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Ultra-Violet Filters for Artificial Light Sources

David Saunders

Introduction

The detrimental effects of radiation in the visible and ultra-violet region of the spectrum on works of art are well established. Deterioration may vary from slight loss of colour or flexibility to complete disintegration [1]. A dual approach has been adopted by most museums and galleries to minimize damage. Firstly, the overall illumination or annual exposure is controlled to a level appropriate for the most sensitive materials present in the object [2]. Secondly, the proportion of ultra-violet radiation in the light reaching the object is minimized. Because the human eye is not sensitive to the ultra-violet region of the spectrum, this radiation may be eliminated without disturbing colour appearance.

Historically, daylight has been a preferred source for lighting works of art. Much research has, therefore, been directed toward the development of daylight control systems and glazing materials which absorb ultra-violet radiation. It is now common practice either to install laminated glazing with an ultra-violet absorbing interlayer or to apply a film or varnish with ultra-violet blocking properties to existing glazing. As a result the daylight entering many museums and galleries has a lower ultra-violet content than those artificial lamps which had previously been regarded as low ultra-violet emitting sources.

The ultra-violet content of artificial lamps

The sections which follow describe those artificial light sources currently available for museum and gallery lighting. Colour temperature, colour-rendering and ultra-violet content data for the lamp types described are collated in Table 1.

Tungsten incandescent lamps

The tungsten incandescent lamp has been used widely for lighting in museums and galleries for a number of reasons. The light emitted is of good colour quality and has an ultra-violet content in the region of 65–75 μW lumen^{-1}, depending on the operating temperature of the filament [3]. The current recommended maximum ultra-violet content of other light sources (less than 75 μW lumen^{-1}) was based upon the emission of the tungsten incandescent lamp which was assumed to have an acceptable ultra-violet content [4].

Fluorescent lamps

The efficacy of fluorescent lamps compared to that of tungsten lamps had led to their use in a great number of museums and galleries. The ultra-violet content of the light emitted varies according to lamp type, but is generally in the region 40–150 μW lumen^{-1} [5]. The theoretical and practical aspects of selecting fluorescent lamps with good colour-rendering properties and an acceptable ultra-violet content have been described in earlier volumes of this *Bulletin* [5, 6].

Tungsten halogen lamps

The tungsten halogen lamp operates upon a similar principle to the tungsten incandescent lamp. A filament of tungsten is heated by an electrical current to a temperature at which it emits light as well as heat. In the tungsten lamp the temperature to which the filament may be heated is limited. If the temperature is increased, evaporation of the filament causes deposition of tungsten metal on the inside of the glass envelope and, eventually, failure of the filament. The introduction of a small quantity of halogen vapour into the envelope establishes a regenerative cycle which prevents metal deposition and allows operation at a higher colour temperature, although filament life is still related to temperature [7]. The ultra-violet output of the lamp depends upon the colour temperature at which the lamp is operating. The 'bluer' the light produced, the greater the ultra-violet content. At 2800 K, which is a typical temperature for a tungsten lamp, the ultra-violet content of the light is 67 μW lumen^{-1}. Raising the operating temperature to 3400 K, characteristic of short-life tungsten halogen lamps, increases the ultra-violet content to 165 μW lumen^{-1} (see Table 1).

Metal halide lamps

Metal halide lamps are mercury discharge lamps doped with selected metal halides. Excitation of these metals gives rise to additional bands in the visible region creating a 'white light' [8]. Most types of metal halide lamp have rather poor colour-rendering properties. As a result such lamps are inappropriate for lighting exhibits when colour is important. Those sources with better colour-rendering indices tend to produce very 'cold' light which is not usually desirable for gallery lighting, although it may be suitable for conservation studios or perhaps as a method of supplementing the natural light passing through a laylight. In situations where colour appearance is not of prime importance, metal halide lamps are available which emit warmer light with moderately good colour-rendering properties. The ultra-violet content of the light emitted varies with lamp type, but can be up to *c*.700 μW lumen^{-1} (see Table 1).

Other lamps

Other types of artificial lamp are not widely used for display purposes in museums and galleries. The very poor colour-rendering properties of most sodium and mercury discharge lamps have prevented their use in situations where colour is important. The colour quality

Table 1 Data for selected light sources.

Lamp Type	Colour Temperature (K) (1)	R_a (2)	R_w	Colour-Rendering Group (3)	UV content (microwatts/lumen) (4)
Incandescent lamp					
Standard tungsten filament	2860	99	98	1a	74
Fluorescent lamps (5)					
Thorn Kolor-rite	3930	89	82	1b	85
Philips 83/Wotan 31	2980	83	52	1b	84
Philips 84/Wotan 21	4030	82	51	1b	89
Philips 93/Wotan 32	3010	94	82	1a	49
Philips 94/Wotan 22	3780	95	86	1a	43
Tungsten halogen lamps					
Short life lamp	3400	100	98	1a	165
Standard (1000 hour) lamp	3190	100	98	1a	127
Long life (2000 hour) lamp	2990	100	98	1a	94
Metal halide lamps					
Wotan HQI-E 250W/D	5010	95	87	1a	471
Wotan HQI-R 250W/D	4900	91	86	1a	167
Wotan HQI-TS 150W/NDL	4300	91	68	1a	697
Wotan HQI-TS 70W/WDL	3050	75	26	2	215
Mercury fluorescent lamps (MBF)					
Wotan HQL 125W	4210	48	33	3	765
Wotan HQL-R 80W deluxe	3270	58	46	3	471
Wotan HQL 125W super deluxe	3110	53	40	3	272
Mercury fluorescent–tungsten lamps (MBFT)					
Wotan HWL 160W	3500	61	48	2	601
Wotan HWL-R 160W deluxe	2940	68	58	2	368
High pressure sodium lamps (SON)					
Wotan NAV-T 400W	2030	23	−47	4	31
Wotan NAV 400W deluxe	2250	63	38	2	24

Notes:

(1) Correlated colour temperature (CCT) indicates the warmth or coolness of the light produced. Lamps may also be classified as follows.

Warm : 3300K > CCT
Intermediate : 3300K < CCT < 5300K
Cold : 5300K < CCT

(2) R_a is the general colour-rendering index; R_w is the lowest (worst) of the eight individual indices.

(3) The colour-rendering group is based upon the general colour-rendering index R_a.

Group 1a : $100 > R_a \geqslant 90$
Group 1b : $90 > R_a \geqslant 80$
Group 2 : $80 > R_a \geqslant 60$
Group 3 : $60 > R_a \geqslant 40$
Group 4 : $40 > R_a \geqslant 20$

(4) Ultra-violet radiation in the region 300–400nm.

(5) More detailed data for a wider selection of fluorescent lamps may be found in references [5] and [6].

of the light from high-pressure sodium (SON) lamps is improved slightly in the 'deluxe' version by increasing the sodium vapour pressure [9]. Although the colour quality of the light produced by 'deluxe' mercury fluorescent (MBF) and mercury fluorescent–tungsten 'hybrid' (MBTF) lamps is improving as new phosphor coatings are introduced [10], for the present such sources should be avoided for display. The properties of these lamps are summarized in Table 1.

Ultra-violet filters

The spectral absorption properties of certain materials have been exploited in the manufacture of film and sheet filters for excluding ultra-violet radiation. Research in this area has aimed primarily at reducing the ultra-violet content of daylight passing into museums and galleries.

In order to assess the effectiveness of ultra-violet absorbing materials, a specification for an acceptable filter has been established [11]. Because some of the materials which comply with the limits imposed by this specification absorb light in the blue region of the visible spectrum as well as ultra-violet radiation, filters containing these substances appear yellow. It has been noted that absorbing the blue, and most damaging, portion of the visible spectrum may reduce certain light-induced damage [12]. Yellow coloured filters will be of use to protect sensitive objects under circumstances where colour appearance is not important.

In many situations, however, colour is of great importance and it is necessary to evaluate the effect of a given filter on transmitted light. Filters which have a slightly yellow appearance will tend to decrease the colour temperature of the transmitted light. The calculated colour temperature shift can be used as an indication of the suitability of a filter. In addition, the filter may absorb a greater proportion of the light in particular regions of the visible spectrum. The colour quality of the light transmitted may be reduced as a result. To assess this effect, the colour-rendering index of the light produced by a specific combination of source and filter may be calculated. Any significant reduction in the colour-rendering index of a light source when the filter is incorporated indicates that the filter may not be suitable.

It is useful to make a distinction between those ultra-violet filters which are stable to heat and those which should only be used with lamps which generate little heat or are placed at a distance from a high temperature source. Generally, the latter are most suitable for use with fluorescent lamps or in laylight systems where lamps are located some way above the glazing.

Filters for low operating temperatures

Because fluorescent lamps operate on a discharge principle, little heat is generated. As a result, the ultra-violet content of the light emitted may be reduced simply and efficiently by using an absorbing sleeve or sheet. The sleeve is a thin polymeric film, commonly a polyester or acetate, in which an ultra-violet absorbing compound has been dispersed. The film is either pressed so that it forms a cylinder around a standard tube, or else is contained within a rigid jacket into which the tube is inserted. These films have a similar formulation to the adhesive films applied to exterior glazing to reduce the ultra-violet content of transmitted daylight. Although the best films reduce the ultra-violet content of light from most fluorescent lamps to between 0 and 5 μW lumen^{-1}, there can be considerable variation between batches. The properties of some selected filters are summarized in Table 2. Transmittance spectra for these filters are shown in Fig. 1.

A second filter type is a sheet of polymeric material, usually of 2–4 mm thickness, which serves to reduce the ultra-violet content of the light transmitted. The same sheet is frequently moulded to serve as a diffuser. The degree to which ultra-violet radiation is absorbed will depend on the thickness and type of polymer used. Certain types of both acrylic and polycarbonate sheet possess satisfactory ultra-violet absorption properties. These materials may also be used in laylight glazing, providing that no high temperature sources are located in the immediate vicinity. Table 2 summarizes the properties of some filters of this type; transmittance spectra for these filters are shown in Fig.2.

High temperature filters

Because the tungsten incandescent source was used to set the recommended maximum ultra-violet content, it has not been the practice to fit these lamps with a filter. The more damaging UV–A and UV–B radiation, with a wavelength of less than *c.*320 nm is generally absorbed by the outer glass envelope.

It was the increasing use of tungsten halogen lamps, particularly those operating at low voltage (typically 12 volt), that prompted us to reinvestigate the variety of materials available for ultra-violet filtration. Because of the high operating temperature, the filament of a tungsten halogen lamp is encased in a quartz rather than glass envelope. The quartz transmits some of the short wave ultra-violet radiation (UV–B) that would be absorbed by the glass envelope of a conventional tungsten source. For this reason it has been recommended that tungsten halogen lamps should be used in conjunction with glass filters [13]. It will be seen from Table 3, however, that whilst 'plain' glass may absorb all radiation below *c.*320 nm, the ultra-violet content of the light from a tungsten halogen lamp is not greatly reduced.

Polymeric films and sheet are usually inappropriate for use with tungsten halogen sources because of the high operating temperature. It would be possible to locate the filter some distance from the envelope, but this would obviate one of the most attractive feartures of this type of lamp — its extreme compactness. Another alternative, which is not always desirable, is to glaze paintings or encase objects with an ultra-violet absorbing polymeric material [14]. These difficulties prompted a new investigation of a number of heat-stable filters. We have evaluated their efficiency in absorbing ultra-violet radiation and their effect upon the colour temperature and colour-rendering properties of the light transmitted [15]. The results of this study will also be relevant when considering metal halide and other high temperature lamps, detailed in Table 1, which have a significant emission in the ultra-violet region.

Assessment of heat resistant filters

Theoretical calculations

A number of heat-stable materials were examined in a search for potential ultra-violet absorbers. Both borosilicate glass and 'plain' window glass were tested, as well as a number of glasses to which an ultra-violet absorber had been added whilst in the molten state. Two filters supplied by lamp manufacturers and designed to be used in conjunction with tungsten halogen lamps were also tested. Finally, two thin-film interference filters were assessed. The effect of the filters on the colour temperature, colour-rendering and ultra-violet content of the transmitted light were calculated [15], and are given in Table 3, whilst their transmittance curves are shown in Fig.3.

The filters can be divided into three groups. The first includes the borosilicate glass, plain glass, Thorn ultra-violet filter and Pilkington MR2 glass. These filters have a minimal effect upon the colour temperature and colour-rendering properties of the transmitted light. Unfortunately, the ultra-violet content of the light transmitted by these filters is still above the current recommended level of 75 μW lumen^{-1}.

The second group, comprising the Erco ultra-violet filter, and the Oralan and Uvilex 1 glasses manufactured by Schott, reduce the ultra-violet content of the transmitted light to below 75 μW lumen^{-1}. Because these filters also have a considerable absorption in the blue region of the visible spectrum, they decrease the colour temperature of the transmitted light and appear yellow. This is most clearly seen in Plate 10 (p.39), which shows a selection of the filters from Table 3 photographed against a white background.

Finally, the two dichroic filters, manufactured by Bausch & Lomb and Balzers, transmit virtually no ultra-violet light and do not significantly change the colour properties of the light. These filters comprise a glass substrate on to which an inorganic coating has been deposited under vacuum. This thin but resilient layer is generally a mixture of metal oxides. Interference effects at the coating interface cause light of particular wavelengths to be reflected whilst light at other wavelengths is transmitted. In the case of the filters tested here, radiation in the ultra-violet portion of the spectrum is reflected whilst visible radiation is transmitted.

Practical assessment

In order to assess the validity of the theoretical calculations, four of the filter materials were compared in a practical study.

Blue wool standards Nos.1, 2 and 3 were used as test samples. Three pieces of each blue wool standard were exposed to the light from a 12 volt 100 watt tungsten halogen lamp for 1000 hours. Three samples of each blue wool standard were placed beneath each of the four filter materials to be tested. The four filters selected were plain window glass, Thorn ultra-violet filter, Erco ultra-violet

Table 2 Data for selected low temperature filters (1).

Filter	Colour Temperature Shift (K) (2)	Colour-Rendering Index (R_a) (3)	UV content (microwatts/ lumen) (4)
None	0	89	85
Erco fluorescent sleeve	−50	89	2
Encapsulite fluorescent sleeve	−50	89	1
Morden fluorescent sleeve	−130	89	1
Chamberlain fluorescent sleeve	−90	89	<1
Plexiglas 209 acrylic sheet (5)	−10	89	12
Plexiglas 201 acrylic sheet	−50	89	11
Lexan polycarbonate sheet	−70	90	2
Perspex VE acrylic sheet	−80	89	<1
Makrolon 281 polycarbonate sheet	−30	89	<1

Notes:

(1) Reference source: Thorn Kolor-rite; colour temperature 3930 K; general colour-rendering index (R_a) 89; ultra-violet content 85 μW/lumen. The first line of data gives the properties of the source alone, subsequent lines indicate the properties of the reference source combined with selected filters.

(2) The colour temperature shift indicates the effect of the filter upon the warmth or coolness of the light transmitted. A negative colour temperature shift indicates that the colour of the transmitted light is warmer, or yellower, than the incident light. A positive shift indicates that the transmitted light is cooler, or bluer.

(3) R_a is the general colour-rendering index of the light produced by the combination of filter and reference source. The greater the colour-rendering index the better the colour quality.

(4) Ultra-violet radiation in the region 300–400 nm.

(5) All sheets tested were 3 mm thick.

filter and Bausch & Lomb thin-film filter. Finally, three pieces of each blue wool standard were maintained in darkness but otherwise under identical conditions to the exposed samples. This procedure was adopted in order that both test and control samples might be subject to the same degree of heating from the source. The positions of the samples were interchanged at regular intervals to ensure even illumination of all test pieces.

The colour of each sample was measured prior to exposure and after 1000 hours exposure at approximately 25,000 lux [16]. The average CIE (Commission Internationale de l'Éclairage) coordinates $L^\star$, $a^\star$ and $b^\star$ were derived for every measurement and used to calculate the colour difference, ΔE, for each blue wool sample [17]. Lastly, the colour differences were corrected to compensate for the differing transmittances in the visible region. The values of ΔE obtained in this way appear in Table 4.

The colour differences noted for the dark control samples are at the level of experimental reproducibility and probably do not reflect any temperature-induced colour change. As expected, all three blue wool standards are affected by exposure to light, standard No.1 being the most fugitive. Greatest fading occurs when no filter is present. The reduction in fading due to each of the filters follows the same pattern for all three blue wool standards. The greatest reduction in fading is provided by the Bausch & Lomb filter followed by the Erco filter, the plain window glass and finally, the Thorn filter. The degree of protection afforded by each of the filters may

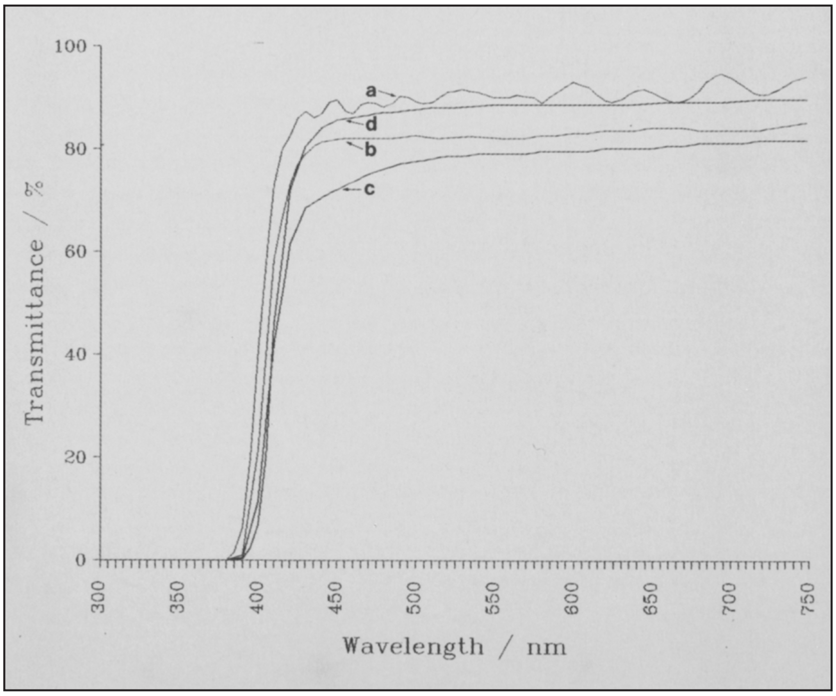

Figure 1 Graphs of transmittance versus wavelength for the ultra-violet absorbing polymeric sleeves detailed in Table 2:
(a) Erco fluorescent sleeve
(b) Encapsulite fluorescent sleeve
(c) Morden fluorescent sleeve
(d) Chamberlain fluorescent sleeve

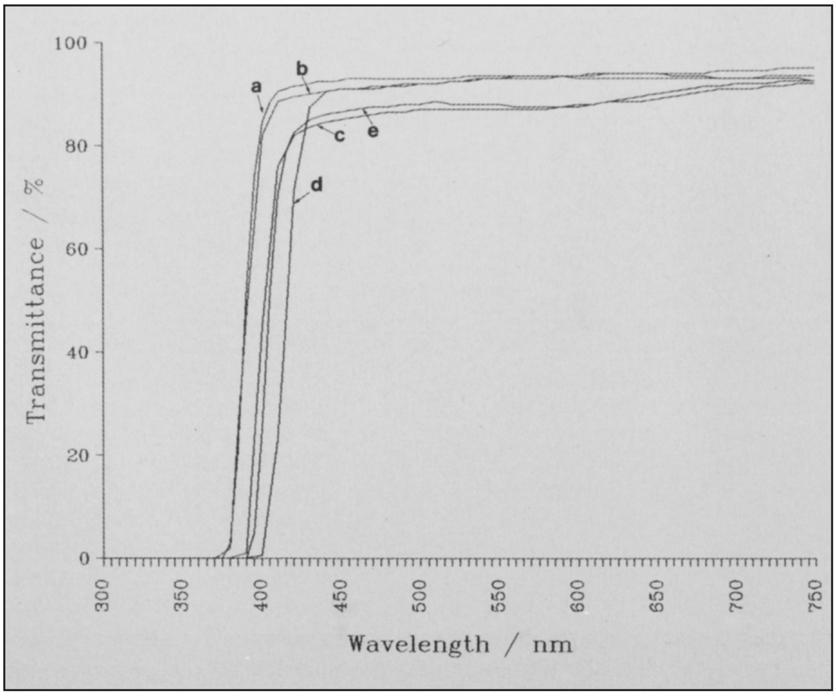

Figure 2 Graphs of transmittance versus wavelength for the ultra-violet absorbing polymeric sheets detailed in Table 2:
(a) Plexiglas 209 acrylic sheet
(b) Plexiglas 201 acrylic sheet
(c) Lexan polycarbonate sheet
(d) Perspex VE acrylic sheet
(e) Makrolon 281 polycarbonate sheet

Table 3 Data for selected heat resistant filters (1).

Filter	Colour Temperature Shift (K) (2)	Colour-Rendering Index (R_a) (3)	UV content (microwatts/ lumen) (4)
None	0	99	165
Borosilicate glass (5)	+10	99	155
Thorn ultra-violet filter (6)	0	99	135
Window glass	+10	100	125
Pilkington MR2 glass	−30	99	84
Erco ultra-violet filter (6)	−110	100	43
Schott Oralan glass	−190	99	33
Schott Uvilex 1 glass	−170	97	7
Bausch & Lomb thin-film dichroic filter	+30	99	<1
Balzers thin-film dichroic filter	−70	99	<1

Notes:

(1) Reference source: 12V, 100W tungsten halogen lamp; colour temperature 3360K; general colour-rendering index (R_a) 99; ultra-violet content 165 μW/lumen. The first line of data gives the properties of the source alone, subsequent lines indicate the properties of the reference source combined with selected filters.

(2) The colour temperature shift indicates the effect of the filter upon the warmth or coolness of the light transmitted. A negative colour temperature shift indicates that the colour of the transmitted light is warmer, or yellower, than the incident light. A positive shift indicates that the transmitted light is cooler, or bluer.

(3) R_a is the general colour-rendering index of the light produced by the combination of filter and reference source. The greater the colour-rendering index the better the colour quality.

(4) Ultra-violet radiation in the region 300–400 nm.

(5) All the samples were between 3 and 4 mm thick, with the exception of the Balzers filter which was 2 mm thick.

(6) Filters supplied by lighting manufacturers for use with tungsten halogen lamps or fittings.

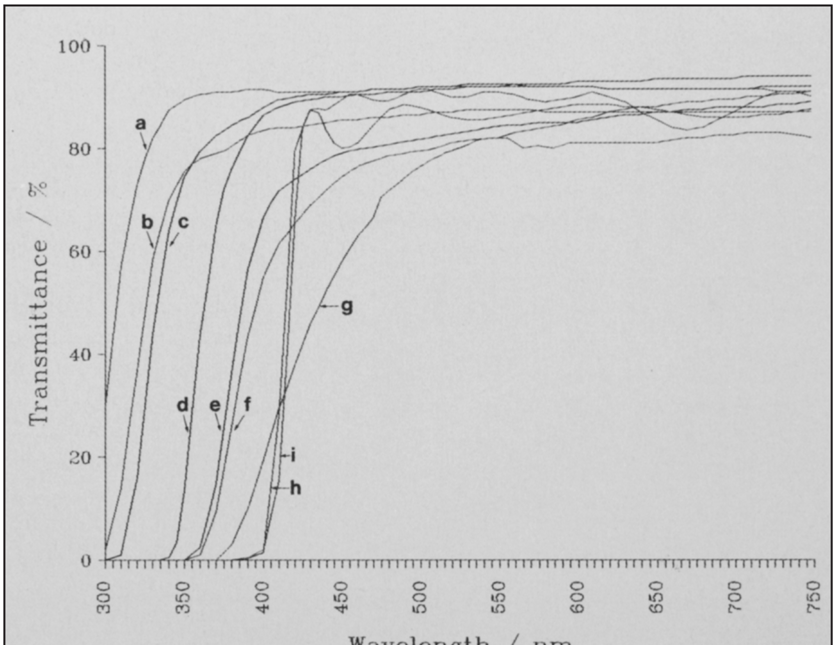

Figure 3 Graphs of transmittance versus wavelength for the heat resistant ultra-violet filters detailed in Table 3:
(a) Borosilicate glass
(b) Thorn ultra-violet filter
(c) Window glass
(d) Pilkington MR2 glass
(e) Erco ultra-violet filter
(f) Schott Oralan glass
(g) Schott Uvilex 1 glass
(h) Bausch & Lomb thin-film dichroic filter
(i) Balzers thin-film dichroic filter

Table 4 Colour change of blue wool standards under different filters.

Filter (1)	Blue Wool Standard No.1 Colour Change (ΔE) (2)	No.2 Colour Change (ΔE)	No.3 Colour Change (ΔE)
None	26.28	21.64	11.12
Thorn ultra-violet filter (3)	26.04	19.57	9.71
Window glass	21.13	14.28	6.11
Erco ultra-violet filter (3)	19.96	11.32	4.88
Bausch & Lomb dichroic filter	14.16	8.09	2.39
Dark control	0.72	0.58	0.81

Notes:

(1) Reference source: 12V, 100W tungsten halogen lamp; illuminance 25,000 lux. Samples were exposed for 1000 hours. Sample positions were interchanged periodically to ensure equal illumination.

(2) The colour was measured before and after exposure using a Minolta CR–200 chroma meter. Entries in the Table derive from the average of three measurements on each of three samples exposed under identical conditions. The colour difference, ΔE, has been calculated using the CMC (l:c) colour difference formula; see reference [16]. ΔE has been corrected to compensate for the differences in visible transmittance of the various filters.

(3) Filters supplied by lighting manufacturers for use with tungsten halogen lamps or fittings.

be seen to relate to the ultra-violet content of the light transmitted, as indicated in Table 3.

It is equally clear, however, that none of the filters eliminate fading, which is caused by both visible and ultra-violet light. This emphasizes the importance of combining ultra-violet filtration with a regime that limits the total light exposure.

Conclusions

Many of the artificial light sources suitable for museums and galleries emit a significant proportion of ultra-violet radiation. Although light-induced damage cannot be prevented by eliminating ultra-violet radiation alone, a number of studies have shown that radiation in the ultra-violet region of the spectrum is considerably more damaging than visible light [18]. Since this ultra-violet light is not necessary for accurate perception of form or colour, it should be eliminated by effective filters whenever possible.

The problem of selecting efficient heat resistant filters for tungsten halogen lamps has led to an acceptance of higher than recommended ultra-violet levels [19]. The results above indicate that with appropriate filters capable of withstanding high temperatures, it is possible to reduce the ultra-violet content of the light from a tungsten halogen lamp to a negligible level. Indeed, the Bausch & Lomb filters tested are about to become generally available, whilst other manufacturers are beginning to introduce low voltage tungsten halogen lamps fitted with a vacuum coated front glass to reduce ultra-violet content.

If film or sheet ultra-violet absorbers are used to reduce the ultra-violet content of daylight and fluorescent light, and heat resistant filters are used with tungsten halogen and other high temperature discharge lamps, then a paradoxical situation is reached in which the source with the highest ultra-violet emission will be the incandescent lamp; previously considered to have a sufficiently low ultra-violet content to act as a benchmark for the filtration of other sources.

There is no reason why incandescent lamps should not be fitted with the same filters as tungsten halogen lamps. It is unlikely that this will be done whilst the accepted maximum ultra-violet light content remains fixed at 75 μW lumen^{-1}. Since the best of the filters described in the preceding sections are capable of reducing the ultra-violet level of all sources to well below 10 μW lumen^{-1}, it is proposed that museums and galleries should in future aim for an ultra-violet content of less than 10 μW lumen^{-1}, particularly for the more light sensitive materials, which would be exhibited at light levels of less than 50 lux under the current recommendations.

Acknowledgements

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Notes and references

1. For a review of the types of damage caused by both visible and ultra-violet radiation, see MICHALSKI, S., 'Damage to museum objects by visible radiation (light) and ultraviolet (UV)', in *Lighting: Preprints of the Bristol Conference on Lighting in Museums, Galleries and Historic Houses*, The Museums Association (1987), pp.3–16.
2. THOMSON, G., *The Museum Environment*, 2nd ed., Butterworths (London 1986), pp.22–34.
3. The ultra-violet content of a light source is usually given in microwatts per lumen ($\mu W\ lumen^{-1}$). This indicates the proportion of radiation in the ultra-violet region. To control the amount of ultra-violet radiation incident on an object it is necessary, therefore, both to minimize the ultra-violet content of the light source and to limit the overall illuminance.
4. THOMSON, G., *The Museum Environment*, *op. cit.*, p.20.
5. THOMSON, G., 'Colour Under Some New Fluorescent Lamps', *National Gallery Technical Bulletin*, **9** (1985), pp.5–11.
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8. HALL, R. and ODELL, E.C., 'Metal Halide Lamps' in *Lamps and Lighting*, *op. cit.*, pp.236–48.
9. MOLESDALE, P.D., 'High Pressure Sodium Lamps' in *Lamps and Lighting*, *op. cit.*, p.210–23.
10. MARTIN, W., 'Mercury Lamps' in *Lamps and Lighting*, *op. cit.*, pp.224–35.
11. The specification for an acceptable ultra-violet filter takes as a reference value the transmittance of the filter at 550nm. An acceptable filter has a transmittance of less than 1% of the reference at both 320nm and 380nm and a transmittance of less than 50% of the reference at 400nm. See THOMSON, G., *The Museum Environment*, *op. cit.*, p.17.
12. COX CREWS, P., 'A Comparison of Clear Versus Yellow Ultraviolet Filters in Reducing Fading of Selected Dyes', *Studies in Conservation*, **33** (1988), pp.87–93.
13. THOMSON, G., *The Museum Environment*, *op. cit.*, p.172.
14. The damage factor (in the visible and ultra-violet regions) has been calculated for a number of artificial sources and the effect of protecting the object with a series of filter materials tabulated. See HILBERT, G.S., *Sammlungsgut in Sicherheit; Teil 2. Lichtschutz, Klimatisierung*, Gebr. Mann Verlag (Berlin 1987), p.76.
15. The computer program developed for this purpose calculates the spectral power distribution of the transmitted light by multiplying the spectral power distribution of a source with the transmittance spectrum of any of the filters for which data is available. The colour-rendering properties, colour temperature and ultra-violet content of the transmitted light are then calculated.
16. Colour measurements were made using a Minolta CR-200 chroma meter. Values of $L^\star$, $a^\star$ and $b^\star$ were calculated for CIE illuminant D65.
17. Colour difference ΔE was calculated using the Society of Dyers and Colourists Colour Measurement Committee recommended formula; CMC(l:c) formula. See CLARKE, F.J.J., MCDONALD, R. and RIGG, B., 'Modification to the JCP79 Colour-Difference Formula', *Journal of the Society of Dyers and Colourists*, **100** (1984), pp.128–32.
18. For a review of the evidence, see MICHALSKI, S., *op. cit.*, pp.13–14, or CUTTLE, C., 'Lighting Works of Art for Exhibition and Conservation', *Lighting Research and Technology*, **20** (1988), pp.43–53.
19. STANIFORTH, S., 'Problems with Ultraviolet Filters', in *Lighting: Preprints of the Bristol Conference on Lighting in Museums, Galleries and Historic Houses*, *op cit.*, pp.25–9.