Extensions in Pen Ink Dosimetry: Ultraviolet calibration applications for Primary and Secondary schools

N. Downs[1*], A. Parisi[1], S. Powell[2], J. Turner[1] and C. Brennan[3]

[1]Faculty of Sciences, University of Southern Queensland, Toowoomba, Qld, 4350

[2]Torquay State School, Hervey Bay, Qld, 4655.

[3]Hervey Bay State High School, Hervey Bay, Qld, 4655.

[*] To whom correspondence should be addressed, email: downsn@usq.edu.au; ph: (07) 46 312727

Abstract

Previously a technique was described for secondary school aged children for making ultraviolet (UV) dosimeters from highlighter pen ink drawn onto strips of paper. This technique required digital comparison of exposed ink paper strips to unexposed ink paper strips to determine a simple calibration function relating the degree of ink fading to measured levels of UV exposure. In this article, the ink calibration process is discussed in relation to activities that can be performed by primary school aged children. Further extension of the technique is discussed in relation to ultraviolet absorption by various transparent materials and a simple exercise is explained that could be used by primary and secondary students to measure and calibrate ultraviolet exposures using a glass plate dosimeter.

Introduction

The terrestrial UV waveband (290 nm to 400 nm) present in natural sunlight can have a significant influence upon the surfaces it strikes. UV degradation of polymers is commonly observed in cracked and brittle plastics that have been exposed to sunlight (Katangur et al. 2006). Colour fading is also caused by exposure to UV radiation. Paints, dyes, inks and pigments are all affected by the energy received from radiation in the UV waveband (Weyermann and Spengler 2008; Smith et al. 2001; Katsuda et al. 1998). UV energy is able to penetrate human skin, with the longer wavelength UVA (320 nm to 400 nm) penetrating the skin deeper than the shorter wavelength UVB (290 nm to 320 nm), where the UVB is primarily responsible for the human sun-burning reaction (Bruls et al. 1984). For humans, the worrying aspect of UV radiation is its ability to impart energy deep into skin cells, potentially causing mutation and skin cancer by affecting the repair

1

mechanisms of the DNA that exists inside the nuclei of skin cells (deGruijl 1999). The energy imparted into the dyes, pigments or colourants in pen or highlighter ink by UV radiation can similarly cause a chemical change in the colourant, altering the ink's chemical structure which may affect a colour change or fade. Reaction with oxygen will also affect the degree of fading. The fading reaction of various inks can be calibrated to the incident UV exposure by measurement with a broadband UV meter. The low cost of these meters has recently made UV experimentation available to schools.

Measurements of the UV prevalent in the outdoor environment are particularly important for school aged children in developing their own understanding of the surrounding physical environment and the health risks associated with using that environment. Two activities are presented here for investigating the local UV environment: the first is designed for primary school aged children and requires using paper dosimeter strips; the second introduces the use of a glass slide dosimeter as an improvement to the originally discussed paper dosimeter technique. Both activities provide students with the opportunity to work scientifically to physically calibrate and investigate the use of pen ink as a UV dosimeter. The activities presented are relevant to some of the following strands of various state science syllabi *'Science and Society'* (QLD), *'Earth and Beyond'* (ACT, NT, QLD and WA), *'Earth and Space'* (SA), *'Physical Phenomena'* (NSW), *'Earth and its Surroundings'* (NSW), *'Level Three Essential Learning Standards'* (VIC), *'Standard Two – Scientific Inquiry'* (TAS) and *'Standard Three – Earth and Space'* (TAS).

Materials

Primary school aged students will need to manufacture pen ink dosimeters and monitor the daily UV exposure using a UV measuring instrument. For this activity, the 'UV checker' pocket UV meter is recommended as this is available for a relatively small cost to schools (approximately \$30) from electronics suppliers or online shops (Deals Direct 2009). Alternatively some schools may have access to existing data logger physics kits. Some of these kits include instrumentation able to measure the visible luminous intensity (lux meters) and the UV irradiance in W m^{-2}. For this activity a UV irradiance meter, measuring the UV radiation in W m^{-2} or mW m^{-2} will be needed. The 'UV checker' measures UV radiation weighted to the human sun-burning response. This is known as the erythemally effective UV. Other meters may not apply the erythemal response to the measured radiation. Typically, if a meter measures substantially more than 250 mW m^{-2} near midday, the meter is measuring more than the erythemal UV. The UVA in natural sunlight has a reduced relative effective role compared to the UVB in causing a sunburn reaction (CIE 1987). Instruments found in schools which do measure the UVA will show measurements significantly higher than instruments that measure UVB or the erythemally effective UV. The ratio of UVA in natural sunlight is approximately 100 times that of UVB depending on the conditions (Kimlin et al. 2002). Teachers that source other types of UV instrumentation should calibrate their dosimeters to the UVB or erythemally effective UV for this experiment. Instruments that measure the UV index are measuring the erythemally effective UV. A pen ink dosimeter can be calibrated to UVB,

2

erythemally effective UV or the UV index. In this article the 'UV checker' measures the erythemally effective UV in mW m^{-2}. A broadband UVB meter will measure the UVB in either mW m^{-2} or W m^{-2}, while the UV index is a dimensionless quantity scaled relative to 250 mW m^{-2} of erythemally effective UV (Downs et al. 2008a). The UV index can be converted to erythemally effective UV in W m^{-2} by dividing by 40. When calibrating pen ink dosimeters to any of these standard units the same procedure can be used as illustrated in the sections that follow, except if the UV index is used, the unit should be first converted to W m^{-2} to allow the total exposure energy to be calculated. Some schools may have access to UV spectrometers, enabling the spectral measurement of UV between certain wavelength ranges. If such equipment is available to a school, this can also be used to calibrate pen ink dosimeters. A good explanation of spectral UV and a method to convert such measurements to an integrated erythemally effective UV measurement in W m^{-2} is provided by Parisi (2005) for teachers who have access to this specialized spectral equipment.

For secondary school aged students and more capable primary school classes, a glass plate will be needed onto which students will be required to scribe lines of highlighter ink. Some transparency pens used commonly by teachers were also found to show an effective fading reaction. A selection of glass plates of various thickness, polycarbonate or other plastics or films can also be tested to measure the UV absorbency of various transparent materials. A method has been described previously to measure the degree of fading in a paper pen ink dosimeter (Downs et al. 2008b). A simple modification to this procedure involves scanning, with a digital scanner, the glass plate after exposing ink lines scribed onto the plate to UV radiation. For this activity, six lines scribed onto a glass plate were exposed at hourly intervals that were successively uncovered by a card on each hour to produce a set of faded ink lines which could be compared easily in a single digital scan.

Dosimeters:	Various highlighters, OHT markers or pens
	Paper strips (approximately 1 cm wide)
	Glass plate or slide of any thickness
UV instrument:	UV checker or UVB meter
	Digital scanner
Safety:	Sun protective strategies need to be implemented by students and teachers performing the ink dosimeter calibration activity, including the active use of hat, sunscreen and exposure avoidance strategies.

Methods and Results

Testing for fading in different highlighter pens

The fading of various inks found in common pens and highlighters was tested for this activity by the year 6/7 Enviroscience Pathway group at Torquay State School over a single autumn day. The activity involved scribing between approximately 10 and 20 different coloured lines onto a single sheet of A4 printer paper and then cutting the paper into two segments, each having the same number of lines. The first half of the paper was put aside and used as the study control, while the second segment was placed outside in the sun for a full day. Following exposure, students compared the exposed pen ink lines to the control ink lines to determine the type of pen best suited for use as a pen ink dosimeter.

Figure 1: Manufacturing and testing for suitable ink that could be used as a UV dosimeter with a primary school aged group. Students tested many different types of highlighters and pens in ruling up this A4 sheet.

Using their scientific reasoning skills, students were prompted to select the best pen from which to manufacture six individual paper dosimeters. These dosimeters were exposed to sunlight on a horizontal plane from 9:00 am and removed individually at 10:00 am, 11:00 am, 12:00 pm, 1:00 pm, 2:00 pm and 3:00 pm. At each hour from 9:00 am to 3:00 pm, the horizontal plane UV was measured in units of mW m^{-2} with the UV checker held at arm's length and the sensor pointing directly toward the zenith.

The instantaneous irradiance measurements (mW m^{-2}) were integrated using a simple bar chart method. Using this technique students were introduced to the concept of integration as "the area under a curve". Students performing the activity were further introduced to the unit of Joules as a measure of energy and Watts as a measure of energy per unit time. Equation 1 was used to calculate the approximate total hourly exposure received by each

4

pen ink dosimeter, where the irradiance in mW m^{-2} is first converted to W m^{-2} by dividing by 1000. Figure 2 represents an example set of dosimeter exposures.

$$Hourly\ Exposure\ (J\ m^{-2}) = \ Irradiance\ (W\ m^{-2})\ x\ 60\ min\ x\ 60\ sec \qquad (1)$$

The exposure of each individual dosimeter was calculated by integrating (adding) individual exposures. Mathematically, the exposure of a dosimeter exposed for an entire school day between 9:00 am and 3:00 pm is represented as:

$$E = \sum_{9:00am}^{3:00pm} I \times \Delta t \qquad (2)$$

where E is the exposure in (J m^{-2}), I is the measured irradiance (W m^{-2}) and Δt is the exposure time interval from 9:00 am to 3:00 pm.
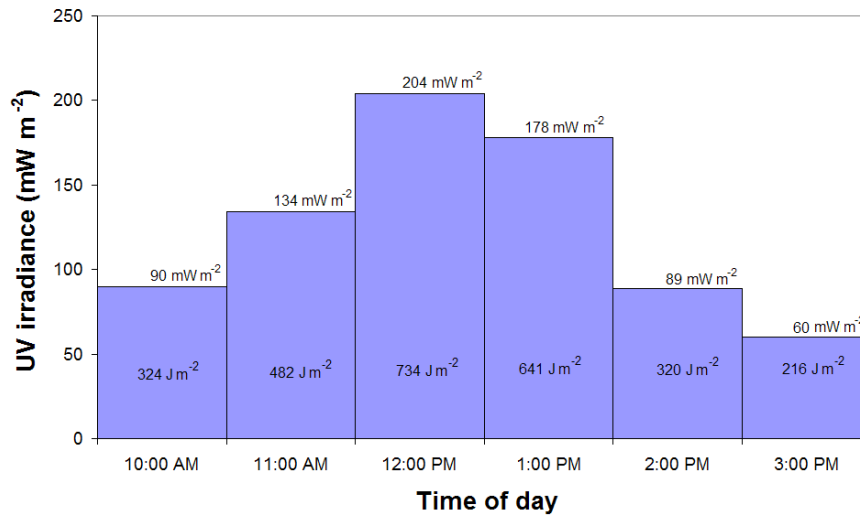

Figure 2: A series of erythemally effective UV irradiance measurements for each of six exposed pen ink dosimeters measured at 10:00 am, 11:00 am, 12:00 pm, 1:00 pm, 2:00 pm and 3:00 pm. The graph is an approximation of the true sun-burning energy received by each dosimeter calculated from a simple stepwise integration. Irradiance measurements are given for each bar (mW m^{-2}). The integrated exposure (J m^{-2}) for each hour was calculated from equation (1).

The total exposure for each dosimeter is the cumulative sum of the exposure calculated for the current hour and the sum of previous hourly exposures. Here, the erythemal exposure of each dosimeter is estimated from a single measurement made at the end of each hourly exposure interval. The erythemal irradiance is therefore approximated to be constant for each hourly exposure. Cumulative dosimeter exposures are presented in Table 1.

5

Table 1: Pen ink dosimeter erythemal exposures measured from 9:00 am to 3:00 pm.

Dosimeter Exposure period	Time removed (representing the end of each hourly exposure interval)	Erythemal UV irradiance measured at the end of each exposure interval (mW m^{-2})	Approximate Erythemal UV exposure for the exposure interval (J m^{-2})	Approximate cumulative erythemal exposure for each dosimeter (J m^{-2})
1 hour	10:00am	90	324	324
2 hours	11:00 am	134	482	806
3 hours	12:00 pm	204	734	1540
4 hours	1:00 pm	178	641	2181
5 hours	2:00 pm	89	320	2501
6 hours	3:00 pm	60	216	2717

Secondary school teachers may prefer to use a more complex integration system than the simple stepwise integration introduced here for primary school aged students. The use of Simpson's rule (provided the correct number of integration steps) or a trapezoidal (mean) integration technique could be used to refine the exposure estimates of each pen ink dosimeter. The use of numerical integration techniques would likely benefit groups studying computational methods of integration.

Calibrating the ink and plotting a calibration curve

A simple method was employed to draw a calibration curve for the pen ink dosimeters. This involved getting the students to draw a graph of the cumulative dosimeter exposure versus the elapsed exposure time. An example of this plot is given in Figure 3 where a 3rd order polynomial has been used to interpolate the calibration curve. Students can estimate the trend in a calibration curve by drawing a freehand sketch. However the use of spreadsheet software makes the task easier and will likely produce more accurate results. Note how the curve slope eventually decreases with increasing exposure time. This is a result of the UV irradiance decreasing after the peak midday period. The greatest increases in the cumulative exposure occur between 2 and 4 hours as can also be seen in Figure 2 between 11:00 am and 1:00 pm. Were the calibration to run past 3:00 pm, the slope in the curve would eventually flatten out to a horizontal line as no further increase in time would result in a notable increase in exposure when the sun begins to set and eventually dips below the horizon at night. Similarly, the gradient of the calibration curve is less early in the morning as can be seen in Figure 3 between 0 and 1 hour of exposure time.
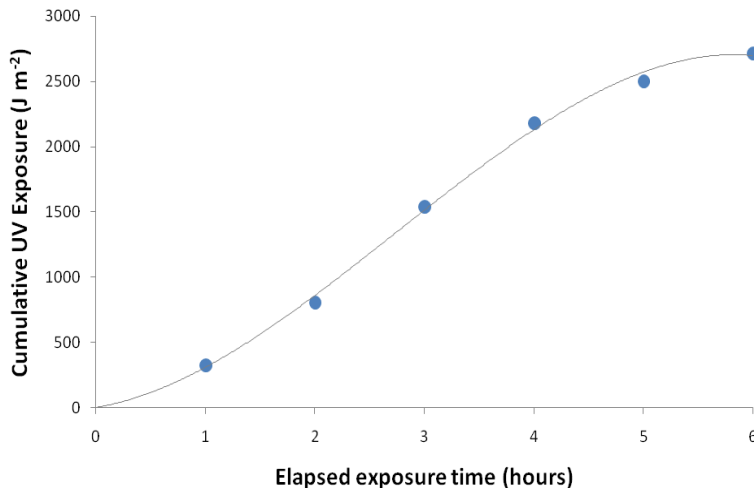
Figure 3: A pen ink dosimeter calibration curve. This curve was produced from the results presented in Table 1. The control variable (elapsed exposure time) is placed on the x-axis, measured cumulative UV exposure is placed on the y-axis. For primary school aged children a freehand sketch is enough to show how a calibration plot can be constructed. More frequent measurements of the UV will produce a more accurate curve. Students may like to investigate this. Cloud cover will also affect the results.

Measurement of UV exposure with ink strip dosimeters

Having constructed the calibration plot, students then manufactured new pen ink dosimeters and placed them in an area of interest. The newly exposed dosimeters were compared to the calibration dosimeters and matched by eye to the closest fade level. Students finding levels of fading in between a calibration dosimeter used their calibration curve to interpolate the UV exposure. The concept of interpolation is valuable to the scientific learning of school students. This activity introduces the concept in a simple way which can easily be understood by primary school aged children. The technique, although simple, demonstrates that UV dosimetry is possible for school aged children and can be easily repeated with upper primary level students.

Glass plate dosimetry

Pen ink dosimeters can also be manufactured by scribing ink onto glass plates or slides. The use of glass plates instead of paper allows the transparency of pen ink to be analysed more accurately provided students have access to the necessary digital scanning equipment. By using a glass plate, the observed fading results from the ink only and changes which may occur to the paper itself are negated. Glass plates are also very easy to scan digitally as they are not easily creased or bent like paper dosimeters during field exposures which may produce some shadow effects when digitally imaged. Furthermore, glass plates can be cleaned for multiple uses. Using a digital scanner, the transparency of ink drawn onto a glass plate can be measured by observing variations in the density of scanned ink lines. The more faded the ink, the greater the transparency of the scanned ink line due to lower absorption by the faded ink. A glass plate pen ink dosimeter is shown in

7

Figure 4. In the figure, a greater degree of fading can be seen on lines scribed on the left hand side of the glass plate due to the successively greater exposure periods received by lines drawn on the left hand side.

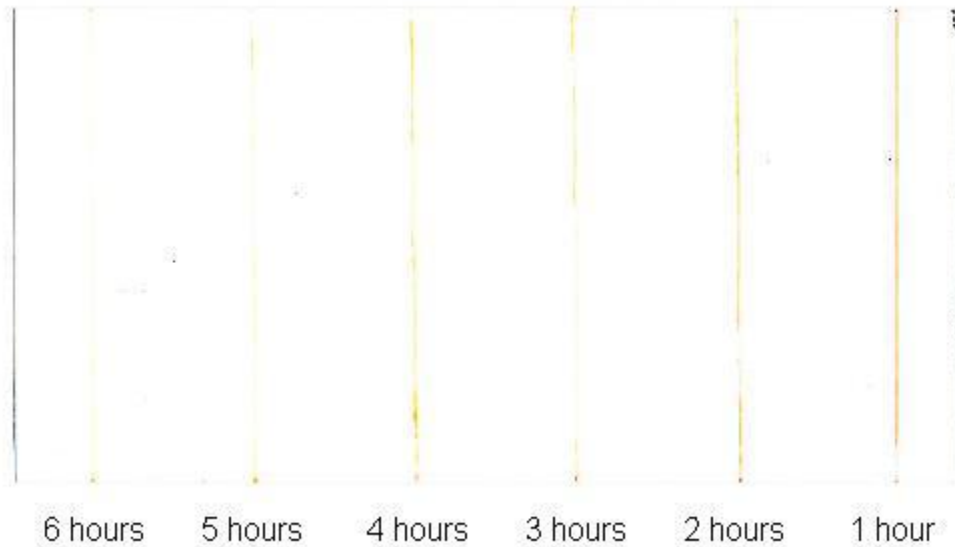6 hours   5 hours   4 hours   3 hours   2 hours   1 hour

Figure 4: A digital scan of a glass plate dosimeter showing the successive fading of several ink lines drawn by the same pen. In the image, lines drawn on the left hand side were exposed for an hour greater than each adjacent right hand line. The lines were exposed on this plate for a period of six hours in summer. After 6 hours exposure, the pen ink has faded almost completely.

A dosimeter response curve for the glass plate dosimeter is given in Figure 5. Here, the cumulative UV exposure is plotted on the y-axis and the transparency of ink (fade level) is plotted on the x-axis. Note that transparency is plotted as the control variable. This is because a dosimeter response curve is being created whereby the transparency is controlled by exposing for set periods of time and plotted for measured levels of UV exposure. Essentially, the dosimeters are manufactured to measure UV radiation, not levels of transparency. That is:

Desired quantity   = calibration factor x measurable control quantity   (3)

For linear equations, the calibration factor is often taken as the gradient of a line and this may be a sufficient approximation for a pen ink dosimeter provided a linear range can be determined. For a linear calibration, equation 3 is of the form $y = mx + c$, where y represents the desired quantity for which the calibration is done, m represents the gradient of the line and c is the y-intercept, which is often zero provided there is no experimental error. For many cases a straight line is sufficient to calibrate for a desired quantity and so the gradient of a straight line calibration plot is sufficient to perform a calibration. For pen ink dosimeters however, there will be a saturation limit. This limit represents the highest practical exposure able to be measured by a particular type of ink and is easily understood if one can imagine what might happen to the ink if left outside to fade for days on end. Eventually, there would be no ink left to continue a calibration.

8

Photochemical reactions such as those observed in the pen ink dosimeter are not linear. However, a linear approximation to the dosimeter response function may be specified within set exposure limits. In Figure 5, a linear approximation may be fitted between the fade levels 20% and 30% with little error. However, a more accurate dosimeter response curve can be fitted to the entire data set by application of an exponential function such as that given in Figure 5.
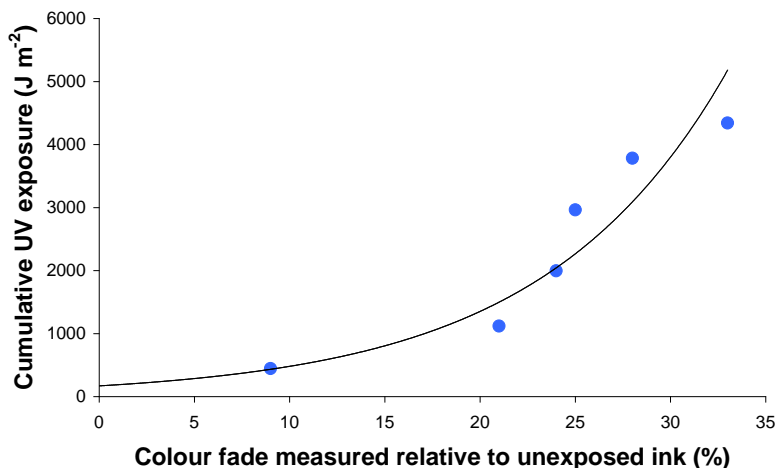

Figure 5: The dosimeter response curve for a glass plate pen ink dosimeter. The curve was produced by exposing pen ink lines over six hours on a single day in summer. The curve shows an exponential trend. Fade level was determined using the method of Downs et al. (2008b).

Students may find it interesting to investigate the saturation limit of a pen ink dosimeter by performing the following activity.

Investigating the saturation limit

1. Draw approximately 20 ink lines from the same pen or highlighter onto a glass plate or paper strips.
2. Measure the UV irradiance in hourly or two hourly intervals and cover each line after is has been measured.
3. Repeat the measurement procedure for several days if necessary until the uncovered lines begin to fade completely.
4. Note the total exposure at which the scribed ink line has disappeared completely. This is the saturation limit of the pen ink dosimeter. Further exposures are not measurable beyond this point. Students should find it difficult to pinpoint the exact exposure at which the ink disappears completely. The last few lines should appear to be very similar. As the amount of ink available to cause a noticeable change disappears, the sensitivity with which the eye can make an accurate judgment is also reduced. There is therefore, a practical limit for each type of pen ink dosimeter.
5. Optional: Measure the fade level of each ink line using a digital scanner and image processing software as discussed previously (Downs et al. 2008b).

9

6. Optional: Plot the cumulative UV exposure versus the fade level to observe where the dosimeter response can be approximated by a linear trend. The dosimeter response plot will begin to curve upwards as the exposure increases. Depending on the total exposure time, students should have plots extending over several thousand J m^{-2}. Again it can be seen that if there is no ink left an infinite exposure will be required to cause a fade change. That is, when the gradient of the dosimeter response curve approaches infinity, the theoretical limit of the dosimeter has been reached.

Students may like to investigate the saturation limit of different ink types and discuss their suitability for different applications. An interesting investigation may involve students finding a long term UV exposure dosimeter that could be used over several days. Alternatively, short term dosimeters could be developed from ink that changes rapidly upon exposure to UV radiation.

UV Filters and the Ultraviolet Protection Factor

Glass itself is an efficient absorber of UVB radiation. This effect can be observed using a glass plate ink dosimeter. Ink lines scribed onto both sides of a glass plate can be observed to undergo different levels of fading. When a glass plate is left in sunlight and supported from the ground surface so that the ink drawn onto the opposite side of the plate does not touch the ground, the ink on the topside of the plate experiences the greatest level of fading. This simple exercise can be used to prove that glass is an effective absorber of UVB radiation. Figure 6 is a scanned image of two ink lines drawn onto opposite sides of a glass plate dosimeter that were exposed simultaneously over several hours in spring. The lighter line in the figure was exposed to direct solar UVB radiation while the darker line was protected on the underside of the glass plate. Students may find it useful to test glass plates of several different thicknesses to determine which is the most efficient UVB absorber. This test can be applied to various other polycarbonates, laminates, sunglasses or plastics of different thicknesses or colours to determine which are the most effective at absorbing UVB radiation. If quartz glass is available, ink lines drawn onto both sides should experience the same level of fading as this glass is optically transparent in the UVB wavelengths.
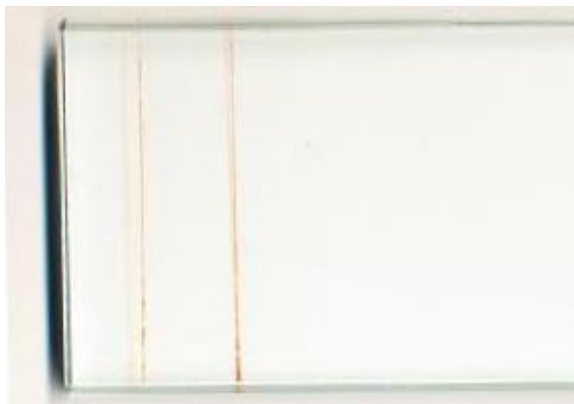

Figure 6: Absorption of UVB by window pane glass results in a noticeable difference in the fading of two pen ink lines scribed onto either side of the plate. The line scribed on the left hand side was exposed

10

directly to sunlight, while the right hand line was protected by the thickness of the 6 mm glass plate. The transmission of the glass plate was also measured with a UVB meter from which it was determined that this window pane glass transmits 7% of the incident UVB.

The ultraviolet protection factor (UPF) of glass or any other solid filter material can be determined using ink lines scribed onto both sides of the filter plate. The UPF is typically used to rate the protection of clothes, hats, shade cloths etc (Wilson and Parisi 2006; Gies et al. 2006; Toomey et al. 1995). The UPF is the ratio of the UV received by an exposed site (E) to the UV received to the same site with some form of protection in place (E_p):

$$UPF = \frac{E}{E_p} \quad (4)$$

Closely woven fabrics for example have a high UPF while loosely woven shade cloths can have a quite low UPF. Theoretically, the UPF can be as high as infinity, provided all of the UV is blocked with some form of protection in place. Students can use glass plate dosimeters to determine the UPF of the glass or filter material tested by determining the quotient of the calibrated topside ink exposure to the calibrated underside ink exposure. By employing the dosimeter response curve of Figure 5, the top and underside window pane exposures were matched with the closest fade level to read off an approximate E and E_p exposure. Using the pen ink UPF method, the UPF of the window pane glass was determined to be 5 compared with a UPF of 14 measured with a broadband UVB instrument. While a little crude, the results demonstrate that the pen ink method of measuring the UPF can be completed simultaneously by a large group of students that have access to pens where the number of UV meters in a class may be limited. Furthermore, by simply scribing two ink lines onto a glass plate, the absorption of UVB radiation can be easily and practically demonstrated to young age groups without the need to employ UV instrumentation.

Discussion

A method has been described and extended from that presented previously showing how to calibrate and measure the UV radiation using a simple ink dosimeter. The activities presented provide some options for use by teachers in primary and secondary schools. Calibration and understanding methods of calibration are essential learning for students undertaking a course in science. The calibration techniques presented here are shown with respect to measurements of the UV environment. Understanding how to measure and quantify the level of UV exposure that exists in the environment from a young age contributes toward educating youngsters of the risks which apply to them. The UV exposures received early in life are those that contribute the most toward the development of skin cancers that develop later in life. It is hoped that the techniques presented will contribute toward developing scientific proficiency and raise awareness of the need to minimise potentially harmful exposures in a young population.

11

The year 6/7 Enviroscience Pathway group were able to apply their learnings from this task when planning gardens to enter into the local Spring Garden Competition. Students redid the task insitu, using these new results to assist them with plant selection and plant placement. The application of this data gave the students the chance to demonstrate applicable Math and Science Essential Learnings for Year 7. The students were also able to witness first hand the practical applications of both of these Key Learning Areas. Finally 11 and 12 year old students have little understanding of the long term skin damage caused by the level of exposure to UV radiation that exists in Australia. Participation in this project and the resulting discussions clearly demonstrated to the students the effects of the Australian sun and the direct link to their long term health and well-being.

Acknowledgements

References

CIE (International Commission on Illumination) Research Note, 1987, "A reference action spectrum for ultraviolet induced erythema in human skin", *CIE- Journal*, vol. 6, no. 1, pp. 17-22.

Bruls W.A.G., Slaper, H., van der Leun, J.C. & Berrens, L. 1984, "Transmission of human epidermis and stratum corneum as a function of thickness in the ultraviolet and visible wavelengths", *Photochemistry and Photobiology*, vol. 40, no. 4, pp. 485-494.

Deals Direct 2009, DealsDirect.com.au, Ingleburn, New South Wales, viewed 4 November 2009, <http://www.dealsdirect.com.au/p/pocket-uv-meter/?utm_source=getprice&utm_medium=cpc >.

deGruijl, F. 1999, "Skin cancer and solar UV radiation", *European Journal of Cancer*, vol. 35, no. 14, pp. 2003-2009.

Downs, N., Parisi, A., McDonnell, B., & Thornton, P. 2008a, "Measurement variation and factors influencing the UV index", *Teaching Science*, vol. 54, no. 2, pp. 8-13.

Downs, N., Turner, J., Parisi, A. & Spence, J. 2008b, "Pen ink as an ultraviolet dosimeter", *Teaching Science*, vol. 54, no. 4. pp. 41-44.

Gies, P., Javorniczky, J., Roy, C. & Henderson, S. 2006, "Measurements of the UVR protection provided by hats used at school", *Photochemistry and Photobiology*, vol. 82, pp. 750-754.

Katangur, P., Patra, P.K. & Warner, S.B. 2006, "Nanostructured ultraviolet resistant polymer coatings", *Polymer Degradation and Stability*, vol. 91, pp. 2437-2442.

Katsuda, N., Otake, K, Omura, T. & Takagishi, T. 1998, "Effect of ultraviolet absorbing agents on photodegradation behavior of a disperse dye", *Dyes and Pigments*, vol. 36, no. 3, pp. 193-204.

Kimlin, M.G., Parisi, A.V. Sabburg, J. & Downs, N.J. 2002, "Understanding the UVA Environment at a sub-tropical site and its consequent impact on human UVA exposure", *Photochemical and Photobiological Sciences*, vol. 1, p. 478-482.

Parisi, A. 2005, "Physics concepts of solar ultraviolet radiation by distance education", *European Journal of Physics*, vol. 26, pp. 313-320.

Smith, C.A., Gerlock, J.L. & Carter, R.O. 2001, "Determination of ultraviolet light absorber longevity and distribution in automotive paint systems using ultraviolet micro-spectroscopy", *Polymer Degradation and Stability*, vol. 72, no. 1, pp. 89-97.

Toomey, S.J., Gies, H.P. & Roy, C.R. 1995, "UVR protection offered by shadecloths and polycarbonates", *Radiation Protection in Australia*, vol. 13, no.2, pp. 50-54.

Weyermann, C. & Spengler, B. 2008, "The potential of artificial aging for modelling of natural aging processes of ballpoint ink", *Forensic Science International*, vol. 180, pp. 23-31.

Wilson, C.A. & Parisi, A., 2006, "Protection from solar erythemal ultraviolet radiation – simulated wear and laboratory testing", *Textile Research Journal*, vol. 76, no. 3, pp. 216-225.