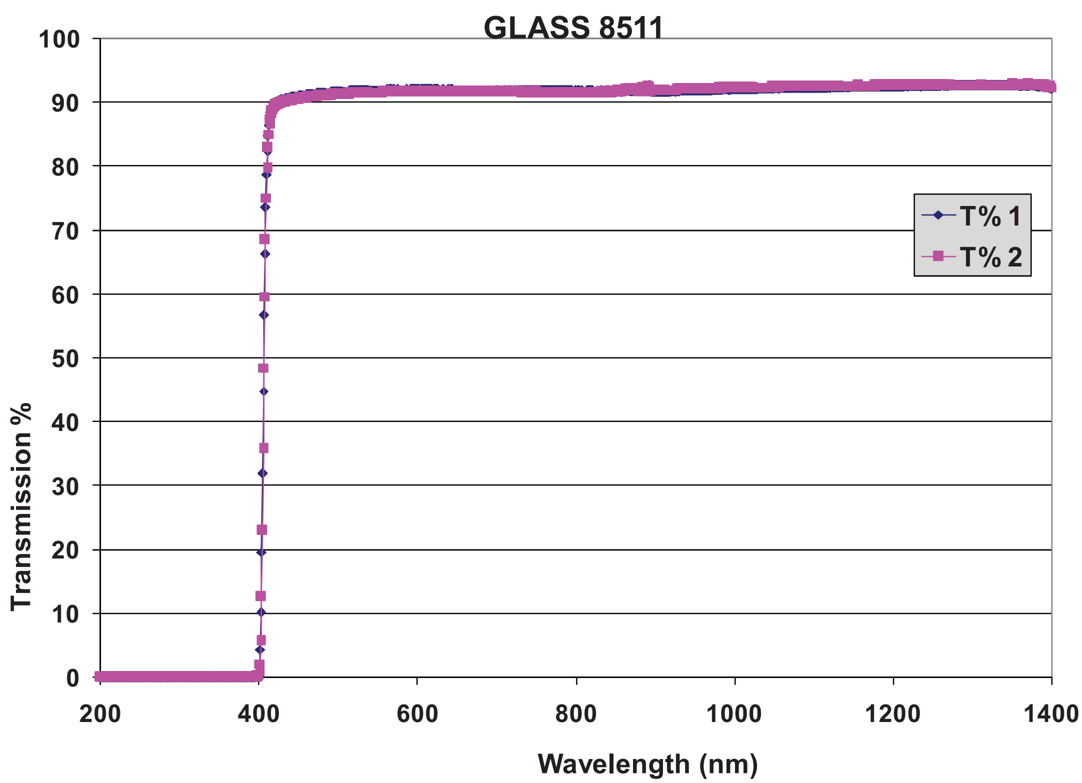


Figure B. Arrangement for exposure method 2.

APPENDIX N

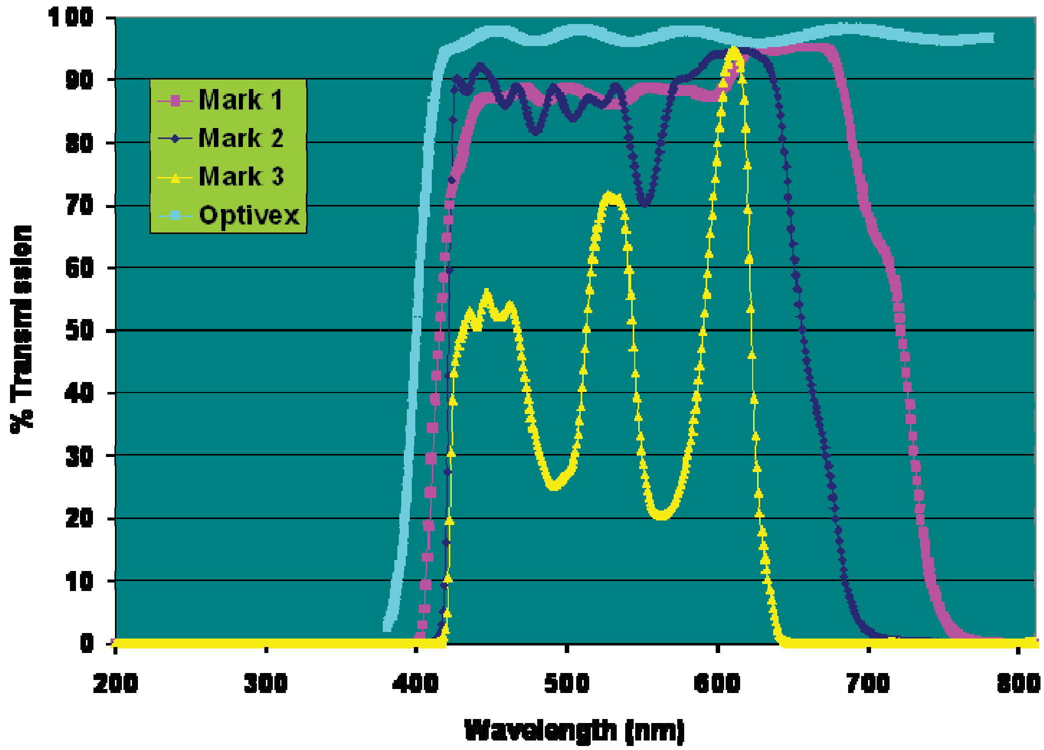
This appendix is related to section 6.1.1 Manufacturing Design of Filter Structures of this document.

The Corning 8511 glass was recommended by Dr. Lisa Zhang of Ross Optical. This glass possesses a UV-VIS cutoff of about 400nm, and being a borosilicate, possesses enhanced thermal stability. This glass was successfully used throughout the project for all filters reported here. It was discontinued by Corning in 2005, and is no longer available. The complex refractive index of the 8511 glass was graciously done for us by J. A. Woollam, Inc. at no charge. The following image is the T% transmission spectra of the glass used for the filters.



APPENDIX O

This appendix is related to section 6.1.2 Manufactured Coating Outcomes in this document. The following figure shows the spectral transmission for an Optivex® (Applied Coatings Group, Inc.) filter (is included for comparison) along with the Mark1, the Mark 2 and the Mark 3.



APPENDIX P

Ultimately, the utility of the filters are assessed by how well they attenuate changes in appearance of objects over periods of exposure to light. GCI exposed a set of pigment samples to light from lamps which was either filtered by UTEP filters or Optivex® filters. Studies on this were carried out both at the Getty Conservation Institute, and at UTEP. The list of pigment samples that were studies and the GCI are listed below.

Code	Meaning of the Code
ACW	Alizarin Crimson Water Color
AUW	Aureolin
B01_1	Blue Wool 1 (From Europe) 1st replicate
B02_1	Blue Wool 2 (From Europe) 1st replicate
B03_1	Blue Wool 3 (From Europe) 1st replicate
B04_1	Blue Wool 4 (From Europe) 1st replicate
B05_1	Blue Wool 5 (From Europe) 1st replicate
B07_1	Blue Wool 7 (From Europe) 1st replicate
B08_1	Blue Wool 8 (From Europe) 1st replicate
BW1	Blue Wool 1 (From USA) 1st replicate
BW2	Blue Wool 2 (From USA) 1st replicate
BW3	Blue Wool 3 (From USA) 1st replicate
BW4	Blue Wool 4 (From USA) 1st replicate
BW5	Blue Wool 5 (From USA) 1st replicate
BW6	Blue Wool 6 (From USA) 1st replicate
BW8	Blue Wool 8 (From USA) 1st replicate
CYG+ZnO	Cadmium Yellow Gouache+ Zinc White

FRG	Flame Red Gouache
GAMW	Gamboge Watercolor
IG	Indigo Gouache
MG	Magenta Gouache
OLLG	Orange Lake Light Gouache
PBW	Prussian Blue Watercolor
PBW+ZnO	Prussian Blue Watercolor + Zinc White
PGDG+ZnO	Permanent Green Deep + Zinc White
RMG	Rose Malmaison Gouache
RTG	Rose Tyrien Gouache
SKG	Sky Blue Gouache
TIVW	Thioindigo Violet Watercolor
TIVW+ZnO	Thioindigo Violet Watercolor + Zinc White

APPENDIX Q

The brightness measurement instrument was created, designed, and built by the Museum Lighting Study Research Study Group. It consists of two cardboard boxes, a stepper motor, two light diffusers, two MR-16 lamps, one light track, two light fixtures, one interference filter (designed by the Museum Lighting Research Team the same as Dirk's Research Team). a external control box, an arbitrary waveform function generator, a piece of matte black cloth and a lux meter.

The brightness measurement instrument was built in the following manner. The two cardboard boxes were glued together using rubber cement aerosol. Then this "box" was painted with a matte black paint in the outside. There were two squares cut in the front of the box where the two light diffusers were placed. The light diffusers were place as close as possible so that the two light sources going through them could be compared to each other. On the right hand side (facing the box from the front) the light track, the light fixture, and the reference 58562 Sylvania lamp were placed and fixed. On the left hand side (facing the box form the front) the stepper motor, the light fixture, and the source 58533 Sylvania lamp with the interference filter were positioned. The stepper motor is connected to both the external control box and the arbitrary wave function generator. The external control box is handled by the subject. The control box has one switch and a button. The switch controls the direction of the motor,

towards the subject or away from the subject. The button controls when the stepper motor should move. If the button is pressed the stepper motor will move, if the button is not pressed the stepper motor will not move.

The arbitrary wave function generator is made by Berkeley Nucleonics Corporation (BNC) the model is 625. For the purposes of this study the instrument is set up in the sine arbitrary waveform. The frequency resolution is set at 100 Hz. The amplitude resolution is set at 10.0 dBm. The function generator was used to create the stepper signal for the stepper motor. The back part of the box is covered with the matte black cloth to prevent any light from leaking out of the box. The lux meter is used to measure the light coming out of the diffusers.

The brightness measurement instrument works in the following manner. All the lights in the Testing Gallery are turned off. The lights inside the brightness box are on (both the Unfiltered and the filtered) and the how the control box is used is explained to the subject. The Unfiltered light is fixed in place as it was mentioned before with a specific brightness; only the filtered light is the one that moves with the control box, though the subject doesn't know which light they are adjusting. The following instructions are given to the subject: "The light on your right is fixed, that one on the left is the one that moves with the control box. You have to set the two lights to an equal brightness based solely on your perception. Ignore the color difference between the two lights and focus on setting the brightness. You have ten minutes to complete this part of the test.

Please let me know when you are done. Do you have any questions? You may proceed." The measurements are recorded in the subsequent manner. There is one initial measurement made of the filtered light, this measurement is done using the Oriel auto-ranging light-meter Goldilux™ with the Oriel cosine probe. This measurement is done with the filtered light on, the Unfiltered light off and all the lights in the gallery off. The light-meter is set as close as possible to the diffuser of the filtered light, without the cosine probe touching the diffuser. Once the lux level stabilizes the fixed value that was determined for the filter being used, the value is recorded. This measurement is taken before the subject arrives to the testing area. The final value is taken after the subject has left the testing area, and it is done in the same manner as it was described. This measurement corresponds to whatever value the subject chose based on his or her perception of the equivalent brightness between the two lights.

In the following photograph the brightness box with the lights on is first shown. This photograph was taken by Monica F. Delgado with a digital camera.

In the following photograph the brightness box with the lights off is shown. This photograph was taken by Monica F. Delgado with a digital camera.

After this brightness test is completed the subject is moved into the testing area for the color vision examination.

Vita

Monica F. Delgado

Ph.D. in Chemistry

Monica F. Delgado earned her Bachelor Degree in Graphic Design with a minor in French from the University of Texas at El Paso, El Paso Texas in 2000. She studied Chemical Engineering at the University of Texas at Austin, Austin Texas where she had to leave one semester before completing her degree in 2002. In 1999 she studied Painting Restoration part of intense program at the Lorenzo D'Medici School in Florence Italy. She joined the doctoral program in the fall of 2003.

Dr. Monica F. Delgado is a member of numerous honor societies such as The National Scholars Honor Society, The Golden Key Honor Society, Chi Epsilon Honor Society, and Sigma Xi Scientific Research Society. She has been a member of numerous professional societies such as Society of Women Engineers, American Chemical Society Student Affiliates, American Institute for Conservation, International Institute for Conservation and the Research and Technical Studies.

While pursuing her degree, Dr. Delgado worked as a research assistant and as a teaching assistant for the department of Chemistry at UTEP, as an

independent freelance Graphic Designer, as an Art Conservation and Museum Lighting consultant, as an Art Conservator for the Stanlee and Gerald Rubin Center for the Visual Arts and as an Art Conservator in Private Practice. She also was a visitor/researcher for the Getty Conservation Institute in the years 2004 and 2005. She was also a visitor/researcher for the Georgia O'Keeffe Museum in 2007.

Dr. Delgado has presented her research as an invited guest speaker for the American Institute for Conservation in 2007. She was an invited guest speaker the Museum Exhibition Class in UTEP on two occasions in 2006. She was an invited guest speaker to the Art History Classes in UTEP in 2006. She was a guest editor for the Journal of the American Institute for Conservation.

Dr. Delgado's dissertation entitled, "Art in a new light: Design and Assessment of Illuminants to Reduce Photochemical Degradation of Works of Art", was supervised by Dr. Carl W. Dirk.

Permanent address: 740 Country Club Road
El Paso Texas, 79932

This dissertation was typed by Monica F. Delgado