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NOTE

Measuring solar UV radiation with EBT radiochromic film

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Abstract

Ultraviolet radiation dosimetry has been performed with the use of a radiochromic film dosimeter called Gafchromic EBT for solar radiation exposure. The film changes from a clear colour to blue colour when exposed to ultraviolet radiation and results have shown that the colour change is reproducible within ±10% at 5 kJ m^{-2} UV exposure under various conditions of solar radiation. Parameters tested included changes in season (summer versus winter exposure), time of day, as well as sky conditions such as cloudy skies versus clear skies. As the radiochromic films' permanent colour change occurs in the visible wavelengths the film can be analysed with a desktop scanner with the most sensitive channel for analysis being the red component of the signal. Results showed that an exposure of 5 kJ m^{-2} (approximately 1 h exposure in full sun during summer) produced an approximate 0.28 change in the net OD when analysed in reflection mode on the desktop scanner which is significant darkening. The main advantages of this film type, and thus the new EBT2 film which has replaced EBT for measurement of UV exposure, is the visible colour change and thus easy analysis using a desktop scanner, its uniformity in response and its robust physical strength for use in outside exposure situations.

Introduction

Ultraviolet radiation (UV) produced by the sun is becoming more dangerous to people as the earth's ozone layer is thinning, allowing more concentrated ultraviolet rays to hit the earth's

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surface. UV wavelengths are in-between the visible light spectrum and the x-ray spectrum (Diffey 1982). It is emitted from the sun in three main defined wavelengths, UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm). Historically UV-A was defined as the wavelength that causes ‘ageing’ in human skin. UV-B was defined as ‘burning’ and UV-C as ‘cancerous’ (Urbach 1991). Today, it is known that all forms of UV radiation are detrimental to humans causing effects such as skin cancer and degenerative effects for our eyes like cataracts (Diffey 1982). It is important to note that UV radiation can also be produced by artificial sources such as welding machines, tanning beds and lasers.

The current film detectors which have been utilized for the measurement of UV radiation have included polyphenylene oxide film (Schouten *et al* 2007, 2009) and polysulfone film (Parisi *et al* 2004). These types of film detectors have been used to assess the ultraviolet exposure with an action spectrum closely matched to erythemal response, i.e. an immediate reddening response of the skin to UV irradiation. One disadvantage of these films is that the change in colouration occurs in the ultraviolet regions and thus requires a photospectrometer device to measure the colour change. This would make two-dimensional mapping of UV exposure difficult to achieve. Other authors have constructed similar film-type detectors (Abdel Rehim *et al* 1992) with colour changes occurring in the visible wavelengths. Other Gafchromic film products such as MD-55 have been known to be sensitive to ambient light sources (Butson *et al* 1998) such as the solar radiation and fluorescent light sources, and various authors have produced results showing the permanent colouration of Gafchromic films which occur with exposure to these light sources (Dini *et al* 2005, Blair and Meyer 2009). However, there have only been qualitative assessments based on time exposure. In this work we aim to investigate if the colouration change is specifically due to ultraviolet radiation and if so, to quantify the colouration change per unit exposure of broad spectrum solar radiation. During the period of this research and study, EBT Gafchromic film became no longer commercially available and was replaced by EBT2 Gafchromic film. Several changes have occurred including a slightly different laminate material and the inclusion of a yellow dye within the active layer. The active radiochromic compound however remains the same. Thus similar effects are expected from EBT2 film as compared to EBT film when exposed to UV radiation (i.e. permanent darkening of the film) however the magnitude and properties may not be exactly the same. Before use of EBT2 film for UV dosimetry, testing should be performed for its characteristics as well.

Materials and methods

Experiments were performed using ISP Gafchromic EBT (ISP 2008) film (Lot no 37122-04I) to assess the response to ultraviolet radiation of the film and provide a quantitative relationship per unit exposure. To assess if the film was responsive to other common forms of electromagnetic radiation in solar exposure (i.e. visible light and infrared light) the following experiments were performed. The films were exposed under an 80 W incandescent light source for a period of 8 days continuously at a distance of 30 cm from the source. The UV content of the light sources was tested (using a high sensitivity UVA+UVB Hand held meter) and found to be negligible. Tests were also performed for the effects of infrared radiation by placing the film in an oven for a period of 12 h at a temperature of 50 °C. In each case, the films were tested for colouration changes due to radiation effects using colouration (OD) testing as described below. It is acknowledged that the film is known to be sensitive to x-ray radiation (Butson *et al* 1996, 1999, 1998, 2000, 2002a, 2002b, 2005, Cheung *et al* 2006) however the contribution from solar x-ray radiation or background radiation was considered negligible for these experiments.

To assess the response of the film to UV radiation, various tests were performed. Firstly the films were exposed to solar radiation in Mangerton, NSW Lat 34° 26′ S, Long 150° 52′ E at various times during the day and at various times during the year. Experiments were performed from 9 am until 5 pm to assess variations in measured response due to time of day. Experiments were performed in summer and winter to assess variation caused by seasonal differences. Differing sky conditions were also assessed which included fully sunny days as well as completely cloud covered day. The films were irradiated for time lengths between 5 min and approximately 4 h depending on the irradiance level and the exposure required. The aim was to assess variations in film response caused by these differing conditions. During these experiments the films were exposed at the same position on a table with a light skin tone backing material behind the film. In this way, the scattering conditions around the film were kept as constant as possible. To calibrate the UV exposure, a UVTEX A+B meter was used to measure irradiance (power per unit area) and exposure (Irradiance integrated over time) in a position next to EBT Gafchromic films. Manufacturer's specifications state that the meter can measure UV irradiance to values of $\pm$ 0.1 mW m^{-2} with an accuracy of $\pm$ 5%.

After the films were irradiated to known UV exposures, they were kept in light tight containers to eliminate any further UV exposure. The films were then analysed 24 h later using reflectance scanning on an Epson V700 desktop scanner. The films were analysed using Image J software on a PC workstation. The Epson Perfection V700 photo scanner was used with a scanning resolution of 50 pixels per inch in reflection mode. The images produced were 48 bit RGB colour images. An area of 2 cm $\times$ 2 cm was used to analyse the pixel values of the film. No filters or correction functions were applied to raw pixel value results. These images were analysed using the red component. The net reflective optical density (ROD) for all films was calculated to evaluate the colouration change due to UV exposure. The net ROD is defined as

$$\text{Net ROD} = \log\,(P_u/P_t) \tag{1}$$

where P_u is the pixel value of the reflected intensity through an unexposed film and P_t is the pixel value of the reflected intensity. Ohuchi (2007) produced a similar definition for reflected optical density. Curves were produced to establish the response of EBT Gafchromic film to UV radiation. Uncertainties in results were calculated as the standard deviation of the measurements repeated over five sets of data including quoted uncertainties of measurement equipment. Scanning for this experiment was performed in reflectance mode on an Epson V700 scanner. This method of scanning was utilized for two reasons. Firstly, the V700 scanner produced a lesser UV exposure effect when in reflectance mode as compared to transmission mode producing less than 2% variation in the colouration of a non-irradiated film when scanned 100 times. This was compared to 7% for transmission mode for 100 scans. Also in reflectance mode with the use of a matt white backing material instead of the glossy reflectance cover, the non-uniformity in response across 80% of the scanners area was less than 3% as compared to 8% for the same measurements in transmission mode. These results are currently being further studied for future work; however they were the basis for using the scanner in reflectance mode for UV exposure assessment.

Results

Figure 1 shows the effects of incandescent light on EBT Gafchromic film when the exposure is performed over an 8 day period. As can be seen there was a very small increase in the optical density of the film with an increase of approximately 4% with a 3% uncertainty over the 8 days exposure. This showed that for a large exposure of visible light only a very small change

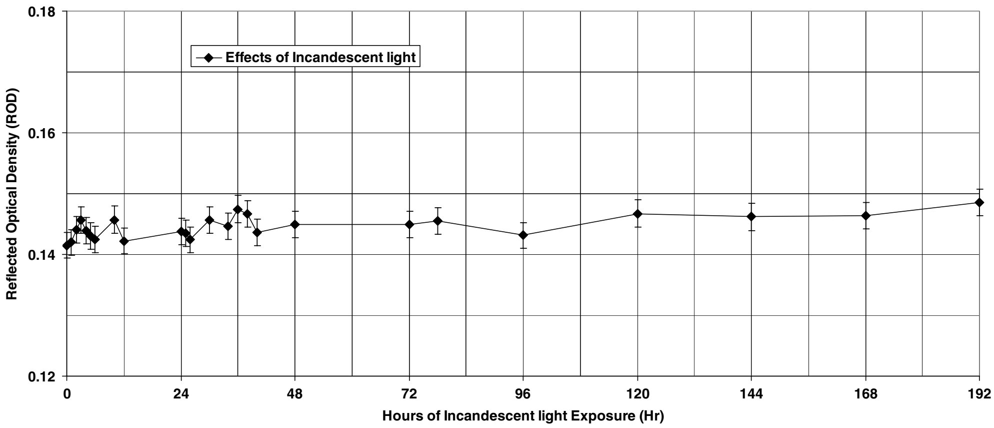

Figure 1. Negligible response or darkening of EBT Gafchromic film to incandescent light sources over an 8 day period.

Table 1. Optical density of Gafchromic film after infrared radiation exposure for 12 h at 50 °C.

Film no	Initial OD	Final OD
1	0.142	0.143
2	0.145	0.144
3	0.143	0.144
4	0.144	0.144
5	0.142	0.143

in colour occurred. As the films were scanned multiple times over the 8 days (approximately 20 scans), it is assumed that the small increase would be due to the UV exposure from the fluorescent light sources used in the desktop scanner. Thus it could be assumed that the film was not sensitive to visible light. This was performed for five pieces of EBT Gafchromic film. Table 1 shows the optical density results for five films which have been irradiated with infrared radiation at 50 °C within an oven over a period of 12 h. Again as can be seen the optical density of the films remained unchanged over this time period at this temperature. The same experiment was performed at 60 °C and the film completely changed colour and formed a red-bubbled appearance. We assume that this was a chemical and physical change in the film caused by melting of the layers. So the results showed that for up to temperatures of 50° (caused by infrared radiation) there was no sensitivity of the film. However at temperatures of 60° the film completely changed. This fact would be of concern when measuring solar radiation as heating of the film could occur if placed on a hot surface whilst experiments were being performed. We noted that during our experimental procedures for solar UV measurement, the films and table temperature never reached above 40 °C as measured by a digital thermometer.

Figure 2 shows the results for the change in the net optical density for EBT film when exposed to solar UV radiation under different seasons and sky conditions. Results were measured in summer and winter, with sky conditions of totally sunny and totally cloudy. During summer, the UV irradiance levels reached a maximum of approximately 300 mW m^{-2} during sunny exposure and a maximum of 220 mW m^{-2} for cloudy summer time exposures.

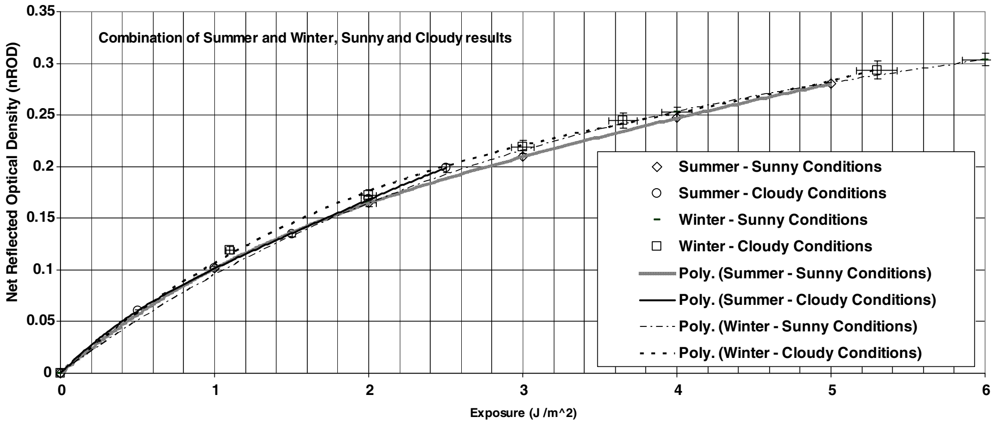

Figure 2. Comparison of the UV exposure versus darkening of EBT Gafchromic film under varying seasonal and sky conditions.

Whilst in winter time the maximum irradiance intensity was measured as 100 mW m^{-2} and 40 mW m^{-2} for sunny and cloudy conditions, respectively. The exposures were always performed in the middle of the day when the sun was placed highest in the sky. As can be seen there was a relatively similar response per unit exposure for all these conditions with EBT Gafchromic film. At exposure levels of around 5 kJ m^{-2} there was an approximately 8% difference in measured net OD for the different exposure levels. These results were reproducible over multiple experiments and multiple films for analysis.

Figure 3 shows a similar response curve relationship for varying times during the day for exposure. Exposures were performed from 9 am in the morning to 5 pm in the afternoon. As can be seen there is a similar sized variation in response for EBT film to measured UV over this time period. The smallest OD change per unit exposure of UV was found for the films irradiated during the middle of the day i.e. 12 noon, whilst from 9 am to 11 am and from 3 pm to 5 pm, the darkening appeared in general to be greater per unit exposure. We assume this to be at least partially caused by the collection angle of the calibrated UV meter which was left at a constant position during each exposure. As such the angle of entry for the solar UV rays would have increased in the morning and in the afternoon resulting in a lower UV exposure level reading on the meter at this time. Tests were not performed to confirm this assumption. Differences of up to $\pm 10\%$ at exposure levels of 5 kJ m^{-2} were seen. This is compared to $\pm 5\%$ for point exposure measurements with our hand held UV meter.

Using these results a calibration curve to quantify the UV exposure per unit colouration of the film can be produced as seen in figure 4. The response is a nonlinear response but is modelled adequately by a third-order polynomial function. As such the film may be able to be used for assessment of broad-spectrum solar UV exposure. It is acknowledged that the response curve produced here may differ depending on the scanner model used as each one may have a different light source, changing the OD to UV exposure response curve. However the calibration process highlighted that EBT Gafchromic film provides a reproducible response to UV radiation and could be utilized for UV assessment and due to its visible colour change adds to the ease of analysis with a desktop scanner. It could be used to produce two-dimensional maps of UV exposure if required. This may provide a characteristic improvement over conventional film detectors such as polysulfone films especially due to the ease of analysis. This work has not tested the wavelength response of EBT Gafchromic film to UV radiation

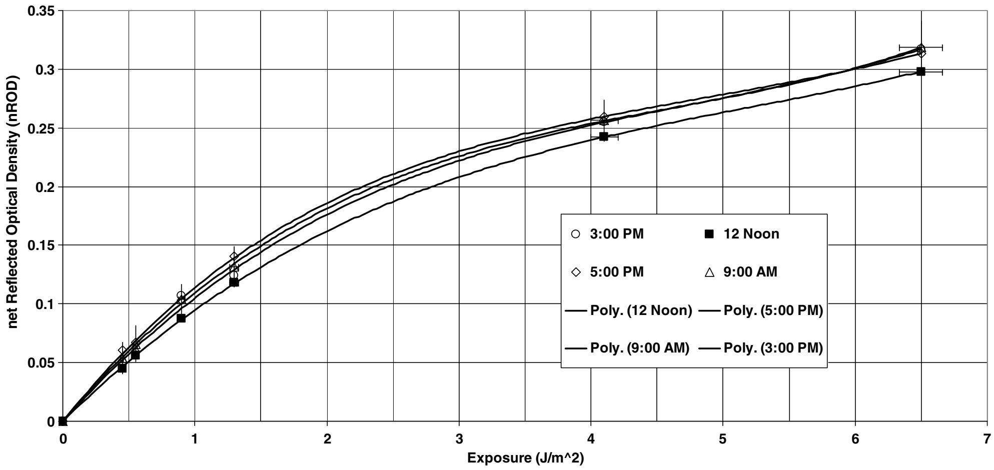

Figure 3. Variations in measured net reflected optical density of Gafchromic film to UV exposure when measured at different times of the day.

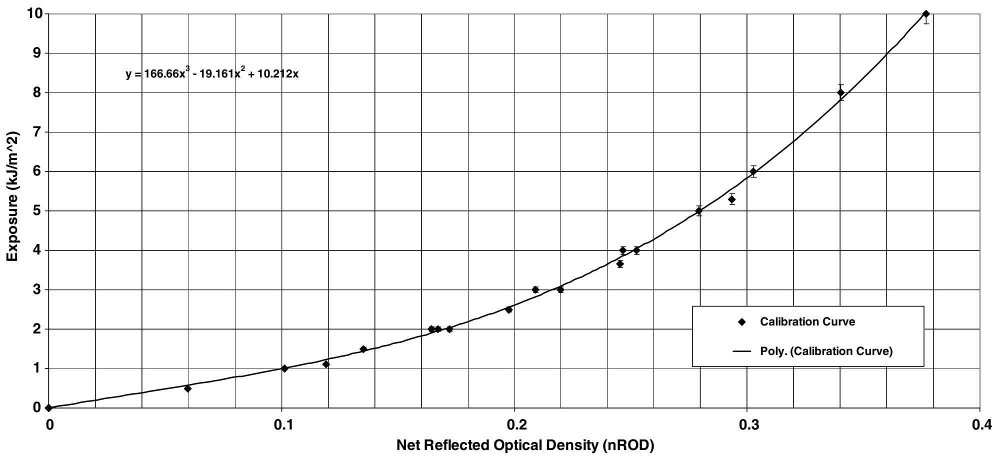

Figure 4. Calibration curve for conversion of EBT Gafchromic film darkening to exposure level of ultraviolet radiation.

or produced an action spectrum response. Future analysis will incorporate this information. However there is potential for this two-dimensional robust dosimeter to be used for ultraviolet radiation analysis for solar radiation exposures.

Conclusion

EBT Gafchromic film has been shown to be a novel ultraviolet radiation exposure meter with a reproducible colour change occurring during exposure. This work has quantified that change and shown that under varying solar radiation conditions such as summer and winter time, sunny or cloudy skies, the film produced a reproducible response within 10% for net change in optical density at around exposure levels of 5 kJ m^{-2}. As the colour change is in the visible wavelengths, the film can easily be analysed with a desktop scanner and thus has potential as a two-dimensional UV dosimeter.

Acknowledgments

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