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Front cover: *The Virgin and Child before a Firescreen*, detail of Plate 1, p. 20.

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Protective Glass for Paintings

DAVID SAUNDERS AND ANTHONY REEVE

For many years glass has been used to protect paintings and other works of art from the harmful effects of the environment such as pollutants, and from physical damage.[1] Unfortunately, the glazing creates reflections, may distort or obscure the image – particularly areas of texture or impasto – and alters the appearance of colours. In the event of conventional protective glass breaking, its brittleness and sharpness can, ironically, cause severe damage.

For a combination of these reasons, the National Gallery has not routinely glazed paintings in the permanent Collection over the past few years. The introduction of air-conditioning in many of the rooms has helped to control the environment and reduce pollutant levels.

When paintings have travelled on loan some protection has often been considered necessary. A sheet of acrylic (Perspex), which offers greater strength than glass and has a less strong colour, has typically been used. Perspex does, however, create reflections and unless specially treated scratches easily.

The well-publicised chemical attack on paintings by Dürer in the Alte Pinakothek in Munich,[2] the increased risk of accidental damage to paintings from the Gallery's numerous visitors (four million per year), and a growth in requests for loans have led to a reappraisal of the best protective materials available.

Fortunately, technological advances in recent years have resulted in improvements in the range and quality of glass types available. Float glass, which possesses flat parallel surfaces, is manufactured in a wide variety of thicknesses from 1 to 25 mm. The slight green tint in ordinary glass can be reduced and the glass strengthened by toughening or lamination. In addition, the glass can be coated to produce low reflectivity, or to provide ultra-violet protection or other properties.

The selection of suitable glazing materials has received considerable attention as a number of, sometimes conflicting, properties were required. The glazing must be unobtrusive and light, yet provide adequate impact resistance. The results of our investigation into some of these materials are presented below.

Glass properties

A number of optical and physical properties were considered:

Reflectivity

The major problem encountered when glazing any work of art is that of unwanted reflections. The polished surface will reflect the surrounding room, the viewer, and in particular any light sources in the field of view. The principal cause of these distracting reflections or glare is light which is reflected at an angle equal to that at which it is incident upon the glass (Fig. 1a). Such reflections, which amount to 8–10 % of incident light, can be reduced by treating the glass in one of two ways. The first method is to etch the surface of the glass to increase the diffuse scatter of the incident light (Fig. 1b). As a result less light is reflected directly to the viewer and the glare is reduced. A second method of decreasing the reflection is the application of an extremely thin coat of metal oxides onto the outer surface of the glass. The thickness and refractive index of these layers are selected so that the light reflected at the air-coating interface interferes destructively with that reflected at the coating-glass interface (Fig. 1c).

There are advantages and disadvantages to the use of these two types of low-reflective glass. The etched glass does not change the colour of the reflected light appreciably. Fig. 2 curve (a) demonstrates that the light reflected by an etched glass is approximately 60% of that reflected by a comparable piece of ordinary glass. The image viewed through an etched glass appears defocused and the use of such materials is not favoured. A coated low-reflective glass does not distort or blur the image. Unfortunately, because the interference effect is dependent on wavelength, the reflected light is not distributed evenly across the visible spectrum, as Fig. 2 curve (b) shows. It is for this reason that light sources and other reflections, while diminished, often appear green or violet in coated low-reflective glass.

This criterion was judged of such importance that glazing materials which cannot be treated at present to lower their reflectivity were not included in the test programme. For this reason the use of plastics, such as acrylic or polycarbonate sheet, was ruled out.

Strength and weight

Strength and weight in a glazing material are often conflicting properties. Untreated float glass is very brittle and its fragments may damage a painting if it is broken. Although the brittleness of glass can be reduced by tempering/toughening, this does not impart sufficient strength for a material of an appropriate thickness and weight for framing to be considered for glazing paintings.

Laminated glass offers several advantages. It has good strength and the interlayer will help to hold slivers of glass in the event of an accident. Because glass generally contributes approximately 2.5 kg m^{-2} per millimetre thickness and a laminate 1 kg m^{-2} per millimetre, a laminate will be lighter, and much stronger, than a glass of the same thickness.

Two methods of lamination are possible. In the first the two sheets of glass are held parallel using an adhesive tape. Resin is poured into the void between the two sheets, which is typically at least 0.5 mm wide. In the second method, the interlayer is placed between the two pieces of glass, softened by heating and bonded to the surrounding glass under pressure.

One problem in the production of low-reflective laminated glass is that the inner surfaces of the two sheets to be laminated must be uncoated. If the low-reflective coating has been applied by dipping it will be present on both sides of the glass and will need to be 'stripped' from one side prior to lamination. Glass onto which the low-reflective layer has been vacuum coated on one side only will not require this pre-treatment.

Colour

The colour of glass depends largely on its chemical composition. Ordinary glass, which has quite a high iron content, often gives a green tinge to the light it transmits. Clear or white glass has either a lower iron content or a second component (for example manganese) added to counteract the coloration caused by the iron. The colour imparted by the glass also depends on its thickness. In laminated glasses, the interlayer which gives the glass its strength and ultra-violet absorbing properties may have a slight yellow colour.

Any coloration is more evident in glass used to glaze paintings than in glass used in windows and roof lights, for two reasons. First, the light reaching the viewer has passed through the glass twice: once on its path from the light source to the painting and again from the painting to the viewer's eye. Secondly, and perhaps more importantly, when the same glass is used for all the windows in a room, the viewer's colour adaptation can compensate for slight changes in the colour of the light. When paintings are glazed with glass which has a slight colour, the viewer does not colour adapt to correct for this, but remains adapted for the general lighting in the room.

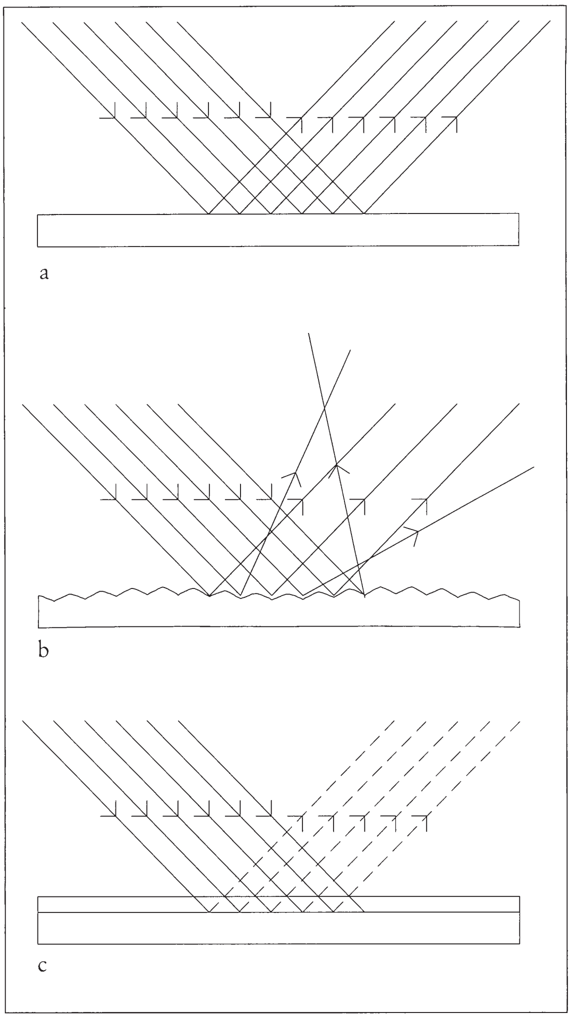

Fig. 1 Schematic representation of the reflection of light from (a) ordinary glass, showing specular reflection, (b) etched glass showing an increase in diffuse reflection and a decrease in specular reflection, and (c) coated glass showing the effect of destructive interference on the strength of the specular reflection.

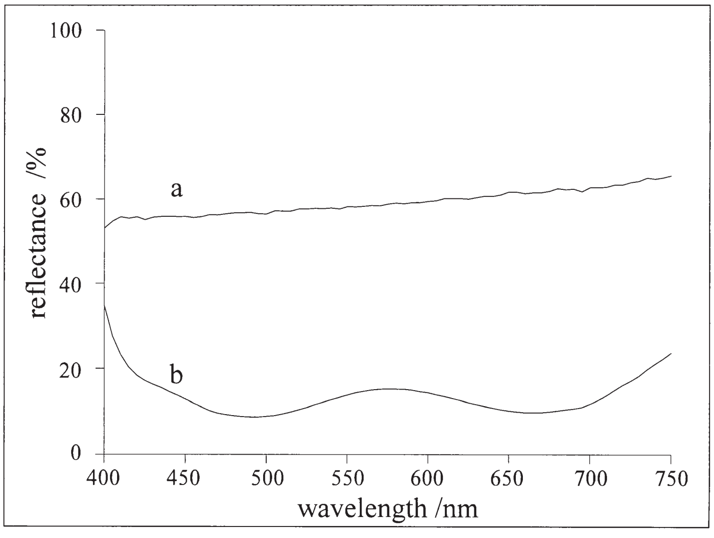

Fig. 2 Reflectance spectra for an etched glass (a) and for a coated glass (b). The reflectance is as a percentage of the reflectance from an untreated glass of the same composition and thickness.

Ultra-violet absorption

The exclusion of ultra-violet radiation is *not* one of the principal purposes of glass for framing. In the Gallery, the ultra-violet content of all illuminants is controlled by fitting appropriate filters to the exterior glazing or artificial light sources. For displays where the ultra-violet levels are above that recommended,[3] additional protection from this short-wavelength radiation is beneficial. The ultra-violet may be excluded by one of two methods. The coating which is applied to reduce the reflectivity of the glass may be modified so that it also rejects radiation of certain wavelengths, in this case those associated with the ultra-violet region.[4] The second method is to use a laminating material which has ultra-violet absorbing properties, for example a polyvinylbutyrate (PVB).

Testing programme

The physical and optical properties of a number of glasses and glass laminates were studied. The samples included ordinary and low-iron float glasses of various thicknesses, with and without low-reflective coatings, and a number of low-reflective laminated glasses. A list of suppliers is included in Appendix 1. The results for some of the glass types tested are summarised in the Table. These data are intended to illustrate the various possibilities and are not an exhaustive list of the materials available.

Reflectivity

The reflectance of a number of low-reflective glasses was recorded in the visible range using illumination at 45° to the surface of the glass and measuring the reflection at 45°. A piece of untreated glass of the same thickness was used as a reference. During measurement the glass samples were placed on a sheet of matt black material.

The relative reflectance from an etched glass and a typical coated glass are shown in Fig. 2, curves (a) and (b) respectively. The spectral distribution of the reflectance from coated glasses can vary with angle so, for example, reflections can appear green from one viewing position and violet from another. Only materials with thin-film low-reflective coatings were considered, as etched glass samples produced a blurring of image that was considered unacceptable. Some materials which do not have low-reflective coatings are, however, included in the Table for comparison.

Strength and weight

The mass per square metre for the glass or laminate is included in the Table. An empirical test alone was made to assess the strength of these glazing materials, which fell into two categories. Those which comprise a single glass layer offer no protection to the painting if it is subjected to attack with a blunt instrument. The laminated glasses of the same or lower weight offer a higher degree of protection. With some slight variation the general rule that glass contributes approximately 2.5 kg m^{-2} per millimetre thickness and a laminate 1 kg m^{-2} per millimetre holds for the samples tested. The thin Noviflex laminate is particularly light for its strength.

Table Physical and optical properties of glasses and glass laminates

Sample	*Glass type*	*Low-reflect*[1]	*Thickness (mm)*[2]	*Weight (kg m^{-2})*[3]	*Colour shift index*[4]	*50% cut-off (nm)*[5]	*Ultra-violet content (μW $lumen^{-1}$)*[6]
Float glass	ordinary	yes	5	12.0	2.25	342	57
Float glass	low-iron	no	5	11.4	0.34	347	56
Float glass	low-iron	yes	5	11.0	0.51	327	59
Float glass	ordinary	no	2	4.6	1.04	332	59
Schott Mirogard	ordinary	yes	2	4.6	0.81	341	54
Viratec Tru-Vue	ordinary	yes	2	5.5	2.50	402	6
Schott Amiran laminate	ordinary	yes	3 + 1 + 3	14.6	2.48	384	19
Rankin laminate	low-iron	yes	3 + 1 + 3	16.4	1.78	398	3
Noviflex laminate	ordinary	yes	1 + 2 + 1	7.4	2.76	373	32
Noviflex laminate	low-iron	yes	2 + 2 + 2	7.5	1.36	366	36

1. 'Yes' indicates that the glass has a low-reflective coating, 'no' indicates no coating.
2. The thickness of laminates is given in the form $x + y + x$ where x is the glass thickness and y is that of the interlayer.
3. Mass in kg m^{-2} for a sheet of the thickness indicated in the previous column.
4. The colour shift index is obtained as described in Appendix 2. For this calculation the reference source is CIE illuminant A.
5. The wavelength quoted is that at which the glass excludes 50% of incident radiation.
6. The ultra-violet content in microwatts per lumen (μW $lumen^{-1}$) is given for light from CIE illuminant A that has passed through the glazing layer. For comparison, the ultra-violet content of the light incident on the glazing is 75μW $lumen^{-1}$.

Colour

The transmittance spectra of a number of glasses and laminates were recorded in the ultra-violet and visible range. In order to assess the effect of the glazing layer on the appearance of colours, a colour shift index was developed. The derivation of this index is explained in Appendix 2. Its main features are that it assumes, as described above, that the light passes through the glass layer twice and that the observer remains colour adapted to the ambient lighting conditions.

The colour shift indices for several types of glazing material are included in the Table. The larger the shift, the greater the distortion in colour produced by the glass. For comparison, the transmittance spectra of 5 mm thick sheets of ordinary (greenish) and low-iron glasses are shown in Fig. 3. It will be seen that whereas the transmittance of the low-iron glass is fairly consistent across the visible range, curve (a), the transmittance for the ordinary glass is greater in the green region of the spectrum centred at about 530 nm, curve (b). The colour shift indices for these glazing materials are 0.51 and 2.25 respectively. The thickness of the glass will affect the colour shift index. Decreasing the thickness of a sheet of ordinary glass from 5 to 2 mm reduces the colour shift index from 2.25 to 0.81.

The effect of the low-reflective coating on the colour shift index seems to be small. For a 5 mm sheet of low-iron glass the application of the coating increases the colour shift index from 0.34 to 0.51, while the application of a coating to a 2 mm ordinary glass substrate decreases the index from 1.04 to 0.81. One exception is the Viratec Tru-Vue Museum Glass™, which gives a rather higher colour shift index (2.50) due, perhaps, to the coatings used to give this material its ultra-violet rejecting properties.

The colour shift indices for laminated glasses are determined by the combined effects of tints in the glass and in the interlayer, but it would seem from the data in the Table that the, usually yellow, coloration of the laminate is the more important factor in determining the overall colour shift index. For example, the Noviflex laminated glass which comprises two 2 mm thick sheets of low-iron glass and a 2 mm thick laminate has a higher colour shift than the 5 mm sheet of low-iron glass. Laminated glasses which have better ultra-violet absorption properties tend to have a higher colour shift due to the increased yellowness of the interlayer.

Ultra-violet absorption

The ability of each of the glazing materials studied to exclude ultra-violet radiation was assessed using the transmittance spectra. The Table gives the wavelength at which the glazing material transmits 50% of incident radiation; the figures are normalised to a

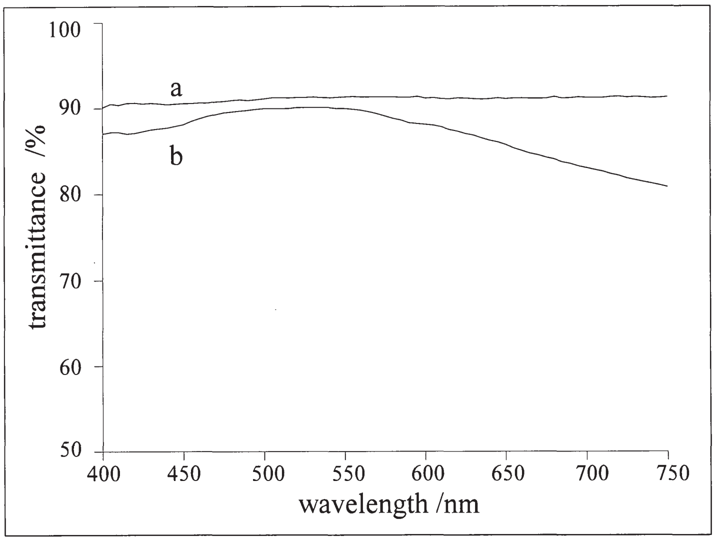

Fig. 3 Transmittance spectra for a low-iron float glass (a) and an ordinary float glass (b). Both spectra are for sheets of 5 mm thickness with low-reflective coatings.

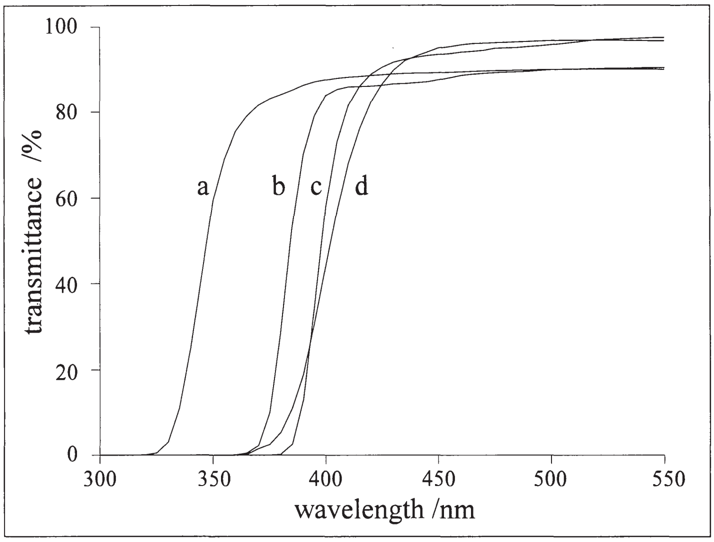

Fig. 4 Transmittance spectra for 5 mm uncoated low-iron float glass (a), Noviflex low-iron laminate (b), Rankin low-iron laminate (c) and Viratec Tru-Vue glass (d).

transmittance of 100% at 550 nm.[6] It can be seen that the first five materials, which are single glass layers, have cut-offs in the range 327–347 nm. The Tru-Vue glass, which has a modified surface coating as described previously, has a cut-off at 402 nm, while the laminated glasses have values in the region 373–398 nm. The transmittance spectra of selected glazing materials are shown in Fig. 4.

It is clear that some of the materials tested offer a degree of protection from ultra-violet radiation, although none meets the general specification for an ultra-violet filter.[6] To quantify the protection provided more fully, the ultra-violet content of light transmitted by each glazing material was calculated. A standard tungsten lamp, which has an ultra-violet content of 75 μW lumen^{-1}, was used as a reference source. The ultra-violet content of tungsten light after it has passed through each of the filter materials is given in the final column of the Table. The ultra-violet content is reduced by all the glasses. In general, the ultra-violet content is linked to the cut-off wavelength. Slight differences may be due to differences in the slope of the cut-off, as for example between the Tru-Vue glass and the Rankin low-iron laminate, see Fig. 4.

Conclusions and recommendations

A number of suitable glasses are available for framing paintings, all of which may be obtained with low-reflective coatings. In one case, the Tru-Vue glass, this low-reflective coating also provides some protection from ultra-violet radiation. Glazing materials which are based on low-iron glass give a lower colour distortion than equivalent solutions using ordinary float glass. Against this improved performance must be set the higher cost of the low-iron glass.

To provide adequate protection for paintings without a prohibitive increase in weight, it is necessary to employ a laminated glass. The thickness of both glass and interlayer can be tailored to the specific needs of the painting to be framed. Most interlayers provide reasonable protection from ultra-violet radiation. If this is an important consideration, further ultra-violet absorbing materials can be added to the interlayer during production. It is likely, however, that this will increase the yellowness of the laminated glass.

It should be borne in mind that while glazing a painting provides some protection from pollutants and the environment, measures should be taken to ensure that a microclimate does not develop within the frame, by providing adequate ventilation or by including suitable humidity buffering material within the frame.[7]

At present, our first choice for glazing paintings would be a low-iron laminated glass with low-reflective coating. There are limits to the sizes of these laminated glasses and their cost is high. A second choice, which is less expensive and available in larger sizes, would be an ordinary glass laminate with low-reflective coating. Less expensive still is a single sheet of low-reflective ordinary glass, although this would not be considered suitable for glazing a painting for loan. Lastly, a sheet of uncoated acrylic or polycarbonate might be used.

In the future it is hoped that the production of plastics with low-reflective coatings will become viable. A small sample of low-reflective polycarbonate sheet tested some years ago showed excellent colour, ultra-violet absorbing and strength to weight ratio properties, and was also treated with a scratch-resistant coating.

Notes and references

1. S. Hackney, 'Framing for Protection', *Environmental Monitoring and Control: Preprints of the Dundee Symposium*, 1989, pp. 91–3.
2. B. Heimberg, 'Säureansschlag auf drei Dürer-Werke in der Alten Pinakothek: Zustandsbefund, Konsievierung und Restaurierung', *Bayerische Staatsgemäldesammlungen Jahresbericht 1987–88*, pp. 10–16 and A. Burmester and J. Koller, 'Säureansschlag auf drei Dürer-Werke in der Alten Pinakothek: Schadensbeschreibung und Wege zur Konsievierung aus naturwissenschaftlicher Sicht', op. cit., pp. 18–24.
3. G. Thomson, *The Museum Environment*, 2nd edn., Butterworths, London 1986, pp. 268–9.
4. The use of thin metal oxide coats to reduce the ultra-violet emission of light sources within the museum is discussed in D. Saunders,'Ultra-Violet Filters for Artificial Light Sources', *National Gallery Technical Bulletin*, 13, 1989, pp. 61–8.
5. Commission Internationale de l'Eclairage, 'Method of measuring and specifying colour rendering properties of light sources', *CIE Publication No.13.2,* 2nd edn., 1974.
6. 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 320 and 380nm and a transmittance of less than 50% of the reference at 400nm. See G. Thomson, op. cit., pp. 16–19.
7. The use of silica gel, or related materials, to provide relative humidity buffering within glazed picture frames is described in S. Edmunds, 'A microclimate box for a panel painting fitted within a frame', *Conservation Today: preprints for the UKIC 30th anniversary conference*, ed. V. Todd, London 1988, pp. 50–3, and M. Cassar, 'A microclimate within a frame for a portrait hung in a public place', *idem*, pp. 46–9.

Appendix 1: Suppliers for glass types listed in the Table

Noviflex Glass
Sloterweg 720
1066 CN Amsterdam
Netherlands
Telephone 3120 614 2525
Telefax 3120 615 3664
(Noviflex laminated glasses)

Rankin Glass Company Ltd
The London Glass Centre
24–34 Pearson St
London E2 8JD
UK
Telephone 071 729 4200
Telefax 071 729 7135
(suppliers of Amiran, Mirogard and Rankin laminated glass)

Schott Glass (UK) Ltd
Drummond Road
Stafford ST16 3EL
UK
Telephone 0785 223166
Telefax 0785 223522
(Amiran, Mirogard)

Viratec Tru-Vue Inc.
1315 N. North Branch St
Chicago IL 60622
USA
Telephone 1312 943 4200
Telefax 1312 943 2938
(Tru-Vue Museum Glass)

Appendix 2: Derivation of the colour shift index

First the CIE L*, a* and b* values for the eight colours defined by the CIE for the calculation of colour rendering indices[5] are calculated under a reference illuminant, in this case CIE illuminant A. The spectral power distribution of the reference illuminant is then multiplied by the transmittance of the glass layer twice. The resulting spectral power distribution is renormalised to 100 at 560 nm and then used to calculate a second set of CIE L*, a* and b* values for the eight reference colours.

For each of the eight colours the difference between the a* and b* values under the reference illuminant and under the illuminant after it has passed through the glazing is calculated according to the equation:

$$\textit{colour shift} = \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2}$$

The colour shift index is the average for the eight colours. The change in lightness (ΔL^*) is thus excluded, as it is deemed to be dependent on the strength of the illumination rather than its colour properties.

Appendix 3 (added at proof stage)

A sample of low-reflective laminated glass comprising two 1 mm sheets of ordinary glass and a 0.38 mm PVB interlayer was supplied by Romag Glass Products Ltd, Patterson St, Blaydon on Tyne, Tyne and Wear NE21 5SG. This material is extremely light, with a mass of 5.8 kg m^{-2}, and has good ultra-violet absorbing properties; the 50% cut-off wavelength is 391 nm and the ultra-violet content for CIE illuminant A after passing through the glass is 13 μW $lumen^{-1}$. The one drawback with this laminated glass is that it has a slight yellow tint, with a colour shift index of 2.13. Although the manufacturer can laminate low-iron glass, the minimum thickness would be greater and the weight would increase accordingly.