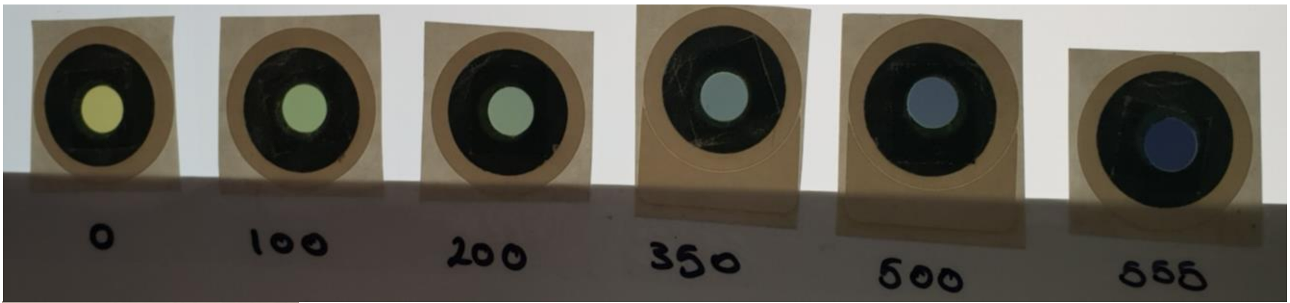
Stockholm Junior Water Prize 2019

Development of an Inexpensive and Deployable Film-based Detector for Accurate Ultraviolet Solar Disinfection (SODIS) of Water



The SODIS Sticker

Macinley Butson, Australia

ABSTRACT

A new, novel and innovative ultraviolet radiation sticker has been developed to accurately measure large UV exposures for Solar Disinfection of water. The SODIS Sticker is capable of accurately measuring the solar UV exposure required to sanitise drinking water through 2 innovative products built together. A high accuracy and transparent UV sensitive film coupled with a partial UV blocking filter, was used to construct The SODIS Sticker. N.B. a new and improved design will be presented in Stockholm.

These design features produced a feature that I believe no other detector has for SODIS UV exposure evaluation. The open design and the transmission / transparent sensitive layer allow both directly incident UV and transmitted / backscatter UV radiation to be measured. This is the same situation as what happens in the water during the SODIS process. Every other detector can only measure directly incident UV radiation because the detectors have opaque backing, or the detector is a solid-state detector which cannot measure reflected UV radiation being only unidirectional. This design is a significant step forward for SODIS UV water disinfection measurement.

The SODIS Sticker, can be used in any situation and was constructed at a cost of less than 1 US cents (1.33 Cents AUD or 0.82 Cents Euro) per sticker. This is substantially cheaper than other comparable products and could also be substantially reduced by mass production.

Testing of water for biological disinfection after 555Whm^{-2} of UVA exposure as measured by the SODIS Sticker showed that faecal coliforms were reduced from an initial count of 6000-10,000 cfu/100 mL to less than 1 cfu/100 mL. When the SODIS process was only partially performed due to thick cloud cover over the WHO “recommended” length of solar exposure time (6 hours) where the SODIS Sticker measured less than 555Whm^{-2} of UVA exposure, the coliform count was reduced from the initial 6000-10,000 cfu/100 mL to 4250 cfu/100 mL. As such, the SODIS process was not performed appropriately. These results show the effectiveness of The SODIS Sticker to determine the competition of solar disinfection, potentially significantly improving sanitation and safety of drinking water for those in need.

ABOUT ME

My name is Macinley Butson and I am an 18-year-old inventor from the East coast town of Mangerton, New South Wales, Australia. This is a town where water is clean, we have amble food and I am blessed to be able to receive quality education. But I have always been profoundly troubled that so many others worldwide do not have these same basic human rights and daily life is a challenge. This inequality has driven me to constantly look for ways to help those in need. I am excited and inspired by the possibilities the Stockholm Junior Water Prize will provide to support the implementation of the SODIS Sticker to aid humanity. I have always had a passion for STEM and today, we all stand at the frontier of a new world, where we can drive change and not be driven by it. The shared responsibility of our planet and the people within it remains at the forefront of my mind, to be a positive impact. Now more than ever we work towards new discoveries, so that we can provide equal access to the fundamentals of life such as clean drinking water. I believe everyone is called to help others in life with empathy and compassion - my opportunity to do this is through science and engineering which has lead to developing The SODIS Sticker.

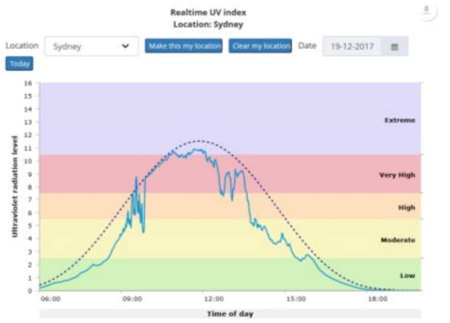
INTRODUCTION

The World Health Organisation (2018) has discussed the need to provide clean, potable, safe drinking water to maintain public health with many water sources have being identified as biologically contaminated. It is estimated that 2 million water sources worldwide are contaminated with faeces which can transmit diseases such as diarrhoea, cholera, dysentery, typhoid and polio (World Health Organisation 2018). I have had an interest in addressing this global water inequality (Unicef 2017) from a young age, since I learnt about this crisis.

One method of biological disinfection is known as solar disinfection, or SODIS (Burton 2012, EAWAG & SANDEC 2002). Water is poured into clear polyethylene or glass bottles and exposed to sunlight for 5 - 48 hours depending on weather conditions. The ultraviolet (UV) rays present in sunlight kill bacteria, protozoan parasites and renders some viruses inactive making it an inexpensive and applicable method for disinfecting water, especially in developing countries. It is estimated that more than 5 million people from Africa, Asia and Latin American countries already successfully use this method (Burton 2012).

The range of times required to successfully disinfect water depends on the solar irradiance of the country, the cloud conditions and the overall exposure. A level of at least 500 Wm^{-2} of all spectral light is required to reach disinfection within 5 hours. More importantly, however, the effective wavelength range of UV-A (≈ 315nm - 400nm) needs to contain 555Whm^{-2} exposure and this is reported to correspond to approximately 6 hours of mid-altitude midday, summer sunshine (SANDEC 2016). However, many factors affect solar irradiance which can include altitude, geographical location, season, time of day and weather conditions. This is evident as shown in Figure 1 which provides UV index / exposure values over 1 day in Sydney, Australia. It shows the substantial difference in UV exposure throughout the day caused only by variances of time and cloud conditions.

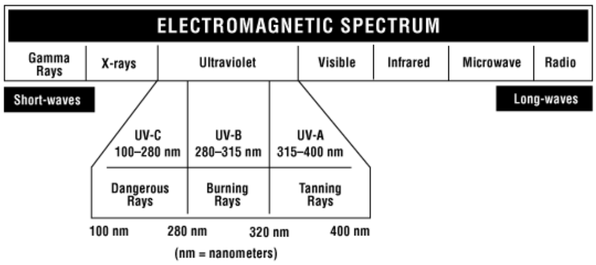
Figure 1: UV index on the 19th Dec 2017 in Sydney Australia showing the variations in UV levels during the day and reductions caused by cloud cover at certain times (Australian Radiation Protection and Nuclear Safety Agency n.d.)



As such, in some instances, less time is required but more importantly often a longer time is required to provide a safe level of disinfection for water potability. If the required UV exposure is not met, the water remains unsafe to drink putting lives at risk unknown to the consumer. The ability to measure and ensure correct UVA exposure of a water source, rather than allotted time periods, would further safeguard the life quality and safety in terms of contaminated drinking water related diseases.

UV radiation is a part of the Electromagnetic spectrum (figure 2) and ranges from ≈100nm - 400nm. UVA, which is effective in removing biological contaminants from water, ranges from 315nm - 400nm (CCOHS 2016)

Figure 2: The Electromagnetic Spectrum with UV and its wavelengths (CCOHS 2016)



Many methods exist for UV radiation measurement, including solid state detection meters (Lloyd 2004) as well as biological spore and chemical films (Manley et al. 2016). Solid state UV meters can accurately measure UV exposure levels however are relatively extensive for developing country or community use and would need to be robust for continued use over many years to make them financially viable. They also require some form of battery to power then during use which adds to the cost of use. These devices also normally have a digital numerical readout out which could complicate the process of deciding whether an appropriate level of UV exposure had been reached by a young child who may be responsible for water collection and SODIS procedure as is often the case in developing communities. As such, a film or simple colour change style detector may be the best and most appropriate detector for use in these situations. A young child could look at a sticker which has been placed on a water bottle and see if it has changed colour (by the appropriate amount) so that SODIS has occurred and the water is safe to drink.

Upon investigating the internet and the scientific market for products already available, there were a few different available. One currently available product was a colour change sticker available for a cost of 40 cents per sticker and provided a colour change from blue to clear with a large UV exposure. There was no clear data on how accurately it measured UVA radiation. The cost however of 40 cents per sticker would be a limiting factor for use in developing communities as this is a significant cost for water sanitation. As such, this project aimed at producing a high quality and accurate film-based sticker to measure UVA radiation which would be substantially cheaper than 40 cents per sticker.

Three different products were found and investigated as the basis for creation of a SODIS sticker /detector for UVA exposure analysis. In this project the first 2 products as discussed below were investigated and found to be the least optimal products to make the SODIS Sticker.

Firstly, evaluation was performed using “Solar paper”. A product available from scientific and art stores called SunPrint was evaluated. It is a product which allows the user to create art work through placing objects over the solar paper to block UV rays. The paper then changes colour through interactions with UV rays. Following this process, the image can be set using a water bath. This product will be evaluated for its usefulness as a SODIS UV detector.

Secondly, photochromic paint will be analysed. The Lumi InkoDye paint changes colour after UV exposure and in used in art work as well mostly for creating pictures on tee shorts or materials. The paint is clear to being with and changes colour to a dark blue colour after UV exposure. For art work printing, a film image or negative of the image you want is placed over the painted material under UV exposure. As the material is exposed the paint changes colour at different rates depending on the darkness of the negative at that point. As such the image is transferred to the material in shades of blue. This can then be fixed by washing the materials after exposure and setting the image.

The third product, a medical Radiochromic film was deemed the best product to construct the SODIS Sticker. So thirdly, UV exposure will be measured using Radiochromic film which was designed for use in measuring x-ray radiation. This type of film has also been shown to exhibit colour changes when exposed to UVA radiation and as such, may be a potentially useful film to measure SODIS UV radiation. Specifically, one of these Radiochromic chemical films types includes Gafchromic EBT3 Radiochromic film made by Ashland Pty Ltd (Covington, Kentucky, US), which will be employed in this experiment. Gafchromic films are used for X-ray dose measurements in diagnostic radiology and therapeutic radiotherapy, however, they are also sensitive to UVA rays and thus can be used to measure UV radiation exposure levels (Katsuda et al. 2015). However, Katsuda et al. determined that this type of film (EBT3 Gafchromic) is very sensitive to UVA radiation and as such may not be appropriate for measurement of exposure level around 555Whm^{-2} due to film saturation. Thereby, if a filter could be constructed to reproducibly reduce the irradiated UV exposure levels so that the effective correlation of the film sensitivity matched the filtered UV exposure levels, an adequate and effective SODIS detector could be created.

It is well known that the UVA exposure required to sanitise water is a relatively high value compared to the UV measurement use factors for the three chosen products for evaluation. The UV Colour SunPrint paper is designed to be left out in the sun for a period of up to ten minutes to reach an adequate colour change and the UV photochromic paint InkoDye is designed to minimise requirements for UV exposure so that the effects can be set into the fabric as quickly as possible, often exposures around 20 to 30 minutes are required. Radiochromic films have shown varying UV sensitivities and may be more insensitive than these other products. As such, to produce a useable UV measurement sticker capable of accurately measuring SODIS appropriate levels of UV, an ultraviolet broadband filter may need to be tested and utilized during the construction of the SODIS sticker. The UV filter characteristics will include the reduction but not complete removal of UVA exposure whilst still allowing visible light through so that the user is able to visually inspect the colour change of the sticker to assess if an appropriate UV exposure has been performed.

Previous experimentation (Mantele et al. 2017) shows that most clear plastics attenuate UVA radiation. Based on this literature, it is suggested that contact paper, a clear plastic, should also attenuate UV and could potentially be used as a pre-filter to the UV art paper / UV photochromic paint or Gafchromic EBT3 film providing a match between solar UV exposure and detector sensitivity. Following testing of clear contact, assessment of other plastics will also be performed to assess which product will provide the optimal UV attenuation properties and usefulness for creation of a UV SODIS sticker.

To conform with the word and page count limitations of this report, final results only for the EBT3 film UV sensitivity and construction of the SODIS sticker will be presented. The other results can be given if required by the judges for examination.

EXPERIMENTAL AIMS

Thereby, the aim of this experiment and work is as follows.

1. Test the UV exposure measurement properties of different UV sensitive products to initially assess which product will show the best potential as a UV dosimeter for SODIS level solar UV exposure.

2. Test the use of various forms of plastics to dampen UVA penetration, in order to measure appropriate UV exposure levels and determine the potential application of this film for solar disinfection.

3. Utilise the findings of the results to create a solar UV dosimeter which can be used for applications in SODIS processes.

HYPOTHESIS

1. All three materials will provide colour change associated with UV exposure. The EBT3 Gafchromic film due to its medical application construction will provide the highest level of accuracy and reproducibility for UV exposure measurement.

2. As the thickness of contact paper or different plastic based filters are placed over the radio chromic film, increases in the level of UV filtering / removal will increase, the degree of colour change of the dosimeter will reduce. This will allow the colour change/filter combination dosimeter to vary and be matched and optimized to the exposure levels of solar UVA radiation for SODIS processes.

3. A combination detector will be able to be produced which will provide a unique detector in a sticker form which will provide easy and accurate visual verification of appropriate UV exposure for SODIS processes.

VARIABLES

During these experiments, many variables both dependant and independent are utilized. These include but are not limited to, the type of UV sensitive paper or film used, the level and type of UV radiation used and the type of plastic used for UV radiation attenuation. In each case, they are divided into independent and dependant variables were one is changed deliberately and the other value is measured to assess the change associated with the initial change. Other factors are kept constant to minimise the interaction of each variable in the experiments performed, thus allowing accurate assessment of the dependant factors to be measured and calculated.

RISK ASSESSMENT

Standard lab procedures and safety measured will be followed regarding the use of general equipment. When UV experimentation is performed outside, use appropriate clothing, hats and sunglasses to minimise solar UV exposure. During the construction phase of all experiments, use hand tools appropriately and safely as per manufacturers guidelines. Plan all work to be performed and use a system to minimise risks. Endeavour to get help when needed for construction using tools and seek advice from qualified experts when using any power tools or electric equipment.

MATERIALS AND METHODS

Experiment 1 : Evaluation of colour change of UV sensitive EBT3 Radiochromic film when exposed to solar UV radiation.

To perform this experiment, EBT3 Gafchromic film will be placed in solar radiation and colour changes quantified compared to UVA exposure levels.

EBT3 Gafchromic film:

The films come in sheets of size 20cm x 30cm and is shown in figure 3. It is originally a light yellowy green colour when unexposed and changes to a dark green to purple colour when exposed to UV radiation.

Figure 3: EBT3 Film

Cut the film into 2cm x 10cm strips and expose the films on top of a black sheet of paper to solar UV radiation. Measure UVA exposure with a calibrated UVTex meter to assess colour change associated with exposure. Repeat the experiment 5 times for reproducibility. The black paper backing is used to minimise variations in reflected solar UV radiation through the film which may be caused by different backing colours . Evaluate the colour change seen in the Radiochromic film per unit UVA exposure and correlate these results via the application of a mathematical equation to determine the effectiveness and qualities for measurement of UV radiation , with particular interest in its ability to measure high UV exposures with a high level of accuracy.

Experiment 2: Evaluation of different plastics to attenuate Ultraviolet radiation.

Figure 4a shows 4 different types of plastics which will be evaluated for UV attenuation properties. These include gladwrap, 1mm thick polycarbonate, 3mm thick Polymethylmethacrylate (PMMA) plastic, and 0.1mm thick book contact plastic. Investigations were also performed on a range of old eye lenses sources from Spec Savers. These are shown in figure 4b. These lenses used different plastics and colouring such as tinted sunglasses mode. There are four main types of plastics used in these eyeglass and sunglass lenses: These being CR39 - plastic, Trivex, polycarbonate, and high-index plastic. All 4 types are used for different applications in eye glass wear. CR-39 is the cheapest, trivex and polycarbonate are scratch resistant and normally block most UV and high index plastic is used for large corrections as they can be made thinner than other plastics. Results for each type of plastic and lens are given and results for UV transmission are measured 5 times for reproducibility.

Analysing the EBT Gafchromic Film

Film Scanning:

Figure 4a: Plastics tested

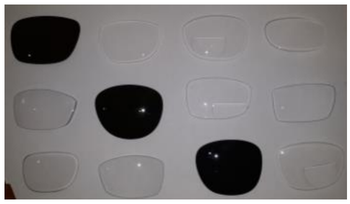


Figure 4b: Lenses tested

The film was scanned on an Epson V800 Scanner using 12-bit transmission mode and 50dpi (dots per inch) resolution using the red channel for analysis. 12-bit mode was used as it provided the highest level of contrast resolution with a pixel value of 65536 defined as complete saturation, and 0 defined as the complete absence of detectable light. Transmission mode measures the light that passes through the film as opposed than a reflection analysis.

Film analysis:

- Analysis was performed utilizing a software program called Image J. Using this software, the colour density of darkness of the film in any defined region of interest can be measured along with statistical parameters such as the standard deviation.
- The film was placed near the centre of the scanner in the same direction to minimize errors associated with film position and ensure reproducibility.
- Using only the red channel, a 1cm x 1cm square region of interest in the centre of each 3cm x 3cm piece of film was selected and the pixel value (colouration value) and standard deviation of each measurement point was recorded.
- The results along with measurements for a control or non-exposed EBT3 film in the same manner were used to calculate the net optical density (net OD) for each experimental film and evaluate the effects of contact on measured film colouration due to incident UV exposure.
- An estimated number of contact layers to provide adequate UV filtering so that EBT3 film could be used as a dosimeter for SODIS at a UV exposure level of 555Whm^{-2} was then calculated.

Perform any other UV attenuation experiments on other known plastic materials to provide an optimal UV filter to Gafchromic film for UV SODIS verification.

Experiment 3: Construction of a UV sticker for SODIS equivalent UV exposure verification.

Utilising the optimal properties and materials discovered in experiments one and two, construct a useful and unique sticker which can be used for verification of SODIS Solar UV exposure.

The optimal UV sensitive material was discovered to be the EBT3 Gafchromic film and the optimal UV plastic attenuator was a 3mm CR-39 plastic lens with no specialised UV coatings. The CR-39 plastic is constructed from allyl diglycol carbonate and is a commonly used plastic in eye lenses.

Use the EBT3 Gafchromic film and the CR-39 eye lens in combination and expose the system to 555 Whm^{-2} of UVA radiation. Place the EBT3 film on a black paper backing and place the lens directly over the EBT3 to completely cover it with no scattered UV incident on the film. Place the detector in Solar UV radiation next to a calibrated UVTex UVA meter and expose the system to known doses. Assess the colour change associated with the varying exposures.

When the system has been exposed to 555 Whm^{-2} remove the EBT3 Gafchromic film from the UV source and scan the film using an EPSON V800 colour matching desktop scanner. The film will be scanned to assess the pixel density and colour values in the red, green and blue components of the spectrum for accurate future colour matching.

Once the scans have been performed create a circular sticker using the EBT3 film colour for a 555Whm^{-2} exposed film at the outer circular colour whilst leaving the centre of the circle as a new piece of unexposed EBT3 Gafchromic film. Use the outer circle colour to define when the SODIS sticker has been exposed to the correct amount of UV radiation by matching the colour of the inner circle (new EBT3 film) to it. Once it is the same colour or darker, the water has been exposed to the correct amount of UV radiation.

RESULTS AND DISCUSSION

Experiment 1: Evaluation of EBT3 film sensitivity to UVA exposure

Gafchromic EBT3 film UV sensitivity

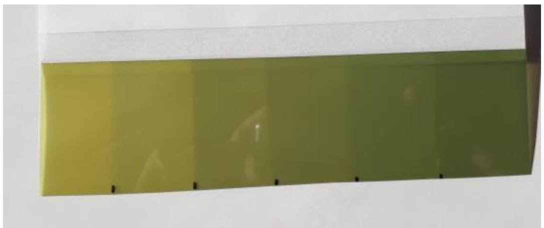


Figure 5: 5-min interval colour changes of film

Figure 5 shows a sample photo of an exposed Gafchromic EBT3 film which was exposed to UV radiation in 5-minute intervals in Mangerton NSW during June 2018. To achieve this exposure, the film was partially covered each 5-minute interval and the covering moved along the film strip. This film shows the lightest green colour of an unexposed part of the film through to a part of the film exposed to 25 minutes of UV. UVA exposure was also measured during this time interval using a UVTex UV meter with a manufacturers quoted accuracy of ± 2.5%. A 40-minute exposure received approximately 18.0 Whm^{-2} of UV radiation during experimentation.

Table 1

EBT3 Gafchromic UV sensitivity analysis								
Solar UV Exposure		Colour density (16 bit) (65536 = white) (0 = black)						
Time (min)	Whm^{-2}	density (16 bit)					Average	St Dev
0	**0**	42362	42372	42557	42586	42387	**42452.8**	**109.2**
5	**2.25**	41552	41528	41288	41652	41523	**41508.6**	**133.9**
10	**4.5**	40283	40228	40512	40128	40175	**40265.2**	**149.6**
15	**6.75**	39887	39765	39572	39771	39136	**39626.2**	**296.4**
20	**9**	38263	38776	38750	38246	38912	**38589.4**	**311.9**
25	**11.25**	37112	37184	36998	37327	37018	**37127.8**	**134.2**
30	**13.5**	36276	36257	36119	36718	35998	**36273.6**	**272.8**
35	**15.75**	35187	35227	35412	35017	35111	**35190.8**	**147.3**
40	**18**	34576	34735	34331	34510	34013	**34433.0**	**275.9**

Table 1 shows the results for 5 separate exposures performed on 5 different Gafchromic EBT3 film samples. Results show the time of exposure and the measured UV exposure. Results also show the colour density of the film measured in the red component of the scanner results obtained with an Epson V800 desktop scanner. Using this 16-bit system per colour component, a colour density of 65536 would means a complete absence of colour or a saturated white signal. A colour density of 0 would mean complete saturation in the red component of the signal which would mean a completely dark image in the blue section of the spectrum.

Table 2 shows a summary of the results with the optical density of each exposed film piece with respect to UV exposure along with the uncertainty in measured results at each time interval. These results are also shown in figure 6.

Table 2

Summary of EBT3 Gafchromic UV exposure measurements				
Time	Whm^{-2}	OD	St Dev	% Uncertainty
0	**0**	**0.1886**	0.0022	1.2
5	**2.25**	**0.1983**	0.0028	1.4
10	**4.5**	**0.2116**	0.0032	1.5
15	**6.75**	**0.2185**	0.0065	3.0
20	**9**	**0.2300**	0.0070	3.1
25	**11.25**	**0.2468**	0.0031	1.3
30	**13.5**	**0.2569**	0.0065	2.5
35	**15.75**	**0.2701**	0.0036	1.3
40	**18**	**0.2795**	0.0070	2.5

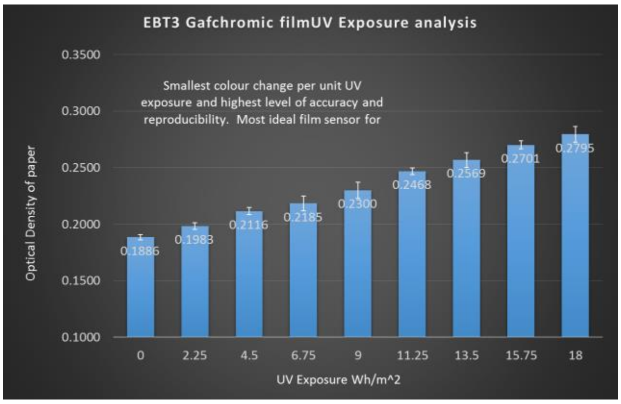


Figure 6: Film Exposure Analysis

Two important facts are discovered by this experiment. Firstly the Gafchromic EBT3 is the least sensitive to UV radiation of all three detectors tested with a colouration change of approximately 0.1 OD units after 40 minutes (approx. 20 Whm^{-2}) of solar UV exposure. The colour change of this film can also keep darkening a considerable amount more than this initial testing level which is a major advantage of this film type. The level of uncertainty in results for the EBT3 film is by far the best and would be considered adequate for a SODIS detector. Results show that on average the uncertainty in measured UV per unit colour change is of the order of 2-3% across the range of exposures tested. As such, these two properties make the Gafchromic EBT3 film the most suited for use in Solar disinfection UV exposure measurement.

During experimentation it was also noted that the construction of the film made the film water resistant and could be easily and accurately used when wet, which is a property not available with the SunPrint Paper or the InkoDye paint samples. As such, the EBT3 film was evaluated as the most appropriate film to use for further testing and construction for SODIS sticker detector.

<u>Experiment 2: Evaluation of the UV attenuation by different types of plastics</u>

Initial testing was performed to evaluate the most appropriate plastic to make a UV attenuator that can be used in conjunction with the Gafchromic EBT3 film to produce an adequate UV assessment tool for SODIS UV exposure measurement. As the level of UV exposure will be high (555 Whm^{-2}), the material best suited to use as a filter will provide a significant amount of UV attenuation. Of the order of 95% of initial UV levels. Combining these factors, an accurate UV SODIS sticker could be produced. As such, testing was performed on many different plastics to evaluate the best material to perform this role. Initially 4 different types of plastics were evaluated, These being glad wrap, contact paper, PMMA and Polycarbonate. Results for these materials along with the results for a variety of eye lenses are given in tables 3 and 4. In these tables the UV intensity measured both incident on the lens and that transmitted through the materials are given. Table 5 shows a summary of the percentage attenuation as well as the uncertainty in measurement. Figure 7 shows these results as well.

Table 3

Type of Plastic	Initial UV intensity							
	microWatts per centimeter squared					Average	St Dev	% Uncertainty
Glad wrap	1250	1232	1269	1270	1255	1255.2	15.6	1.2
Contact Paper	1258	1277	1280	1265	1265	1269.0	9.2	0.7
1mmPolyCarbonate	1255	1280	1246	1266	1263	1262.0	12.7	1.0
3mm PMMA	1255	1250	1244	1260	1268	1255.4	9.2	0.7
CR-39 Eye Lens	1260	1272	1280	1268	1245	1265.0	13.3	1.1
PolyCarbonate Eye Lens	1250	1255	1270	1275	1265	1263.0	10.4	0.8
Darkened Poly Carbonate Lens	1280	1285	1265	1276	1272	1275.6	7.6	0.6
Trivex Eye lens	1284	1296	1298	1275	1260	1282.6	15.7	1.2
Darkened Trivex lens	1276	1260	1280	1268	1269	1270.6	7.7	0.6
High Index Plastic Eye Lens	1288	1274	1283	1269	1279	1278.6	7.4	0.6

Table 4

Type of Plastic	Transmitted UV Intensity							
	microWatts per centimeter squared					Average	St Dev	% Uncertainty
Glad wrap	1245	1233	1235	1236	1259	1241.6	10.8	0.9
Contact Paper	1240	1215	1235	1220	1221	1226.2	10.7	0.9
1mmPolyCarbonate	15	22	15	35	46	26.6	13.6	51.0
3mm PMMA	350	347	387	379	326	357.8	25.0	7.0
CR-39 Eye Lens	75	83	65	67	61	70.2	8.8	12.5
PolyCarbonate Eye Lens	7	3	12	7	8	7.4	3.2	43.4
Darkened Poly Carbonate Len	6	13	9	2	5	7	4.2	59.8
Trivex Eye lens	3	8	1	0	4	3.2	3.1	97.3
Darkened Trivex lens	6	8	2	3	9	5.6	3.0	54.5
High Index Plastic Eye Lens	22	21	15	3	12	14.6	7.7	52.7

Table 5

Summary of UV Attenuation	% UV Attenuation	% Uncertainty
Glad wrap	1.1	0.9
Contact Paper	3.4	0.8
1mmPolyCarbonate	97.9	1.1
3mm PMMA	71.5	2.0
CR-39 Eye Lens	94.5	0.7
PolyCarbonate Eye Lens	99.4	0.3
Darkened Poly Carbonate Lens	99.5	0.3
Trivex Eye lens	99.8	0.2
Darkened Trivex lens	99.6	0.2
High Index Plastic Eye Lens	98.9	0.6

Results show that a large range in UV attenuation is seen for different materials. The glad wrap and contact paper provide low levels of UV attenuation. However, this is expected as they are very thin materials. It is expected that multiple layers of these materials could be used to increase the total attenuation of UV rays. For example, the contact paper provides approximately 3.3% attenuation. As such, it could be expected that 10 layers would provide an attenuation of 33% if a linear relationship was seen. Materials such as polycarbonate and Trivex provided the largest amount of UV attenuation where 99 to 100% absorption was seen. These values are also expected based on literature reviews as these materials include an internal structure which is largely UV opaque and additives are included in the material to block UV rays. Of interest in our results are those for the CR-39 plastic lens. CR-39 is a plastic polymer. CR-39 is an abbreviation for "Columbia Resin #39", the 39th plastic of that type made by Columbia Resin, the company that developed the polymer (https://www.eyebuydirect.com/blog/what-are-glasses-lenses-made-of/). This lens provided approximately 95% blocking for UVA rays. A literature review showed that the UV that CR-39 allows through is in the wavelength range of 380nm to 400nm. This is the range of UV that kills biological pathogens in the SODIS process, allowing 5% of UVA through also allows an appropriate relationship between the EBT3 film sensitivity to UV radiation and the total UV exposure required for SODIS applications. So the combination of a CR-39 lens and the EBT3 is the most promising for a SODIS sticker.

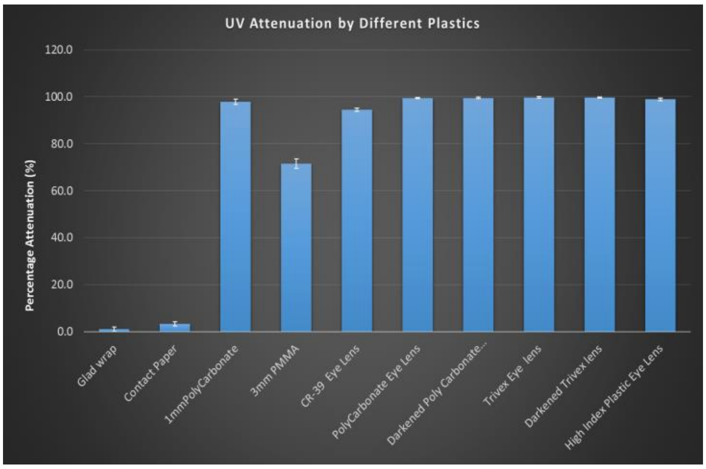


Figure 7: Summary of UV Attenuation of Different Plastics

<u>Experiment 3: Construction of The SODIS Sticker for UV exposure assessment</u>

Experiments 1 and 2 showed that the optimal products to make a UV sensitive detector for SODIS UV measurement would be Gafchromic EBT3 film as the active layer and a CR-39 plastic lens (3mm thick) and the UV filter. The design brief for construction needed to include the following considerations.

1. The SODIS detector must be small enough so that is does not block UV radiation incident on the PET Water bottle itself.
2. The SODIS detector must be able to be placed either on or next to the PET Water bottles containing the water for sanitation.
3. The colour change of the EBT3 Gafchromic film must be able to be easily seen visually without occulation and be able to be compared to the film colour when the EBT3 film has been exposed to the correct amount of UV exposure.
4. The EBT3 film needs to be completely covered by the filter during the whole duration of the exposure process. (which may be up to 10 hours).
5. The detector must be water and dirt resistant to withstand rain, spilt water or dirty areas of application.
6. The SODIS Sticker must be very simple to use and interpret when enough exposure has been received.
7. The SODIS sticker must be a very cheap product which is cost effective in a developing community. That is, it should cost less than a few cents per sticker.

To incorporate all these design options within the brief, the following approach to develop the SODIS sticker was performed:

The colour change of the EBT3 film utilizing the CR-39 filter was measured and assessed over a large UV exposure range from 0 up to 1000Whm^{-2} as shown in figure 8. This colour change was assessed visually and measured numerically through assessment of change in film optical density using red channel analysis in image J software.

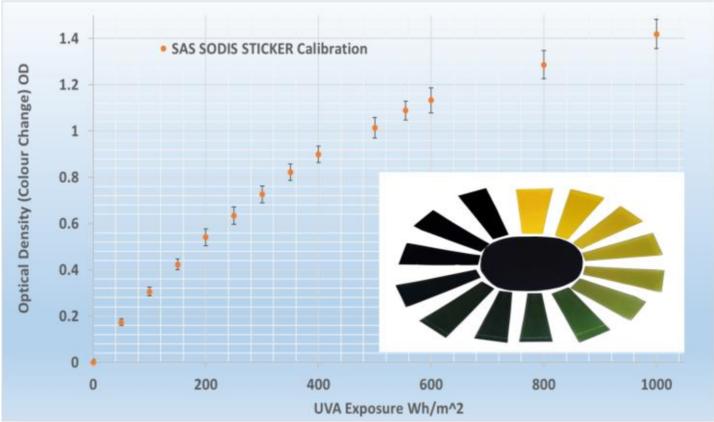


Figure 8: SODIS Sticker Calibration Curve

The colour change of the film when exposed to exactly 555Whm^{-2} (the SODIS colour) was captured and transferred to an image document for incorporation into the background colour of a small circular sticker which could be used for SODIS applications. Transfer of the SODIS colour was complicated by the process of colour matching when printing was performed. Figure 9 shows some variations of the SODIS colour incorporating variations in brightness and contrast so that the most accurate visual match would be achieved after printing was performed.

Figure 9: SODIS Sticker Colour Variations

Once a correct colour match was found, the sticker could be created. A background sticker was used for the SODIS sticker which incorporated a hole design to allow the UV rays to be delivered to the stickers active layer from both the front and back of the sticker.

This design feature produces a feature that no other detector has for SODIS UV exposure evaluation. The open design and the transmission / transparent sensitive layer allows directly incident UV and transmitted and backscatter UV radiation to be measured. This is the same situation as what happens in the water during the SODIS process. Every other detector can only measure directly incident UV radiation because the detectors have opaque backing or the detector is a solid state detector which cannot measure reflected UV radiation.

This design is a significant step forward for SODIS UV water disinfection measurement.

Figure 10a & 10b: The SODIS Sticker Construction

Over a white base sticker with a hole cut in the "active zone", a 5 mm x 5 mm square of Gafchromic EBT3 film is placed. This is the active UV sensitive component of the SODIS Sticker.

The SODIS Colour background that was printed was cut using a circular dye at a size smaller than the white sticker background and then a smaller inner circle was also cut so that a donut of the background colour could be placed over the EBT3 film. This SODIS colour was also printed on a sticker material so that when placed over the EBT3 film is stuck together to form one complete SODIS sticker as shown in figure 11a. The SODIS Detector is completed with the inclusion of the 3mm CR-39 plastic lens (Figure 11b) on the top and the bottom so that UV intensity is calibrated from both directions.

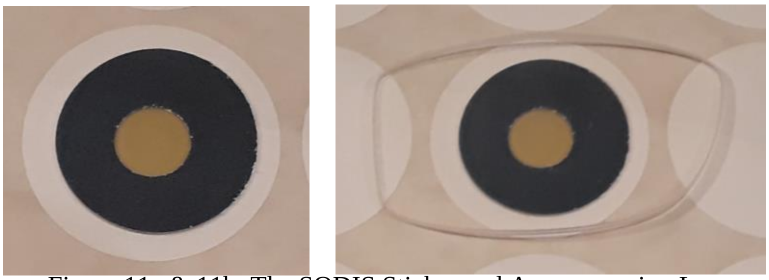


Figure 11a & 11b: The SODIS Sticker and Accompanying Lens

The SODIS detector is complete and when required can be placed over or under a PET bottle to be sanitised. Only 1 sticker is needed per batch of water to be sanitised as long as all bottles are kept in the same solar conditions (Figure 12). (That is, all in the sun or in the same area with no shadows covering some of the bottles and not the other).

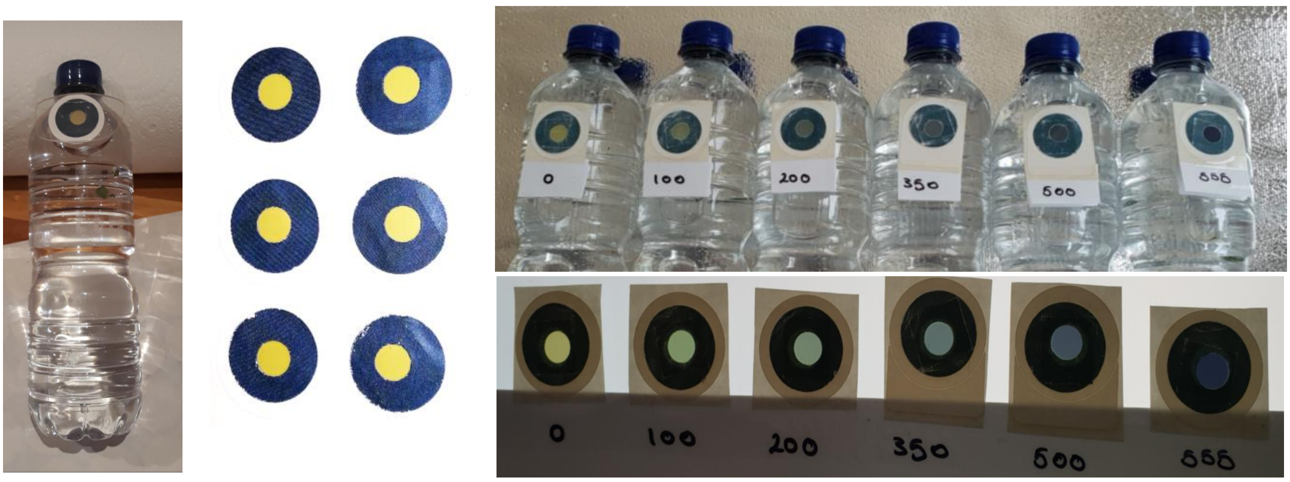


Figure 12: The Completed SODIS Sticker and In Field Use

The breakdown of costs of the sticker are as follows. The EBT3 Gafchromic film costs $10 US for one 20cm x 30cm sheet. For each sticker, a 5mm x 5mm square is required. Thus 40 x 60 = 2400 squares can be cut from the one sheet. Thus each piece of Gafchromic film costs 0.417 US cents. The white background stickers cost $4.90 for a pack of 2400. Thus each one costs 0.20 US cents. The SODIS colour top costs the same as the background sticker but with the additional cost of printing which was estimated to cost approximately 0.05 US cents per sticker bring the total cost for the SODIS colour top to 0.25 US cents.

Thus the total cost per sticker is 0.417 + 0.20 + 0.25 = 0.867 US cents. The UV filter lens was a reject lens from Specsavers but it is assumed that a 3mm thick 2cm x 2cm piece of CR-39 plastic with attached elastic strap to hold it onto the Pet bottle would cost in the order of 10 US cents. This UV filter is reusable and can last a long time with appropriate care.

This the SODIS Detector has been developed at a total cost of less than 1 US cents per sticker with a 10 US cent initial outlay for the SODIS detector UV covering filter.

Importantly, these costs are with me buying them at retail pricing. I expect that with wholesale and large volume purchases, the cost will be significantly reduced. The original design brief has been accomplished. The SODIS detector :

1. Is small enough to be placed over the lid of a bottle, it does not block UV rays reaching the water.
2. Can be placed on top of or next to a water bottle for Solar disinfection.
3. The colour change section of the SODIS sticker is easily seen visually and in not blocked by any parts of the detector and can be assessed by a child for a colour match.
4. The UV filter lens can easily cover the SODIS sticker and be reused many times to produce accurate SODIS UV exposure verification.
5. The SODIS Sticker and UV filter are water resistant due to the plastic coating of the EBT3 films active layer. (no water penetration up to 6 hours soaking in water).
6. The results of UV exposure are very easy to interpret with a visual colour change needed to make the inside circle darker than the outside circle for an effective SODIS process to occur.
7. The SODIS detector is estimated to cost less than 1 US cents per sticker with an upfront cost of 10 cents for the original UV filter which is reusable over a long period of time with proper care.

As such, the SODIS sticker can provide an effective method to accurately measure and determine whether Solar disinfection of biologically contaminated water is achieved and will help many communities world wide and has the potential to reduce disease and sickness associated with drinking biologically contained water.

FINAL FIELD TESTING

Field Testing was performed with the SODIS Sticker to determine if appropriate solar biological disinfection was able to be performed with the UV exposure level that was delivered when the SODIS Sticker reached the colour change produced to match the outside calibration colour of the sticker.

Figure 13: Bottles of water prepared for SODIS solar UV exposure with SODIS Stickers in place in front of and behind the water.

The stickers were placed on the top side and bottom side of the SODIS PET bottles and placed out in the sun on a reflective blanket to provide UVA exposure. This is shown in figure 13.

This process began at 9am. The bottles were left out over various periods until the SODIS sticker had changed colour to a level that matched the outside of the sticker. Various stages of the colouration are shown in figure 14 which also shows the level of UVA exposure they had received to produce this colour change. As can be seen the SODIS sticker active component changed colour from the original yellow colour to a royal blue colour with UV exposure. At 555Whm^{-2} UVA exposure the visible colour change matched the outside colour and thus showed the appropriate use of the SODIS Sticker for UVA exposure estimation for SODIS processes.

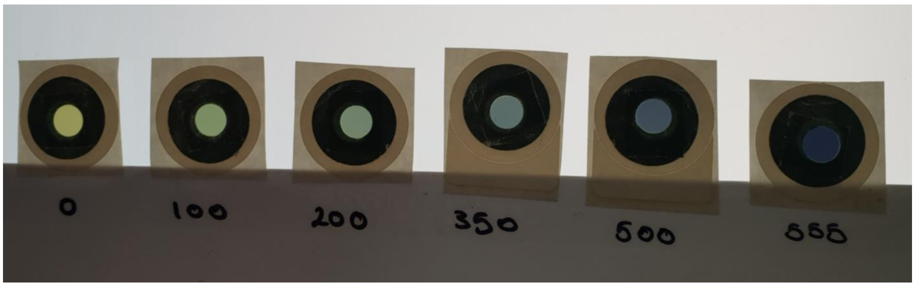


Figure 14 : Colour change of the SODIS sticker with calibrated UVA exposure.

The time required to reach 555Whm^{-2} varied dramatically as expected with this taking between 4 hours and more than 12 hours over the investigation period. This is a significant finding as the WHO recommendation are for the bottles to receive 6 hours of Solar Exposure. However, there is a caveat in this that the level of solar exposure is based on an average solar irradiation at a certain latitude during a certain season. These details cannot be obtained by those who need water to be disinfected from biological pathogens. Thus sometimes the bottles may not be biologically disinfected which holds significant and substantial health issues. Sometimes they will be over irradiated which is not a problem but can slow the release of water for consumption which may be a problem in hot dry times or when more water is required for consumption. The water originally had a faecal coliform count of between 6000-10000 cfu/100 mL and testing showed that after appropriate exposure as measured by the SODIS Sticker, the count had reduced to <1 cfu/100 mL and thus the water was safe to drink.

As a consequence of the UVA exposure versus time results where an adequate UV exposure had not been reached from 6 hours exposure, testing was performed for faecal coliform counts when the level of SOLAR exposure over 6 hours but had received less than the appropriate UV exposure as measured by the SODIS stickers. The values of UV exposure were not accurately measured but the stickers showed that a lower colour change had occurred. For these experiments the results showed that with an initial coliform count of 6000-10000 cfu/100 mL in the water, the values had reduced to an average of 4250 cfu/100 mL after exposure. These results show that SODIS HAS NOT been performed over 6 hours in this case. Thus, the water would not be safe for drinking as would be thought based on the 6 hours exposure requirements.

The SODIS sticker provides a substantial improvement in the quality control for the Solar disinfection process and could potentially improve the life quality and life safety of those in need who are reliant on water that needs to be biologically disinfected before consumption

The other major improvement of the SODIS Sticker over other methods of Solar exposure evaluation is the transmission style measurement of UV using this type of detector. It is well known that UV radiation can be reflected and absorbed in any angle. As such, UV which is incident directly from the sun will be measured by other opaque detectors which have a backing material to them. This could be another form of sticker or a solid state device which has electronics behind it. Initial results show however that when a reflective material is placed behind the water, up to 25% extra UV is reflected back through the water. This UV will ONLY be measured by the SODIS sticker and not other detectors. This is all because of the partially transparent makeup of the SODIS Sticker as shown in figure 15.

This unique feature gives the SODIS sticker an advantage for total UV exposure measurement over other detectors. This minimises the risks associated with wrong UV exposure measurement especially when different backings are used behind SODIS bottled. These backing could be reflected sheets or just the dark dirt on the field which have significant differences. In either case the SODIS Sticker would accurate evaluate the UV exposure level of the bottles.

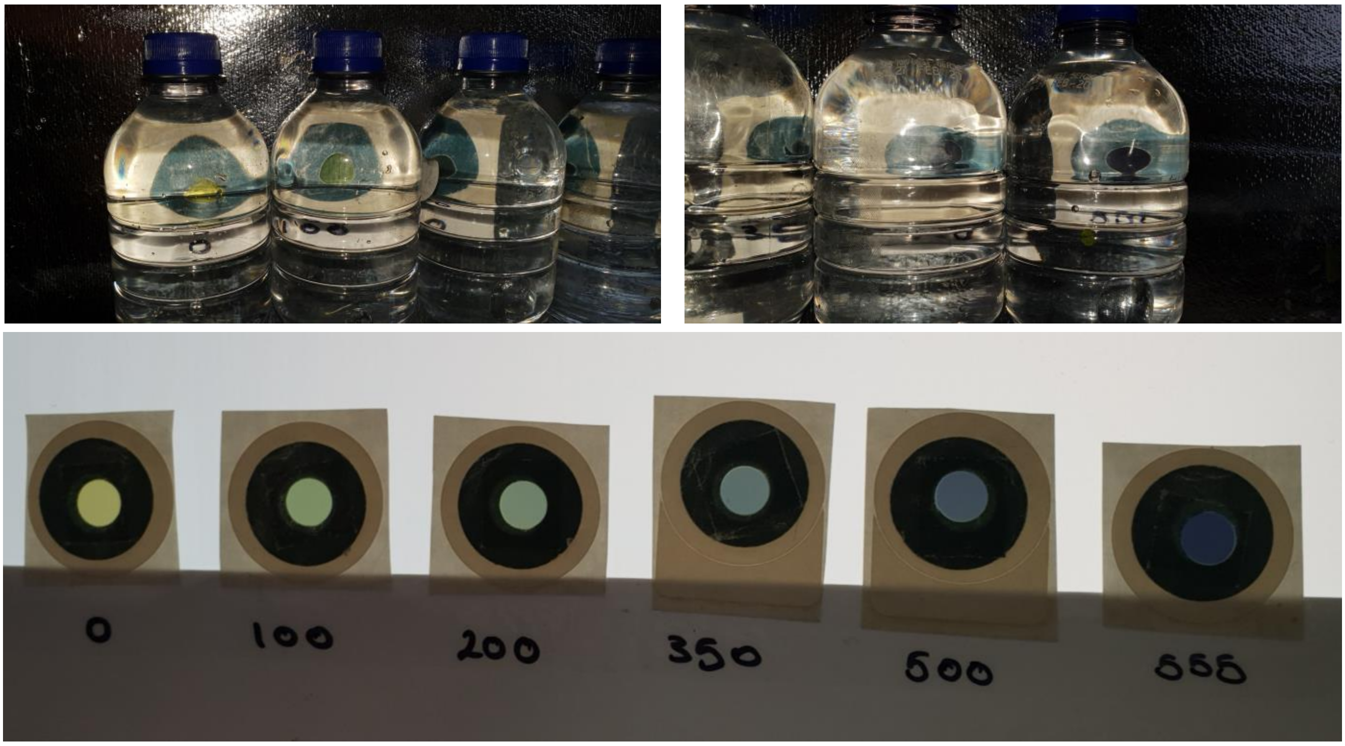


Figure 15: The partially transparent, SODIS Stickers that can measure both direct and reflected UVA exposure.

CONCLUSION

A new novel and innovative Ultraviolet radiation sticker has been developed to accurately measure large solar UV exposures for Solar Disinfection of water. The SODIS sticker is capable of accurately measuring the solar UV exposure required to sanitise drinking water through the use of 2 innovative products built together. A high accuracy transparent, UV sensitive film coupled with a partially UV blocking filter was used to construct the SODIS Sticker.

This design feature produces a feature that no other detector has for SODIS UV exposure evaluation. The open design and the transmission / transparent sensitive layer allows directly incident UV and transmitted and backscatter UV radiation to be measured. This is the same situation as what happens in the water during the SODIS process. Every other detector can only measure directly incident UV radiation because the detectors have opaque backing, or the detector is a solid state detector which cannot measure reflected UV radiation. This design is a significant step forward for SODIS UV water disinfection measurement.

The SODIS Sticker, can be used in any situation and was constructed at a cost of less than 1 US cents per sticker. This is substantially cheaper than other comparable products.

Testing of water for biological disinfection after 555Whm^{-2} of UVA exposure as measured by the SODIS Sticker showed that faecal coliforms were reduced from an initial count of 6000-10,000 cfu/100 mL to less than 1 cfu/100 mL. When the SODIS process was only partially performed due to thick cloud cover over the same length of solar exposure time (recommended 6 hours) where the SODIS Sticker measured less than 555Whm^{-2} of UVA exposure, the coliform count was reduced from the initial 6000-10,000 cfu/100 mL to 4250 cfu/100 mL. As such, the SODIS process was not performed appropriately. These results show the effectiveness of the SODIS STICKER to determine the effective solar biological disinfection of water and could potentially significantly further improve the sanitation of drinking water for those in need and improve their life quality and life safety.

FUTURE WORK

The construction and testing of these dosimeters showed that they were useful in quantifying the solar radiation exposure required for SODIS processes to be achieved. Future work would be the actual use in the SODIS sticker in a developing country for actual deployment. It would also be useful to assess the lifespan of the dosimeter when stored. The active material in the sticker is UV sensitive and may darken slightly with age and this still needs to be evaluated.

PRELIMINARY NEW WORK ON UV FILTER / COATING

Following the research work performed for this project and write up I have been working on a improved UV filter to work in conjunction with the UV sensitive film. At present I am very excited at the possibility of the use of a thin film / coating that I have developed which can provide the appropriate filtration to produce a viable improved SODIS Sticker which does not require the use of a separate UV filter. This coating has undergone initiate testing and been shown to allow a distinct colour change in the film when exposed to 555 Whm^{-2} of UVA rays. The coating is also waterproof and will coat both the front and back of The SODIS Sticker active film thereby allowing the stickers to be used in any environment. Results are not finalised however I plan to show these results at my presentation when in Stockholm.

ACKNOWLEDGEMENTS

This project was performed as a Physics research report for my IB studies. I would like to thank my Teacher, Mr John Kennedy for his input into project design and reading and comments on the mathematical processes I used for this project. All research, project selection and mathematical calculations were performed by myself. The engineering design and construction processes were performed by myself with input and discussions with my older brother Ethan. This project started as an idea to extend my previous work on solar water sterilisation for medical use in developing communities which I had the honour of presenting at the Stockholm Junior Water Prize in 2017.

REFERENCES

Australian Radiation Protection and Nuclear Safety Agency n.d., *Ultraviolet radiation index*, accessed 22 April 2018, <https://www.arpansa.gov.au/our-services/monitoring/ultraviolet-radiation-monitoring/ultraviolet-radiation-index>.

Burton, A 2012, ‘DRINKING WATER QUALITY: Purifying Drinking Water with Sun, Salt, and Limes’, *Environmental Health Perspectives*, vol. 120, no. 8, August, pp. 305-306.

Canadian Centre for Occupational Health and Safety 2016, *Ultraviolet Radiation*, accessed 22 April 2018, <https://www.ccohs.ca/oshanswers/phys_agents/ultravioletradiation.html>.

Katsuda, T, Gotanda, R, Gotanda, T, Takuya, A, Tanki, N, Kuwano, T & Yabunaka, K2015, ‘Comparing three UV wavelengths for pre-exposing Gafchromic EBT2 and EBT3 films’, *Journal of Applied Clinical Medical Physics*, vol. 16, no. 6, 1 November, pp. 449-457.

Lloyd, J 2004, ‘Variation in calibration of hand-held ultraviolet (UV) meters for psoralen plus UVA and narrow-band UVB phototherapy.’, *British Journal of Dermatology*, 1 June, accessed 5 May 2018, <https://www.ncbi.nlm.nih.gov/pubmed/15214904>.

Manley, M, McCavana, J, 2016, ‘Variation in calibration of hand-held ultraviolet (UV) meters for psoralen plus UVA and narrow-band UVB phototherapy.’, *European Journal of Medical Physics*, vol. 32, no. 7, 1 July, accessed 5 May 2018, <https://www.ncbi.nlm.nih.gov/pubmed/15214904>.

Mäntele, W & Deniz, E 2017, ‘UV-VIS absorption spectroscopy: Lambert-Beer reloaded, *Spectrochimica Acta A Mol Biomol Spectroscopy*, February, pp. 965-968.

Safely managed drinking water 2017, Unicef, pdf, accessed 7 April 2018, <https://data.unicef.org/wp-content/uploads/2017/03/safely-managed-drinking-water-JMP-2017-1.pdf>.

SODIS Manual 2016, SANDEC, pdf, accessed 7 April 2018, <https://www.sodis.ch/methode/anwendung/ausbildungsmaterial/dokumente_material/sodismanual_2016.pdf>.

Solar Energy Development and Operations n.d., Vaisala, accessed 22 April 2018, <https://www.vaisala.com/en/lp/what-makes-solar-resource-data-bankable>.

Solar Water Disinfection 2002, EAWAG & SANDEC, pdf, accessed 7 April 2018, <http://www.sodis.ch/methode/anwendung/ausbildungsmaterial/dokumente_material/manual_e.pdf>.

van Battum, LJ, Huizenga, H, Verdaasdonk, RM & Huekelom, S 2015, ‘How flatbed scanners upset accurate film dosimetry’, *IOP Science*, February, pp. 625-650.

World Health Organisation 2018, *Drinking-water*, accessed 7 April 2018, <http://www.who.int/en/news-room/fact-sheets/detail/drinking-water>.