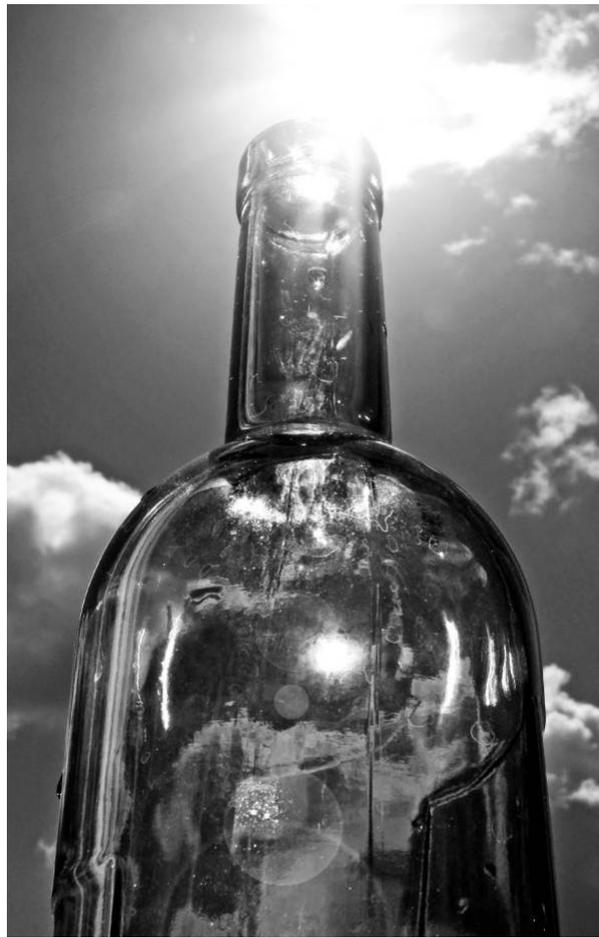


The Effect of Ultraviolet Light on Wine Quality



Glass offers wine some protection from ultraviolet light that can affect wine quality. The correct choice of glass colour and modifications to glass composition or glass coatings can further enhance the protection of the wine.

WRAP helps individuals, businesses and local authorities to reduce waste and recycle more, making better use of resources and helping to tackle climate change.

Written by: Andy Hartley



Front cover photography: Empty wine bottle with sunlight passing through.

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Executive summary

This report has been prepared as part of the WRAP-funded GlassRite suite of projects which are intended to reduce the volume of packaging entering the UK waste stream. The GlassRite projects aim to encourage the lightweighting of glass containers as a means of reducing the tonnage of glass in the waste stream. The GlassRite Wine project has the additional objectives of seeking to promote the bulk importation of wine into the UK to be filled in lightweighted bottles and also to encourage importers of bottled wine to consider the use of clear glass.

Filling wine in clear and/or lighter, thinner bottles has implications for its quality, as the bottle will offer less protection to the detrimental effects of light and this could be perceived as a barrier to the adoption of lighter or clear bottles for use in the wine trade. This report seeks to address this barrier by presenting information relating to the effects of light on wine and the changes that can be made to glass compositions to modify optical properties. Whilst the report is able to offer precise information on the critical wavelengths that affect wine and the filtering abilities of various glasses, it is limited in its practical interpretation by the considerable variation in light exposure experienced between different products. By necessity the GlassRite Wine project is focused on the high volume, entry-level market for wine, much of which spends most of its life boxed in cardboard packaging seeing little light until it is unpacked and displayed on the retailers' shelves. The report thus informs on technical opportunities but requires interpretation as to the applicability to any given product.

Wine makers are aware of the chemistry whereby light can damage their product and the topic has been well researched and documented. Glassmakers are aware of the optical transmission properties of their material and how it can be modified to block specific wavelengths of light. This report seeks to aid the development of lighter wine bottles with improved light-filtering properties by providing technical information on how light interacts with both glass and wine. The report is thus primarily intended for those members of the wine industry involved in decisions on changes to packaging format and who require technical information. The report informs those involved in specifying packaging of the opportunities that exist to improve the light-protecting properties of glass bottles at the manufacturing stage. The report will also help the glassmakers to meet the needs of the wine industry by providing context to the technical challenges that so-called "light-strike" presents to wine makers.

Of specific use to the glassmakers is a mathematical tool that has been created through the project, which enables users to model the light-filtering effects of glass batch modifications. The tool, produced to run in an Excel format, has been refined for use with wine by applying weightings to those wavelengths known to be injurious to wine. The predictive tool will be made freely available to interested parties as part of the GlassRite Wine project.

This report is concerned with the detrimental effects on wine from light and, in particular, the short wavelength portion of the spectrum which is known to be particularly harmful to wine stability. It provides an understanding of the mechanisms through which light can damage and prematurely age wine, and gives some details as to the remedial action that can be taken to mitigate these effects by modifying the packaging.

Wine makers have long known that light can damage their product. The simplest - and most effective - solution would be to sell wine in opaque containers. However, when other issues including customer appeal are considered, glass has become the material of choice for the majority of wines sold.

Glass does afford some measure of protection against light with amber (brown) bottles offering near total protection against ultraviolet light and good protection in the visible region. However, despite its excellent light-blocking credentials amber glass is not the winemakers' usual choice. Green glass is the most common format for wine bottles and significant quantities of wines are now also being filled in clear bottles. The lack of customer complaints would suggest that for wines best drunk young these more transparent glass colours do provide adequate protection.

The evidence gathered in this report clearly shows a simple hierarchy of effectiveness with amber glass typically able to block 90% of all harmful light whilst green and clear glasses block only 50% and 10% respectively.

The mechanism of light-strike on wine is complex but now well understood. Essentially, light at short wavelengths in the ultraviolet and blue end of the spectrum is able to initiate chemical reactions within the wines which produce unpleasantly tasting and smelling compounds.

Some wines are more susceptible to degradation by light than others. Tannins are natural inhibitors of the light-strike reactions and, whilst they are present in most wines, they typically occur in higher concentrations in red wines.

Light-strike damage will occur under normal artificial lighting and this may be the principal mode of exposure for many wines. Artificial lighting can produce a discernable change in wine bottled in clear glass within a few hours. In-store measures relating to the intensity and direction of lighting can be taken which will reduce damage and so increase shelf life. Depending on the lifecycle of the product, these may be a more effective means of reducing light-strike than applying modifications to the packaging.

A narrow range of wavelengths is responsible for these adverse reactions and this raises the possibility of modifying the glass to 'filter out' the harmful wavelengths without resorting to amber bottles. Wavelengths of 340, 380 and 440 nm are most commonly cited as being critical to producing light-strike reactions. As some of these wavelengths are in the visible part of the spectrum, a completely transparent product that blocks out all harmful radiation would thus not seem technically feasible.

Glass technologists are aware of many minerals that can be added to a standard glass to improve its light-blocking properties. Unfortunately, the use of many of these materials imparts a strong colour to the glass. Producing a clear glass with good protection is a technical challenge. Currently, cerium oxide offers the best route but large additions would be required to achieve comparable protection to an amber glass and the cost would be high. A more cost-effective solution may be found by using smaller amounts of different additives whose combined effects can provide wider spectral cover.

Coatings could be used to protect the wine. The coatings could be sprayed and baked onto the bottle and a number of companies market such products which can be tailored to filter out specific wavelengths. Coating technology could be combined with lightweighting, and the production of a very thin-walled glass bottle having good strength and light-blocking properties is considered technically feasible. Such coatings could be applied in the form of a sleeve. Sleeving is already a common practice in the beverage industry usually done for marketing purposes for higher valued items such as premium beers and lagers. Existing sleeves will offer some improved light protection and producing them to give specific protection would again be technically feasible.

Coatings and sleeveings do however represent an additional cost. The practice is commonplace in the premium beer and larger market where price is less of an issue, but with low profit margins on the entry-level wines the additional cost would become a major issue and the sleeves may also cause a problem with recycling.

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1.0 Introduction

This report seeks to provide those involved in the purchase and specification of wine bottles with information relating the effects of light on wine and the influence that the wine bottle can have in avoiding or minimising any detrimental effects. Wine is predominantly filled in glass bottles and anecdotal evidence suggests that the reported incidence of wines sold in the UK that are spoiled as a result of exposure to light is very low. However, the technical evidence suggests that wine bottled in clear or even green glass is susceptible to some degree of spoilage. The GlassRite Wine project has the dual objectives of encouraging fillers to use lighter weight, thinner bottles and to consider a switch to clear bottles where appropriate. This report seeks to investigate if the use of thinner bottles and/or a switch to clear glass will lead to an increase in the incidence of light spoilt wines. The report gives an overview of the mechanisms through which light can impair wine, the current protection offered by various glass colours, and some indication of how this protection can be improved if required.

Light is a form of radiation which conveys energy. Light at shorter wavelengths, which include the ultraviolet and blue portion of the spectrum, carries more energy than the longer wavelengths found in the red portion of the spectrum. These more energetic parts of the spectrum can damage wine. The processes involved are complex; the high energy, short wavelengths of ultraviolet (UV) light able to cause damage in their own right with even "visible" light at the blue end of the spectrum able to trigger some unwelcome chemical reactions. Generally light activates chemical reactions of the sulphurous compounds which naturally occur in wine. The result of these reactions is to prematurely age the wine by producing so called "light-struck" flavours and aromas.

Glass wine bottles do provide some protection from UV and visible light radiation with the darker amber glasses offering much better protection than their clear counterparts. Green glass offers only intermediate protection but despite this fact, wine is still most commonly filled in these coloured bottles. Winemaking and bottling predates our knowledge of electromagnetic radiation by several centuries; historically green bottles would simply have been the easiest to produce in relatively large quantities.

The effects of light on wine have been known in empirical terms from an early stage but it is only with the advent of sensitive analytical instruments that we have begun to understand the actual mechanism of the reactions.

This paper gives details of the chemical processes that contribute to light-strike and considers how the choice of glass can reduce these effects. It also considers how glass could be modified to improve its light-protecting properties or how the protection of existing bottles could be enhanced by the application of an outer sleeve or coating.

A mathematical tool has also been developed under the auspices of this project, specifically for use by glassmakers. The tool will enable users to model the UV blocking properties of various glass additives and takes into account the key absorptions for the riboflavin excitation process which has been identified by many workers as the critical mechanism in the light-strike process. This report provides details of the tool and includes screen shots of the input and output pages.

2.0 Understanding Light

2.1 The electromagnetic spectrum

Visible light spans a range of waves from approximately 400 to 750 nm (nanometre: 1 nm being 1 millionth of 1 millimetre). Within this range fall all the colours of the rainbow from red to violet. Infrared (from the Latin infra, below) and ultraviolet (from the Latin ultra, beyond) sit either side of the visible spectrum. Radiation at shorter wavelengths carries more energy and thus potentially can be more harmful.

In the context of wine quality it is the blue end of the visible spectrum and, more importantly, the ultraviolet regions that are of interest. Figure 1 below shows the electromagnetic spectrum up to the visible region.

Figure 1 The Electromagnetic Spectrum.



2.2 The Optical Properties of Glass

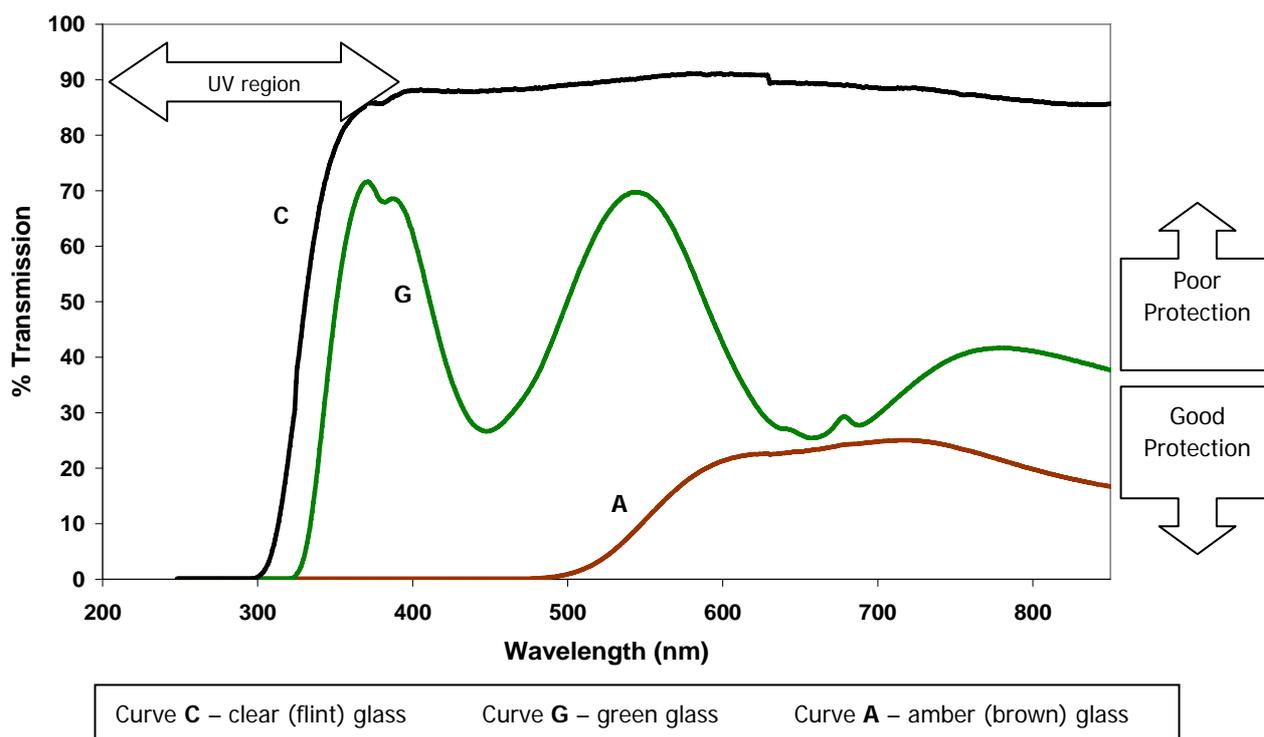
Glass has many properties that make it a valued material. However, above all it is its optical properties that set glass apart from other materials. The transparency of clear glass is simply due to the fact that it allows all wavelengths of visible light to pass. This property is used by merchants to display their products to best effect. Spirit and cosmetic manufacturers will pay a premium for very pure “flint” glass to enhance their product’s appeal.

Wine sellers, however, have somewhat different considerations. Firstly, wines come in a range of colours and hues. The appearance of some of these wines benefits from a clear bottle - rosé being a prime example. However, many white wines look somewhat insipid in clear glass and are best displayed in coloured bottles. Fortunately, glass can easily be produced in a wide range of colours at little extra cost and with no loss in its food contact properties.

The winemaker has, however, another consideration with regard to packaging; his product can be tainted by light. Short wavelength ultraviolet (UV) light can cause damage in its own right but even visible light at the blue end of the spectrum can trigger some unwelcome chemical reactions which release sulphurous compounds within the wine and can impart an unpleasant taste.

The critical part of the UV wavelength spectrum runs from 200 to around 400 nm. Clear glass is obviously transparent to visible light, and fortunately this transparency does not extend into the full range of the ultraviolet region of the spectrum. Figure 2 shows that up to 300nm, glasses of all colours effectively stop all UV radiation. The graph shows the wavelengths at which various coloured glasses (**C**lear, **G**reen and **A**mber) are transparent to light, including UV radiation.

Figure 2 UV to visible light transmission of clear, green and amber glasses as measured by GTS.



The protection offered by clear glass falls off steeply towards the upper region of the UV spectrum, giving poor protection at some critical wavelengths. Clear glass allows around 90% of light with a wavelength of 350nm to pass. Green glass gives better protection than clear but at 370nm it still allows about 70% of light to pass. By contrast, amber glass gives excellent protection over the full UV spectrum and even well into the visible region.

The protection afforded by clear glass is seen to diminish rapidly at wavelengths longer than 300nm. Green glass, the traditional choice of the wine maker, is seen to provide intermediate protection between clear and amber glasses. The curves also demonstrate the excellent filtering properties of amber glass.

Table 1 gives a summary of the spectral data used to plot the curves in Figure 2 in simple values showing the average protection to UV radiation given by the principal glass colours.

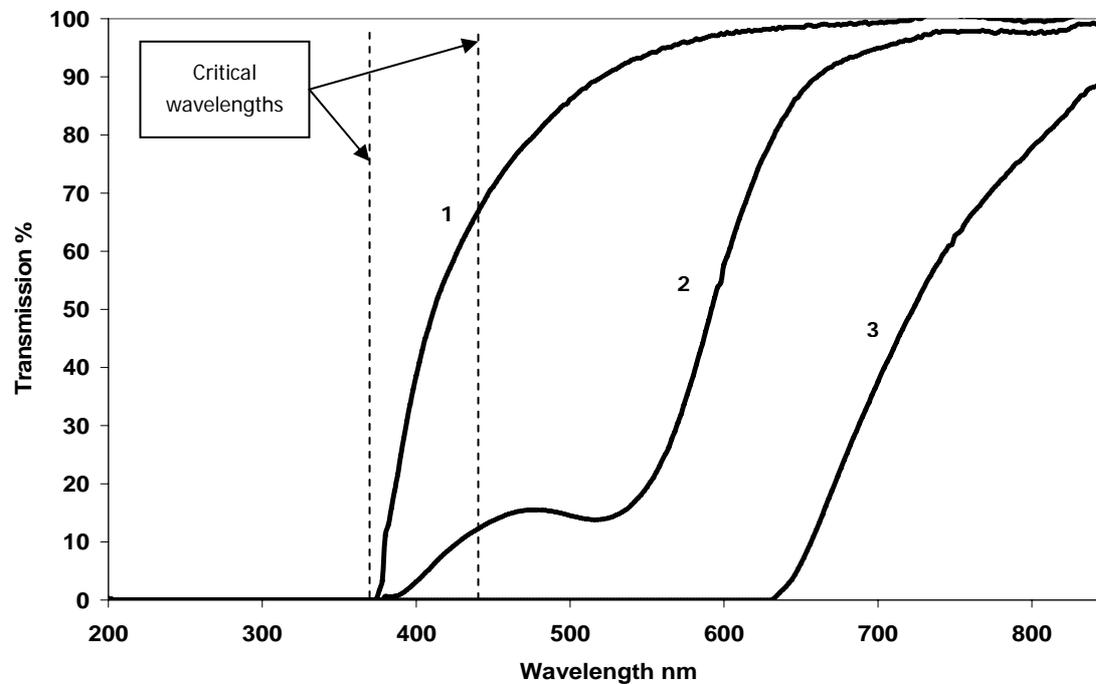
Table 1 UV Light Protection and Glass Colour.

Glass Colour	Clear	Green	Dark Amber	Light Amber
% Total UV stopped	66.9	79.2	99.9	97.4

2.3 The Optical Properties of Wine

For light to damage wine it must first pass through the bottle, so the glass transmission properties shown in Figure 2 are important. Having passed through the bottle the concern now shifts to those wavelengths that are absorbed by that wine. Figure 3 shows transmission curves measured by GTS for the three most common wines; white (curve 1), rosé (curve 2), and red (curve 3). It can be seen that up to wavelengths of around 380nm any wine will absorb all the UV radiation to which it is exposed.

Figure 3 UV to visible light transmission of white (1), rosé (2) and red (3) wines.



As would be expected, white wine allows the passage of most of the visible light whilst the rosés and red wines tend to absorb at the shorter wavelength end of the visual range (the blues, greens and oranges) allowing only the redder colours to pass. All the wines absorb strongly in the upper end of the UV spectrum. Wavelengths of 375 and 440nm have been identified as critical in promoting harmful reactions. All the wines absorb strongly at 375 nm. At 440 nm, which lies in the visible region, only the red and rosé display strong absorption whilst the white wine is seen to allow approximately 70% of this light to pass.

3.0 The Interaction of Light and Wine

3.1 Theoretical Basis of Light-Struck Reactions

Exposure of wine to light results in what is known as light-struck flavours and aromas. These are produced by the initiation of chemical reactions in the wines, resulting in the formation of sulphurous compounds with an unpleasant smell and taste. The reactions can occur within minutes of exposure to light and a tiny amount of the sulphurous compounds can impart a noticeable (bad) taste and aroma to a wine. Much research into the subject has been undertaken but perhaps the most comprehensive has been by Maujean^[1,2,3] working at the University of Reims in the heart of the Champagne region. Maujean's work focussed on the effect of light on champagne. The key reaction was found to be between sulphur-containing amino acids, such as methionine and cysteine, and photochemical activators such as riboflavin (B2) or pantothenic acid (B5), all of which naturally occur in the wine.

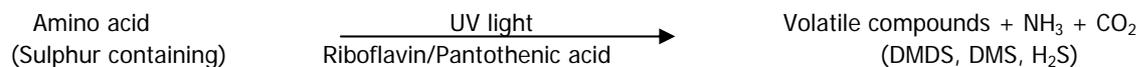
¹ Maujean, A., Haye, C., and Feuillat, M., Contribution on the study of light flavour defects in Champagne. Influence of light on oxidation/reduction potential. Correlation with contents of thiols in the wine, *Connaissance de la Vigne et du Vin.*, 12, (4), p277-290, 1978.

² Maujean, A. and Seguin, Sunlight flavours in Champagne wines. 3- Photochemical reactions responsible for sunlight flavours in Champagne wine, *N., Sci. Aliment.*, 3, p589-601, 1983.

³ Maujean, A. and Seguin, Sunlight flavours in Champagne wines. Study of an oenological solution to prevent sunlight flavour, *N., Sci. Aliment.*, 3, p603-613, 1983.

Catalysed by UV radiation, these complex compounds react to form volatile compounds such as dimethylsulphide (DMS), dimethyldisulphide (DMDS), and hydrogen sulphide (H₂S). Once produced, these volatile compounds give the wine an odour and taste which the average palate can detect at extremely low levels and which is usually perceived as unpleasant.

The reaction can be expressed as below:



The riboflavin molecule was found to be temporarily placed in a more energetic (excited) state by UV and visible light at a wavelengths of 375nm and 440nm respectively. Normal sunlight contains both these wavelengths and is thus capable of exciting the riboflavin. Maujean found that when the excited riboflavin reverted back to its normal (unexcited) state it transferred its excess energy to other constituents of the wine, causing the amino acids to oxidise, degrade and produce the volatile sulphide compounds.

Wine naturally contains between 1g/l and 4g/l of cysteine and methionine amino acids. The light-catalysed reactions with riboflavin form hydrogen sulphides and the more complex, but equally unpleasant, sulphurous chemicals called mercaptans; notably 3-methyl-2-butene-1-thiol (MBT). MBT is responsible for the skunky odours, smelling pungently and variously described as leek, onion, cooked cabbage, wet wool or soy^[4].

Some natural constituents of wine act to prevent the odours and flavours associated with light degradation. Work by Kolb et al⁵ showed that phenols, which occur in both white and red wines, gave such protection. White wine generally has a lower phenolic content than red and thus has less natural protection against light than red wine. Tannins are a particularly effective phenolic compound with respect to light protection and are present in dark grape skins. Red wines naturally have higher phenolic content, due to the dark coloured grape skins, and this helps to explain why, despite having a higher riboflavin and pantothenic acid content, they are less susceptible to light-struck flavours than white wines.

3.2 Experimental Studies into Factors Influencing Wine Quality

As the GlassRite Wine project is seeking to have a significant impact on the volume of glass that enters the waste stream, it is by necessity focused on the high volume entry level market for wine. As much of this wine is boxed in cardboard packaging soon after filling, to be transported in sealed containers to the UK, it may not have had much exposure to light until it is unpacked and displayed on the retailer's shelves. Consequently much of this technical review concentrates on the influences of artificial lighting in stores and on wine storage conditions

Collectively, the wine industry funds an extensive research and development programme aimed at improving the quality of its product, and a great deal of information has been published and is now publicly available. The effects of light on wine quality are the subject of two reviews by recognised experts. The first is by Emond^[6] from Campden and Chorleywood Food Research Association (CCFRA), which provides a good review of scientific papers, while the second is a short article by Easton^[7] that discusses the experiences and practices of winemakers, brand owners and supermarkets.

A sensory study by Dozon and Noble^[4] investigated the effect of fluorescent lighting on sparkling and still wine. Bottles were placed 35 centimetres away from two 40 watt fluorescent lamps in a room at a constant temperature, and were exposed to the lighting for 0, 24 and 72 hours. Fluorescent lighting emits UV radiation and the results showed an increase in measured sulphur compounds in the wine, leading to odours described as "cooked cabbage" and "wet dog". Still and sparkling wines bottled in clear glass showed an appreciable increase in aroma after just 3.4 and 3.3 hours respectively. In the green bottles, comparable aromas were detected only

⁴ Dozon, N. and Noble, A., *Sensory study of the effect of fluorescent light on a sparkling wine and its base wine*, *Am J. Enol. Vitric.*, 4, p265-271, 1989.

⁵ Kolb, C., Kopecky, J., Riederer, M., and Pfundel, E. *UV screening by phenolics in berries of grapevine*, *Functional Plant Biology*, 30, (12), p1177-1186, 2003.

⁶ Emond, S, *Literature search on the effect of light on the quality of wine*, Report No: PPD/REP/60772, CCFRA Technology LTD, Chipping Campden, UK, 2001.

⁷ Easton. S., *Blighted by the lights?*, *Harpers*, , 25-27, 17th March 2006.

after longer periods of 18 and 31 hours respectively. Dozon concluded that white wine is extremely sensitive to light and should not be bottled in clear glass, unless a UV-screening agent is used.

The Australian Wine Research Institute conducted a similar trial comparing coated and non-coated bottles. A Chardonnay wine was held for 21 days at 500mm from a UV light emitting source at 360nm. Subsequent tests, using a range of standard quality indices, revealed that the wine in the coated bottles gave better results in most categories including those for freshness and for fruit characters.

As artificial shop-lighting is often the principal source of light exposure for many wines, several researchers have sought to simulate the effect of this lighting on wine quality. MacPherson^[8] ran an accelerated test for 200 and 500 hours using fluorescent lighting which replicated normal shop lighting on white, rosé and red wine bottled in various colours of bottles. All wines suffered a loss in quality, the white wine having deteriorated more than the red. Amber bottles were found to give better protection than the green and clear bottles.

A study by Majeau^[1] simulated the light conditions normally encountered on the top shelf of a supermarket and found that white wine and Champagne in clear bottles suffered deterioration. Majeau exposed the white wines to light from a 30 W tube at a distance of 350mm. He applied filters to remove light at wavelengths thought to be damaging; namely <340, <380, <441 and <523nm. Changes in wine quality were determined by the measurement of the wine's redox potential, which gives an indication of oxygen content of the wine. The wines in clear bottles all displayed a much larger change in this redox quality indicator than did the other coloured bottles. Majeau found that complete protection could only be achieved by filtering out all light up to the 523nm wavelength. Although the test conditions were harsh they were felt to be representative of those experienced by wines stored on the top shelf of a typical supermarket.

Emond^[6] in her review speculated that the main difference between Maujeun's and Beech's results was the type of wine, red wines being less affected due to the presence of natural tannins, which prevent the formation of flavours associated with light-degradation, the so called "light struck" or "sun struck" effect. Her review also includes the work done by Beech into the effects of sunlight on wine quality. White and red wines were stored in amber, green and clear bottles in a cabinet with a series of fluorescent tubes which emitted light giving a good approximation to sunlight. These wines were also held at an elevated temperature 26.7°C (80°F). The results, after 10 to 25 weeks exposure, showed that all the samples had significantly changed, with the notable exception of the wine stored in the amber bottles. The study concluded that light had a more significant effect than heat and so, wherever possible, wine should not be stored in direct sunlight.

Emond^[6] highlights the principal wavelengths creating problems in clear and rosé wines as 350 to 500nm with peaks at 370 and 440nm. At these wavelengths riboflavin, which is typically present in concentrations of 0.4mg per litre in wine, is chemically excited. Her review confirms the protective benefits of the high tannin content associated with red wines, explaining that this is due to the fact that when tannins accept the energy released from excited riboflavin reverting to its normal stable chemical state, fewer damaging compounds are produced. Emond also reports that amber glass bottles are able to filter up to 98% of the UV band, whereas comparable dark green glass bottles removed only 63% and clear just 10%. Thus, as regards protection, the Beech and the Emond studies are in agreement that only amber bottles provide good protection against the light-struck type of spoiling.

The research shows that whilst there may not be complete unanimity as to the chemical mechanisms of light-strike, collectively the weight of evidence points to the importance of certain wavelengths of light in the light-strike mechanism and to a hierarchy of effectiveness of glass colours in their ability to filter out these wavelengths. If artificial lighting is the principal source of exposure, the option of applying filters around light fittings rather than modifying the bottles should be considered.

3.3 Effect of Bottle Shape and Direction of Light

Not all the light that falls on a bottle is absorbed; some is reflected. The relative proportions of light that are reflected and absorbed are dependent on several factors which include the direction of the light and the shape of the bottle. Some work on this topic has been done for the beer industry and has relevance to wine. Taylor⁹ developed a test method to measure light transmission through beer bottles, and showed that when lit from above, long bottle necks and a shallow angle on the bottle shoulder are significantly more effective in protecting

⁸ MacPherson. C., *Seventh Wine Subject Day on Shelf Life, Long Ashton Research Station, 1982.*

⁹ *American Society of Brewing Chemistry [unable to find full reference]*

the beer from being light-struck than a short neck or sharp shoulder angle. The proportion of light reflected i.e. not able to cause tainting of the beer, increased rapidly with angles of incidence greater than approximately 50° to 60° and reached 100% for grazing incidence.

3.4 Summary of Technical Evidence

The technical evidence provided by researchers into wine quality clearly indicates that a relative short exposure to light, including the normal form of artificial illumination used by retailers, is sufficient to damage wine. The researchers have identified a few specific wavelengths which are of particular importance and have provided evidence that amber and to a lesser extent green bottles are able to reduce the harmful effects. The main findings of the research are listed below:

- sulphurous compounds are an integral constituent of wine which under certain circumstances will breakdown into smaller constituents, some of which have an extremely unpleasant smell and taste;
- UV radiation in particular and, to a lesser extent, visible light promotes (catalyses) these unwanted reactions;
- certain wavelengths are particularly detrimental, raising the possibility of devising specific filters. Critical wavelengths have been identified at 340, 380 and 440 nm;
- wine also contains other chemical compounds which naturally inhibit the light-driven reaction. These inhibiting compounds are commonly associated with tannins which are more prevalent in red wines;
- standard container glass, including the clear variety, will block the very damaging shorter wavelength portion of the UV radiation spectrum;
- glass colour is an important factor in blocking the less energetic but still potentially damaging longer waves which occur at the higher end of the UV spectrum and into the visible region. In relative terms amber glasses afford the best protection, followed by green and then clear glasses;
- conventional fluorescent lighting generates more energy at the shorter wavelengths which include the damaging wavelengths which can produce a detectable change in the wine in a matter of hours;
- where artificial lighting is the principal source of light exposure the option of using special low-UV lighting or applying filters around light fittings rather than modifying the bottles should be considered;
- the location and direction of display lighting is of importance and the bottle's shape can help reduce the damaging effects of such lighting by increasing reflection;
- degradation may become a greater issue as tungsten filament lamps in the home are replaced by fluorescent lights; and,
- the size and positioning of labels can also assist in reducing exposure.

The GlassRite Wine project is seeking to persuade wine makers to consider using lighter weight bottles, which would by necessity, have thinner walls, or even to consider changing from green to clear bottles. The technical evidence presented thus far describes only the mechanism whereby light damages wine, it does not quantify the effects nor offer any method to avoid or minimise them. The following section considers in detail the implications of using thinner bottles and how any lessening in protection can be avoided by realistic changes in glass compositions or by the use of coatings or other technologies.

4.0 Developments in Glass Protection

4.1 An Overview

The ideal glass bottle for use with wines would absorb all natural and artificial light over a wide wavelength range, from the UV region to wavelengths of around 520nm in the visible spectrum. A bottle having these optical properties would have to be thick-walled and very dark in colour.

The evidence from wine researchers identifies 375nm and 440nm as the critical wavelengths that activate riboflavin and promote the reactions causing light-struck flavours. In practice a commercially produced wine bottle will be manufactured with a wall thickness of approximately 2 to 3 mm and thus the glassmaker should be seeking to produce bottles that can absorb these critical wavelengths at the working thickness.

As demonstrated in Figure 2, clear glass provides total protection only up to wavelengths of 300nm, whilst green and amber offer total protection to 320 and 480nm respectively. Therefore the simplest and most cost-effective method to avoid light spoilage is to fill wine in amber coloured bottles. However, many winemakers place their product in green or clear glass but know from experience that their chosen format offers adequate protection.

Irrespective of the bottle's colour, a decision to lightweight the bottle and reduce glass thickness carries the risk of increasing the possibility of light spoilage. Any wine maker considering a change in packaging format must take this factor into consideration. The research work detailed in this report offers a method to quantify the effects of using thinner or even different coloured bottles. The survey of work done on glass chemistry, coatings and sleeving provides a mechanism whereby any loss in light protection due to lightweighting can be mitigated by technically simple solutions.

There are currently two technical approaches to improve the protection that glass containers provide from UV and visible light radiation:

1. adding UV-absorbing species to the glass, to create a UV-absorbing glass chemistry; and,
2. treating the glass surface with a UV-absorbing coating.

The following sections look at the current UV and visible light absorbance of glass containers, before exploring available technological solutions to provide UV protection by modifying the glass chemistry or by applying a coating.

4.2 Current UV and Visible Light Absorption of Glass Containers

In order to compare the filtering abilities of different glasses it is necessary to devise some index or scale. Essentially, any index will represent the area under a typical transmission curve as represented by Figure 2. However, the area calculation must be performed between wavelengths and as these have not been standardised, different workers will use different parameters. For the purposes of this study the method proposed by Pajeau^[10] who developed the concept "filtering power" for measuring the UV absorption has been adopted. Pajeau's method is based on the area below the transmission curve between wavelengths of 300 and 450 nm.

Pajeau defined filtering power (PF) as:

$$PF = \frac{(1 - A) \times 100}{B}$$

Where PF = filtering power, A = area below transmission curve and B = total plot area. Typical values for PF as determined by Pajeau are given in Table 2.

Table 2 Filtering power (PF) of different coloured bottles as determined by Pajeau.

Glass colour	PF %
Amber	99
Oak	94
Champagne	82
Dead leaf	74
Beer green	53
Blue	18 to 28
Clear	18

Filtering power is influenced by the thickness of the glass, but the relationship is not linear and relatively good protection is quickly achieved by quite thin glass. Perscheid^[11] measured various absorption spectra and calculated the filtering power for a (limited) range of glass colours and thicknesses. Perscheid's results are given in Table 3. The relationship of glass filtering power to glass thickness is of considerable importance and is covered in more detail in Section 4.4

¹⁰ Pajeau, G., Agniel, Y., Floriot, P., *Verre d'emballage et protection UV, Verre, 12, 23-27, 2006.*

¹¹ Perschied, M, Zuern, F, Penndorf, G, 1978, Effects of the light transmission characteristics of glass bottles on the quality of wine, *Weinwirtschaft, 114, (18), p496-501, 504, 1978.*

Table 3 Filtering power (PF) as determined by measurements made by Perscheid.

Glass colour	Glass thickness (mm)	PF (%)
Amber	3.5	100
	1.8	95
Green	4.2	93
	3.5	54
Clear	3.0	10

Whilst Pajean's method provides a good method to give a broad comparison of glasses it is not end-user specific. The mathematical modelling tool developed by the University of Sheffield (see section 4.4) under the auspices of this project has been refined and reports the transmissions at the critical wavelengths identified in literature on wine degradation for the riboflavin excitation process.

4.3 UV Absorbing Glass Chemistry

Standard container glass can be modified to change its UV absorption characteristics. Essentially small amounts of various metal oxides which have a large influence on the optical properties can be added to the glass during melting. This section provides an overview of the subject and mentions a few technological solutions.

According to Pajean^[10], elements having a pronounced effect on UV absorption in glass include: cerium, vanadium, manganese, titanium, iron polysulphides and hexavalent chromium. Since some of the wavelengths that are deleterious are in the visible part of the spectrum, a completely transparent product that blocks out all harmful radiation cannot be made, and indeed many of these UV-absorbing species also absorb weakly in the visible range.

Improving the protection offered by clear glass produces the greatest challenge as many of the best candidates are strong colorants. Indeed, the occurrence of a critical "riboflavin" wavelength at 440nm, which is within the visible region, makes it a technical impossibility to remove this wavelength and produce a totally clear glass.

If the filtering power of clear glass is to greatly improved, albeit with some discolouration, then ceria (cerium oxide, CeO₂) is perhaps the best candidate. It can be added to container glasses in the range of 2 to 4 % to give protection from light at the wavelengths that promote chemical activity and taint. Ceria absorbs strongly in the UV region, whilst only affecting the visible region slightly. Ceria is already being added to some UK clear glass batches as a replacement for selenium which acts as a decolouriser. Its limited use as a decolouriser can be justified on economic grounds as selenium is a very expensive batch material. Unfortunately, the large percentage additions of ceria that would be needed to make clear glass with good UV protection would not be economically viable for mass produced containers. However, if ceria were to be added simply to compensate for any loss in protection due to the use of lighter bottles, much smaller quantities would be needed.

Vanadium and titanium also absorb UV radiation. After hexavalent chromium, vanadium (added as vanadium pentoxide, V₂O₅) is the most effective absorber of UV radiation. According to Volf¹² 1 % of V₂O₅ is equivalent to 5 % CeO₂ or 22 to 25 % titania (titanium oxide or TiO₂). Unfortunately, vanadium imparts a green colour to the glass so could not be used in sufficient quantities in clear glass, but could be used to enhance the UV filtering power of green glasses. Cerium, vanadium and manganese oxides have also been successfully used with coloured beer bottles.

Co-doped Glasses

Whilst good UV protection can be achieved by the addition of some single species, the relatively high concentrations required are unlikely ever to be commercially viable for the mass packaging market. However, in some instances the added material can interact with one of the other components of the glass ("co-doping"),

¹² Volf, M. B., *Chemical approach to glass*, Elsevier Science Publishing Company, p322-3, 330-1, 400-1, 1984.

either already present or perhaps specifically added, with the combination then enhancing the UV absorbing powers.

Glass technologists are aware of many combinations of additives that would act in concert but the majority are not viable on the grounds of costs or toxicity. Ceria working in conjunction with titania is perhaps the best combination of candidates to produce a clear glass with enhanced UV absorbing properties¹³, and the subject has been investigated further by workers at University of Sheffield as part of the GlassRite Wine project. The mixture works because the titania acts to reduce the ceria and place it in its Ce³⁺ state which is a far more potent UV absorber than its usual less active Ce⁴⁺ state.

The addition of a ceria/titania mix to a standard clear glass allows the glassmaker to target the upper regions of the UV spectrum without having to introduce unwanted colouration. Figure 4 demonstrates how a 1% addition by mass of a 50:50 mixture has moved the profile to longer wavelengths but has retained the important rapid transition from low to high transmission rates – the so called “sharp edge” which then still allows high transmission levels throughout all the regions of the visible spectrum

Figure 4 The Extension of UV Protection Produced by the addition of a 1% addition of a 50:50 Mixture of Ceria/Titania.

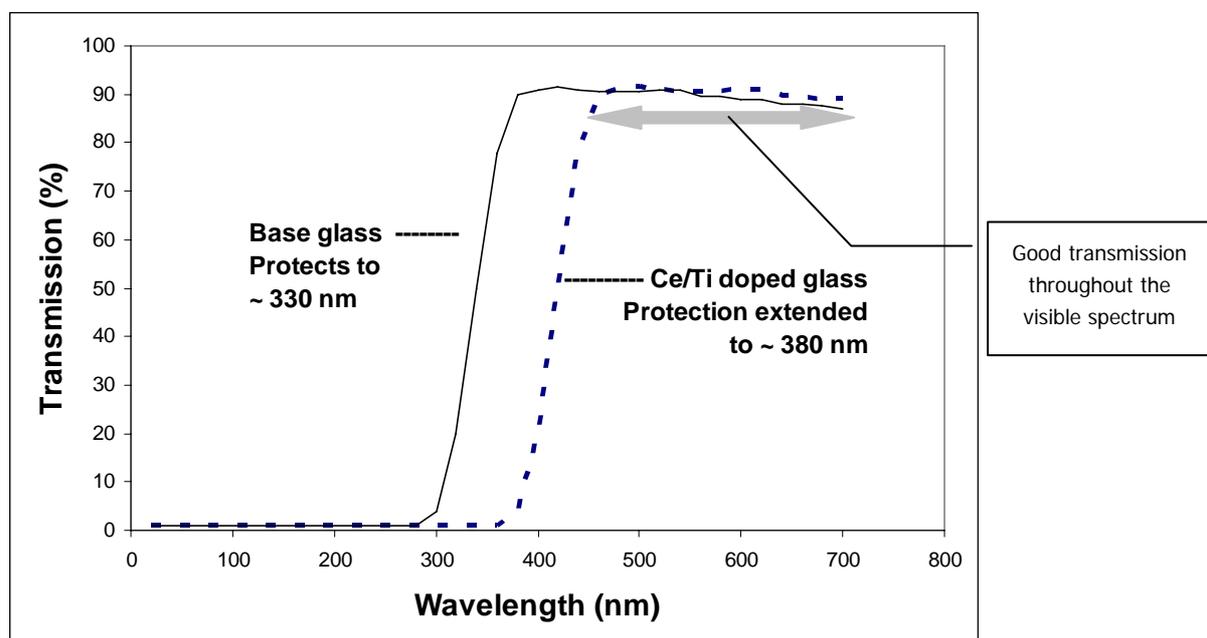


Table 4 below details the results of measurements made by adding various mixtures of ceria and titania to a clear glass. The base glass used in this instance was very pure and thus its initial filtering power was lower than a typical clear container glass. The UV absorption index produced by 1% ceria addition is seen to be almost matched by a 1% addition of a 50:50 mixture of ceria and titania. Titania is however considerably cheaper than ceria so such a mixture may offer an affordable method to improve UV protection for clear glasses. The limited melting trials considered only a 50:50 mixture of ceria and titania and it is possible that greater savings could be made by optimising the mix.

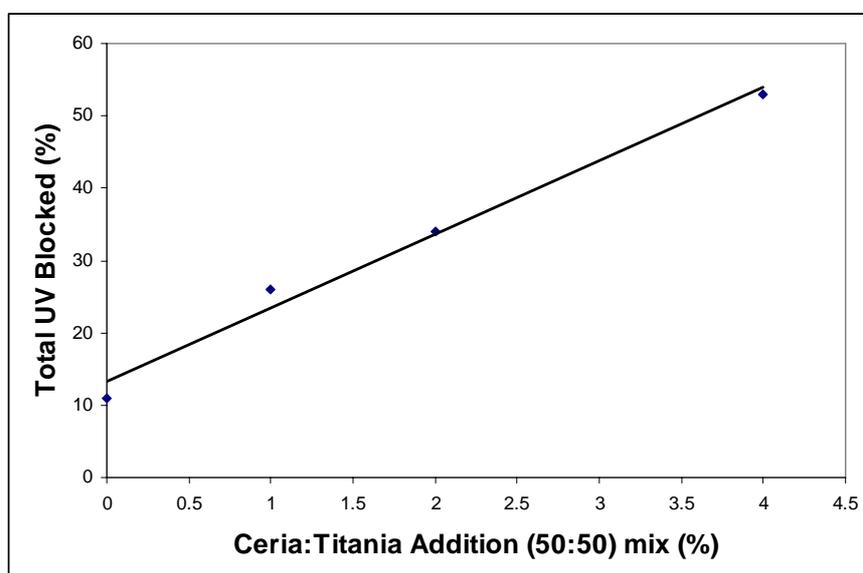
¹³ M A Sainz, A Durán, J M Fernández Navarro, Titanium and cerium colouring in glasses, Glass Tech., **32**, 99, 1999.

Table 4 The effect of ceria and titania mixtures on UV absorption and UV edge.

CeO ₂ wt%	TiO ₂ wt%	UV edge nm (50% transmission)	UV blocking (350 to 450nm)
0	0	334	11%
0	1	352	12%
1	0	384	31%
0.5	0.5	382	26%

The UV blocking properties of 50:50 mixtures of ceria and titania shows a near linear relationship between the level of addition and the amount of total UV blocked (Figure 5). The mixture imparts slight yellowish tinge with 4% addition being that practical maximum addition as past this point the glass becomes distinctly yellow.

Figure 5 Ceria:Titania mixture as a UV Blocking Agent.



High levels of ceria additions would add several £'s to the batch costs which comprise a significant proportion of overall manufacturing costs. However, its addition would have financial implications beyond UV protection which would affect the economic case. The following additional considerations may affect the economic argument and merit further study:

- ceria assists in the decolourisation of iron by oxidation of ferrous ions to ferric; it may be possible to reduce the levels of selenium added to the batch;
- ceria is also reported to assist in refining and so reductions in sulphate content may also be possible;
- the present study has made no attempt to optimise the ceria:titania ratio. Since titania is significantly cheaper than ceria this may offer a further cost saving;
- the consequences of adding ceria and titania on temperature-viscosity relationships, on devitrification and hence on processing temperatures need to be identified; and,
- the long term effect of ceria build-up in the glass stream due to recycling would eventually reduce the batch additions of the material to the melting process.

Clear glasses used for container manufacture invariably contain low levels of iron, higher levels of which tend to impart a greenish tinge to the glass. The iron does however also react with ceria to produce the more potent UV-blocking Ce^{3+} form. This iron/ceria combination at low levels of addition has been examined in more detail using the tool developed by the University of Sheffield and is described in the following section.

4.4 The Development of a Mathematical Modelling Tool

As an aid to glass melters seeking to improve the UV filtering properties of their glass by batch modification, a mathematical tool has been developed within the scope of the GlassRite Wine project. The tool is essentially an Excel-based spreadsheet into which the glassmaker enters the current batch formulation and from which the tool calculates the transmission spectrum of the glass in the region covering the UV and visible spectrum. From the spectrum, the tool calculates the colour co-ordinates of the glass, the filter factor and determines the transmission at key wavelengths. The tool also links optical properties to glass thickness, which is of importance if a move to thinner glass is being considered. Finally the tool incorporates a cost model which enables users to determine the economic viability of any modifications. The tool is an extension of an earlier version developed for Colourite^[14], which enables users to calculate the effect of batch additions to glass colour.

The technical literature review found that the key wavelengths that cause the degradation of wine are not confined to the UV but also extend at least to 440nm which lies in the visible range. The review also found methods of assessing and comparing the protective capacity of different glasses. The tool builds on the method developed by Pajean^[10] which is based on the total transmission in the near UV and blue end of the spectrum (300 to 450nm), measured directly from the transmission spectrum. The new tool incorporates a computerised spectral fitting programme which improves accuracy. Additionally, the tool could easily be developed to take account of the key absorptions for the riboflavin excitation process by applying weightings to the critical wavelengths identified in literature on wine degradation.

One immediate use of the tool is to calculate the effect of the container wall thickness on UV light absorption. Because the UV edges in many clear glasses are steep (see Figure 4), the effect of reducing wall thickness is not linear and is much less than might be anticipated. This is illustrated in Table 5 for a clear glass. In relation to lightweighting, a 20% reduction in bottle weight would not be accompanied by a 20% loss in UV protection. The tool has been used to predict the effects on filtering power of 10% and 20% reductions in wall thickness of a standard clear glass bottle as might have been achieved through a lightweighting programme. The tool demonstrates that a 20% reduction in wall thickness is only accompanied by a 6.7% reduction in filter power.

Table 5 Wall thickness and the UV filtering capacity of a clear glass.

Wall Thickness (mm)	Filtering Factor (%)	Reduction (%)
3.0	30	n/a
2.7	29	3.3
2.4	28	6.7

The tool has been developed to the extent that it includes all the key metal oxides likely to be present in the glass so that it can describe accurately the optical absorption in both the visible and ultraviolet regions of the spectrum. The tool also takes into account the different oxidation states found for the key metal ions. The species modelled include in particular Fe^{2+} , Fe^{3+} , Ce^{3+} and Ce^{4+} but consideration is also given to Ti, Cr, and V in their various oxidation states.

The loss in filtering power due to a thinner wall could be restored by the addition of various additives. The tool can be used to predict how much of a given additive would be required, its cost and its effect on the colour of the base glass, which is of particular importance in the case of clear glasses. Table 6 gives details of the amounts of ceria that would be needed to give the 2.4mm clear glass used in the example above, the same filtering power as the original 3.0mm glass.

¹⁴ Colourite Project – Maximising Cullet Additions in the Glass Container Industry, WRAP Report, March 2006.

Table 6 Improvements in UV filtering power arising from low level Ceria additions.

Wall Thickness (mm)	Filtering Factor (%)	Ceria Addition (ppm)	Batch Cost (£ per tonne)	Colour Coordinates (Red-Green)
3.0	30	0	39.21	-12
2.4	28	0	39.21	-12
2.4	30	6	39.22	-12

As can be seen, an addition of just 6ppm of ceria is sufficient to restore the filtering power lost by a 20% reduction in wall thickness. In this instance the effectiveness of the ceria is enhanced by the presence of iron in the base glass which acts to ensure that most of the ceria present is in the more effective UV-blocking Ce^{3+} ionic state. The additional batch costs at this level of ceria additions are negligible; batch costs are increased by just £0.01 per tonne of glass produced. Although not apparent from the figures in Table 6, the ceria additions would also produce a slightly less green glass as measured on the standard red-green scale used to define glass colour

Adding more ceria improves filtering power but the relationship is not linear and the benefits rapidly diminish at higher levels of addition. In this instance the filtering power would not exceed 48% even at an economically unviable level of 5% ceria addition. Indeed, 50% of the total increase in filter power (to 39%) would be achieved by the addition of just 55ppm of ceria at an additional batch cost of just £0.07 per tonne of glass.

Once the tool has been fully tested and validated it will be made available to glassmakers via the WRAP website (www.wrap.org.uk/retail) and can be used to reassure customers that a move to a lighter bottle will not cause light-related problems. Users will be able to model the light-blocking properties of various additives and the associated batch costs.

The tool may also have wider applications in the food industry as the shelf life of many food products is influenced by light driven reactions. The tool will be available as an Excel spreadsheet, and screen shots details of the input and output pages are provided in Appendix 1.

4.5 UV Absorbing Organic Coatings

An alternative method of providing UV protection is to coat the bottle. Several proprietary products are currently available; many are based on so called “sol-gel” technology in which a thin film is baked onto a surface. Teflon is perhaps the best example of such an approach.

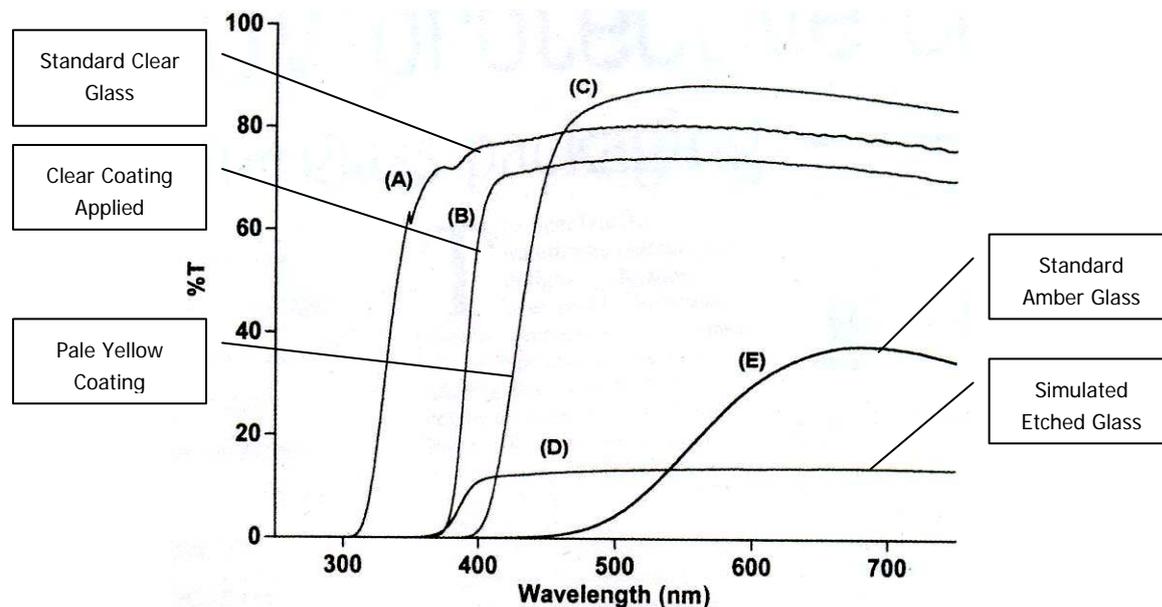
The addition of any coating to a bottle will obviously add to unit costs but the coating could be used to enhance the brand appearance of the product and so could be justified on the grounds of increased sales.

Companies such as Ferro¹⁵ and Deco-Glas¹⁶ produce commercially available organic UV protective coatings. Ferro have developed their SpecTruLite UV blocking organic coating which is able to filter out UV radiation. Various levels of protection can be achieved dependent on the coating applied. Figure 6 is taken from Kapp^[15] and shows the light transmission characteristics of a standard container glass (A) coated with the SpecTruLite products. Curve (B) is opaque to UV light, but at the threshold of the visible region becomes transparent and so produces a clear bottle. Curve (C) blocks out all the UV and some of the visible regions and thus appears pale yellow in colour. Curve D is a simulated etched glass, which will be relatively opaque. Curve E is a commercial amber glass added for comparison.

¹⁵ Kapp, D. C., and Maitland, P. UV protection coatings for glass packaging, *Glass*, March, p58-59, 2003.

¹⁶ Böttger, P., UV protection for container glassware, *Glass Int.*, March, p41, 1989.

Figure 6 Light transmission curves of different commercial glasses.



The benefits of combining organic and inorganic UV absorbers have been explored. Recent work by Mahltig^[17] has found that UV protection can be optimised by such a combination. Commercially available organic absorbers Tinuvin 213TM and SEMA 20613TM were embedded into a titania sol-gel coating and the UV to visible spectrum transmission measured. Although the trial did not achieve complete protection in the UV region it did enable a model to be produced which could allow the design of recipes to give optimum UV protection.

Light-protecting coatings could also be used to strengthen the glass. Garcia-Heras^[18] has studied cerium-silica sol-gel thin films and concluded that such a coating may be able to protect bottle glass from physical damage and, in addition, protect the contents from light-strike.

Pepe et al^[19] have also worked with ceria doped sol-gel coatings. The work determined that ceria showed two main absorbance bands at 320 and 365nm, assigned to Ce³⁺ and Ce⁴⁺ ionic states respectively. Cerium ions do not provide significant absorption below 250nm but normal impurity levels of iron give substantial absorption in this region.

Overall, the results from the studies into cerium are encouraging and they may provide the basis of a coating that would be suitable for protecting wine-bottle glass. Combining ceria with a material that has a good absorption in the 440 to 500nm range to produce a co-doped coating could be one possible solution.

The Pilkington Technology Centre has developed a laminated window glass which incorporates a yellow dye and UV absorber into the polymer interlayer and which blocks all UV light and the more energetic portion of the visible spectrum up to a wavelength of 480nm. The glass was originally developed for a teenage girl from Merseyside who suffered from actinic prurigo, a skin condition that is acutely sensitive to UV light between 280 and 400nm²⁰ but the method could be applied to commercial glass manufacture.

¹⁷ Mahltig, B., Böttcher, H., Rauch, K., Dieckmann, U., Nitsche, R., and Fritz, T., *Optimized UV protecting coatings by combination of organic and inorganic UV absorbers*, *Thin Solid Films*, 485, p108-114, 2005.

¹⁸ Garcia-Heras M, Jimenez-Morales A, Casal B, Galvan, J C, Radzki S, Villegas M A, *Preparation and electrochemical study of cerium-silica sol-gel thin films*, *Jour. of Alloys and Comp.*, Vol. 380, p. 219 – 224, 2004.

¹⁹ Pepe, A, Aparicio, M, Ceré, S, Durán A, *Preparation and characterization of cerium doped silica sol-gel coatings on glass and aluminium substrates*, *Jour. of Non-Cryst. Sol.* Vol 348, p. 162 – 171, 2004.

²⁰ News item, *Glass Technology*, 32, p34, 1991.

4.6 Protective Sleeves

Shrink-sleeve labels have long been used in beer, spirits and food packaging and are being used by such companies as Beringer, E. & J. Gallo and Rosemount Estate wineries in niche areas. The champagne producer Louis Roeder also uses a UV-absorbing cellophane wrapper to protect their premium Cristal product.

Making the sleeves to be a good UV barrier would not be technically difficult. The contents of a sleeved bottle would not necessarily be visible and the practice may not appeal to some wine buyers. However, it could offer good marketing opportunities and brand differentiation.

The use of sleeves would allow the fillers to be less discerning about the bottle colour. Bottles could be produced from glass having a 100% recycled content which conceivably would have a variable colour but could be marketed as an "Eco" glass.

Sleeves may not however be welcomed by the glass reprocessors, as they would mask the colour of the base glass making colour sorting more difficult, and once the sleeve has been separated, it would require disposal or recycling. Coloured sleeves could also confuse the public when visiting the bottle banks and lead them "post" the bottle into the wrong receptacle.

4.7 Summary of Glass Developments

All colours of commonly used container glass block the very damaging short wave ultraviolet radiation. Clear glass and most shades of green glass do however allow the passage of some UV light. Amber glass by contrast affords near-complete protection but, in many instances, it lacks the visual appeal required by the brand owner.

The protection provided by bottles is related to glass thickness and this should be an active consideration when undertaking any lightweighting programme. The relationship between protection and glass thickness is not linear. Reducing the wall thickness of a typical clear glass by 20% would be accompanied by a 7% fall in UV filtering power.

It is technically feasible to modify glass to improve its UV protection by adding certain minerals, but many of the better candidates also discolour the glass. Indeed a clear glass cannot provide complete protection for wine as one of the critical wavelengths leading to light-strike lies within the visible portion of the light spectrum.

Ceria would appear to offer the most promise in the development of a clear glass with good light-protecting properties but its use would add several £'s to batch costs and as such its use is not considered to be an economically viable option. However, ceria can be used in conjunction with titania to improve UV protection at lower, less expensive levels of addition. Work would be required to determine the optimum mixture but this would still add significantly to batch costs.

Very small additions of ceria could be used to compensate for any loss in protection due to the use of thinner bottles. The additions would add little to batch costs. Ceria can also be used as a decolouriser for clear glass as a replacement for the increasingly expensive and scarce selenium that has been the glassmaker's traditional choice for this task.

Other metal oxides that improve light protection include: vanadium, manganese, titanium, iron and chromium. These materials would be used most effectively with green glass and, as with ceria, would prove too expensive to add in large quantities but could be used more sparingly to compensate for thinner bottles.

The mathematical modelling tool developed under the auspices of this project has been designed for use with wine bottles inasmuch as it gives specific consideration to those wavelengths that excite riboflavin, the crucial mechanism for light-strike. The tool allows users to quantify the reduction in light protection resulting from a change in glass thickness. Its other features allow the user to make batch changes and calculate their effect on the optical properties of the glass and, of equal importance, the cost.

Organic coatings that can be tailored to give the desired level of protection are currently available on the market. The addition of any coating to a bottle will obviously add to unit costs but the coating could be part-used to enhance the appearance of the product and so could be justified on the grounds of increased sales.

The standard glass container manufacturing process currently includes a 2-stage coating process. The coating processes give the bottles lubricity to prevent scuffing during filling and in general use. It has however long been the goal of the manufacturers to develop a single stage coating process having additional benefits. Most

development work seems to be directed into producing a lubricious coating that would also improve the strength of containers. The possibility therefore exists that a coating could be developed which would incorporate some UV protection. Ideally a coating could be produced which would enable the production of a lighter, thinner bottle that had better strength and light-protecting properties than its conventional counterpart.

Sleeves are an alternative to coatings and can provide total protection. The practice would open up some marketing opportunities and could enable the bottles to be produced with very high recycled content. Sleeving may however hamper the recycling effort by making the colour sorting process less efficient.

5.0 Conclusions

Wine is damaged by light. Ultraviolet light is particularly harmful but some regions of the visible spectrum can also have a detrimental effect on wine quality. Critical wavelengths have been identified at 340, 380 and 440 nm, the latter being located in the visible region.

The damaging reactions occur rapidly; a detectable loss in quality can occur in a matter of hours.

The fluorescent lighting used in many stores emits the shorter wavelengths that include those known to produce unwanted chemical reactions. Shelves displaying wine should therefore be illuminated with lighting that is free from ultraviolet emissions. Such lighting is commercially available. Where lighting is to be applied from above the shape of the bottle can have an important influence, with bottles having a less pronounced shoulder able to reflect more light.

The reactions that cause the taint involve sulphurous compounds that are an integral constituent of wine which cannot be removed. However, certain constituents of wine, notably tannins, act to inhibit the damaging reactions.

Only amber glass provides good protection for wine against light and is able to block more than 90% of all harmful exposure. Green glass is a less effective blocker able to stop around 50% of damaging light, whilst clear glass affords only 10% protection.

The protective properties of clear and green glasses can be enhanced by the addition of various metal oxides but will never meet that afforded by amber glass. Most of the better candidates to improve protection are strong colorants and all add significantly to batch costs.

Adding combinations of additives which act in concert could conceivably give good protection to clear glass at a reasonable cost and merits more study. The interaction of iron, ceria and titania would appear to offer the most promising route to such a solution.

The relationship between glass thickness and the protection it affords to light protection is not linear. A relatively large reduction in thickness will be accompanied by a much smaller fall in protection.

The small reductions in protection that would arise from the use of thinner glass could easily be restored by the addition of very small quantities of various metals. In the case of clear glass, the addition of less than 10ppm of ceria would be sufficient to compensate for a 20% reduction in wall thickness. Ceria additions are especially effective if small amounts of iron are present in the glass; fortunately most container glass does have some iron present. Thinner green glass could have its protective properties restored by the addition of small quantities of vanadium.

Light protection can be achieved by sleeving the bottles, but as with chemical additives the process adds cost. A fully effective barrier will not be completely transparent as in order to provide full protection part of the visible spectrum must be removed.

A mathematical tool has been developed under the auspices of this project that will enable users to model the UV blocking properties of various glass additives. The model specifically takes into account the key absorptions for the riboflavin excitation process which have been identified by many workers as the crucial mechanism in promoting the light driven reactions that taint wine.

Appendix 1: Screen shots of the Mathematical Modelling Tool

INPUTS			
Glass Thickness	<input type="text" value="2.4"/>	mm	
Addition	g/mix	weight	g/2t sand
Selenium	<input type="text" value="0"/>	<input type="text" value="0.0"/>	
Cobalt		<input type="text" value="0.0"/>	
Ceria	<input type="text" value="20"/>	<input type="text" value="20.0"/>	
Neodymium	<input type="text" value="0"/>	<input type="text" value="0.0"/>	
Erbium	<input type="text" value="0"/>	<input type="text" value="0.0"/>	
Furnace redox factor	<input type="text" value="-10"/>		
Cullet loading	kg/mix	% of mix	% of final glass
internal cullet	<input type="text" value="0"/>	<input type="text" value="0.0"/>	<input type="text" value="0.0"/>
external cullet	<input type="text" value="0"/>	<input type="text" value="0.0"/>	<input type="text" value="0.0"/>
plate cullet	<input type="text" value="0"/>	<input type="text" value="0.0"/>	<input type="text" value="0.0"/>

External cullet quality	
flint %	<input type="text" value="98"/>
green %	<input type="text" value="1.5"/>
amber %	<input type="text" value="0.5"/>
misc %	<input type="text" value="0"/>
moisture %	<input type="text" value="0"/>
organics %	<input type="text" value="0"/>
ferrous metal %	<input type="text" value="0"/>

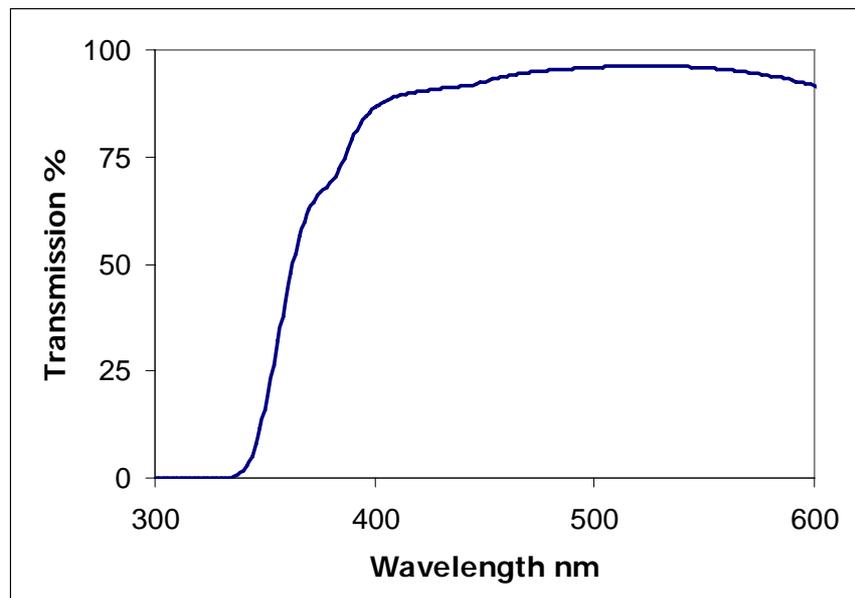
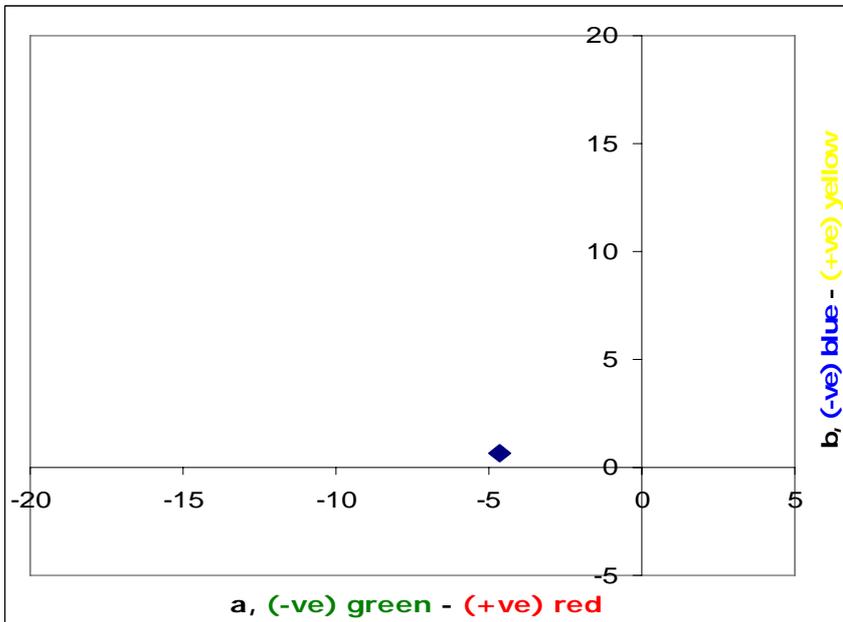
Batch Recipe kg/mix	
Sand	<input type="text" value="2000.00"/>
Soda ash	<input type="text" value="620.00"/>
Limestone	<input type="text" value="480.00"/>
Dolomite	<input type="text" value="115.00"/>
UK dolomite	<input type="text" value="0.00"/>
Neph syenite	<input type="text" value="60.00"/>
Calumite	<input type="text" value="80.00"/>
Salt cake	<input type="text" value="20.00"/>
~	<input type="text" value="0.00"/>
~	<input type="text" value="0.00"/>
~	<input type="text" value="0.00"/>
Sand carbon ppm	<input type="text" value="0.00"/>
selenium	<input type="text" value="0.00"/>
cobalt	<input type="text" value="0.00"/>
ceria	<input type="text" value="0.02"/>
neodymium	<input type="text" value="0.00"/>
erbium	<input type="text" value="0.00"/>
Cost / tonne batch	<input type="text" value="36.56"/>
Batch Redox	<input type="text" value="-2.11"/>

OUTPUTS

Filtering factor	26
Transmission at 375 nm	67
Transmission at 440 nm	91

Batch Fe2O3 %	0.028
Batch Cr2O3 %	0.000

Colour co-ordinates	40	mm
L	98	
a	-5	
b	1	



**Waste & Resources
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