Article: On the Illumination of Light-Sensitive Photographs
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On the Illumination of Light-Sensitive Photographs

Mike Ware

Abstract

The types of light source used to illuminate photographs for copying and study are reviewed, and it is noted that the recent development of UV-free solid state light sources offers a valuable new option for particularly light-sensitive photographs. In order to inform curatorial decision-making, it is shown how the risk of light-damage to a photograph can be assessed from the total dose of light and the sensitivity of the object, expressed in terms of the 'Just Noticeable Difference', to quantify the 'cost' of copying in terms of perceptible change. Controlled photo-flash is shown to be preferable to continuous illumination, and the minimized dose of light is calculated for typical photographic camera parameters to recommend standards of practice for copying such objects.

Introduction

Light, the very agency for creating photographs, can also destroy them. The problem of 'fixing' photographic images was not fully solved by the pioneers of the art-science for some years following its invention in the late 1830s. Consequently, early images were not robust; there exist today in some photograph collections a number of precious and historically significant specimens that are still vulnerable to light (Ware 1994, 1999). The purpose of this paper is to suggest a means of assessing quantitatively the risk to such an object caused by exposing it to light, for various purposes: private study, photographic copying, scanning, photocopying, conservation work, and public exhibition. It is generally acknowledged that the more energetic radiation of shorter wavelengths is intrinsically more damaging (Thomson 1986), so the attenuation, or preferably complete removal, of the ultraviolet (UV) content of any illumination is a primary objective, and a *sine qua non*. The spectral region of concern is the UVA, having wavelengths from 315 nm, where window or picture glass begins to transmit, up to about 400 nm, at the deep blue edge of the visible. However, as a potential cause of damage, there still remains the visible light – and this we cannot do without, if the photograph is ever to be viewed by human eyes. The principal focus of this paper is to assess the effects of visible light on historic photographs.

Light Sources and their UV Content: Preliminary Review

According to the Museums Commission of the UK, Class I Museum Gallery Standard of illumination permits a maximum UV content of 75 microwatts per lumen (μW/lm) (Thompson, 1978). The reason for these rather complex units is that the lumen is a measure of the intensity of *visible* light, and therefore cannot be used to quantify the invisible UV. The UV radiation does however possess energy, so is measured by its energy flux per second, as watts (or, more conveniently, microwatts) and expressed as a proportion of the visible light intensity. In the past, the figure of 75 μW/lm was deemed tolerable because it happens to be the natural UV content of the unfiltered emission from an ordinary incandescent tungsten lightbulb, with a colour temperature of 2860 K. A light intensity of 50 lux (= 4.65 foot-candles in US units) is widely accepted as the most stringent Class 1 Gallery Standard for exhibition and viewing of sensitive works. Since one lux = one lumen per square meter (lm/m^2), at 50 lux this level of UV content corresponds to a UV irradiance of 3.75 milliwatts per square meter (mW/m^2), which is about 5% of the visible light energy flux (1 lumen at 555 nm has an energy flux of 1.47 mW, so 50 lux provides a visible irradiance of *ca.* 74 mW/m^2) but it is still needlessly high and can now be substantially reduced by careful filtration, or even totally eliminated by a more appropriate choice of light source, as seen below.

Five main types of artificial lighting are used for the purposes of copying, study and exhibition:

1) **Incandescent tungsten** filament bulbs. These usually emit 60-80 μW/lm. Tungsten-halogen lamps also fall in this category but have higher UV emission, *ca.* 165 μW/lm. It has been shown that steep-cut interference filters can reduce these UV emissions to less than 1 μW/lm without prejudicing the colour rendition (Saunders 1989). The infrared (IR) emission of tungsten bulbs can also cause undesirable heating of illuminated objects, by radiation and convection.
2) **Photo-flash** units (commonly, but inappropriately, called "strobe units" in the USA) are xenon gas discharge tubes; these are rich in UV, emitting around 300 μW/lm, so must be fitted with efficient UV-absorbing filters, which are usually supplied by the manufacturer. Data on the absorption spectra of these filters are not widely published, however, and the extent of their attenuation of the UV is often taken on trust. Photo-flash has the advantage that it only delivers the minimal light dose to the object needed to record its image in the camera, in contrast to copying methods that employ continuous illumination (Saunders 1995, Michalski 1996).
3) **Fluorescent light** sources are mercury gas discharge tubes, internally-coated with phosphors, and can emit substantial UV, present in the mercury atomic emission spectrum, in the order of 200 μW/lm. When used for copying illumination they must be filtered; sheets of UV-absorbing Plexiglass™ (UK: Perspex™) Type UF-4 provide good attenuation. This is often the type of built-in light source of commercial scanners and photocopiers; before such machines are used on sensitive material it is important to seek information from the manufacturer on their UV emission and filtration – if any.
4) **High Intensity Discharge** (HID) lamps use a plasma discharge in a vaporized metal halide; they include the alchemically-named "Hydrargyrum Medium-arc Iodide" (HMI) lamp, presumably a mercury discharge. They often contain xenon as a starter gas, so are sometimes inaccurately called "xenon lamps". All emit large amounts of UV, in the order of 275-300 μW/lm. Their high colour temperature and efficiency make them very popular for studio photography, but they should not be used to illuminate sensitive objects.
5) **Light Emitting Diode** (LED) sources represent the most recent solid state lighting (SSL) technology, which can claim several advantages: it is safe and fully controllable electronically, economic in energy-efficiency, enjoys a very long lifespan and great robustness. From the published emission spectra, and recent measurements, 'white' LEDs appear to contain no UV wavelengths whatsoever, and no IR radiation either, which can cause undesirable radiant heating (Noll 2008). The emission spectrum does not have the 'blackbody' distribution of sunlight or incandescent tungsten, but the Color Rendition Index (CRI) of the 'daylight balanced' variety of LED has now been improved to a value of 90% or greater, which fulfills the Museum standard. As this technology develops, it seems set on course to offer the best option of a controllable UV-free light source for photographic copying, object conservation tasks, and possibly even gallery exhibition illumination. A commercial LED unit is now available, emitting 100 watts of daylight-balanced white light of Color Temperature (CT) 4400 K with a CRI = 91%, specifically designed for both viewing and photographic copying of sensitive objects. The output is

precisely controllable down to low levels for setting-up, with no color shift, and the unit can be synchronized with a camera shutter to ensure that the object only receives the minimum dose of UV-free light necessary to record its image. Thus, the LED unit has the virtue of photo-flash illumination with none of its disadvantages (Geffert 2008).

A STRATEGY FOR RISK ASSESSMENT OF ILLUMINATION

The safe copying and exposure of photographs, and other objects potentially sensitive to light, is assisted by the knowledge of the following two parameters:
(a) the total light exposure inflicted on the object by the copying process, or period of exposure, and
(b) the object's sensitivity to light, measured by the change it suffers per unit of light exposure (Schaeffer 2001). The purpose of this document is to show that a comparison of these two figures (expressed in the same units) can provide:
(c) an assessment of the 'potential damage' to the object, *i.e.* the notional 'cost' of making one copy, and thus inform curatorial decision-making in a semi-quantitative manner. These factors will now be quantified as far as current knowledge allows.

(a) The total dose of light to the object

This is the exposure sustained by the object during the entire process of acquiring a copy image, or digital image file, by a specified procedure – whether by analogue or digital photography with appropriate external lighting or photo-flash illumination, or by a scanner, or a photocopier, with their built-in light sources. Light exposure is the product of light intensity (illuminance) and duration; to quantify this exposure, the preferred Système Internationale (SI) units are lux seconds (lx s). It is convenient to build in a factor of one thousand, so kilolux seconds (klx s) will be used here as the appropriate units for camera exposures, but lux hours (lx hr) may be more convenient for measuring light exposure through exhibition or study: 1 lx hr = 3.6 klx s.

A number of workers have previously assessed the total exposure for many typical copying set-ups and systems; see Table 1 below for values and references. However, it is essential that individual photographers should evaluate the light dose for their own copying procedures: if the illumination at the copying easel is continuous (and checked to be UV-free) its illuminance should be measured with a lux-meter, and then multiplied by the total estimated time in seconds that the object is irradiated while setting up and making one copy, to give the overall light dose in klx s.

However, as observed above, employing photo-flash illumination can minimize the light dose to the object. The flash exposure for a given distance, as expressed in the Guide Number of the photo-flash unit, determines the camera parameters that must be set by the photographer: an effective arithmetic speed, S, in ISO (ASA), and a lens aperture setting expressed as an f/stop number, A. These two parameters are all that is needed to calculate the light dose to the object, a formula for which is derived in the Appendix. From this it may be seen that, for example, a camera set to a lens aperture of f/11 and an effective speed of 100 ISO, (e.g. for 'fine grain' film or 'low noise' digital imaging), the minimum light exposure of the object is calculated to be 0.36 klx s or 0.1 lx hr, if the camera image is about 1/4 the size of the original object (*e.g.* an object *ca*. 10x8 in. photographed on medium format '120' roll film).

For comparability these calculations all assume a common, nominal camera exposure setting. If the film speed is not 100 ISO (ASA) or the lens aperture number A differs from f/11, the figure should be adjusted accordingly. With flash, the light exposure of the object is just sufficient for the correct exposure of the camera film, so it depends only on the camera parameters, and not the model of flashgun, which is assumed to be set correctly by the photographer.

Typical Equipment	Reference	Light Level (klx)	Exposure Time	Light Dose (klx s)
Scanning CCD camera	(Blackwell 2000)	2	15 minutes	1500
Flat bed scanner	(Vitale 1998)	various		3.6 - 54
Photocopier		various		7.2 - 36
35 mm SLR camera		0.6 *	~3 s **	1.8
" with photo-flash	Appendix	(f/11 @100 ISO magn. 1/8)		0.3
120 Roll film camera		1.5	~3 s	4.5
" with photo-flash	Appendix	(f/11 @100 ISO magn. 1/4)		0.4
5x4 in. studio camera		6	~3 s	18
" with photo-flash	Appendix	(f/11 @100 ISO magn. 1/2)		0.5
Exhibition Class 1		0.05	10 hours/day	1800/day

Table 1. Typical light doses for various copying systems compared with exhibition

* assuming a very basic illumination system of two 100 watt tungsten bulbs at 60 cm distance.

** 3 seconds is about the minimum total time for the lights to be switched on and become thermally stable, and for the camera exposure, which is generally in the order of one second, to be made.

Some of the figures in Table 1 remain highly machine-dependent, and are likely to change with advancing technology, so the guidelines for scanners and photocopiers, which were typical of the 1990s, may require updating and re-calculating.

The setting-up exposure: 'modeling lights'

The light exposure inflicted by the actual photography is only part of the total dose sustained by the object being copied: the exposure when setting-up, framing and focusing the image can be even greater. For instance, even if the setting-up is conducted under a low light level of 50 lux, one minute spent doing this will incur an exposure of 3 klx s, which in some cases is greater than that of the actual photographic exposure. It is important that the operating protocols for copying should minimize unnecessary additional exposure of this kind, either by using very low level modeling lights, or preferably by setting-up on a 'dummy' or surrogate object of the same size, and only substituting the precious object at the last moment when ready. It is important to assess, and include in the evaluation, any exposure incurred in this way. On past occasions, more damage has been done to precious sensitive photographs by neglectful and unnecessary exposure to the full illumination at the copying easel, than has been caused by the photographic exposure itself.

(b) The sensitivity of the object to light

This is conveniently expressed as the light exposure (also in klx s) which causes a Just Noticeable Difference (JND) in the object. The condition of the object before and after exposure cannot be directly compared, so either identical reference specimens or 'controls' are required, or precise densitometer readings must be taken, of accurately-located image regions, before and after exposure. A caveat here: densitometers generally have very intense light sources (*ca.* 500 klx) and can cause perceptible damage to very sensitive objects over the sample area within a short time. The readout from a densitometer is in optical density, which is defined as $\log_{10}$(opacity), where the opacity is defined as: incident light intensity/ transmitted or reflected light intensity, depending on the mode. The optical density has no units – it is a pure number.

The JND for human visual perception has been found experimentally, on average, to be a difference in optical density $\Delta D = 0.01$ (Henry 1986). Differences less than one JND are generally imperceptible to the unaided human eye for areas of smooth mid-tone grey, placed side-by-side under good lighting, but they can be measured with sufficiently sensitive instrumentation (densitometers reading to 0.001).

The use of optical density as the measurable unit of change presupposes a monochrome object – which is usually the case with 19thC photographs. However, if a color shift in the object is a significant possibility, the criterion for a JND is more properly expressed according to the measurements of color science, and the change of coordinates in a color space, such as the CIE L*a*b* system, as measured with a color meter (chromameter). In this system, a color change of $\Delta E = 1$ or 2 is approximately one JND. If there is no color shift, $\Delta E = \Delta L^*$, where the lightness scale L* in the CIELAB system runs from 0 (black) to 100 (white). A practical JND of $\Delta E = 1.5$ is widely quoted for colored objects.

The JND is a convenient benchmark for the onset of 'perceptible damage' to an object. It will be useful to call the exposure causing a change of one JND in any significant area of an object, the *Threshold Exposure*. Information on these Threshold Exposures for various types of photographic object is as yet rather sparse (Ware 1994 and 1999). Often we only have an upper limit of exposure, at which no change has yet been observed or measured (McElhone 1993), rather than the true Threshold Exposure, whose determination experimentally would entail notional damage to the object, and may therefore be deemed unethical to attempt. If the Threshold Exposures of precious historical specimens could be determined without arousing serious conservatorial qualms, it would ultimately benefit our knowledge of how best to protect these sensitive objects.

The invention ten years ago of the 'micro-fading tester' (Whitmore, Pan, and Baillie 1999, Whitmore 2002) has brought this hope much closer. These instruments have so far been used mainly for painted artworks, which are much more robust than photographic specimens, so they have powerful light sources (*ca.* 10 Mlx) which can fade a Blue Wool #1 specimen by one JND in about 2 minutes. Based on this instrument, a 'micro-fading spectrometer' has recently been developed (Lerwill, Townsend, Liang, Thomas, and Hackney 2008) which irradiates a disc of the object only 0.25 mm in diameter, and is substantially portable. With an attenuated light source it would be well-suited to the investigation of sensitive photographs.

The exposure of photographs on exhibition is an issue closely-related to that of exposure for copying purposes, and requires similar reasoning but generally involves much longer exposures (Severson 1986). As a qualitative guide to lighting policy, it has been suggested that photographs can be placed in four broad categories of sensitivity (Wagner, McCabe and Lemmen, 2001): (1) Extra- (2) Very- (3) Moderately- and (4) Less- sensitive. The reader is referred to the conservation experience of these authors, with a wide range of photographic objects, to find recommendations for the total exposure per year for exhibiting these various types of photograph. Their proposed categories are adopted in Table 2, below.

What little information on Threshold Exposures that has so far been gleaned for photographs falling in these categories is summarized in Table 2. It is to be hoped that more additions will soon be made to this table. Nearly all treatments of photographic fading published to date tend to assume that the Law of Reciprocity holds; *e.g.* the change (which may be fading or fogging) caused by exposure to a light source of 5000 lux for one hour, will be the same as the change caused by a source of 50 lux in 100 hours. While this may be generally true for silver images (Ware 1994), it certainly is not valid for cyanotypes, which recover from fading by aerial reoxidation (Ware 1999).

Category & Process	**Reference**	**Threshold Exposure (klx s)**	**Comments**
1) Photogenic Drawing	(Ware 1994)*	600	Talbot salt-stabilized
1) Cyanotype @ 4 klx	(Ware 1999)**	720 @ 4000 lx	Herschel's process
2) Cyanotype @ 50 lx	(McElhone 1993)	>36,000 @ 50 lx	NB non-reciprocity
3) Salted Paper Print	(McElhone 1993)	54,000	Thiosulphate fixed
3) Albumen Print	(Pretzel 1991)***	80,000–2,880,000	Highly variable
4) Silver-gelatin print		>1,800,000	Modern processing
Blue Wool Standard Fade	(Colby 1992)	1,440,000	(ISO #1) B.S. 1006
LightCheck® dosimeter	(LightCheck Co.)	18,000	Ultrasensitive version
		216,000	Sensitive version

Table 2. Guide to the categories of sensitive photographs

* Most Talbot prints were stabilized with sodium chloride, but some images were stabilized with potassium iodide – it is thought the sensitivity of the latter may be comparable, but they tend to fade rather than fog.

** Note the failure of the reciprocity law in this case.

*** The conspicuously wide range of values cited here for the threshold exposure of albumen prints is an indication that less stable 'mavericks' can lurk in any population of historic photographs, because of uncertainties concerning the quality of processing.

The British Standard Blue Wool Scale # 1 is too insensitive for the purpose of monitoring the exposure of photographs, but the recent European Commission sponsored project (Light Dosimeter Project) has developed a more sensitive colorimetric photochemical dosimeter on paper strips which offers a useful monitor of light dose, when used as a comparator with a standard color chart calibration (LightCheck® Company UK, 2008).

(c) The 'cost' of making one copy

This is expressed in terms of the 'potential damage' to the object as the quotient of light dose (Table 1) and the Threshold Exposure (Table 2):

$$\mathbf{c = a/b}$$

so **c** is **the number of JNDs inflicted on the object by the copying procedure**.
Curators and conservators are thus assisted in formulating their own criteria as to what may constitute an acceptable value of **c,** as a compromise between the conflicting demands of conservation ethics, commercial factors, and scholarship. An acceptable value of **c** will usually be fractional, i.e. smaller than 1 – probably much smaller – so a more convenient way of expressing the 'cost' is:

$$\mathbf{1/c = b/a}$$

where **1/c** can be usefully regarded as ***the number of times that the object could be copied with the specified method before it begins to sustain a 'perceptible change'*** *i.e.* the accumulated exposure reaches the Threshold Exposure. This assumes, of course, a 'worst case scenario' that the potential damage is arithmetically cumulative, which may not always be the case; for example the assumption of exposure reciprocity is not valid for the fading of cyanotypes, which recover their densities on exposure to air in the dark.

EXAMPLES OF CALCULATING POTENTIAL DAMAGE BY COPYING LIGHTS

(1) A halide-stabilized Photogenic Drawing copied by a commercial scanning CCD camera:
The total light dose **(a)** would be *ca.* 1800 klx s (Table 1).
The sensitivity **(b)** as indicated by the Threshold Exposure in Table 2 is *ca.* 600 klx s.
The 'cost' **(c)** of 1800/600 ≈ 3 JND's is calculated for copying by this means.
This is a measurable and perceptible density change, and in most judgments would be deemed unacceptable damage, and copying therefore not attempted by this means.

(2) A halide-stabilized Photogenic Drawing copied by a large format (e.g. 4x5 in.) studio camera using filtered photo-flash, a speed S = 100 ISO, and an aperture of f/22, (two stops, or 4 times, smaller than our standard, f/11):
The typical exposure light dose (see Table 1) would therefore be 4 x 0.5 = 2 klx s. To this must be added the light dose entailed in the setting-up – perhaps a minute at 50 lux = 3 klx s – to give a total light dose **(a)** = 5 klx s.
The sensitivity is as in (1) **(b)** = 600 klx s. So the 'cost' **(c)** is 5/600 = 0.0083 JNDs only.
In other words, the object could be copied **1/(c)** = 1/0.0083 = 120 times by this means, before the Threshold Exposure for one JND was reached in theory.

(3) A cyanotype photographed by photo-flash illumination, using a 35 mm camera set to a speed of 25 ISO (arithmetic) and an aperture of f/16:
The light dose **(a)** is calculated from the value 0.3 klx s (Table 1) for 100 ISO at f/11 (assuming a magnification of 1/8) modified thus: there are two 'stops' less film speed, and one stop smaller aperture, meaning three stops more light exposure is needed in all, arithmetically: 2x2x2 = 8 times, so the light exposure = 8 x 0.3 = 2.4 klx s.

Again, we must add the setting-up exposure, say 3 klx s, to give a total **(a)** = 5.4 klx s.
The sensitivity **(b)** of cyanotype under high intensity illumination is *ca*. 720 klx s.
So the cost **(c)** is 5.4/720 = 0.0075 JNDs, which is perfectly 'safe'. The cyanotype could be photographed in this way 1/0.0075 = 133 times before reaching the theoretical Threshold of perceptible damage.

(4) One of the most treasured items in the photograph collection of The Metropolitan Museum of Art, New York, is a unique album containing 36 photogenic drawings sent by W. H. F. Talbot to fellow botanist Antonio Bertoloni in 1839-40. It was decided by the Museum's curatorial and conservation staff to make its contents accessible to the public, so the Bertoloni album was photographed 'in house' with all appropriate precautions. It was illuminated by two CDI LED units (light source 5 above) delivering *ca.* 500 lx at the baseboard with undetectable UV content, a CRI of 91% and a CT of 4400K. Exposures were 2 seconds at f/16 with a medium format digital camera set to 100 ISO.
Setting-up was under very low light, so the light dose **(a)** was little more than 1 klx s.
The highest sensitivity **(b)** of this material is likely to be 600 klx s.
It follows that **(c)** = 1/600, so the object could be copied 600 times by this means before reaching the Threshold Exposure. This large safety margin was deemed acceptable curatorially to justify photographing this precious and very sensitive item, with the excellent outcome which may be now viewed on the Museum's website (Metropolitan Museum 2008).

APPENDIX

LIGHT EXPOSURE OF AN OBJECT PHOTOGRAPHED BY CONTROLLED PHOTO-FLASH

The following theory demonstrates that the light dose to an object exposed by photo-flash is determined only by the setting of the camera lens aperture and the effective speed (of film or digital sensor) used to photograph it. Assuming that the photographer operates correctly, the sensor calculator of the flash unit (or Guide Number) ensures that the correct illumination is delivered for the camera exposure. The benefit of this is that the light dose to the object is minimized and *it is unnecessary to know any technical details of the photoflash output.* The starting point for this calculation is the equation derived by Jones and Condit (James 1977) to connect the illumination of an object with the illuminance at the focal plane of a camera photographing it. When typical parameters are assumed for various features of the camera optics, we are left with the simplified Jones-Condit Equation:

$$L = 5A^2E \quad \text{lx}$$

Where:
L = object luminance in apostilbs
= illuminance in lux for a diffuse white object of Reflectivity = 100%
A = lens aperture expressed as f/stop number
E = illuminance in lux at the camera film plane
We need the Object Exposure = illuminance x duration:

$$Lt = 5A^2Et \quad \text{lx s}$$

Where:
t = exposure duration in seconds
This connects the object exposure, Lt, with the film exposure, Et.
To evaluate the latter, we make use of the definition of ISO Film Speed, S :

$$S = 0.8/H_m$$

Where:
S = film speed on the ISO (arithmetic or ASA) scale
H_m = exposure of film in lux seconds to yield a film density of 0.1 above the filmbase+fog, for specified conditions of development, so:

$$H_m = 0.8/S \quad \text{lx s}$$

Now for a frontally-lit scene, a white highlight is ~50 x brighter than the darkest shadow exposure H_m (Dunn & Wakefield 1981), so the correct film exposure for the diffuse white highlight is:

$$Et = 50 \times H_m = 50 \times 0.8/S = 40/S \quad \text{lx s}$$

and since the object exposure:

$$Lt = 5A^2Et \quad \text{lx s}$$

we can now substitute for Et to get the approximate relationship:

$$Lt = 0.2\, A^2/S \quad \text{klx s}$$

e.g. inserting values of A = 11 and S = 100 for our 'standard' exposure of f/11 at 100 ISO gives:

$$Lt = 0.2 \times 11^2/100$$

$$= 0.242 \quad \text{klx s}$$

The foregoing is a simplified derivation, for the camera lens focused nearly at infinity. To take account of the magnification, due to near-focus used in copying, we need a more accurate version of the Jones-Condit equation:

$$Lt = 0.189(1+m)^2\ A^2/S \quad \text{klx s}$$

where: m = magnification = image size/object size

Magnification m	**Factor $0.189(1+m)^2$**	**Light Dose Lt for A=11 and S=100 klx s**	**lx hr**
1/∞	0.189	0.229	0.0636
1/10	0.229	0.277	0.0769
1/8	0.239	0.289	0.0803
1/6	0.257	0.311	0.0864
1/5	0.272	0.329	0.0914
1/4	0.295	0.357	0.0992
1/3	0.336	0.407	0.1131
1/2	0.425	0.514	0.1428
1/1	0.756	0.915	0.2542

Table 3. Minimum copying light dose as a function of magnification.

Table 3 shows the effect of magnification on the light dose. These figures all assume an aperture f/stop, A = 11 and a camera speed, S = 100 ISO (ASA)**.** The figure for any other aperture or speed setting can be calculated by scaling appropriately, as illustrated in the numerical examples. There are, admittedly, approximations and assumptions involved in reaching these theoretical values for object exposure, but their essential correctness can be independently checked by accepted practice. For instance, that widely-used photographic light-meter, the Pentax Spotmeter V, is supplied with a manufacturer's conversion (Asahi Optical Co.) for obtaining luminance values from the Exposure Value (EV) readings taken from an illuminated standard greycard. When the units of Luminance B (cd/m^2) are converted to those of Illumination L (lx) by the relation $L = \pi B/R$, where R = 0.18 is the reflectivity of the standard greycard, the working calibration equation for the meter is found to give:

$$Lt = 0.244\ A^2/S \quad \text{klx s}$$

which agrees well with the values derived above.

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REFERENCES

Asahi Optical Company Ltd. *Instruction Manual for Pentax Spotmeter V.* Tokyo, Japan.

Blackwell, B. 2000. Light Exposure to Sensitive Artworks during Digital Photography. *Spectra* (November). Museum Computer Network. www.mcn.edu/
[*Note:* This paper quotes values for UV contents of illumination that are in error by a factor of 1000, owing to the mistaken use of units of mW/lm (milliwatts per lumen) instead of μW/lm (microwatts per lumen).]

Colby, K. M. 1992. A Suggested Exhibition Policy for Works of Art on Paper. *Journal of the International Institute for Conservation, Canadian Group* 17:3-11.
www.lightresource.com/policy1.html (Accessed 31 Dec. 2009)
[*Note:* The definition of Just Noticeable Fade (JNF) used in this paper is not given explicitly, but related to the British Standard BS 2662, in which one JNF is said to correspond with Geometric Grey Scale GGS4 - which seems not to be freely accessible to the public. The fading effects of light are predicated on the British Standard Blue Wool Lightfastness Scale, BS 1006 (now the ISO Standard R105) in which the category of highest sensitivity requires a Threshold Exposure of 400 klx hr (1440 Mlx s) for one JNF. Many historical photographs lie well below this value, so the categories of the Blue Wool Lightfastness Scale are not applicable to them.]

Derbyshire, A. and J. Ashley-Smith. 1999. A proposed Practical Lighting Policy for Works of Art on Paper at the V&A. ICOM-CC Conference. Triennial meeting (12th), Lyon, 29 August-3 September 1999. Preprints 1. London: James & James. 38-41.
[*Note:* The authors review the Blue Wool Standard categories adopted by Colby 1992, with broad agreement, but suggest additionally the creation of a "zero tolerance" category for highly sensitive materials, which is appropriate for historical photographs in Categories 1 and 2 above.]

Dunn, J. F., and G.L. Wakefield. 1981. *Exposure Manual*. Watford: Fountain Press.

Geffert, S. 2008. Center for Digital Imaging Inc., New York.
www.cdiny.com/CDI_LED_Press_Release.pdf (Accessed 31 Dec. 2009)
www.cdiny.com/products.html (Accessed 31 Dec. 2009)

Henry, R. J. 1986. *Controls in Black and White Photography*, 2nd ed. Boston & London: Focal Press.

James, T. H. (ed.) 1977. *The Theory of the Photographic Process*. 4th ed. New York: Macmillan.

Lerwill, A., J. H. Townsend, H. Liang, J. Thomas, and S. Hackney. 2008. A Portable Micro-fading Spectrometer for Versatile Lightfastness Testing. *e-Preservation Science* 5:17-28.
www.morana-rtd.com/e-preservationscience/2008/Lerwill-22-01-2008.pdf (Accessed 31 Dec. 2009)

Light Dosimeter Project, European Commission. 2003.
http://www.lido.fhg.de/ (Accessed 31 Dec. 2009)

LightCheck® Company.
www.lightcheck.co.uk/ (Accessed 31 Dec. 2009)

McElhone, J. P. 1993. Determining Responsible Display Conditions for Photographs. *Topics in Photographic Preservation* 5:60-72. Proceedings of the AIC PMG Meeting, Austin, Texas, 1993.

The Metropolitan Museum of Art, New York. Collection Database. Photographs. "The Bertoloni Album".
http://tinyurl.com/mumxrf (Accessed31 Dec. 2009)

Michalski, S. 1996. The Effect of Light from Flashbulbs and Copiers. *Abbey Newsletter* 20(6). http://palimpsest.stanford.edu/byorg/abbey/an/an20/an20-6/an20-607.html (Accessed 31 Dec. 2009)

Neevel, J. G. 1994. Exposure of objects of art and science to light from electronic flash-guns and photocopiers. In *Contributions of the Central Research Laboratory to the field of conservation and restoration*. Amsterdam: Central Research Laboratory for Objects of Art and Science. 77-87. [*Note:* The light and UV exposures caused by several different models of photocopier have been measured and the results are expressed as the number of copies that can be made to reach a total light dose of 50 lx hr (180 klx s)].

Noll, S. J. 2008. Light Emitting Diode Spectral Scans & Measurements.
www.big-list.com/leds.html (Accessed 31 Dec. 2009).

Pretzel, B. C. 1991. Analysis of Comparative Colour Changes Occurring in a Set of 19th Century Photographs by Lady Hawarden. *Science Section Report*, Conservation Department, Victoria & Albert Museum, London.

Pretzel, B. C., and E. Martin. 1991. *History of Photography* 15(2):149.

Saunders, D. 1989. Ultra-Violet Filters for Artificial Light Sources. *National Gallery Technical Bulletin* 13.

Saunders, D. 1995. Photographic Flash: Threat or Nuisance? *National Gallery Technical Bulletin* 16:66-72.

Schaeffer, T. T. 2001. *Effects of Light on Materials in Collections: data on Photoflash and Related Sources*. Los Angeles: Getty Conservation Institute.
[*Note:* A compilation and overview of the current literature for the whole range of museum objects, including photographs. The author's conclusions are based on a 'standard flash exposure' estimated to be only 0.007 klx s (see pp. 17 & 32) - which seems very low, compared with Saunders, 1995, and Neevel, 1994, who cite a range of exposures by typical photo-flash units to be 0.6-1.25 klx s, and 0.35-6 klx s, respectively; this range of values also agrees well with the theoretical results derived in the Appendix.]

Severson, D. 1986. The Effects of Exhibition on Photographs. *Topics in Photographic Preservation* 1:38-42.

Thomson, G. 1986. *The Museum Environment*. London: Butterworths.

Vitale, T. 1998. Light Levels Use in Modern Flatbed Scanners. *RLG Diginews,* 2(5) (October)
http://worldcat.org:80/arcviewer/1/OCC/2007/08/08/0000070511/viewer/file3642.html#technical

(Accessed 31 Dec. 2009)

Wagner, S., C. McCabe and B. Lemmen. 2001. Guidelines for Exhibition Light Levels for Photographic Materials. *Topics in Photographic Preservation*, 9.
[*Note:* This publication uses the US unit of illumination: the footcandle (ft-c) = 10.764 lux]
It has recently been updated at:
www.nps.gov/hfc/products/cons/ex-con-technotes.htm (Accessed 31 Dec. 2009)

Ware, M. 1994. *Mechanisms of Image Deterioration in Early Photographs, the sensitivity to light of WHF Talbot's halide-fixed images 1834-1844*. London: Science Museum and National Museum of Photography, Film & Television.

Ware, M. 1999. *Cyanotype: the history, science and art of photographic printing in Prussian blue.* London: Science Museum and National Museum of Photography, Film & Television.

Ware, M. 2003. A Blueprint for Conserving Cyanotypes. *Topics in Photographic Preservation* 10:2-18.
www.mikeware.co.uk/mikeware/conservation.html (Accessed 31 Dec. 2009)

Whitmore, P. M., X. Pan and C. Baillie. 1999. Predicting the fading of objects: Identification of fugitive colorants through direct nondestructive lightfastness measurements. *Journal of the American Institute for Conservation* 38:395-409.
http://www.cmu.edu/acrc/Publications/lightfast%20measures.pdf (Accessed 31 Dec. 2009).

Whitmore, P.M. 2002. Pursuing the Fugitive: Direct Measurement of Light Sensitivity with Micro-fading Tests. In *The Broad Spectrum: The Art and Science of Conserving Coloured Media on Paper,* eds. H. K. Stratis and B. Salvesen. London: Archetype Publications. 241-243.
http://www.cmu.edu/acrc/Publications/LightSensitivity.pdf (Accessed 31 Dec. 2009).

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