PLASTIC BAGS FOR WATER TREATMENT:

A NEW APPROACH TO SOLAR DISINFECTION OF DRINKING WATER

by

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Abstract

Waterborne disease is the cause of death for over 1.6 million people annually, and it is contracted primarily through inadequate access to safe drinking water, inadequate sanitation facilities, and inadequate hygiene practices. Solar disinfection (SODIS) is a low-cost water treatment technology that uses resources that are commonly available in much of the developing world, the most important being plastic beverage bottles. SODIS relies on solar ultraviolet radiation to kill germs in contaminated water contained in these plastic bottles, so that water can be rendered safe for consumption. However, in remote regions plastic bottles are often unavailable, or are prohibitively expensive. For this reason there exists a need for an alternative to plastic bottles for SODIS use in remote regions of the world. In this study, real and artificial sunlight exposures, standard microbiological enumeration methods, and tensile strength and optical transmittance measurement methods, were used to evaluate whether a plastic SODIS bag is a potential alternative to SODIS bottles. SODIS bags were found to yield as much as 74% higher treatment efficiencies than SODIS bottles, which may be because the bags were able to reach the elevated temperatures that are shown to cause accelerated treatment. The physical wear of hanging SODIS was approximately half the rate (47%) of SODIS bags' wear and this suggests that hanging SODIS bags may have a longer useful life. A curve relating water depth and the efficiency of the water treatment process in SODIS bags under certain representative treatment conditions was generated and used to predict the optimal geometry of SODIS bags. Additionally, a new method was proposed for calculating the solar UV dose, which may be more appropriate than conventional methods. These findings suggest that SODIS bags may be an appropriate alternative to SODIS bottles. The findings further provide information to guide the design and implementation of SODIS bags.

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Nomenclature

CFU – colony forming units

CPC – compound parabolic reflector

DNA – deoxyribonucleic acid

IR – infrared

NGO – nongovernmental organizations

MCL – maximum contaminant level

NOM – natural organic matter

NTU – nephelometric turbidity units

PET – polyethylene terephthalate

SODIS – solar disinfection

UV – ultraviolet

UVA, UVB, UVC – ultraviolet A, ultraviolet B, ultraviolet C

UVT – ultraviolet transmittance

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1 Motivation

This project was born out of the needs of a non-government organization called Water School, which implements community health education projects in developing countries. As a part of a program of health interventions, Water School teaches SODIS (solar disinfection) as a simple means for low-income families to treat their own drinking water, using locally available plastic water bottles and the light of the sun.

However, as Water School expands it has begun working in remote regions where plastic bottles are not locally available, so they currently ship bottles into these communities from the nearest urban center. In many cases, this is expensive and inefficient because bottles cannot be packed very tightly. For this reason Water School is interested in investigating whether bags can be developed to serve as an alternative to SODIS bottles for places where the bottles are not locally available. Bags pack much smaller than bottles, and can be shipped at lower cost, so they represent an economically preferable alternative to SODIS bottles in these remote communities.

There are many important considerations which will weigh on the ultimate decision of whether or not plastic bags can be an appropriate product for SODIS use, but this study only addresses a few of the technical factors. Other organizations are also interested in developing SODIS bags, and a loose group of collaborators is working in different roles around the world, investigating various important aspects. This study represents only one component of the work underway to address this need.

2 Introduction to Solar Disinfection

It is difficult to find a satisfactory summary of what is currently known about SODIS, so this introduction attempts to provide such an overview by giving a synopsis of the current state of each relevant field of study (microbiology, chemistry, etc) and presenting the history of the technology. Then the introduction focuses with further detail into the specific topics that are investigated within this document: photonics, dose calculation, and several topics related to SODIS bags.

2.1 The Problem: Waterborne Disease

The quality of drinking water is a concern all over the world. Over 1.6 million people die every year due to diarrhea from waterborne diseases, and 1.1 billion people do not have access to an acceptable source of drinking water (Anon.; Anon.). There are an estimated 6 to 60 billion cases of gastrointestinal illness annually (Caslake et al. 2004). The majority of these deaths are in children under 5 years of age, usually in rural areas.

2.2 The Solution: Disinfection

To avoid contracting a waterborne disease, water should be disinfected before consumption or use. Disinfection is the process of rendering microorganisms unable to infect. Some disinfection technologies achieve this by actually killing the microorganisms, and some simply make a pathogens unable to produce offspring, and thus unable to infect a host. But all methods of disinfection of water use one (or more) of three mechanisms: damaging or destroying the physical structure of the cell, interfering with the metabolism and energy production processes of the cell, and interfering with biosynthesis and growth (Anon. 1985).

The most common disinfection method is chlorination. Chlorine-based disinfectants form HOCl (hypochlorous acid), which is very effective at killing microorganisms, and has the added benefit of providing residual protection against regrowth (Snoeyink and Jenkins 1980).

Another type of disinfection of water uses ultraviolet (UV) radiation as the disinfectant. In UV disinfection radiation is absorbed by the DNA and/or RNA of the microorganism. This causes the formation of thymine dimers, which inhibit the reproduction process, rendering the microorganism unable to infect (Anon. 1985). This process is used in irradiation with ultraviolet lamps, and is a rapidly growing method of water treatment in many parts of the world. However, UV-disinfection is usually cost-prohibitive in poor regions of the world, and is limited as well to regions with access to reliable electric power.

2.3 SODIS Overview

UV radiation is also available in the form of solar electromagnetic radiation in sunlight. The use of solar radiation to treat water is called SODIS, or **So**lar Water **Dis**infection.

Invented by Aftim Accra in the 1970s (Aftim Acra et al. 1980), SODIS is an extremely simple method of treating biologically contaminated water. Many studies have found SODIS to be an appropriate water treatment method in regions where finances, resources, and education are in short supply (Rose et al. 2006; Ronán M Conroy et al. 1999; Gurung, Grimm, and Autenreith 2009; R M Conroy et al. 2001). To provide improved drinking water in regions where lack of potable water leads to high prevalence of waterborne disease, the technology relies on the ability of sunlight to inactivate or kill pathogens in water.

SODIS is performed as follows:

- The user selects a 500mL - 2L bottle, usually made of polyethylene terephthalate (PET) because pop bottles are very widely available, although it can also be made of glass or other plastics.
- If the source water is cloudy (defined by most research as having a turbidity greater than 30 NTU (Hirtle 2009), though this metric is often of limited utility in the field) pretreatment is recommended, because particulate matter in the water can absorb UV radiation and shade pathogens from being exposed to the rays of the sun. A common rule of thumb for determining whether pretreatment is necessary is the "finger test," where the users holds the bottle in his or her hand, and only if all four fingers can be seen through the bottle it is deemed clear enough for SODIS. Pretreatment usually involves a settlement process, in which the suspended solids are given time to settle out. Alternatively, the water can be pretreated by physical size exclusion, by passing the water through a piece of cloth to retain particulates before SODIS treatment. More complicated pretreatment methods have been proposed (Hirtle 2009), but they tend to subtract from the simplicity of the process, which is an important characteristic for achieving community behavior change (Moser and Mosler 2008).
- The bottle is cleaned, its label is removed, and it is filled with water from a natural source (such as a lake or river) or from a well.

- The bottle is then placed in the direct sunlight, in many cases on a “SODIS table” of corrugated sheet metal, for 1 day if it is sunny or two days if it is cloudy. This allows more than enough solar radiation to reach the water, because research suggests that an exposure time of 3-5 hours may be sufficient (Oates, Shanahan, and Polz 2003).
- When the exposure period is complete the water can be consumed.

Cleaning the bottle with brushes is not recommended, because it is more likely to increase the light absorption than decrease it, since most brushes scratch the plastic. Scratches quickly attract bits of dirt or microorganisms seeking refuge and these surface contaminants absorb radiation that could otherwise pass into the water (Hirtle 2009).

One of the most important operational factors regarding SODIS is that, once treated, the water does not need to be transferred to another container before it is consumed. Transfer between containers is a significant mechanism of recontamination in household water treatment systems in the developing world, so skipping this step minimizes the risk.

2.4 Microbiology of SODIS Treatment

2.4.1 Mechanisms of Solar Disinfection

SODIS is not yet thoroughly understood, but researchers are coming closer to a complete understanding of the process. It is known that the following mechanisms play a role in the process.

- First, UV radiation is absorbed by DNA, which causes thymine bases to bond covalently, forming dimers. These thymine dimers terminate the DNA replication process prematurely (K. G. McGuigan et al. 1998; A. Acra, Raffoul, and Karahagopian 1984). Furthermore, incorrect repair of thymine dimers can cause genetic mutation. The DNA absorbance of UV radiation is strongest in the UVC region, peaking at about 265 nm, which is known as the “germicidal wavelength” (Setlow 1974). This is the dominant mechanism in UV disinfection systems that use artificial light sources, and it is also thought to play a role in solar disinfection. Figure 1 shows the action spectrum of UV absorbance of the DNA, which peaks in the UVC region. The so-called “germicidal wavelength” of 253.7 nm (the wavelength that creates thymine dimers in DNA) is often assumed not to play a large role in SODIS because this wavelength is mostly absorbed before it can reach the organisms. However, even though most UV-C is absorbed in the atmosphere and in the plastic of the bottle, UV-C is a very high-energy form of radiation, so the little that gets through may still play a significant role in disinfection. Also, a sufficient dose of UVA and UVB radiation, which ranges from 320-400 nm, can still inactivate microorganisms. There is more UVA than UVB in sunlight, but studies conflict on whether UVA or UVB is more important to the SODIS process (King et al. 2008; Wegelin et al. 1994).

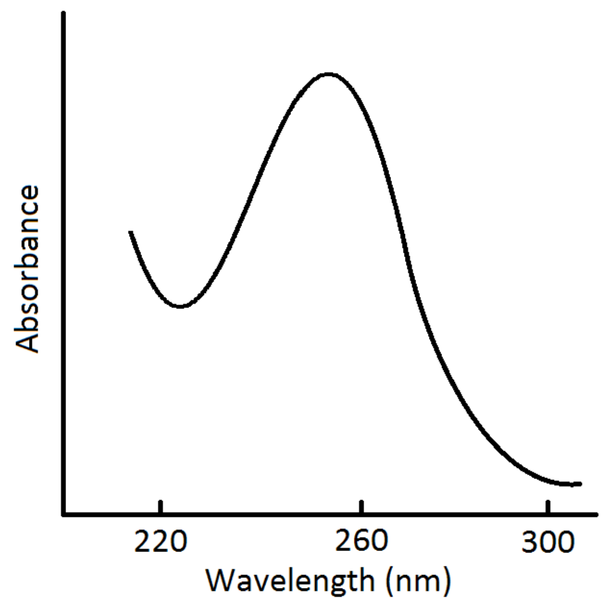

FIGURE 1 ABSORBANCE SPECTRA OF DNA

- Second, when the naturally occurring dissolved organic matter in the water absorbs UV radiation, photochemical reactions produce reactive oxygen species, such as hydroxyl radicals (OH), superoxides (O_2^-), and hydrogen peroxide (H_2O_2) (Reed 1997; Stumm and Morgan 1995). These oxidize cellular components of microorganisms, thereby damaging or killing them (K. G. McGuigan et al. 1998; Reed 1997). This causes protein damage, which is a crucial part of the inactivation process (Franziska Bosshard, Riedel, et al. 2010). Cellular functions such as DNA transcription and translation, amino acid synthesis, amino acid degradation, respiration, synthesis of ATP, glycolysis, and others are targeted by these reactive oxygen species (Franziska Bosshard, Riedel, et al. 2010; Kramer and Ames 1987; Franziska Bosshard, Bucheli, et al. 2010). Through these mechanisms, sunlight speeds up the natural senescence systems of the cell, causing inactivation and early death. Oxidative stress is accumulative – if not enough stress is reached, the organism can reconstitute, but an organism that has been partially stressed is also more susceptible to other forms of stress (Franziska Bosshard, Riedel, et al. 2010).

- Third, red and infrared radiation is absorbed by the water, which raises the water temperature. Beyond the maximum growth temperature, additional heat causes denaturization, impeding protein function and often killing the organism (Brock et al, 2000). This heat energy has a synergistic effect with the UV mechanisms at and above 45°C (K. G. McGuigan et al. 1998). When the temperature exceeds 50°C only one third of the fluence is required for SODIS to work effectively, compared to solar disinfection at lower temperatures (Wegelin et al. 1994). The rule of thumb is that below these temperatures 3 to 5 hours of solar radiation above 500 W/m^2 is adequate to render microorganisms inactivated (Oates, Shanahan, and Polz 2003).

Further research into the inactivation mechanisms is ongoing. It has been shown that the primary damage of *E. coli* cells due to SODIS treatment effects cytoplasmic membrane transport processes (F Bosshard et al. 2009). Future investigations will use a variety of methods to gain insight into the way the cells are injured and killed, including determining the ATP content of cells and traditional plating procedures (Anon.). The hope is that by detecting damage at the protein, lipid, and DNA levels the details of the inactivation mechanisms will become clear.

2.4.2 Reconstitution of Inactivated Microorganisms

Different microorganisms have different levels of susceptibility to UV radiation (Anon. 1985), and some microorganisms can even combat the effect of exposure through dark reactivation or photoreactivation. Dark reactivation occurs when the built-in “self check” of the DNA or RNA sequences of a microorganism finds and repairs the error caused by UV exposure (Charles and Zimmerman 1956). Photoreactivation occurs when low doses of UVA radiation cause the release of photolase, an enzyme that breaks up thymine dimers, restoring the viability of the organism (Harris et al. 1987). Besides these forms of reconstitution, if a sample of water is disinfected and then removed from the UV radiation source, the few remaining microorganisms that have not been inactivated can undergo normal reproduction cycles to increase the concentration again with time, provided that the right nutrients and other environmental factors (such as temperature) are suitable (Amin and Han 2009).

However, if a sample is “overdosed” with SODIS treatment (exposed for longer than the minimum recommended period) these reconstitution mechanisms can be overcome, and full disinfection can be achieved. For this reason, it is often recommended to expose SODIS bottles for a full day (and two days if it is cloudy), rather than the 3-5 hour minimum recommended exposure time (Pierik 2010).

2.4.3 Use of Fecal Coliform as an Indicator Organism

It would not be feasible to test a water sample for the presence of every possible pathogen, so indicator organisms are often used to assess a water treatment method's effectiveness. Thermotolerant coliforms are often used as indicators of fecal contamination (Schlosser et al. 2001). Fecal coliforms, and one type of fecal coliform in particular, *Escherichia coli*, are the most commonly used indicator for fecal contamination, largely because they has been thoroughly studied, are well understood, and are easy to use (Schlosser et al. 2001). The recommendation of the World Health Organization's guidelines for drinking water quality state that 0 *E. coli* and 0 thermotolerant coliforms should be present per 100mL of water for a given water supply to be deemed safe for consumption (Organization 1985).

A fecal indicator organism must be one that is always present when fecal contamination is present, but indicator organisms are also selected because they usually respond to treatment in a way that is representative of their respective classes of organisms. However this is not the case for all methods of water treatment, because the mechanisms of inactivation vary greatly from one method to another. For example, adenovirus is quite resistant to UV disinfection, but is very susceptible to chlorination. *E. coli* and fecal coliform are particularly susceptible to UV irradiation, which is the primary inactivation mechanism in SODIS, so it can be expected that using these organisms to model microbial response to SODIS may yield an optimistic result. Nonetheless, fecal coliform and *E. coli* counts remain the industry standard for SODIS testing.

For this reason, numerous studies have been conducted to determine the effectiveness of SODIS, using fecal coliform and *E. coli* as indicators. One study found that *E. coli* concentration was reduced by 6 logs in just an hour of SODIS exposure (Fujioka and Yoneyama 2002). Other studies find that *E. coli* is reduced by 3 logs when exposed to 5 hours of summer sun at mid-range latitudes (Wegelin et al. 1994), and fully disinfected in 7 hours (TM Joyce et al. 1996). Even at very high turbidity (300 NTU) full inactivation can be achieved after 8 hours (Kehoe et al. 2001). Fecal coliform can be fully disinfected in 3 to 6 hours (Reed, Mani, and Meyer 2000).

2.4.4 SODIS Tests on Other Indicator Organisms

E. coli is a convenient and widely accepted test organism, but because it is particularly susceptible to UV-based treatment methods, many researchers have performed tests on other microorganisms to try to determine the efficiency of SODIS to inactivate more resilient pathogens.

A number of SODIS tests have been performed on *Shigella dysenteriae* type I, the bacterium responsible for the strong resurgence of dysentery in much of the world since the late 1960s. It has been found to be inactivated at fairly low exposure times (Kehoe et al. 2004; M. Berney, Weilenmann, and Egli 2006), such as 1.5 hours (Kehoe et al. 2004), *Vibrio cholerae*, the bacterium responsible for cholera, is even more susceptible to SODIS than *E. coli* (Michael Berney, Weilenmann, and Egli 2006). *Salmonella Typhimurium*, a bacterium that causes salmonella, can be inactivated by 4-5 log in 5 hours of exposure (Kramer and Ames 1987). Tests show that *Streptococcus faecalis* can be inactivated at rates ranging from 3-4 log in 5 hours (Reed 1997; Fujioka et al. 1981) up to 6 logs in less than 3 hours (Reed 1997). Dejung et al. (Dejung et al. 2007) report that dose response of non-spore forming bacteria tend to be very consistent across different organisms; however, there is high variability in the results of these experiments, which may be due in part to the wide range of test conditions.

Protozoa tend to be more resistant to SODIS treatment than bacteria, due in part to the fact that during part of their life cycle they become cysts, which are resistant to harsh conditions. Of particular concern in public health circles are *Cryptosporidium* oocysts and *Giardia* cysts, the protazoan parasites responsible for two common gastrointestinal diseases, cryptosporidiosis and giardiasis. It had been found that it takes 4 hours to inactivate *Giardia muris* cysts (KG McGuigan et al. 2006). One study found that *Cryptosporidium* oocysts were inactivated by up to 90% in 1 hour (King et al. 2008), while another reported that they were not fully disinfected until 10 hours of exposure (KG McGuigan et al. 2006), and yet another found that 88% of

Cryptosporidium oocysts were inactivated in 12 hours when the turbidity was 0 NTU, but at high turbidity (300 NTU) the reduction was only 47% (H. Gómez-Couso, Fontán-Saínz, et al. 2009). The results of microbiological tests can vary for many reasons, and it is common for similar tests to yield results that are not statistically equivalent.

Viruses are the source of many water-borne diseases, but they tend to respond less favorably to SODIS treatment than both bacteria and protozoa (Dejung et al. 2007). Fujioka and Yoneyama showed that under conditions that reduced bacteria by 6 logs, viruses were only reduced by 1 – 2.5 logs (Fujioka and Yoneyama 2002). A dose of 555 Wh/m2 inactivates rotavirus and F2 by approximately same efficiency as *E. coli* (3 logs), but picornavirus is twice as resistant (Wegelin et al. 1994). Wild coliphage, a virus that infects *E. coli*, was reduced by just 1 log in a full day of exposure (10 hours) (Dejung et al. 2007). T2, another bacteriophage, demonstrated 2 log inactivation in just 3 hours when treated in a special reflective reactor (Safapour and Metcalf 1999). Poliovirus was found to respond minimally to SODIS at 25°C, although when the temperature exceeded 40°C it was inactivated quite effectively (W. Heaselgrave et al. 2006).

2.4.5 Geographic Limitations of SODIS Treatment

The solar UV radiation that reaches the earth's surface is primarily in the UVA and UVB regions, which consist of the wavelengths from 280-315 nm and 315-340 nm, respectively. This part of the radiation is capable of providing disinfection to drinking water.

Solar intensity varies with location, time of day, season, weather conditions, and many other factors. Because the areas near the equator get the most direct sunlight, it is generally recommended for SODIS to be used with the latitude range from 35°N to 35°S. The majority of underdeveloped regions of the world lie in these latitudes, which is where low cost water treatment is most needed.

However, the recommended latitude range appears to be based on supposition, because little experimental evidence for this claim has been published. Several recent studies conducted in Canada, substantially outside of the recommended latitude range, show that *E. coli* concentration can be reduced by 2.7 to >6 logs using SODIS in the summer (Hirtle 2009; Pierik 2009). However, no further direct SODIS data has been collected to support conclusions regarding SODIS at altitudes outside of the recommended range.

2.5 Chemistry of SODIS Treatment

2.5.1 Chemical Impacts of SODIS Treatment on Water Quality

SODIS treatment relies on chemical reactions that generate reactive oxygen species (ROS's) in the water (Franziska Bosshard, Riedel, et al. 2010), but these ROS's are very short lived; on the order of microseconds (Halliwell 1991). In general, these ROS's cause no significant changes to the water chemistry. SODIS alone does not remove chemical contaminants from water, it only inactivates pathogens.

2.5.2 Leaching of Chemicals from Plastic Bottles into Drinking Water

There has been significant research regarding the leaching of potentially harmful chemicals from PET bottles into commercial bottled water. It has been found that carbonyls, DEHP, phthalates, and other endocrine disruptors can leach into drinking water from commercial bottled water (Biscardi et al. 2003; Montuori et al. 2008; Wagner and Oehlmann 2009; Keresztes et al. 2009). The rate of leaching increases with both temperature and contact time (Keresztes et al. 2009).

These studies of leaching in commercial bottled water are relevant to SODIS, but conditions of commercial bottled water are significantly different than SODIS water. For example, contact time and possibly temperature (e.g. during shipment) of commercial bottled water tends to be very different than SODIS water – and these are the two most important factors in determining the extent of leaching that can occur from the plastic into the water. For this reason, several research groups have specifically investigated leaching specifically under the conditions of SODIS.

There has been some concern regarding the leaching of antimony into water contained in PET bottles, especially in the case of SODIS, because SODIS bottles are used for a prolonged period of time in direct exposure to sunlight's heating and photodegradative effects. This fear began after a paper was published by Dr William Shotyk in 2007 (Shotyk and Krachler 2007), which showed that antimony was leaching into commercial bottled water. Antimony is a regulated contaminant and possible carcinogen. However, a recent study measuring antimony concentrations in nine common, commercially available PET water bottles showed that the antimony concentrations in the water from the nine bottles ranged from 0.095 to 0.521 ppb. This range is substantially lower than the US Environmental Protection Agency (USEPA) maximum contaminant level (MCL), which is 6 ppb (Westerhoff et al. 2008). In other studies, antimony levels have been found to remain below the EU guidelines, not exceeding 1ng/ml even after 3 years of storage time (Keresztes et al. 2009).

Regarding other chemicals of concern, one study found no evidence of genotoxic risks in normal SODIS water, though genotoxicity was detected once the water had been exposed to 2 months of continuous sunlight exposure (which is much greater than the 1-2 days of SODIS exposure used in practice) (Eunice Ubomba-Jaswa, Fernández-Ibáñez, and McGuigan 2010). Levels of plasticizers were found to be no higher in SODIS water than in water not treated with SODIS (Schmid et al. 2008), and researchers found no evidence that photoproducts or additives were leaching into SODIS water.

Further confidence in the safety of SODIS with respect to leaching can be found in the words of Dr Shotyk himself, who is the scientist who first discovered the antimony-leaching phenomenon in PET bottles. The following is an excerpt from a personal correspondence that Dr Shotyk wrote to the president of The Water School, an NGO implementing SODIS projects in Africa.

> *Without reservation, I fully endorse the work of The Water School in bringing clean water to the people of Africa... The extent to which antimony is expected to be released by a few hours of exposure to the sun is so small that it represents no potential harm to the consumer… I very much hope that your important work will continue* (Shotyk 2007).

2.6 Design and Optimization of SODIS Treatment Containers and Conditions

2.6.1 Effects of Operating Conditions on SODIS Treatment

A wide range of secondary operating parameters have been shown to affect SODIS treatment, including wind speed, air temperature, geometry and orientation of the container, and water quantity (Saitoh and El-Ghetany 2002). Orienting the bottles in an inclined position (to maximize solar exposure) can increase efficiency by 10-20% (Amin and Han 2009). Within the range of 0.5 – 2 L, bottle volume seems to have no significance on treatment efficiency (S. C. Kehoe et al. 2001; Meera and Ahammed 2008). Moderate levels of turbidity (38 NTU) have been shown to actually improve SODIS treatment, though no explanation is provided (Meera and Ahammed 2008), and it has been shown that higher turbidity of 100 NTU does decrease treatment efficiency (Amin and Han 2009).

A multi-factorial mathematical model investigating the interactions of radiation intensity, turbidity, and time found that all these factors were important, but that radiation intensity and exposure time were much more significant than turbidity (Hipólito Gómez-Couso, Fontán-Sainz, et al. 2009).

2.6.2 Attempts to Improve the SODIS Process

There have been many attempts to accelerate and improve the efficiency of the SODIS process through the addition of extra steps, additives, and apparatuses. A number of researchers have investigated scaling up SODIS to treat volumes in the 25-40 L range, either in flow-through or batch configurations. These studies generally conclude that this larger scale approach can work reasonably well, and that the cost per unit volume of treated water is quite low (Caslake et al. 2004; Sommer et al. 1997; Eunice Ubomba-Jaswa et al. 2010; Vidal and Diaz 2000; R H Reed, Mani, and Meyer 2000). However no examples could be found of this approach gaining long-term traction in field implementations. This is probably because the upfront cost of these purpose-built units is significantly higher than the conventional SODIS bottles (Eunice Ubomba-Jaswa et al. 2010), which is a prohibitive barrier to their use.

There has been extensive research into the benefit of adding solar concentrators / reflectors to the SODIS apparatus. Many of these studies use non-tracking compound-parabolic collectors (CPCs), which were originally developed for solar energy applications, but apply quite well to solar disinfection as well. Most of these studies conclude that the reflectors increase treatment efficiency, though one study found the reflector was only beneficial in low light conditions (Shibu K Mani et al. 2006). Besides increasing the UV exposure, solar concentrators also can increase sample temperature, which can improve the process efficiency. For example, in one case a reflector cause temperatures to reach 65 degrees, while without the reflector it only reached 50^{o}C (A. Martín-Domínguez et al. 2005).

Another area of study for the acceleration of SODIS is the addition of photocatalysts to the system, especially TiO_2, to increase the production of •OH and thereby increase oxidative stress on microorganisms (F.M. Salih 2002). This is usually done by coating the inside of the reactor wall (be it a bottle or a larger scale system) with TiO_2. There is no consensus on whether it helps significantly, as some studies find that TiO_2 makes a measureable contribution to the disinfection process, as much as doubling the treatment efficiency (Gelover et al. 2006), while others find little or no improvement (McLoughlin, Kehoe, et al. 2004; McLoughlin, Ibáñez, et al. 2004), and still others find irregular responses as different concentrations and particle sizes (F. M. Salih and Pillay 2007). It has been shown that TiO_2 can contribute the ability to remove chemical contaminants or natural organic matter (NOM) in addition to killing many microorganisms (Shibu K Mani et al. 2006; F.M. Salih 2002; Gelover et al. 2006). However, even with photocatalysis certain organisms are resistant to treatment, such as cysts (Lonnen et al. 2005).

A number of chemical additives have been investigated to accelerate the SODIS treatment process. Rather than relying on the solar UV radiation's reaction with NOM to generate reactive oxygen species, researchers have tried adding H_2O_2 directly to the SODIS container, and found that it significantly enhances the treatment efficiency (Sciacca et al. 2010). Other research has suggested that, because oxygen is such an important reactant (V. Meyer and Reed 2004), the bottles should be shaken up before treatment to increase the oxygen level in solution (K G McGuigan et al. 1998; R H Reed, Mani, and Meyer 2000). However a conflicting study found that shaking the bottle actually decreases the efficiency of the process (S. C. Kehoe et al. 2001). Other additives that have been shown to improve efficiency include riboflavin (Wayne Heaselgrave and Kilvington 2010), methylene blue (Wegelin et al. 1994), and various forms of iron and Fenton's reagent (Lonnen et al. 2005; V. Meyer and Reed 2004).

These attempts to improve the efficiency of SODIS tend to be of limited value in the field where the simplicity of the process is an important strength. SODIS implementers often encounter anecdotal accounts reports and testimonials describing instances in which these complicating factors have significantly hindered the uptake of SODIS because they introduced extra room for error or misunderstanding, or because they rely on materials that are not widely available or affordable in the developing regions where SODIS is most appropriate. For an approach that relies primarily on education and local resources, it is unlikely that extra complications will add to the effectiveness of the intervention, especially when the technology is very effective well in its simplest form. Nonetheless, it is worthwhile to understand the nuances of these extra options.

2.6.3 Effect of Temperature on SODIS Treatment Efficiency

Another area of study investigates the interplay between UV radiation and temperature. There is no variation in treatment efficiency in the range of 12-40^{o}C; the process is not accelerated by temperature until at least 40 degrees (Carey et al. 2011). However, a number of studies have shown that when the temperature exceeds 45 or 50 degrees treatment accelerates significantly

(Wegelin et al. 1994; TM Joyce et al. 1996), even if turbidity is high (K G McGuigan et al. 1998; Eunice Ubomba-Jaswa et al. 2010), and at these temperatures organisms that are otherwise resistant to SODIS treatment can be effectively disinfected (W. Heaselgrave et al. 2006; V. Meyer and Reed 2004). For example, one study demonstrated that SODIS treatment can effectively kill *Giardia duodenalis* and *Entamoeba histolytica* when the water gets above 50 degrees (Mtapuri-Zinyowera et al. 2009). It is speculated that this phenomenon is due to a synergistic effect between temperature and UV radiation (Wegelin et al. 1994).

It has been shown than when simulating SODIS exposure in the high-temperature range above the threshold where SODIS is accelerated by heat, it is important to mimic the actual time-temperature profile of treatment, rather than just leaving the sample at the maximum temperature for the duration of treatment (E. Ubomba-Jaswa, Boyle, and McGuigan 2008).

Researchers have developed an indicator to show when a given target temperature has been reached. A tube contains wax that remains solid, in the top of the tube until the threshold temperature is achieved, and then liquefies and drops to the bottom so the SODIS user can see that the indicator has been triggered (Safapour and Metcalf 1999). Resetting the indicator is as simple as allowing the wax to cool and solidify again, and turning it over for the next use.

2.7 SODIS Implementation Strategies and Health Impacts

2.7.1 The Challenge: Behavior Change

In general, there is consensus that the most difficult aspect of achieving long term community health improvement seems to be the challenge of generating sustained behavior change. There is significant ongoing effort to understand what strategies are the most and least effective

(Tamas, Mosler, and Gutscher 2009), and this work tends to suggest that building a network of opinion leaders to act as SODIS promoters is a very effective approach (Moser and Mosler 2008; Mtapuri-Zinyowera et al. 2009). Furthermore, several psychological elements are shown to have positive impacts on SODIS uptake, including involvement/engagement, perceived ability, and self persuasion (Kraemer and Mosler 2010), as well as social factors such as mass media, social influence, and entertainment-style education (Heri and Mosler 2008). It has been found that level of motivation is closely tied to sustained use of SODIS (du Preez, McGuigan, and Conroy 2010a), and that knowledge about hygiene is also a very important predictor of continued use (Graf et al. 2008). One paper suggests that partnering with governments on SODIS implementations, though generally slower than working with non-profits, is more scalable and sustainable than other strategies (Gurung, Grimm, and Autenreith 2009).

However, SODIS alone can only address disease that comes directly from consuming contaminated drinking water. Studies show that besides drinking unsafe water, other risky behaviors are also responsible for a large percent of diarrhea-causing sicknesses, such as poor sanitation and hygiene. For this reason, SODIS is usually taught hand-in-hand with sanitation and hygiene education. This is particularly effective at reducing a community's disease burden because SODIS itself requires community education, which can easily been extended to other health training modules in tandem. Together water, sanitation, and hygiene programs are referred to as "WASH," which is roughly an acronym for Water, Sanitation, and Hygiene.

2.7.2 The Goal: Community Health Improvement

An important area of research attempts to understand the health impacts of SODIS interventions in their target communities. This can be difficult for several reasons:

- The communities tend to be remotely located, so long-term data collection is often challenging and expensive.
- The implementations are often run by non-profit organizations that have significant budgetary limitations. In many cases this causes impact reporting to be given low priority or to be neglected entirely.
- Proper health impact assessment is a complex, involved process, requiring that many variables be monitored and controlled.

For these reasons, the available literature on the long-term effectiveness of SODIS implementations is not very abundant or rigorous. While better data would be tremendously valuable, this trend is unfortunately typical of water and health interventions that focus on developing countries. However, though the papers may not be especially rigorous, they do suggest certain encouraging trends and are worthy of attention.

Rose et al. (Rose et al. 2006) found a 40% reduction in diarrheal disease, though even during and after the intervention most water that the community consumed was untreated. In this case it is difficult to attribute the health improvement to the SODIS intervention. Others found reductions in waterborne disease of 16% in an area with very cloudy water (over 200NTUs in every case) (Ronán M Conroy et al. 1999), and noticeable reductions that were not statistically significant using the limited research methods (du Preez, McGuigan, and Conroy 2010a). Conroy et al. (R M Conroy et al. 2001) conducted a study with limited sample size which suggested that the rate of cholera in children under 6 was 73% lower than in non-intervention households.

2.8 Photonics of SODIS Treatment

The solar electromagnetic radiation reaching Earth includes visible, infrared (IR), and ultraviolet (UV) radiation. Figure 3 shows the visible light region of the electromagnetic spectrum, which is bordered by the UV and IR regions.

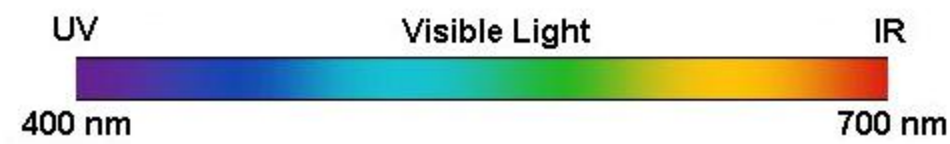

FIGURE 2 VISIBLE LIGHT SPECTRUM

2.8.1 Sunlight Simulators

Rather than using natural sunlight, many SODIS researchers use sunlight simulators to achieve a greater degree of control and repeatability over experimental conditions than natural sunlight allows. When choosing an artificial radiation source, most researchers select one with a spectrum similar to that of natural sunlight (K G McGuigan et al. 1998; S. C. Kehoe et al. 2004; KG McGuigan et al. 2006; W. Heaselgrave et al. 2006; Sommer et al. 1997; Vidal and Diaz 2000; Carey et al. 2011; Graf et al. 2008; du Preez, McGuigan, and Conroy 2010b), such as the example shown in Figure 4 (K G McGuigan et al. 1998).

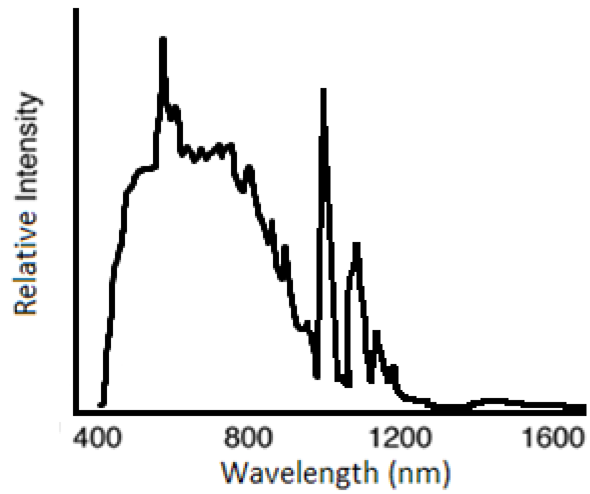

FIGURE 3 SPECTRAL EMISSION OF A XENON LAMP

In several SODIS publications sunlight simulators were used which did not attempt to mimic the intensity profile of natural sunlight (Wegelin et al. 1994; Franziska Bosshard, Bucheli, et al. 2010; M. Berney, Weilenmann, and Egli 2006; Michael Berney, Weilenmann, and Egli 2006; Anon.; Fisher et al. 2008), as seen in the example in Figure 5, which uses a radiation source with a series of monochromatic peaks rather than a smooth, polychromatic curve like natural sunlight (Wegelin et al. 1994). A study has been published that questions whether monochromatic radiation is a valid substitute for natural sunlight in SODIS simulations (Kramer and Ames 1987), which brings the validity of this approach into question.

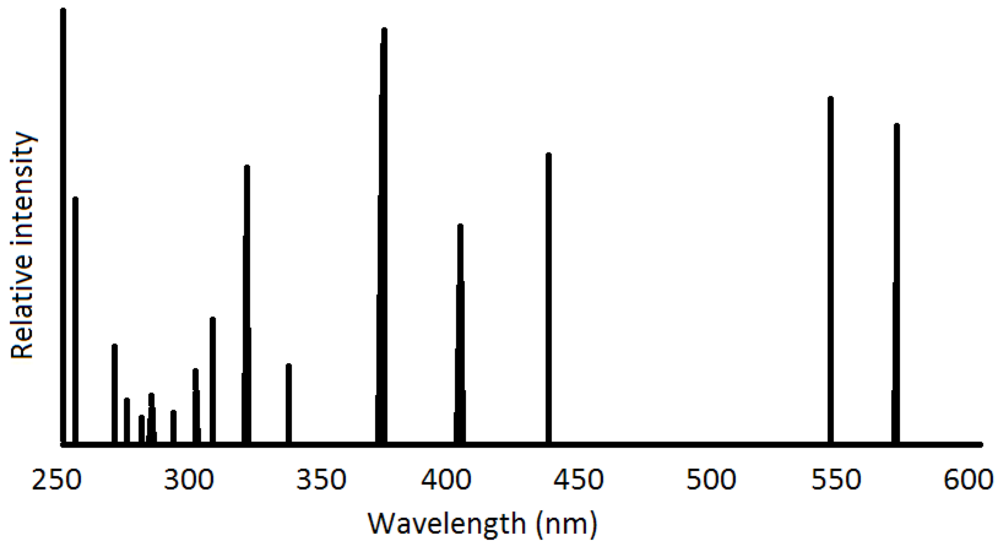

FIGURE 4 SPECTRAL EMISSION OF A MEDIUM PRESSURE MERCURY LAMP

Researchers have made a number of other interesting findings related to the types of radiation exposure that are appropriate for SODIS simulation and exposure. The reciprocity law states that a given dose should have the same effect regardless of whether it was reached with a high intensity for a short time, or a low intensity for a long time. However, it has been claimed that the reciprocity law does not apply to SODIS, so SODIS experimentation should use radiation intensity in the range of real sunlight (Kramer and Ames 1987). Furthermore, because of the possibility of pathogen reconstitution, SODIS exposure should be continuous and uninterrupted (Eunice Ubomba-Jaswa et al. 2009). Several researchers have developed mathematical models to predict whether the guideline of 3-5 hours of sunlight over 500 W/m^2 per day is attainable in various global locations (Oates, Shanahan, and Polz 2003; Fadhil M. Salih 2003).

2.8.2 The Roles of Emission Spectra and Absorbance Spectra

The radiation emitted by the sun has different intensities at different wavelengths, which together constitute its spectral output, as shown in Figure 6 (Anon.). This radiation has to pass through a number of barriers on its journey from space to the pathogens that SODIS treats, and at each stage different wavelengths are attenuated.

- First is the earth's atmosphere, which reflects some radiation, and effectively filters out the nearly all the UV-C wavelengths, as well as some of the radiation in the UV-A and UV-B regions.
- Next the radiation must pass any cloud cover and airborne pollutants that may be present before reaching the bottle itself. This often results in the radiation being scattered, rather than following a direct path from the sun to the bottle; in fact, natural sunlight consists of approximately 60% direct light and 40% scattered light (Eunice Ubomba-Jaswa et al. 2010).
- Upon reaching the bottle, even if the bottle is clean and there are no films or scratches to block the radiation, the bottle material itself will still absorb some of the radiation. (The air-plastic and plastic-water interfaces cause bending of the radiation as well, so the radiation will not be evenly distributed inside the bottle.)
- Then, once inside, the radiation must penetrate the water. UV radiation is absorbed by suspended solids and dissolved inorganic compounds such as iron in the water.

At each of these stages radiation is absorbed according to the respective materials' spectral absorbance, which is a correlation between wavelength and UV absorbance. By the time the radiation reaches the organisms, only a fraction of the initial radiation energy remains. In general, lower wavelengths are absorbed more easily than higher wavelengths (although the action spectra tend to be uneven and they vary from material to material) so it is primarily UV-

A radiation that reaches the organism, together with a small percentage of the sun's original UV-B radiation.

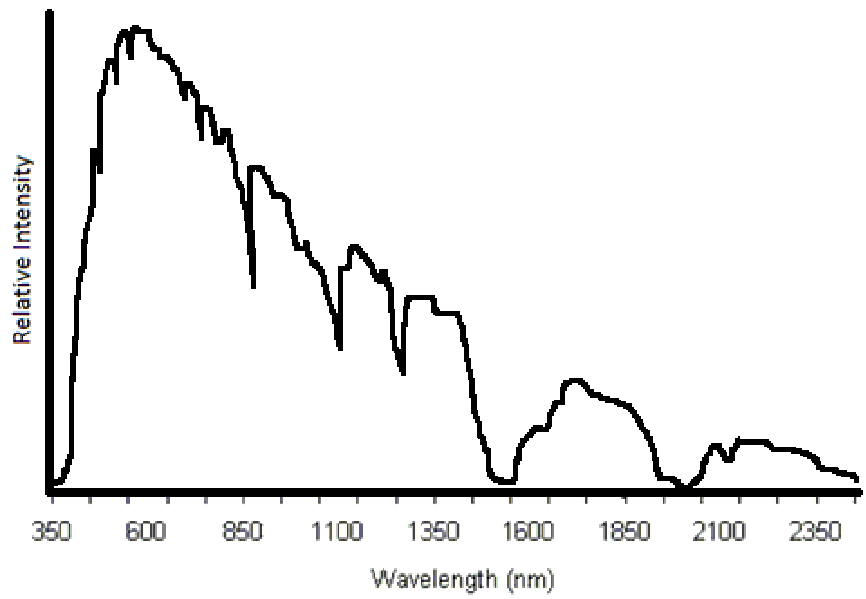

FIGURE 5 SPECTRAL EMISSION OF THE SUN

2.8.3 The Importance of Water Layer Depth

To date the design of SODIS bottles has not been an area of significant focus, because most SODIS projects rely on the standard plastic bottles that are widely available from the beverage industry. There are many manufacturers of these bottles, and the large beverage companies each use their own design elements, such as ridges, grips, and various profiles. However, these bottles are usually quite uniform; the material, wall thickness, and general geometries are more or less the same for most major manufacturers, so their design can be considered fixed.

However, there is a current shift toward the use of SODIS bags for certain applications, instead of only using SODIS bottles. SODIS bags are purpose-built, so their design can be optimized with respect to many design parameters, such as volume, wall thickness, and shape. For this reason, while historically the geometry of SODIS containers has been determined by the shape of the widely available plastic bottles, for SODIS bags it is a parameter that can be optimized.

In the design of SODIS bags, some geometric parameters may be inflexible due to limitations on cost. For example, a rectangular shape is a preferable shape from a manufacturing standpoint, because rectangular bags can be easily produced from a roll of lay-flat tubing, which is very simple to manufacture at low cost. However, other design parameters such as wall thickness, and length and width of these rectangular bags (which determines the filled bag's geometry as well) are open to investigation and optimization.

Water layer depth (or simply "water layer") is the average length of radiation's path through the water during treatment. Water layer is important because radiation is attenuated as it passes through the water so as depth increases radiation intensity decreases. Like many chemical engineering parameters, the design of water layer is a trade-off: too high and insufficient radiation will be available for treatment, and too low and the volume of treated water suffers. This tradeoff can be partially overcome by increasing the reactor's surface area (i.e. using a large, shallow container). This is one of the strengths of using SODIS bags instead of SODIS bottles.

A common rule of thumb that guides selection of bottles for SODIS suggests that the water layer should be approximately 10 cm or less (S. C. Kehoe et al. 2001). This is roughly the diameter of standard 2 L plastic bottles, so bottles 2 L and smaller are considered appropriate for SODIS use. However, for the design of SODIS bags, there is a need to investigate this aspect more deeply to more fully understand the impact of water layer depth on SODIS treatment efficiency.

2.9 Calculation of UV Dose

UV dose is defined as UV intensity times the duration of exposure, and is the most important parameter in UV-based processes. When properly calculated according to the conventions for UV disinfection, dose takes into account every phenomenon that affects the amount of radiation that reaches the water itself (Wright 2000). These include (in the case of SODIS) the radiation source's spectral emission and intensity (and any changes of intensity during the treatment period), the container's spectral absorbance and wall thickness, the water's spectral absorbance, the water layer depth, and the duration of exposure. It is important to consider these parameters so that the results depend only on dose, and are independent of the nature of the experiment. This means that a given dose has the same effect regardless of the condition under which it was reached.

However, there currently exists no method of reporting SODIS dose for which this is the case. SODIS dose has some additional complexities that conventional UV-Disinfection does not face, and these complexities make it very difficult to report dose in a way that is consistent and meaningful across experimental conditions.

2.9.1 Surface Dose

It is the convention in most SODIS research to only report the dose in terms of radiation incident on the surface of the SODIS container (Wayne Heaselgrave and Kilvington 2010; Eunice Ubomba-Jaswa et al. 2009), but to not provide enough information to calculate the true dose within the sample (Wright 2000). Researchers use a wide range of radiation detectors and meters which each have different ranges and spectra of sensitivity, so different studies measure and report different wavelengths. Furthermore, some studies use natural sunlight

(Aftim Acra et al. 1980; McLoughlin, Kehoe, et al. 2004; M. Boyle et al. 2008) and others use a variety of sunlight simulators (K G McGuigan et al. 1998; F Bosshard et al. 2009; Fisher et al. 2008), creating additional complexities which are difficult to fully account for. Due to complexities like these it becomes difficult to compare the results of different studies because the meaning of the reported dose often varies significantly. For this reason an improved means for reporting dose is needed.

2.9.2 Method for Calculating Dose in UV Disinfection

$$Dose = \sum_{\lambda} I_{avg}(\lambda) G(\lambda)\, t$$

$$\text{units: } \left(\frac{power}{area}\right) = \sum \left[\left(\frac{energy}{area}\right) \times (unitless) \times (time)\right]$$

$$\text{where } I_{avg}(\lambda) \; = \; I_0(\lambda) \; \times \; Morowitz\ Factor$$

$$\text{and } Morowitz\ Factor = \left(\frac{1-exp\left[d\ \ln\left(UVT(\lambda)\right)\right]}{-d\ln\left(UVT(\lambda)\right)}\right)$$

EQUATION 1

Equation 1 is used to calculate dose for UV-Disinfection conducted in a collimated beam (Wright 2000). In a standard collimated beam apparatus a beam of collimated UV light from a low or medium pressure mercury arc lamp shines on a sample from above, and the sample sits on stir plate to ensure continuous mixing. Because this is a widely used method for a variety of UV water treatment processes, UV disinfection of this type will be referred to herein as "conventional UV disinfection."

In Equation 1 *G(λ)* is the wavelength-dependent action spectra of the pathogens being disinfected (the relative importance of each wavelength in the disinfection process), and $I_{avg}(\lambda)$

is the intensity experienced by an average volume element within the sample at wavelength λ. $I_0(\lambda)$ is the intensity of radiation at wavelength λ incident on the surface of the sample, and the "Morowitz Factor" scales this intensity from $I_0(\lambda)$ to $I_{avg}(\lambda)$; that is, from the intensity at the sample surface to the intensity experienced by an average volume element within the sample. The Morowitz Factor does this by accounting for the water's $UVT(\lambda)$ (the ultraviolet transmittance at each wavelength), as well as the sample depth d.

For conventional UV disinfection (in the absence of particle associated pathogens), the apparent inactivation constant is in fact constant; that is, the slope of the concentration of pathogens vs. time graph during is linear. This means that a given dose results in given log inactivation, regardless of how the dose was reached. In other words, samples can have different water quality, container material and geometry, and irradiation intensity, but as long as they receive the same UV dose, the resulting log inactivation of pathogens should be identical. This is a very convenient property for calculations and designs relating to conventional UV disinfection.

However, this characteristic does not necessarily apply to SODIS because the dose equation is based on several assumptions that are valid for conventional UV disinfection, but are not necessarily true for SODIS treatment.

2.10 SODIS Bags: A New Approach

Plastic bottles are available in every major urban center in the world; in fact, most large cities have bottle-producing factories, so around urban areas these bottles can conveniently be collected for SODIS use. However, as SODIS spreads in rural areas, implementers begin to encounter regions where bottles are not readily available for SODIS. A current practice is to ship bottles in from the nearest urban center, but this can be quite costly. Plastic bottles cannot be packed very tightly, so their shipment is very inefficient. For this reason, there is interest in the potential for SODIS to be performed using plastic bags instead of bottles. Bags pack much tighter than bottles, so their shipping costs are much lower than those of bottles. This could potentially make SODIS an appropriate water treatment technology in regions where it is currently impractical due to the unavailability of plastic bottles.

In the first papers published on SODIS bags, were used instead of bottles (Aftim Acra et al. 1980), because the oral rehydration solution that SODIS was originally meant to treat was often stored in bags. Once major beverage corporations had brought plastic bottles to most regions of the world, it made became logical for SODIS users to take advantage of these durable, transparent containers, so they began using plastic beverage bottles for SODIS treatment. However, because there is now a need for SODIS containers that are easier to ship, SODIS bags are being revisited. The relevant research to date is summarized below.

In the late 1990s, it was found that SODIS bags with a water layer of approximately 1 cm to 6 cm reached higher temperatures more easily than in SODIS bottles, and treated *Vibrio cholerae* more effectively. It was assumed this was because of the improved surface area to volume ratio in SODIS bags (Sommer et al. 1997). This study also found that bags achieve more efficient treatment than bottles (Sommer et al. 1997).

A study conducted by a group of researchers at Nestlé (Walker, Len, and Sheehan 2004) found that SODIS bags could inactivate *E. coli* by 5 logs and viruses by 3.5 logs in 6 hours of sunlight exposure in New England during the fall and winter, which has much less intense sun than the typical location of SODIS use.

A Harvard thesis (Melinda Foran) found that SODIS bags should be exposed for at least 4 hours on sunny days, and for a whole day on cloudy days. Following this, a heat sealer was prototyped and tested at MIT (Quinlan 2005) to produce these SODIS bags on-location in the communities where they will be used. A technical note from EAWAG comparing SODIS bags and bottles states that SODIS bags provide more efficient inactivation of bacteria and viruses, but can give the water a plastic smell, can be more difficult to handle, and require a second container to drink from (Anon.).

2.11 Efficacy of Lying SODIS Bags

If SODIS bags are to be used as a substitute for SODIS bottles in some contexts, it is very important to understand whether the bags work better or worse than the bottles they are meant to replace; that is, whether SODIS users should be more or less confident with the quality of their water when using SODIS bags compared to bottles.

Solar disinfection using bottles is well established and widely proven to work (Wegelin et al. 1994; Fujioka and Yoneyama 2002; TM Joyce et al. 1996; S. C. Kehoe et al. 2001; R H Reed, Mani, and Meyer 2000), but to replace the reaction vessel with something new is certain to raise questions in the minds of users and implementers alike regarding whether the treatment process is still trustworthy using this new approach. For this reason, it is important for SODIS bags to be designed to perform as well or better than the conventional SODIS bottles. If they perform worse, their uptake is expected to struggle significantly because they will be, rightly, perceived as an inferior product.

2.12 Efficacy of Hanging SODIS Bags

SODIS has historically been performed by lying bottles on surfaces such as roofs or SODIS tables where they undergo mild but repeated wear. When a SODIS user puts the bottles in place, it is common to slide them along the table a little bit, which over time causes small scratches to form on the surface of the bottles, especially if the surface has any amount of dirt and grit – which they usually do, since they are always outside and are rarely washed. This form of wear is the limiting factor for a SODIS bottle's lifetime, because once the bottles are covered in many scratches, dirt becomes lodged in the tiny scratches and the bottles become less transparent. Once the bottles become cloudy in appearance and no longer pass the "finger test" of clarity (described in Section 2.3), they need to be replaced. The bottles usually last about one to two years.

Bags tend to be less durable than bottles because their walls are thinner and less rigid, so they may have a shorter lifetime, as discussed in detail later herein. However, since SODIS bag durability is expected to be of concern, it may be possible to extend the useful life of the product by changing the method of their use to decrease wear. If SODIS bags are hung up instead of laid down it is likely they will undergo less wear, because they will not be in contact with a hard, gritty surface to create scratches.

This change would have significant implications for all aspects of SODIS use, including the following technical concerns that need to be addressed.

- It would be most convenient to hang SODIS bags in a vertical orientation, but in most cases this would decrease the amount of sunlight that the bag will intercept. At noon, when the earth receives the highest intensity solar radiation, the sunlight's angle of incidence is close 90^{o}, and a vertically oriented container receives significantly less light energy than a horizontal container. Since SODIS performance is directly related to the amount of sunlight the water receives, this could decrease the efficiency of the process.
- The change in orientation would change the distribution of water in the bag. Whereas water is fairly evenly distributed in a bag lying on a flat surface, a hanging bag is expected to take a teardrop-like shape, bulging outward at the bottom and thinning to a point at the top. This has significant implications for water layer thickness and, as a result, sunlight penetration.
- When a bag lies on a flat surface, radiation can only enter through one side of the bag. When it hangs, however, radiation can enter from both sides, increasing the effective surface area. Prior research shows that sunlight consists of 60% direct radiation and 40% scattered rays (Madronich 1997). This suggests that while having radiation enter through both sides will not double the total amount of radiation in the bag (since it can only receive direct radiation from one direction), it may still significantly increase the total radiation received by the water. Furthermore, this phenomenon decreases the effective water layer thickness.

2.13 Degradation of SODIS Bag Material

SODIS containers gradually degrade during use due to physical wear and UV degradation, and a number of design parameters are expected to play important roles in determining the rate of this degradation process. These include:

- material thickness
- orientation (lying flat or hanging up)
- physical use
- sunlight exposure

Increased material thickness correlates to increased strength, but trades off with UV transmittance because thicker material will allow less radiation to penetrate to the water. It is important to gain some insight about the optimum thickness of the bag to sustain SODIS use. However, they should not be thicker than necessary, because as the bag material gets thicker more radiation will be absorbed in the plastic, and SODIS treatment efficiency is expected to suffer.

Orientation is important because (as described in Section 2.13) a lying bag is expected to undergo much more physical wear than a hanging bag, since it is in constant contact with a hard surface.

During all the steps of physical use of a SODIS bag (i.e. being filled and emptied each day, being manipulated as the slide lock is put on and off, and putting the filled bags into position for exposure) the bag material goes through some amount of physical wear. In addition, the material experiences photodegradation when it is exposed to the rays of the sun, which are known to be damaging to plastics; especially thin films of transparent plastic like the ones that SODIS bags are made from. However, it is not known the extent to which physical degradation and photodegradation each contribute to a SODIS bag's overall degradation, and whether independent types of degradation influence each other or are simply additive.

2.14 SODIS Knowledge Gaps

Based on the information provided in this introduction, the following are some of the issues that need to be addressed for SODIS bags to be considered possible substitutes for SODIS bottles in certain contexts.

- The treatment efficiency of lying SODIS bags in comparison with conventional lying SODIS bottles.
- The treatment efficiency of hanging SODIS bags in comparison to lying SODIS bags.
- The effect of material thicknesses, orientation, sun exposure, and daily use on SODIS bags' degradation.
- The effect of water layer depth on SODIS treatment efficiency.
- The effect of the stirring assumption on SODIS dose calculation, and whether an improved SODIS dose calculation method can be proposed.

The research presented herein seeks to increase understanding of SODIS bags by investigating these knowledge gaps.

3 Research Objectives

The goal of this research was to develop an understanding of certain key technical considerations of SODIS bags and their application, to inform decisions regarding their potential application. To achieve this, the following objectives were identified:

- To compare the treatment efficiency of SODIS when performed using bags that are lying down and bags that are hanging up, relative to conventional SODIS treatment using bottles.
- To assess the effect of material thicknesses, orientation, sun exposure, and daily use on SODIS bags' rates of degradation.
- To determine the effect of water layer depth on SODIS treatment efficiency.
- To develop a new method of calculating SODIS dose, and to test its applicability in relation to current methods.

4 Research Methodologies

4.1 Laboratory Experiments Using Natural Sunlight

Experiments using natural sunlight were conducted to compare the efficacy of SODIS treatment in containers of different types. The first objective was to compare SODIS bags in a lying orientation with SODIS bottles (also lying), to determine the effectiveness of the SODIS process in bags compared with the conventional bottle approach. The second objective was to compare lying SODIS bags to hanging SODIS bags. It was hypothesized that hanging bags would have a longer lifetime due to decreased wear, but their treatment efficiency relative to lying SODIS bags had to be studied before any conclusion could be made about the appropriateness of this new approach.

The lying samples were exposed to sunlight on a piece of corrugated sheet steel, which is typical in normal SODIS use, and the hanging samples were suspended from hooks on a rod. These set ups are shown in Figures 7 and 8.

FIGURE 6 EXPOSURE OF LYING BAGS AND LYING BOTTLES

FIGURE 7 EXPOSURE OF HANGING BAGS

The SODIS bags came from a roll of UV stabilized linear low density polyethylene (LLDP) lay-flat tubing. These bags were 170 mm in width and 230 mm in length, sealed along three sides, and open along one of the 170 mm ends. The bag material was 25 μm thick.

Plastic slide-locks were used to seal the open side during testing. Slide locks are simple devices that consist of a cylindrical outer sheath and an inner rod. The outer sheath has a slot along its length on one side, which the bag is slid through to seal it. The bag sealing process is shown in Figure 9.

FIGURE 8 CLOSURE OF SODIS BAGS

As the photos in Figure 9 show, the user seals a bag by folding over the bag to form a loop at the top, and sliding the slide lock across the loop such that the bag is held between the rod and the sheath. Once the slide lock is fully in place, it seals very effectively, even when great pressure is applied.

Three lying SODIS bags and three hanging SODIS bags were each filled with 0.5 L of water, and were sealed. For consistency, each bag was sealed in the same location: 170 mm from the bottom. Because of this the effective dimensions were 170 mm by 170 mm, rather than 170 mm by 230 mm. This geometry gave a water layer depth of 62 mm when the bags were lying down. For comparison, three SODIS bottles (Nestlé Pure Life 500ml bottles) were exposed as well.

Diluted primary effluent wastewater was used to simulate the highly contaminated natural waters that are typically treated with SODIS. This water was acquired from a nearby research facility that collects fresh samples weekly. To ensure that the “challenge water” would be more contaminated than the worst natural waters SODIS needs to treat, water with a fecal contamination level of approximately 400,000 CFU/100mL was used. It was found that this level of contamination could be consistently achieved by mixing purified Milli-Q water with wastewater in a 10:1 ratio, and filtering through a 4μm membrane filter before use. This filter selectively filters particle-associated bacteria, while allowing free-floating bacteria to pass. This filtering stage was included because it was necessary to remove particle-associated bacteria, which can be sheltered from the radiation, and therefore respond irregularly to SODIS treatment. This phenomenon is shown in Figure 10.

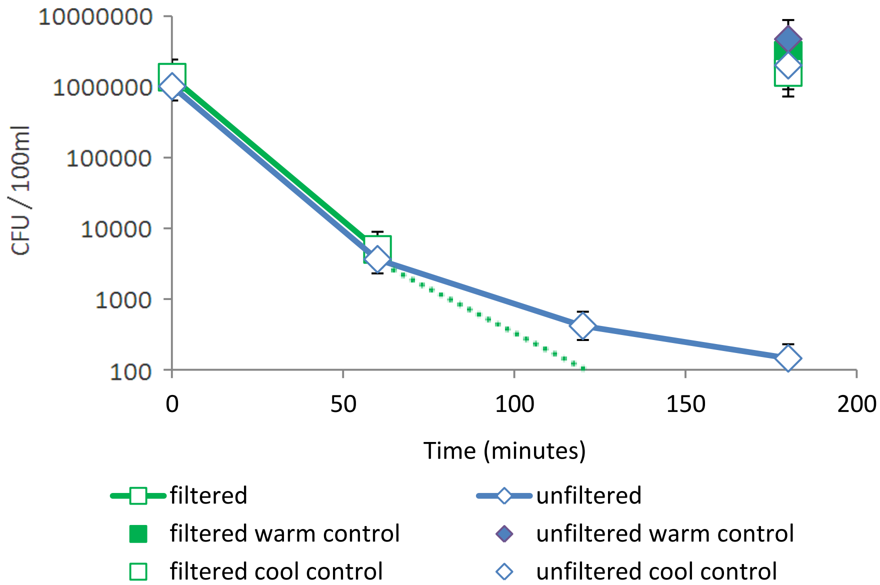

FIGURE 9 INACTIVATION CURVES OF FILTERED AND UNFILTERED SAMPLES

(ERROR BARS SIGNIFY 95% CONFIDENCE LIMITS)

In this and all subsequent graphs, lines are to connect sequential points, and do not signify regression, and dotted lines indicate that the following data-point was below the methodology's detection limit of 100CFU/100mL. Dotted lines indicate the worst-case scenario, but treatment in this region may have occurred at a more rapid rate than the dotted line indicates.

The figure shows that while the fecal coliform concentration in the filtered sample decreased straight to non-detect, the unfiltered sample appears to asymptotically approach a constant, non-zero concentration. This is because particle-associated microorganisms in the unfiltered sample can be sheltered from radiation exposure by the particle they are adhered to or embedded in. The concentration decreased rapidly in the first hour as the non- sheltered microorganisms were inactivated at the same rate as in the filtered sample, but then in the second and third hours the unfiltered sample exhibited significantly lower efficiency as non-particle-associated microorganisms were all inactivated and primarily particle-associated microorganisms were left. For this reason, particle-associated microorganisms should not be present in the challenge water for SODIS experimentation to achieve repeatable, log-linear results.

To determine the relative performance of lying SODIS bags, hanging SODIS bags, and lying SODIS bottles, the six bags and three bottles were simultaneously exposed to direct solar radiation. A control sample was wrapped in aluminum foil to block any radiation exposure, and was left with the exposed samples for the duration of the experiment.

A time-zero sample was collected in triplicate at the start of the experiment, and 10ml samples were taken from each exposed SODIS container during each of the three subsequent sampling times. Samples were not taken from the control until the end of the exposure period. All samples were sealed and refrigerated after being collected to avoid regrowth of fecal coliform in the time between collection and analysis. The samples were analyzed using the Membrane Filter Technique for Members of the Coliform Group #(1) proposed by the American Water Works Association (Anon. 1999).

At each sampling time the solar radiation intensity was recorded using an International Light Technology ILT1700 radiometer with an unfiltered SED623 detector.

4.2 Field Experiments Using Natural Sunlight

The primary driver for the investigation of SODIS bags is cost – the bags will only be of value if they are more cost-effective than SODIS bottles in at least some parts of the world. A key factor in this economic consideration is the lifetime of the bags.

To determine the effects of the various operating parameters on degradation rates of the bag material, SODIS bags were "aged" under a variety of circumstances. These circumstances were permutations of the following parameters: material thicknesses, orientation, sun exposure, and daily use. After the aging process was complete, the bags were tested for both optical and physical degradation.

Because this work was generously carried out by a team of SODIS trainers in Africa, there were logistical limitations on the number of combinations that were reasonable to include, and the duration of the use periods. It was decided that rather than generating replicated results by subjecting multiple bags to each use scenario, it would be appropriate to only put one bag through each scenario, and perform replicated analyses on each bag. Eighteen SODIS bags were used in this experiment for periods of two months.

The use conditions for each bag are shown in Table 1.

TABLE 1 USE CONDITIONS FOR AGED BAGS

Material Thickness	Type of Wear	Orientation	Duration
50 μm	sun only	hanging	2 months
50 μm	sun only	lying	2 months
25 μm	sun only	hanging	2 months
25 μm	sun only	lying	2 months
50 μm	use only	hanging	2 months
50 μm	use only	lying	2 months
25 μm	use only	hanging	2 months
25 μm	use only	lying	2 months
50 μm	sun + use	hanging	2 months
50 μm	sun + use	lying	2 months
25 μm	sun + use	hanging	2 months
25 μm	sun + use	lying	2 months
50 μm	sun only	hanging	4 months
50 μm	sun only	lying	4 months
25 μm	sun only	hanging	4 months
25 μm	sun only	lying	4 months
50 μm	use only	hanging	4 months
50 μm	use only	lying	4 months
25 μm	use only	hanging	4 months
25 μm	use only	lying	4 months

The lying bags were placed on a SODIS table as shown in Figure 11. The hanging bags were suspended from above as shown in Figure 12.

FIGURE 10 EXPOSURE OF LYING SODIS BAGS

FIGURE 11 EXPOSURE OF HANGING SODIS BAGS

All exposures took place in Kampala, Uganda, because this location has climate conditions which are typical of most places where SODIS is used. This was done from February to June, which overlaps with both Uganda's dry and rainy seasons.

The bags used for this experiment were prepared according to their respective aging protocols. Half of the bags were 25 μm thick, and half were 50 μm thick. These bags were all made from linear low density polyethylene (LLDP).

The bags were subjected to the various parameters as follows.

- Material thickness – The thin bags were made of 25 μm plastic, and the thick bags were made out of 50 μm plastic.
- Orientation – Lying bags were placed on a SODIS table, the same way SODIS bottles are used. Because in actual practice it may be useful to print instructions on one side of each SODIS bag, and the printed side should always be on the bottom so as to avoid blocking light, the lying SODIS bags in these tests always had the same side facing downward. The hanging bags were suspended from hooks on a rope, similar to clothes on a clothesline. All the exposed bags were placed in locations where they would not be sheltered from the sun or other weather at any point during the day.
- Type of use – "Sun only" bags were placed in their respective locations at the beginning of their exposure periods, and were not moved for the duration of their exposures. This was done to isolate the effects of photodegradation, so physical use would not be a significant contributor to these bags' degradation. "Use only" bags were subjected to a full set of use cycles (opening and closing, filling and emptying, and lying or hanging) but were not exposed to sunlight. This way the physical use could be studied in isolation, without photodegradation playing a role. "Sun and use" bags were filled each morning and laid in the sun, and were emptied each evening, so the two parameters would work in combination, just as they would in actual use.

- Duration – Some bags were subjected to their use scenarios for two months, and some were subjected for four months. Because of the logistical limitations of the experiment, no “sun and use” bags were used for four months, only the “sun only” and “use only” bags underwent this longer use period.

Upon completion of these use periods, the samples were analyzed for the following properties.

- Physical strength – The bags’ tensile strength was measured using a 952KRC1000 mechanical testing machine from Com-Ten Industries. The tensile tests were conducted by preparing test specimens according to the geometric specifications in ASTM D638–10, and elongating each specimen until failure while recording tensile forces. As specified in the ASTM guideline, a total of five specimens were tested for each bag. Their ultimate tensile strengths were recorded and averaged.
- Optical transparency – Each bag’s UV transmittance (UVT) at 254 nm (the standard wavelength used for comparison in the UV water treatment industry) was recorded using a Cary 300 spectrophotometer. This parameter is designated as $\%T_{254}$. To account for variations across the surface of the bag, UVT was recorded for 10 locations on each bag, and the bag’s UVT was calculated according to the average of these values. During SODIS use, lying bags only need to transmit radiation through one side, so for these bags all UVT readings were conducted through the upper surface. Hanging bags transmit radiation through both sides, so their UVT readings were taken on both surfaces.

4.3 Laboratory Experiments Using Simulated Sunlight

Experiments were conducted under simulated sunlight to determine the effect of water layer depth on efficiency, and to study the impact of stirring on the dose calculation process. Water layer depth is an important parameter in the SODIS process because water attenuates UV radiation, so as depth increases the intensity of UV radiation decreases, thereby decreasing the speed of the treatment process. Dose calculation is important as well, because dose is the basic unit of measure for UV treatment processes, yet a satisfactory method of calculating SODIS dose does not currently exist. These experiments employed simulated sunlight because the climate of the testing location only allowed limited work using natural sunlight, so the experiments that did not require natural sunlight used simulated sunlight.

Before conducting these experiments, the sunlight simulator was built using a 300 W Cermax® xenon arc lamp with a built-in elliptical reflector from Perkin Elmer. The lamp was equipped with a filter to cut off UVC wavelengths, which simultaneously adjusts the spectrum to closely match the spectrum of sunlight, and avoids the production of ozone. This sunlight simulator used a PS300-12 Open Frame Supply, a R400-1 housing and fan, and an R400-1 Y1711FM 300 Watt Module (all from Perkin Elmer).

The spectral output of the xenon lamp is compared to the spectrum of sunlight at sea level in Figure 13 (K G McGuigan et al. 1998). Although the spectra of the lamp and the sun are a bit dissimilar in the visible and IR ranges, the match in the UV range (below 400nm) is quite good. This is the most important region of the electromagnetic spectrum for SODIS, which is why this type of lamp was chosen.

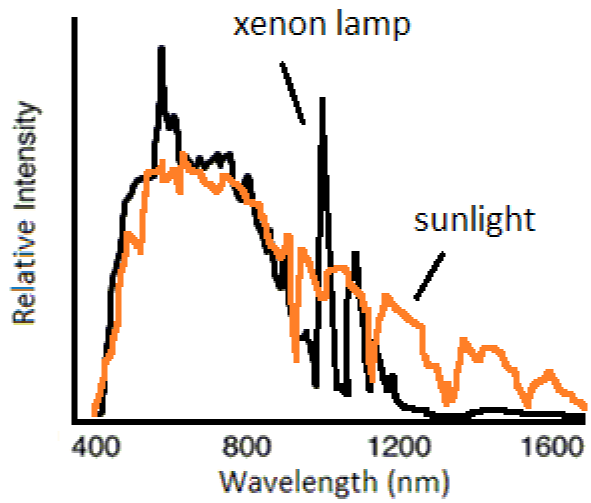

FIGURE 12 COMPARISON OF EMISSION SPECTRA OF XENON LAMP AND NATURAL SUNLIGHT

The sunlight simulator was mounted and oriented such that it shone downward on a lab bench. Because this produced an uneven, donut-shaped intensity profile, an optical diffuser made of sand-blasted quartz was placed in the light beam to make the beam more uniform. Photos of the sunlight simulator before and after this optical diffuser was added are shown in Figure 14.

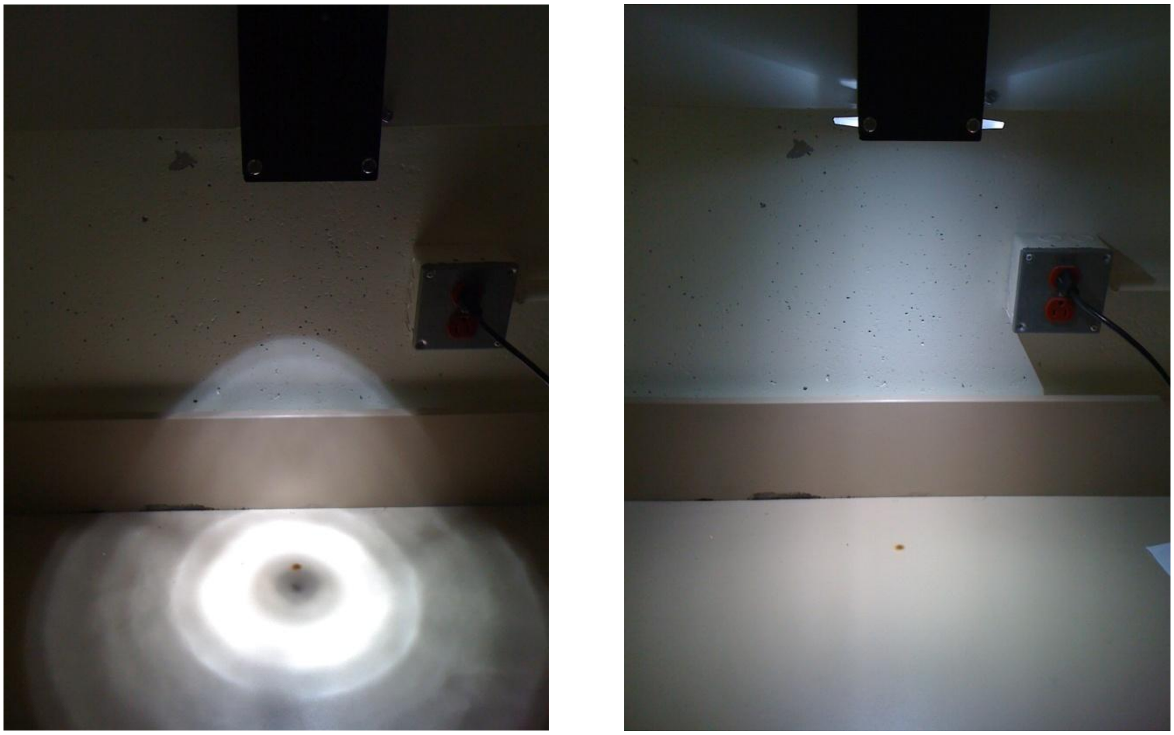

FIGURE 13 SUNLIGHT SIMULATOR BEFORE AND AFTER ADDING OPTICAL DIFFUSER

The photos demonstrate the effect of the optical diffuser in creating a much more even distribution of light than the sunlight simulator could achieve without this component.

Below this was placed a constant temperature bath, which was fitted with a stand to hold four samples simultaneously and a cover to keep evaporation and condensation from the bath from interfering with the experiment.

Cylindrical glass sample vessels were prepared for tests at three sample depths: 2 cm, 4 cm, and 6 cm, each with a diameter of 56 mm. The geometry of these vessels approximates the shape of a vertical segment of a SODIS bag lying flat. Over each sample was placed a layer of plastic made from the SODIS bag material that is being tested (25 μm LLDPE), such that the radiation must shine through the bag material before reaching the water sample (just as in actual SODIS use). To best represent a full SODIS bag, each layer of plastic was carefully placed on the surface of its water sample such that no air bubbles were trapped underneath. The challenge water was prepared using primary effluent wastewater as described in Section 4.1. The samples in the constant temperature bath are shown in Figure 15.

FIGURE 14 SAMPLES IN CONSTANT TEMPERATURE BATH

Figure 16 shows an example intensity profile of the light beam over the sample area, which was measured using an International Light Technologies ILT1700 radiometer with an unfiltered SED 623 detector. Ideally the profile would be flat, so that the samples would receive an even intensity of light across their whole surface. However, as the figure shows, the profile is not flat, but nonetheless, the radiation distribution is even enough that four samples could be clustered around the beam and remain fully inside the region that was within 15% of the average intensity. This set of measurements was repeated periodically to account for gradual changes in the lamp’s output power.

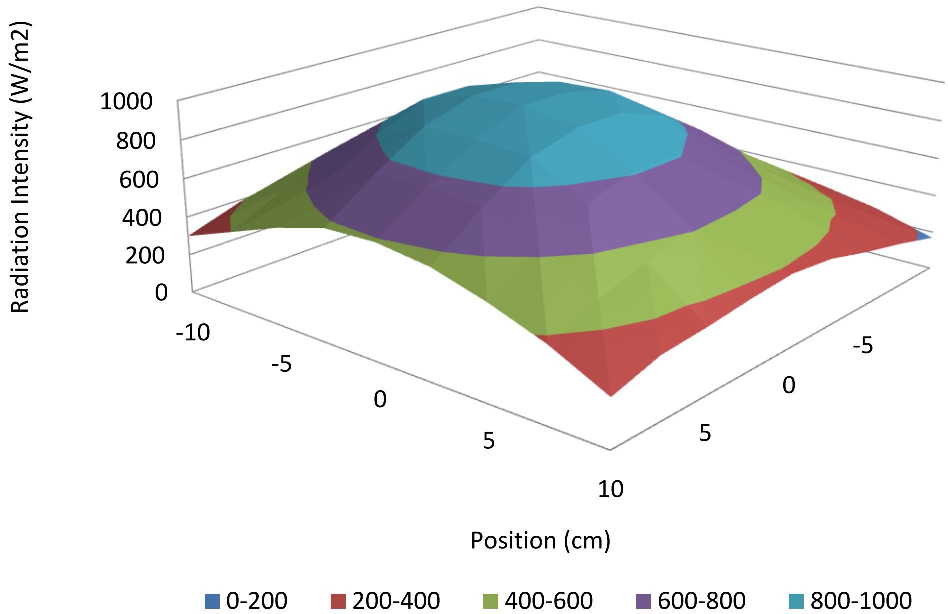

FIGURE 15 EXAMPLE SUNLIGHT SIMULATOR INTENSITY PROFILE

Bioassays were performed for each sample depth. Each bioassay consisted of six data points:

- an initial t=0 sample
- two samples evenly spaced during the exposure
- a final sample at the end of the exposure period
- a cool control, held at 20-25^{o}C outside the light beam
- a warm control, held under the light in the constant temperature bath with the test samples, but covered with aluminum foil to avoid any radiation exposure

To ensure repeatability, the bioassays were conducted in triplicate for each of the three sample depths; so a total of 12 bioassays were conducted.

Using the Membrane Filter plating method for fecal coliform enumeration (Anon. 1999), the samples from each bioassay were analyzed within 48 hours of sampling. To account for variances in the water's optical properties, transmittance spectra were recorded for each batch of challenge water using a Cary 300 spectrophotometer. The same was done for each plastic bag. These spectra are necessary for dose calculation.

As was stated in Section 2.9.2, the method of calculating dose relies on some assumptions that are not necessarily valid for the case of solar disinfection. This section will look at these assumptions in more detail:

- The dose equation assumes that $G(\lambda)$ (the action spectrum of the treatment process) is known. However, $G(\lambda)$ is not known for SODIS, so the calculation of dose must assume it is simply constant across the UV range; that is, $G(\lambda)$ = 1 for all λ = (200 nm, 400 nm). This is a very important assumption, and may contribute a large amount of error to the dose calculation.
- The dose equation assumes that the sample is well-stirred. This is usually true in conventional UV disinfection, because it takes place in purpose-built reactors that are designed to provide sufficient stirring. But, in SODIS there is little stirring; there is just a small amount of natural convection due to slight thermal gradients that are created from the warmth of the sunlight during treatment.

Because these assumptions may not be valid for SODIS, it is anticipated that the conventional dose calculation method may prove to be a relatively poor predictor of SODIS performance. If this is found to be the case a more improved method of calculating SODIS dose is still needed, even though the method of calculating dose has strengths beyond those of the very simple Surface Dose method.

The first assumption describes a challenge that would require a great deal of research to overcome (that is, to determine the action spectrum of SODIS treatment), and this is beyond the scope of the current project. The second assumption is less daunting, and can be investigated within the confines of the current research. However, before trying to improve the dose calculation method, it would be valuable to understand the significance of stirring to SODIS treatment efficiency. To do this, an experiment was conducted in which unstirred samples and stirred samples were exposed to SODIS treatment under identical circumstances.

This experiment used the apparatus described above, with two changes. First, the constant temperature bath was removed, and a stir plate was positioned in its place. For the unstirred case the stir plate was turned off, and for the stirred condition the stir plate was set such that it caused visible stirring to take place, but did not create a vortex. A vortex would alter the water sample's geometry and disrupt the water's contact with its plastic cover layer. Second, the comparison was done with challenge water that consisted of 50% wastewater. This was done to maximize the impact of the mixing assumption for more accurate measurement. The results of this experiment are shown in Figure 18. Error bars indicate 2 standard deviations.

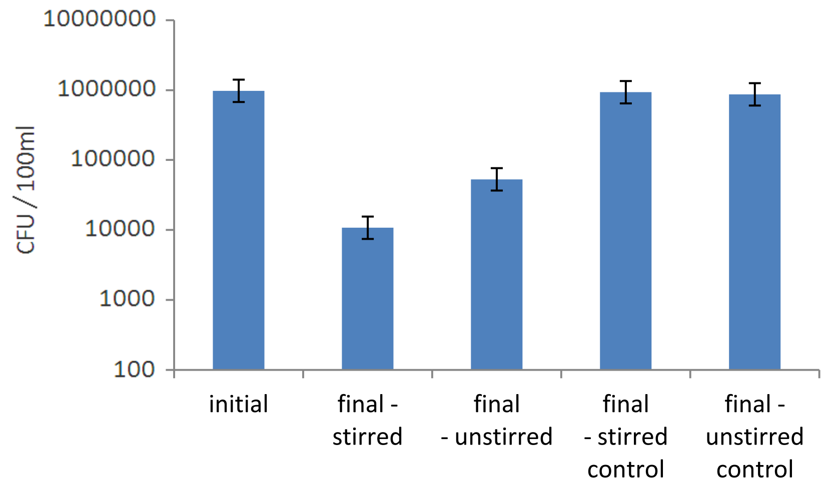

FIGURE 16 INACTIVATION CURVES FOR UNSTIRRED AND STIRRED SAMPLES (50% WASTEWATER)

(ERROR BARS SIGNIFY 95% CONFIDENCE LIMITS)

Figure 18 shows that the difference was significant (55% difference in log reduction). This suggests that the assumption that SODIS water is well-stirred is invalid, at least when water quality is poor. The challenge water passed the "finger test" described in Section 2.3, so according to this common convention for SODIS use, the water's clarity was in the appropriate range.

Because SODIS is normally conducted with no stirring, and because this experiment showed that stirring causes a significant increase in treatment efficiency, the assumption that SODIS water is well stirred can be considered invalid for this case.

It may be possible to decrease the impact of the stirring assumption with calculations alone. For the stirring assumption to be true for SODIS would require that the SODIS vessel was one well-stirred container, meaning that a given particle would spend equal time in each part of the vessel. At the other extreme, for the assumption to be completely false would require that there be no stirring at all, so each particle in the sample spends the whole treatment period in the same location. However, the truth probably lies somewhere between these two extremes: the SODIS container is not well-stirred or unstirred, but is partially stirred.

To model the SODIS container as a partially stirred reaction vessel, it can be modeled as a stack of small vessels, each comprising a layer of the complete container. As shown in Figure 19, each layer is well-stirred, but there is no stirring between layers.

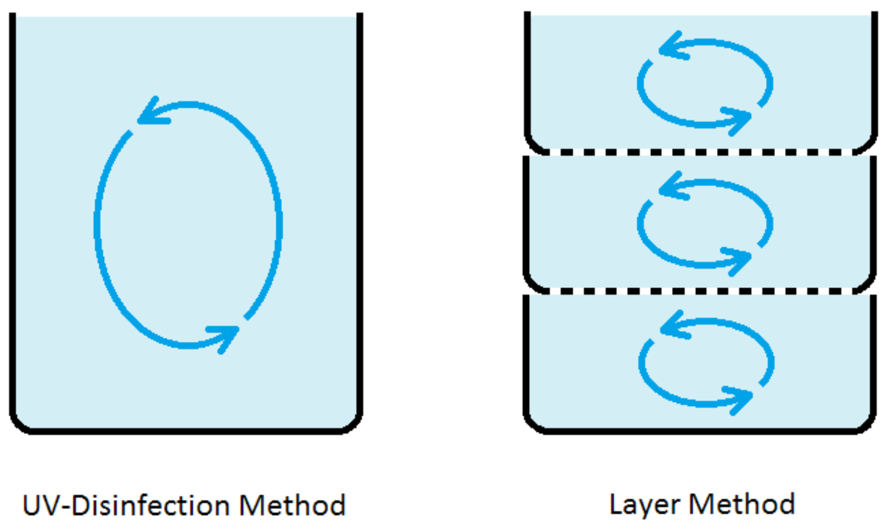

FIGURE 17 MODELS OF FULLY STIRRED REACTION VESSEL AND PARTIALLY STIRRED REACTION VESSEL

Depending on the number of layers the original container is broken into, different degrees of partial-stirring can be approximated. A 6 cm deep cylindrical sample vessel could be broken into just two layers of 3 cm each, and this would simulate a fairly well-stirred sample. Or the same 6 cm deep vessel could be thought of as 12 layers of 0.5 cm each to simulate a much lower degree of stirring, because of the assumption none of these 12 layers interact with each other.

To determine the dose from this method is not as straightforward as simply applying an equation. The reaction kinetics for a single layer must be determined before the calculation can be performed. The necessary steps for this “Layer Method of Calculating Dose” are described below.

- Determine the desired number of layers, and calculate layer thickness.
- Conduct a bioassay to determine the reaction kinetics in a single layer of this thickness.
- Measure the spectral transmittance of the water, to enable the degree of attenuation to be calculated for each layer.
- Treating the layers as separate batches, apply the conventional dose equation to each layer, calculating the expected final concentration in each layer from this kinetic constant.
- These can then be averaged to determine the average final concentration in the whole vessel.
- Using the reaction kinetics from the bioassay again, this average final concentration can be used to back-calculate the effective dose that was received in the sample on average.

By applying this process, varying degrees of partial-stirring can be approximated, rather than assuming that the reaction vessel is fully stirred as the conventional UV-Disinfection Method of Calculating Dose does.

5 Comparison of SODIS Efficiency in Lying Bottles, Lying Bags, and Hanging Bags

To compare the treatment efficiency of SODIS in lying bags, SODIS in hanging bags, and SODIS in bottles, natural sunlight was used to conduct several bioassays simultaneously. To do this, bags and bottles of equal volume (0.5 L) were prepared and placed in direct, natural sunlight. The bags were made of transparent LDPE, had identical geometries, and were sealed across the opening to enclose the water. The bottles used were Nestlé Pure Life water bottles in an effort to make the experiments as repeatable as possible, because these bottles are widely available. The lying bags and bottles were placed on a sheet of corrugated steel (which is the most common method of exposure in SODIS application), and the hanging bags were suspended from a horizontal rod. Each container was filled with 0.5 L of challenge water, which was made by diluting wastewater.

As in the Laboratory Experiments Using Simulated Sunlight (discussed in Section 4.3), bioassays were conducted in triplicate, for a total of 9 bioassays. Each bioassay included an initial sample (taken before the exposure commenced), three samples evenly spaced during the exposure, and a control wrapped in foil and held on the sheet steel with the exposed samples. Each sample and control was analyzed using the Membrane Filter plating method for fecal coliform (Anon. 1999), so that they could be compared based on the rate of fecal coliform inactivation. At each sampling time the solar radiation intensity was recorded to enable calculation of UV dose.

The result of the experiments comparing SODIS treatment efficiency in lying bottles, lying bags, and hanging bags are shown in Figure 20, and the full numerical values are tabulated in Appendix A. The experiments were conducted in triplicate, and the average value at each sampling point is shown in the figure. Dotted lines indicate samples below the detection limit of 100 CFU / 100ml. The detection limit is 100 CFU / 100mL because the dilution process used sub-samples of 10 mL volume per plate, and counts below 10 CFU per plate are considered non-detect. This yields a detection limit of 100 CFU / 100mL. It should be noted that the present study uses the industry-standard assumption that the inactivation kinetics are first order, even when the inactivation curves appear to be slightly curved.

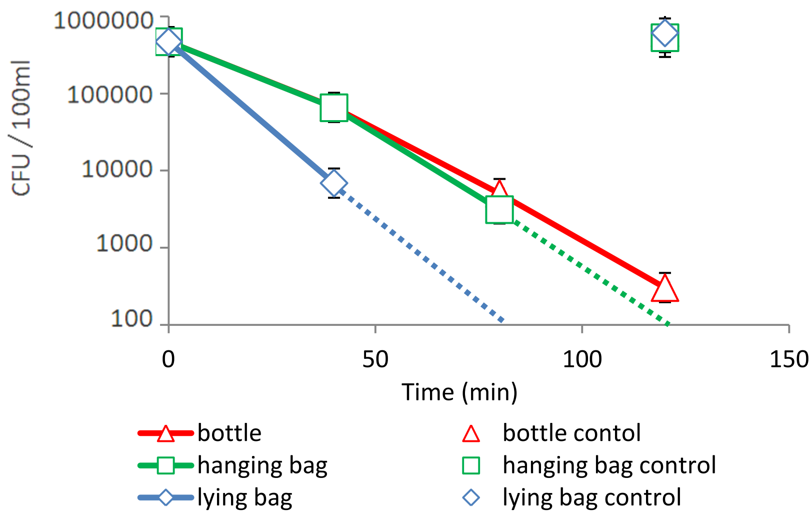

FIGURE 18 INACTIVATION CURVES FOR LYING BOTTLES, LYING BAGS, AND HANGING BAGS (ERROR BARS SIGNIFY 95% CONFIDENCE LIMITS)

The figure shows that the lying bag exhibited significantly higher efficiencies than the lying bottle, and the treatment efficiency of the hanging bag was only slightly better than the conventional SODIS bottles. The respective efficiencies for the lying bottles, hanging bags, and lying bags are 0.02678, 0.03355, and 0.04667 log/min. The 95% confidence intervals for these values are 0.02566 - 0.02790, 0.03036 - 0.03674, and 0.04493 - 0.0484 log/min, respectively, showing that these results are statistically distinct. This means that hanging bags are 25% more efficient than lying bottles and lying bags are 74% more efficient than lying bottles. The following factors are thought to be relevant in explaining this difference in treatment efficiency:

- spectral transmittance of the container
- temperature
- effective surface area

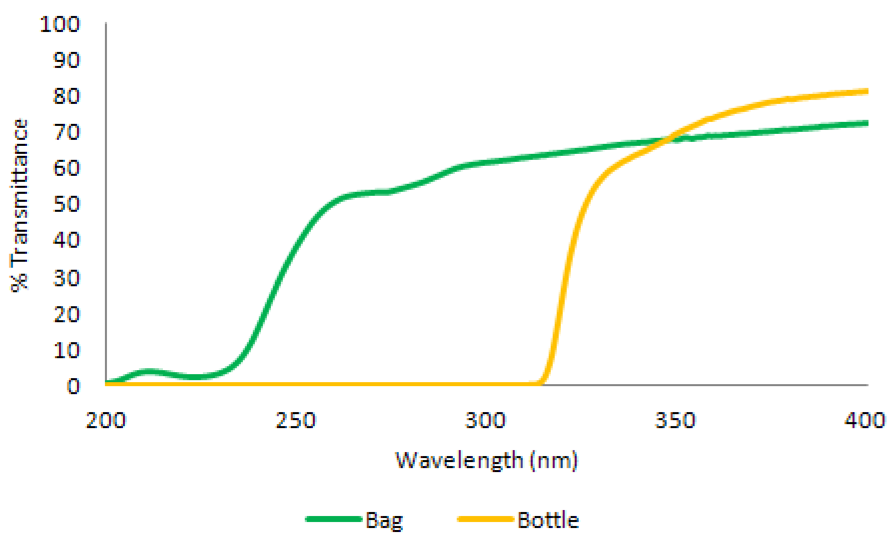

FIGURE 19 TRANSMITTANCE SPECTRA FOR BOTTLES AND BAGS

The transmittance spectra are shown in Figure 21. At first glance, Figure 21 appears to show that the SODIS bag is capable of transmitting more UV radiation than the SODIS bottle, because across about 75% of the UV spectrum the SODIS bag's percent transmittance is higher than that of the SODI-S bottle. The action spectrum of SODIS treatment (that is, the relative importance of each wavelength for the SODIS treatment process) is not known, but lower wavelengths are generally more powerful for UV treatment processes. This would suggest that the SODIS bag has a more favorable spectral transmittance. However, the majority of solar UV light is in the range 350-400nm, where the bottle has higher transmittance than the bag. Because of these conflicting uncertainties, no conclusion can be reached regarding whether the SODIS bags or bottle has a more favorable spectral transmittance. Besides, the material of the hanging bags was identical to that of the lying bags (they were literally cut from the same sheet of lay-flat tubing), so the difference in performance of the lying and hanging bags cannot be attributed to any different in spectral transmittance.

TABLE 2 TEMPERATURES OF LYING BOTTLES, LYING BAGS, AND HANGING BAGS

Sample	Maximum Temperature (^{0}C)
hanging bag1	34
hanging bag2	35
hanging bag3	35
lying bag1	47
lying bag2	46
lying bag3	46
bottle1	37
bottle2	37
bottle3	37
control	46

The maximum temperatures reached in each sample are shown in Table 2. It has been shown that when SODIS water exceeds 45^{o}C the solar disinfection process becomes accelerated (Wegelin et al. 1994; TM Joyce et al. 1996). In this experiment the lying bottles and hanging bags did not exceed 45^{o}C, while the lying bags did exceed the threshold. It is likely that this temperature difference was responsible for at least some of the higher efficiency that the lying bags exhibited relative to the other samples. The hanging bags had lower temperatures than the lying bags or the lying bottles. This is probably because the hanging bags had more exposure to the surrounding air, so convective cooling played a greater role in their equilibrium temperature than it did for the lying bags and laying bottles.

Regarding surface area, the total surface area of the container is not the most relevant parameter to consider, because it does not reflect the fact that the bag's a pillow-like geometry allows it to catch more sunlight than the approximately cylindrical bottles, and it does not account for the angle of incidence of solar radiation. The relevant parameter must account for the actual surface area through which radiation enters the bag, referred to herein as the "Effective Surface Area."

It has been found that sunlight consists of 60% direct rays, and 40% scattered rays (Eunice Ubomba-Jaswa et al. 2010). The sun's direct rays enter the SODIS container through the surface area projected on a plane perpendicular to the sun's direct rays, because this is the surface area that actually intercepts radiation.

Furthermore, this surface area changes with the sun's position throughout the day. To account for this, at the midpoint of each exposure period the samples were photographed. Each photo was taken such that the camera's shadow fell directly onto the samples, thus ensuring that the plane of each photograph was perpendicular to the sun's rays. Using the bags' 22.5 cm slide locks as a reference for the scale, these photos were overlaid with a grid, and analyzed to determine the "effective surface area" of each sample at each sampling time. Figure 22 demonstrates this process.

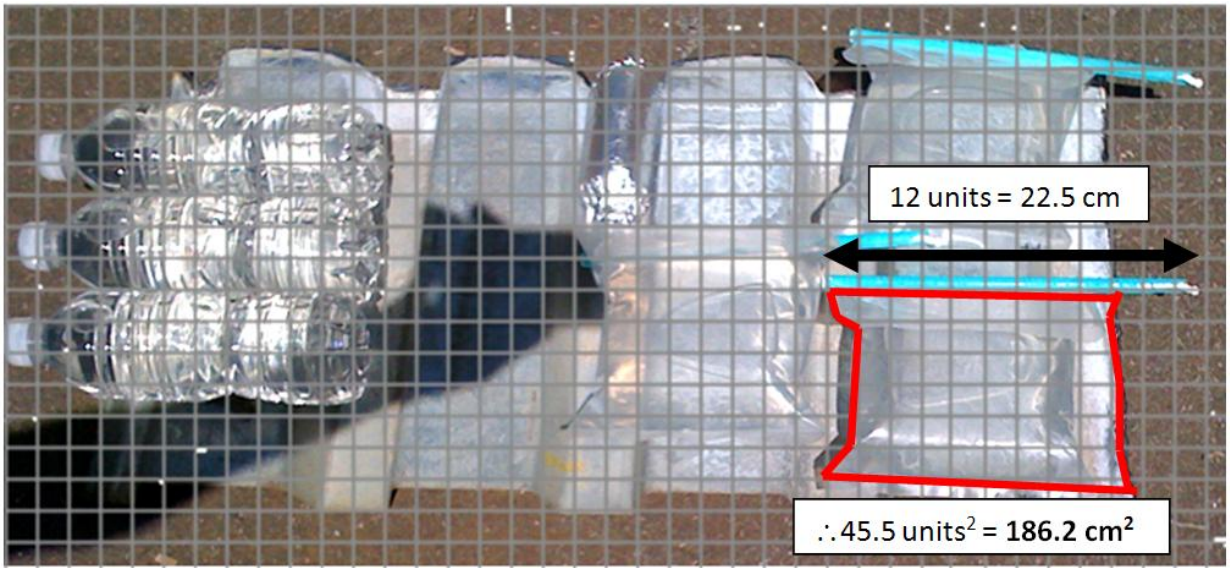

FIGURE 20 EXAMPLE OF USE OF GRID TO DETERMINE "EFFECTIVE SURFACE AREA"

The figure shows that the 22.5 cm slide lock is 12 units long in this case, thus establishing the scale of the grid. Thus, the bag's surface area can be calculated to equal 186.2 cm^2. This process was repeated for each bag in the middle of each exposure period.

The sun's scattered rays enter the water through the whole exposed surface area of the container. For SODIS bags and bottles lying on a SODIS table, this is assumed to equal half of the container's total surface area. The effective surface area relates to these two components according to Equation 2.

$$effective\ surface\ area = 0.6 \times projected\ surface\ area + 0.4 \times total\ exposed\ surface\ area$$

EQUATION 2

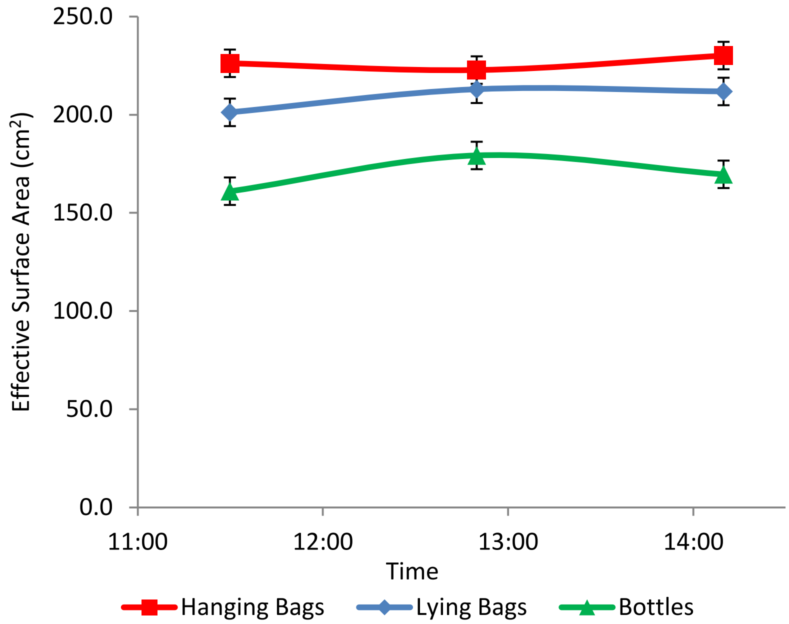

FIGURE 21 CHANGE OF EFFECTIVE SURFACE AREA WITH TIME

(ERROR BARS SIGNIFY 95% CONFIDENCE LIMITS)

The samples' effective surface areas are plotted against time in Figure 23. The figure shows that once these parameters (the sun's changing position and the fact that the radiation was 60% direct and 40% scattered) were accounted for, the lying bags had a higher effective surface area than the bottles. This provides further explanation for why the SODIS bags had higher treatment efficiencies than the bottles.

For the hanging SODIS bags, the effective surface area must account for the fact that the bag is not lying down, so both sides of the bag allow radiation to enter, which doubles the surface area through which diffuse radiation can enter the bag. However, the bags are in a vertical orientation, so they have a small projected surface area and thus intercept less direct radiation. The net impact of these conflicting factors is that the hanging SODIS bags have only a slightly higher effective surface area than the lying SODIS bags, as the figure shows.

Another important parameter is water layer thickness, because as the water layer thickness increases, the treatment efficiency decreases. However, water layer thickness is not an independent parameter; it is coupled with surface area. Because all the samples had the same volume of water (500 mL), and because average water layer thickness can be calculated by dividing volume by surface area, the difference in water layer depth is accounted for in these other parameters.

Clearly the efficiency of the bag was much higher than for the bottle. While it is not clear whether the spectral transmittance of the bag is more or less favorable than that of the bottle, the values for the other relevant parameters are more favorable for the bag than the bottle:

- The maximum temperatures of the bags were high enough to cross the 45ºC threshold and achieve accelerated treatment, while the bottles' temperatures did not get this high.
- The effective surface area of the bags was significantly higher than that of the bottles as well.

Because these parameters show how the conditions for SODIS treatment were significantly more favorable in the bags than in the bottles, it is not surprising that the efficiency of the bags was so much better than the bottles. SODIS bags need to perform as well or better than conventional SODIS bottles to be considered for real-world interventions, so this result is a very positive sign.

The fact that the hanging bags had slightly higher effective surface areas than the lying bags would suggest that, all else being equal, the hanging bags should have exhibited slightly faster treatment. However, all else was not equal, and the hanging bags had a significantly lower treatment efficiency than the lying bags.

The hanging SODIS bags exhibited significantly lower treatment efficiency than the lying bags, but had a greater disinfection rate than the conventional SODIS bottles. If the lying bags' rapid disinfection is attributable to the elevated temperatures that these samples achieved, as the data suggests, the lower hanging bags' kill rate is logical since these elevated temperatures were not reached in the hanging SODIS bags. The fact that the hanging bags have two exposed surfaces allows more radiation to enter the bags as discussed above, but it also allows for increased convective cooling. This is the likely explanation for why the hanging bags achieved significantly lower temperatures than the lying bags, which only experience convection on one surface.

Ultimately, the most important result is that the SODIS bag performed with greater efficiency than the SODIS bottle, which means that SODIS bags can be adopted without the risk of poorer treatment efficiency than conventional SODIS.

It is important to qualify these conclusions with some observations about the variability of the treatment conditions. The exposures described herein took place in a courtyard where wind was negligible; however, actual SODIS exposures can take place in any imaginable wind conditions. The temperatures that the SODIS containers achieve is closely related to the wind conditions.

To investigate the significance this phenomenon, a set of outdoor SODIS exposures was conducted in rural Uganda under different experimental conditions, and each sample was monitored for temperature. The findings are shown in Figure 24.

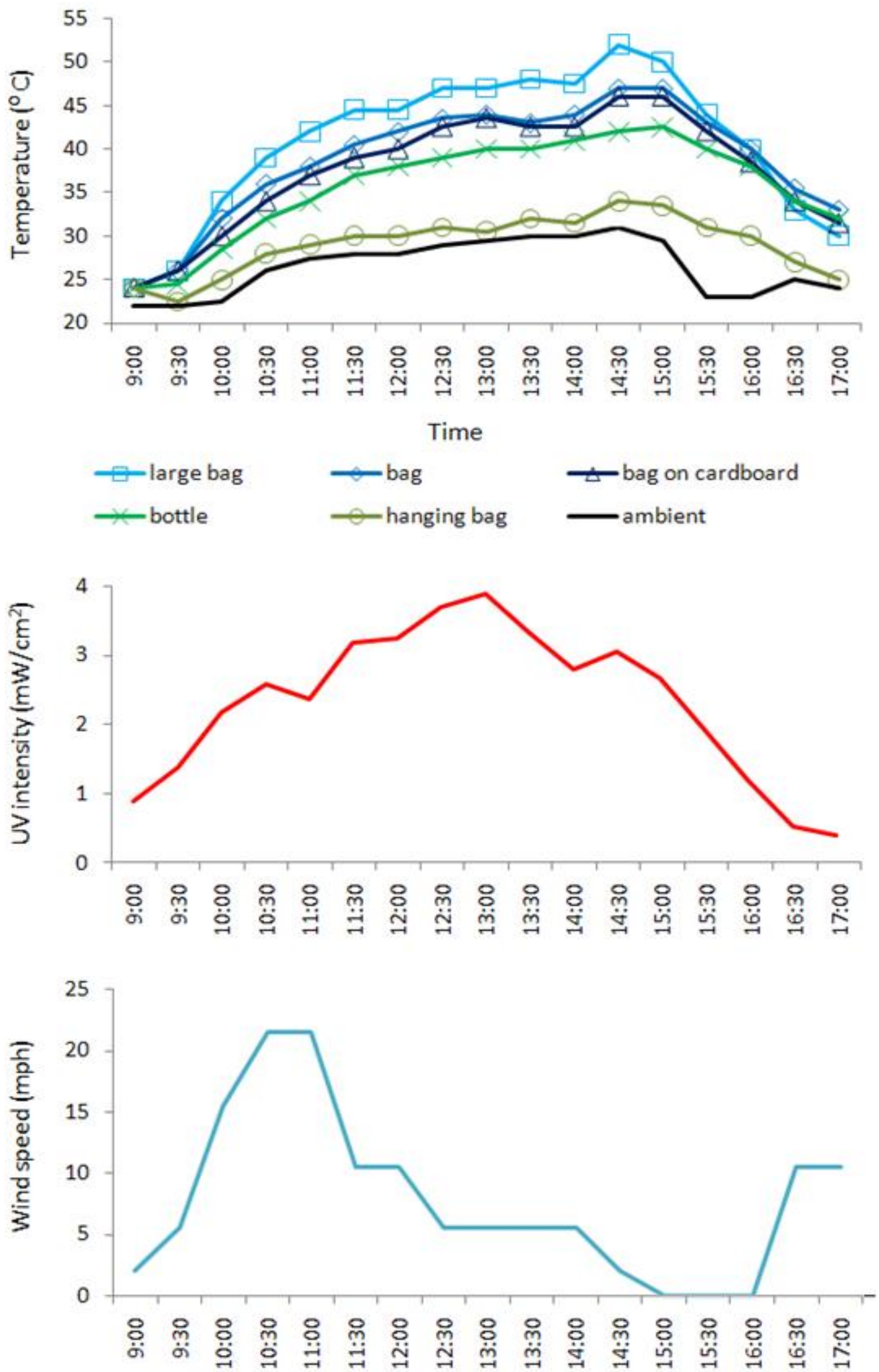

FIGURE 22 VARIATION IN TEMPERATURE, UV INTENSITY, AND WIND SPEED OF SEVERAL SAMPLE TYPES

The temperatures of each of the SODIS containers increased with solar radiation intensity in the morning. However from 1:00 pm to 3:00 pm the intensity of solar radiation decreased, dropping from the daily maximum of 3.88 mW/cm^2 to 2.67 mW/cm^2, but the temperatures of the SODIS containers increased by 6.00% to 9.84%, even though sun intensity was well past its peak. It is hypothesized that this was due to the wind speed dropping off in the in the afternoon, from approximately 5.5 mph at 1:00 to non-detect at 3:00. Because there was little wind, there was little convective cooling to draw warmth from the SODIS containers, and their temperatures rose significantly despite decreasing solar radiation intensity.

This was only a small preliminary investigation using non-rigorous experimental methods, but it suggests that wind speed can play an important role in determining the temperatures that are reached during SODIS.

The present study finds that the SODIS bags experience greatly increased treatment efficiency relative to conventional SODIS bottles, which appears to be because the bags reached higher temperatures during treatment and have a greater effective surface area. It is likely that the temperature played the largest role in the bags' accelerated treatment rates, because former research has showed that crossing the threshold of 45^{o}C leads to faster treatment (K G McGuigan et al. 1998), and because the treatment rate accelerated after the first 40 minutes, once the water had a chance to warm up. However, because of the role of wind as a confounding factor, it cannot be assumed that this will happen every time SODIS treatment is conducted in bags.

6 Effect of Various Parameters on Degradation of SODIS Bags

To determine the contribution of material thicknesses, orientation, sun exposure, and daily use to degradation of SODIS bags, 20 SODIS bags were subjected to different usage conditions for 2 to 4 months. For the bags that required it, radiation exposures were done outside in Kampala, Uganda, because Uganda has climactic conditions representative of the places where SODIS is most commonly used. All of the bags were made of transparent LDPE, had identical geometries, and were sealed across the opening to enclose the water.

To test material thickness, "thick" bags were made of 50 μm plastic film, and "thin" bags were made of 25 μm plastic film. To test orientation, "lying" bags were laid flat on a sheet of corrugated steel, and "hanging" bags were suspended from hooks on a rod. To test type of use, "sun only" bags were left outside for the full exposure period of two months with no further treatment, "daily use" bags were filled and emptied daily with no sun exposure, and "both" bags were left outside for the duration, and were also filled and emptied each day. This combinatorial approach to testing the type of use was chosen to because it was hypothesized that sun exposure and daily use might have some combined impact that would not be apparent from only studying these parameters separately.

After the bags were treated according to their respective conditions for two months, they were tested for optical transparency and physical strength to determine whether and how much each parameter had caused the bags to degrade. Logistical limitations prohibited generation of multiple samples for each set of conditions, but optical transparency tests were repeated 10 times per sample and physical strength tests were conducted 5 times per sample.

The results of these measurements are shown in Figures 25 and 26, and the full numerical values are tabulated in Table 3. Because error bars would overlap and become indistinguishable, the confidence limits are given in Table 3, but not in the figures. Note that 254 nm is an industry-standard wavelength for optical transparency tests, but because this wavelength is not present in natural sunlight, each sample's transparency is also reported at 400 nm. As shown below, the 254 nm values and 400 nm values generally scale together.

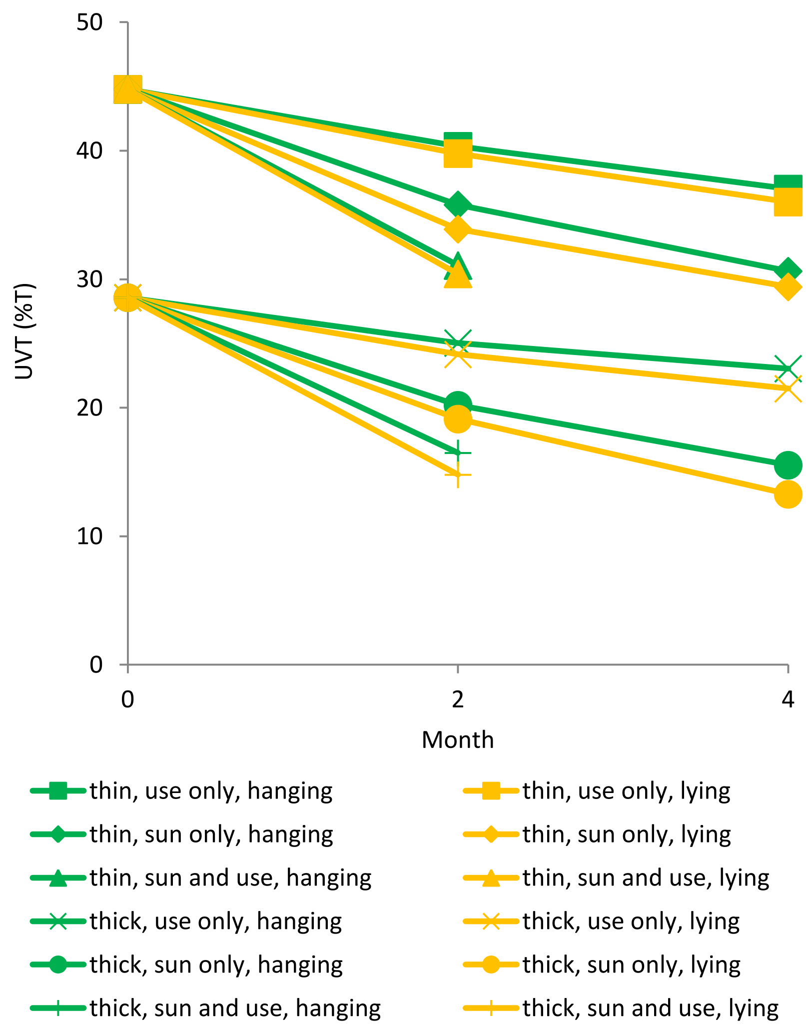

FIGURE 23 EFFECTS OF PARAMETERS ON UVT OF SODIS BAGS

(CONFIDENCE LIMITS ARE PROVIDED IN TABLE 3)

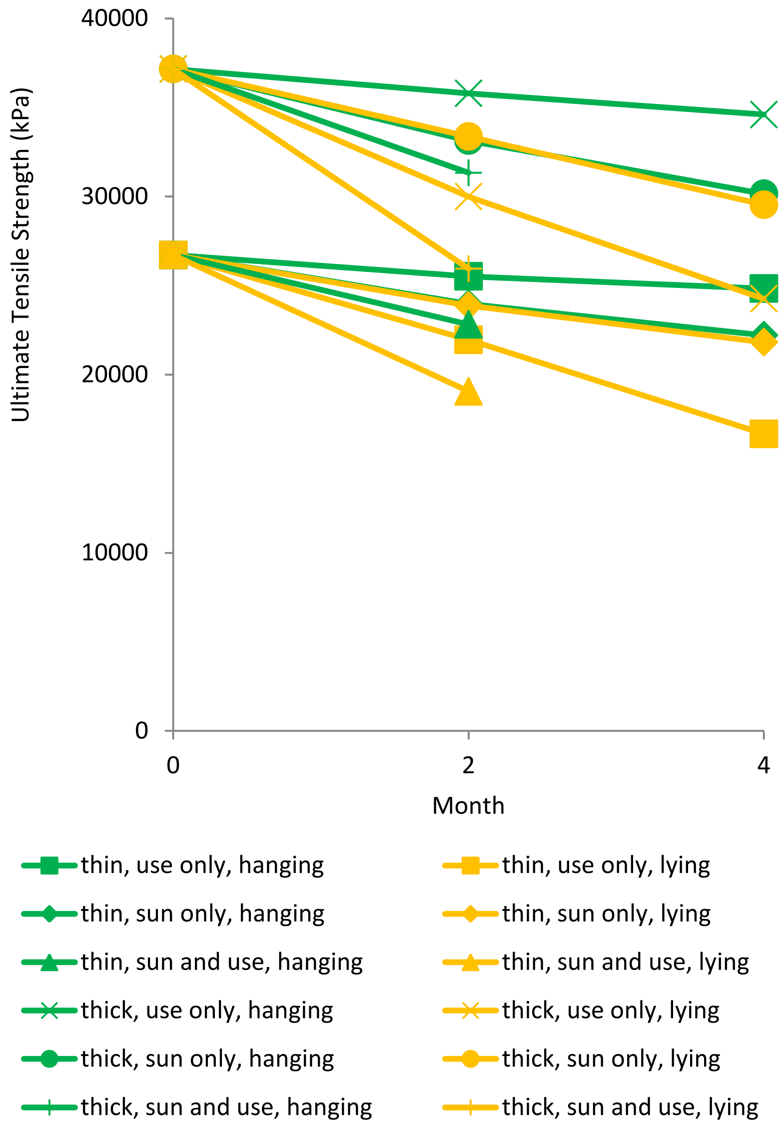

FIGURE 24 EFFECTS OF PARAMETERS ON MATERIAL STRENGTH OF SODIS BAGS

(CONFIDENCE LIMITS ARE PROVIDED IN TABLE 3)

TABLE 3 RESULTS OF DEGRADATION TESTS (MEASURED VALUES)

thick

hanging		sun only			use only			both		
		UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)
	0 months	28.57	58.73	37160	28.57	58.73	37160	28.57	58.73	37160
	95% C.L.	*0.19*	*0.43*	*1281*	*0.19*	*0.43*	*1281*	*0.19*	*0.43*	*1281*
	2 months	20.20	44.19	33140	25.04	50.38	35792	16.49	34.60	31330
	95% C.L.	*0.64*	*1.43*	*1997*	*1.02*	*1.39*	*1087*	*1.02*	*1.39*	*1025*
	4 months	15.53	33.53	30158	23.05	46.81	34599			
	95% C.L.	*0.19*	*0.43*	*1181*	*0.50*	*0.77*	*3145*			

lying		sun only			use only			both		
		UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)
	0 months	28.57	58.73	37160	28.57	58.73	37160	28.57	58.73	37160
	95% C.L.	*0.19*	*0.43*	*1281*	*0.19*	*0.43*	*1281*	*0.19*	*0.43*	*1281*
	2 months	19.12	41.90	33369	24.15	48.58	29995	14.79	31.59	25946
	95% C.L.	*0.71*	*0.59*	*815*	*5.25*	*10.16*	*1796*	*0.35*	*0.95*	*9641*
	4 months	13.27	27.63	29535	21.49	46.50	24267			
	95% C.L.	*3.54*	*6.90*	*9276*	*2.85*	*5.54*	*1032*			

thin

hanging		sun only			use only			both		
		UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)
	0 months	44.79	96.79	26714	44.79	96.79	26714	44.79	96.79	26714
	95% C.L.	*0.19*	*0.59*	*1280*	*0.19*	*0.59*	*1280*	*0.19*	*0.59*	*1280*
	2 months	35.80	74.57	23963	40.36	85.65	25519	31.08	65.63	22825
	95% C.L.	*0.45*	*0.92*	*1798*	*0.19*	*0.43*	*1262*	*1.47*	*2.84*	*1302*
	4 months	30.63	63.34	22211	37.03	81.01	24834			
	95% C.L.	*2.77*	*3.74*	*1651*	*0.71*	*0.59*	*935*			

lying		sun only			use only			both		
		UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)	UVT254 (%T)	UVT400 (%T)	strength (kpa)
	0 months	44.79	96.79	26714	44.79	96.79	26714	44.79	96.79	26714
	95% C.L.	*0.19*	*0.59*	*1280*	*0.19*	*0.59*	*1280*	*0.19*	*0.59*	*1280*
	2 months	33.90	68.19	23878	39.79	85.20	21953	30.43	63.62	19058
	95% C.L.	*0.19*	*0.43*	*1624*	*0.65*	*0.98*	*1193*	*1.19*	*2.11*	*1005*
	4 months	29.41	64.22	21822	36.01	71.93	16673			
	95% C.L.	*1.19*	*2.11*	*880*	*0.19*	*0.43*	*1288*			

For easier comparison, the same results are shown Table 8 using percents instead of measured values. “% change” indicates the change from each sample’s original measurements of “0 month” values.

TABLE 4 RESULTS OF DEGRADATION TESTS (PERCENT CHANGES)

		sun only			use only			both		
		UVT254 (% change)	UVT400 (% change)	strength (% change)	UVT254 (% change)	UVT400 (% change)	strength (% change)	UVT254 (% change)	UVT400 (% change)	strength (% change)
thick										
hanging	2 months	-29.30%	-24.76%	-10.82%	-12.35%	-14.21%	-3.68%	-42.29%	-41.09%	-15.69%
	4 months	-45.63%	-42.90%	-18.84%	-19.33%	-20.30%	-6.89%			
lying	2 months	-33.07%	-28.65%	-10.20%	-15.47%	-17.28%	-19.28%	-48.24%	-46.22%	-30.18%
	4 months	-53.56%	-52.96%	-20.52%	-24.80%	-20.82%	-34.70%			
thin										
hanging	2 months	-20.07%	-22.96%	-10.30%	-9.89%	-11.51%	-4.48%	-30.61%	-32.20%	-14.56%
	4 months	-31.60%	-34.56%	-16.86%	-17.33%	-16.30%	-7.04%			
lying	2 months	-24.31%	-29.55%	-10.62%	-11.16%	-11.97%	-17.82%	-32.07%	-34.27%	-28.66%
	4 months	-34.33%	-33.65%	-18.31%	-19.59%	-25.68%	-37.59%			

For the UVT tests, the confidence limits are small, and all UVT data-points are statistically distinct. However, due to larger variations between measurements, the confidence limits for the samples’ strengths are larger. In some cases there are enough statistically distinct data-points to draw conclusions, while in other cases the strength data is not conclusive.

The implications of these results for each parameter are discussed below.

- Material thickness – In both figures the results lie in two groupings, because the plots progress from two initial values. For UVT the upper group of plots corresponds to the thin bags (because they have higher transmittance), and for tensile strength the upper group of plots corresponds to thick bags (because they have higher strength). For UVT the thick bags exhibit greater percent reductions than the thin bags (20.8% and 30.1%, respectively), suggesting that thick bags are more susceptible to optical degradation than thin bags. Furthermore, because the thick bags start at a lower UVT, their subsequent decrease in UVT is all the more significant because less and less radiation is allowed to pass into the water. For tensile strength, the thick bags and thin bags have statistically significant differences in strength (averaging 31,595 $\pm$ 2,727 kpa and 22,866 $\pm$ 1364 kpa, respectively, after 2 months of aging) but they exhibit similar percent reductions (14.4% and 14.9%, respectively), suggesting that they are equally susceptible to physical degradation.

- Orientation – In the figures, hanging bags are indicated by the markers in the left column of the key and lying bags are indicated by markers in the right column. For both UVT and strength, the hanging bags exhibited statistically significant lower levels of degradation than the lying bags. After the first 2 months the average decrease in UVT of the hanging bags was 24.0%, while the average decrease in UVT of the lying bags was 26.9%. This is a relatively small difference, suggesting that orientation has only a small impact on the rate of optical degradation of SODIS bags. However, for the same period the average decrease in tensile strength of the hanging bags was just half (47%) of the average decrease in tensile strength of the lying bags (9.2% and 19.4% decrease, respectively). The difference here is much larger, suggesting that lying SODIS bags undergo physical degradation at a rate more than double that of hanging SODIS bags.

- Type of use – Different samples were subjected to sun exposure alone, physical use alone, or combined sun exposure and physical use. For UVT, the sun exposure impacted transmittance approximately twice as much as physical use (averaging 12.2% and 25.9% reduction in UVT, respectively). However, for tensile strength the impacts of use and sun exposure were approximately equal and statistically indistinct (averaging 11.3% and 10.4%, respectively). This suggests that sun exposure causes significantly more optical degradation than physical use does, but that sun exposure and physical use are of comparable importance in causing physical degradation. Interestingly, the tests combining sun exposure and physical use suggest that for both UVT and tensile strength, the impact of each "sun and use" test approximately equals the sum of the impacts from the corresponding "sun only" and "use only" tests, with no evidence of synergy or interference. For example, in the case of thin, hanging SODIS bags, sun exposure caused a UVT reduction of 20.07%, physical use caused a UVT reduction of 9.8%, and sun exposure combined with physical use caused a UVT reduction of 30.6%. This suggests that the impacts of the sun exposure and physical use are simply additive. There is no evidence of interactions between the two causes of degradation.
- Duration – As expected, degradation progressed further in the 4 month samples than the 2 month samples. It appears that for UVT the decrease was not linear (on average, the samples' decrease in UVT was 19.0% during months 1 and 2, but just 7.6% during months 3 and 4) while the decrease in tensile strength was closer to being linear (varying from 10.9% during months 1 and 2 to 8.1% during months 3 and 4). However,

more research would be required to confirm these results, because three data points per sample is insufficient to draw conclusive findings with respect to linearity.

These results provide some interesting insights into the degradation of SODIS bags, such as the observations that sunlight exposure has a much greater impact on optical degradation than physical use does, and that there appears to be no synergistic effect between physical and optical degradation. All bags were still functional at the end of the testing periods, suggesting that SODIS bags can withstand greater than 4 months of regular use. Hanging SODIS bags may have a significantly longer lifetime than lying SODIS bags due to decreased rates of physical degradation in hanging SODIS bags.

7 Effect of Water Layer Depth on Treatment Efficiency and Calculation of Dose

To compare the treatment efficiency of SODIS for different water layer depths, and to investigate the merits of the various dose calculation processes, a sunlight simulator was used to conduct several bioassays. For each bioassay, samples of highly contaminated challenge water (prepared by diluting raw wastewater) were exposed to radiation from the sunlight simulator for varying periods of time. The samples were held in a constant temperature bath to allow a temperature of 37^{o}C to be maintained during each exposure.

Each sample was contained within a cylindrical glass sample vessel, to simulate a portion of the water in a lying SODIS bag. Experiments were conducted using sample vials of varying depths; one batch with samples of 0.5 cm deep, 2 cm deep, 4 cm deep, and 6 cm deep. During exposure, each sample was covered with a layer of plastic SODIS bag material to simulate the upper surface of the SODIS bag through which radiation must pass to reach the water.

Bioassays were conducted in triplicate for each depth, for a total of 12 bioassays. Each bioassay included an initial sample (taken before the exposure commenced), three samples evenly distributed during the exposure period, a cool control wrapped in foil and held at room temperature outside of the light beam, and a warm control wrapped in foil and held in the constant temperature bath under the lamp with the exposed samples. Each sample and control was analyzed using the Membrane Filter plating method for fecal coliform (Anon. 1999), so that they could be compared based on the rate of fecal coliform inactivation.

For simplicity, this investigation assumed that the light-source is always directly overhead, removing the impact of the sun's ever-changing angle. This assumption is reasonable because SODIS is recommended for use in geographic regions with a high solar altitude, meaning the sun passes more or less overhead relative to the SODIS bags or bottles being exposed.

Conveniently, the data collected from these bioassays could be analyzed to shed light on both of the research needs mentioned above. Thus, water layer depth and the stirring assumption could be studied with one set of experiments.

7.1 Effect of Water Layer Depth on Treatment Efficiency

The results of these experiments are shown in Figure 27, and the full numerical values are tabulated in Appendix B. Each experiment was completed in triplicate, and this graph shows the average of each set of repetitions.

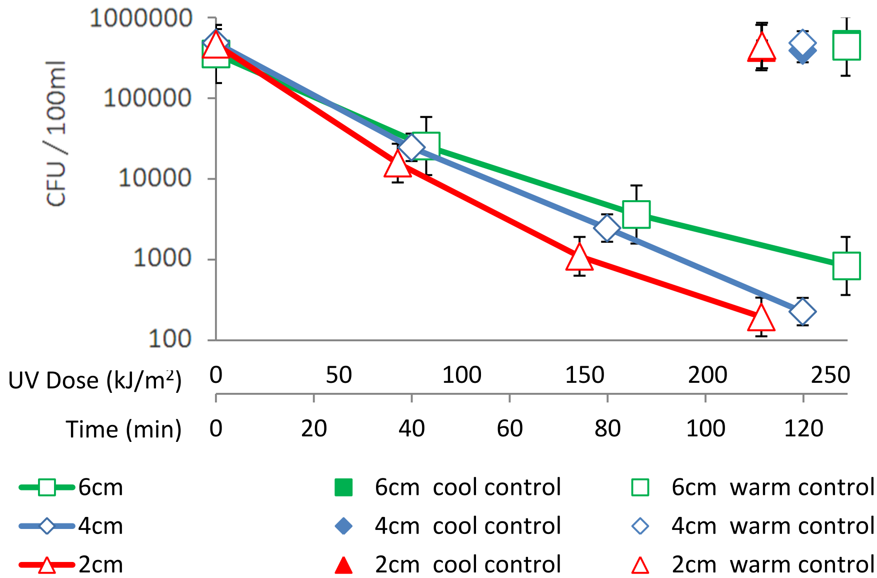

FIGURE 25 INACTIVATION CURVES FOR VARIOUS WATER LAYER DEPTHS (ERROR BARS SIGNIFY 95% CONFIDENCE LEVELS)

As expected, the figure shows that the efficiency of SODIS treatment increases with decreasing water layer depth. The respective efficiencies for the 2, 4, and 6 cm samples are 0.03649, 0.02768, and 0.02176 log/min. The 95% confidence intervals for these values are 0.03088 - 0.04210, 0.02657 - 0.02880, and 0.0194 - 0.02408 log/min, respectively, showing that these results are statistically distinct. The treatment efficiencies fall within the range of what is expected based on published literature, achieving 2-3 logs of fecal coliform inactivation within 1-2 hours of exposure (Wegelin et al. 1994; TM Joyce et al. 1996). It should be noted that the present study uses the industry-standard assumption that the inactivation kinetics are first order, even when the inactivation curves appear to be slightly curved.

Dose was calculated using the Surface Dose Method. This means that the radiation incident upon the surface of the SODIS container was measured and reported as dose. While there are important drawbacks to this approach, it is the most common method of calculating dose in SODIS research. A convenient benefit of the Surface Dose Method of calculating dose is that when used with a light-source with constant intensity, dose varies linearly with time. This allows time and dose to be plotted on the same axis, as shown in the figure.

The graph in Figure 27 shows that the experiments were quite repeatable, because the error bars are small relative to the overall measurements. Furthermore, both the warm and cool controls exhibited very little change in concentration during the experimental period, which strengthens the conclusion that the respective dose responses were a result of the SODIS exposure, and not of some confounding parameter.

The apparent inactivation constants (the slopes of the dose response curves) of these samples vary significantly with sample depth. Ideally, the constant should not vary with depth; however, this variation was expected because the Surface Dose Method of calculating dose does not account for the parameters relating to water quality and geometry. The shallower samples are treated more rapidly than the deeper samples because the radiation has to pass through less water in the shallower samples, so less radiation is absorbed in the water, and more radiation arrives at an average bacterium in the water.

The relationship between water layer depth and rate constant is shown more clearly in Figure 28. The figure shows that as the water layer increases, the rate of treatment decreases. This is because the radiation is attenuated as it passes through the water, so a deeper sample receives less radiation on average than a shallow sample does.

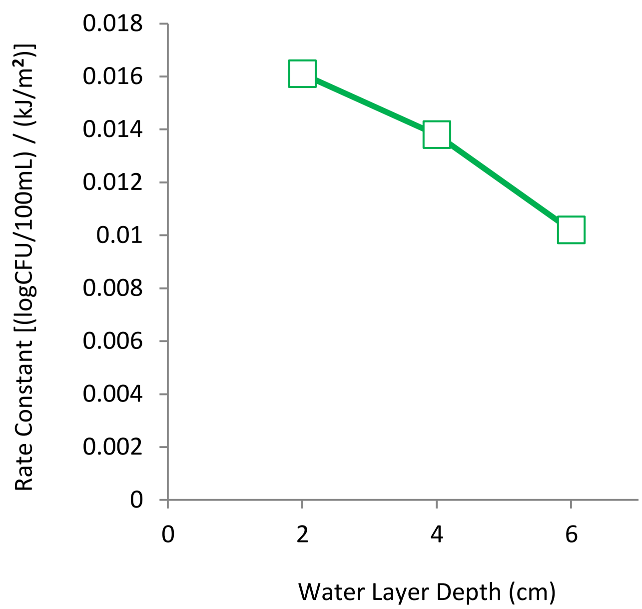

FIGURE 26 INACTIVATION RATES FOR VARIOUS WATER LAYER DEPTHS

This graph can be used to interpolate and, to some degree, extrapolate expected rate constants for other water layer depths with a moderate degree of confidence. For example, based on these results it would be reasonable to expect that a water layer depth of 5 cm would result in a treatment rate of approximately 0.012 (log CFU/100 mL) / (kJ/m^2) under similar treatment conditions, and using the same method of calculating dose. This is a useful tool because determining water layer depth is a crucial design parameter for SODIS bags.

7.2 Effect of the Stirring Assumption on the Calculation of Dose

This experiment was simply a reworking of the results from Section 7.1. The data from that experiment was analyzed using the Layer Method of Calculating Dose described in Section 4.3. Figures 29, 30, and 31 show the data from the experiments on 6 cm samples from Section 7.1, as interpreted by each of the three dose calculation methods. Figure 29 shows the 6 cm data plotted against dose according to the Surface Dose Method, Figure 30 shows the 6 cm data plotted against dose according to the UV-Disinfection Method, and Figure 31 shows the 6 cm data plotted against dose according to the Layer Method of calculating dose. Note the changing scale on the horizontal axis. Error bars have not been included in these graphs; however, as in the original plotting of this data in Figure 27, the differences between each curve's efficiency are statistically significant.

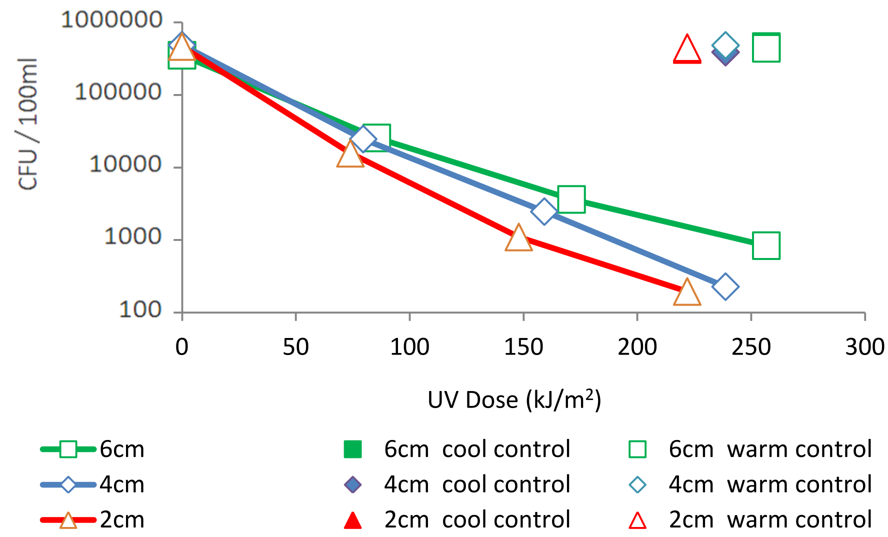

FIGURE 27 INACTIVATION CURVES FOR SURFACE DOSE METHOD OF CALCULATING DOSE

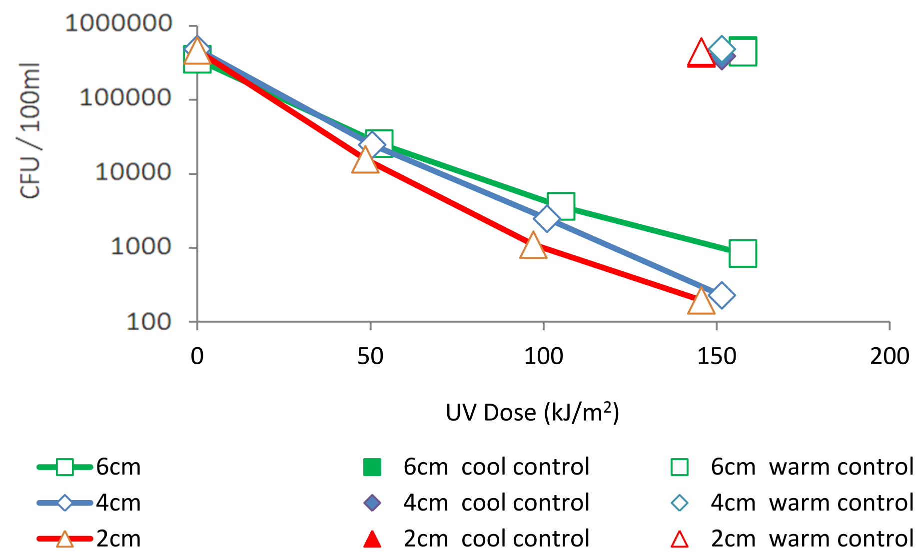

FIGURE 28 INACTIVATION CURVES FOR UV-DISINFECTION METHOD OF CALCULATING DOSE

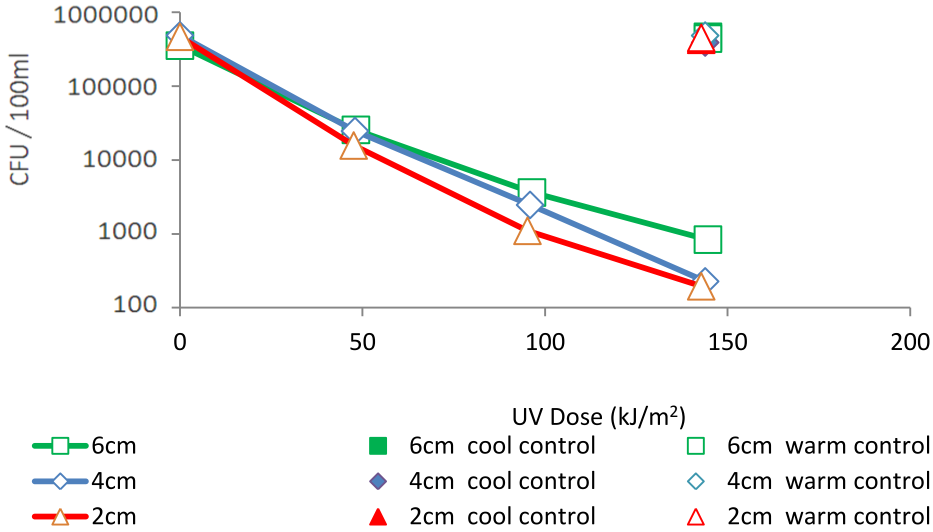

FIGURE 29 INACTIVATION CURVES FOR LAYER METHOD OF CALCULATING DOSE

Comparing the three figures, two important differences must be noted. First, the scale of the horizontal axis varies significantly between different runs. Second, the three curves "bunch" more closely together with each subsequent dose calculation method. These two observations are discussed in detail below.

Regarding the scaling of the horizontal axis: for the sake of easier comparison, Figure 32 shows the set of experimental data for 6 cm samples plotted according to the three dose calculation methods side-by-side on one set of axes.

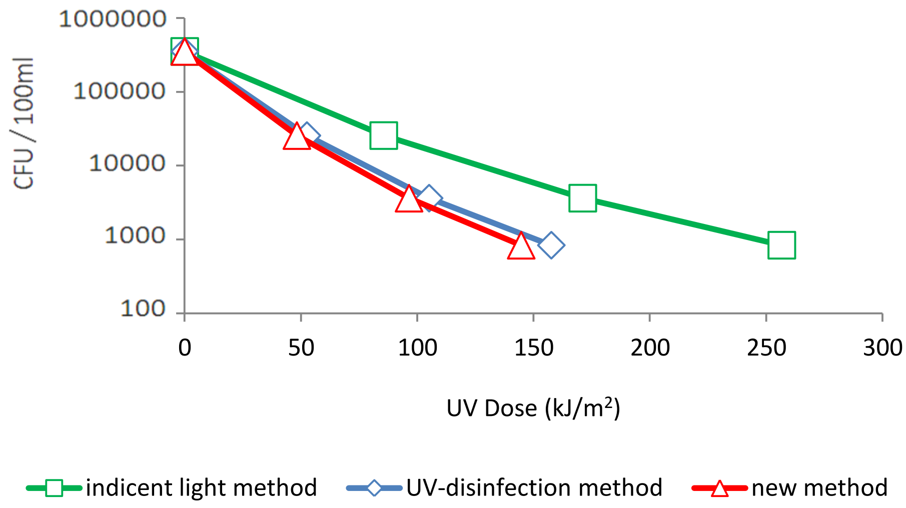

FIGURE 30 COMPARING INACTIVATION CURVES FOR THE THREE METHODS OF CALCULATING DOSE

The figure shows that the different dose calculation methods have significantly different results. This is because each method accounts for different parameters, so the resulting dose value varies with the different methods. Table 3 shows how these parameters vary. Proceeding from Surface Dose Method to conventional UV-Disinfection Method to Layer Method, each approach accounts for more parameters and thus, relies on fewer assumptions than the previous one.

TABLE 5 COMPARING PARAMETERS ACCOUNTED FOR IN THE THREE METHODS OF CALCULATING DOSE

Parameter	Surface Dose Method	UV-Dis Method	Layer Method
spectral intensity of the light-source	X	X	X
the duration of exposure	X	X	X
the spectral transmittance of the container (SODIS bottle or bag)		X	X
the spectral transmittance of the water		X	X
the limited stirring condition			X
the action spectrum of the treatment process			

Thus, as more parameters are accounted for, the resulting dose value decreases. This is because these parameters each account for ways in which radiation is absorbed before reaching the bacteria, so with each additional set of parameters the bacteria receive less radiation.

Regarding the observation that the three curves “bunch” more closely together with each subsequent dose calculation method: recall that a smaller variation in apparent inactivation rates indicates a better dose calculation method, because in the ideal case the apparent inactivation constant would be truly constant, regardless of treatment conditions. With reference to Figure 32, for an accurate dose calculation (one that deals properly with all the relevant variables) these four curves should have the same apparent inactivation constant (slope), and thus should lie directly on top of each other.

Clearly this is not the case for the Surface Dose method, for reasons already described. However, when the same data is plotted according to the other two dose calculation methods, the apparent inactivation constants vary less. In Figures 30 and 31 the results are plotted according to the conventional UV-Disinfection Method and the Layer Method, respectively.

These figures show that the three runs lie closer together on the graph with each subsequent dose calculation method. This is because these dose calculation methods account for more of relevant parameters, as tabulated in Table 3, so the results that they yield are progressively closer to the ideal case in which inactivation constants are not dependent on treatment conditions.

Looking at these three graphs qualitatively, the differences between the three dose calculation methods are fairly subtle. However, the differences can be seen more clearly by considering the degree of variation in inactivation rate for each method. The percent variations in rate for each dose calculation method are shown in Figure 33.

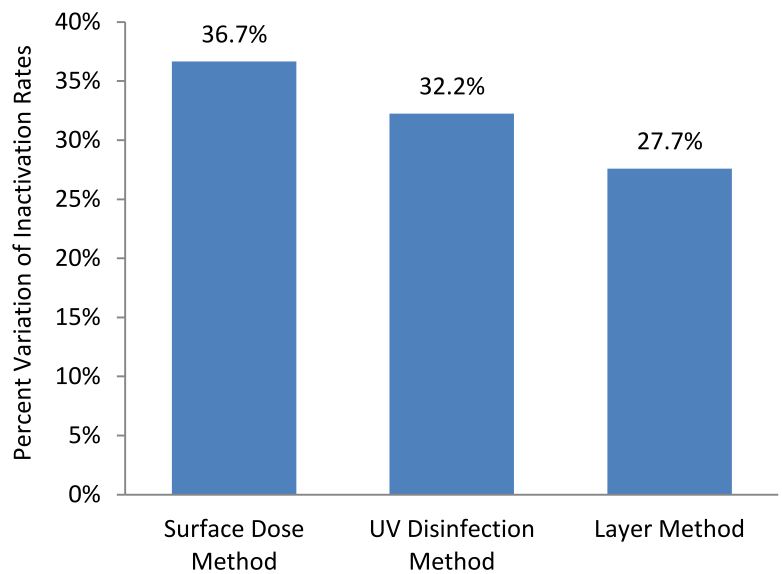

FIGURE 31 COMPARING DEGREE OF VARIATION FOR THE THREE METHODS OF CALCULATING DOSE

In effect, Figure 33 quantifies the "tightness" of the grouping of curves in each of the three graphs above – a smaller variation in disinfection rate corresponds to more tightly grouped dose response curves, and hence, a better dose calculation method. The Surface Dose Method yields a 36.7% variation in inactivation rates, the conventional UV Disinfection Method yields a 32.2% variation in inactivation rates, and the Layer Method yields a 27.7% variation in inactivation rates. This shows that the Layer Method of calculating dose is the best of the three, because its results are closest to the ideal case of 0% variation of apparent inactivation rate between runs.

Considering that the goal is to have a dose calculation method that yields consistent dose response (0% variation in rate, subject only to experimental error), the relative improvements of these modified methods of dose calculation are fairly small. However, they do exhibit a meaningful improvement, which suggests that the proposed modifications to the dose calculation do help to some degree. Though it is still far from ideal, the reductions from 36.7% to 32.2% to 27.7% variation in rate are steps in the right direction.

The Layer Method may be further improved by experimenting with different layer thicknesses. Because the Layer Method is intended to account for some moderate level of stirring (rather than assuming there is complete stirring), setting the layer thickness is equivalent to deciding the degree of mixing in the sample. The current study only tests one case rather than attempting to test for multiple levels of mixing to see which gives the best results. The current study uses a 5 mm layer thickness simply to test the concept, but further experiments with other layer thicknesses may determine that some other option yields better results.

However, because the improvement realized by this Layer Method (at least in this first attempt at its application) is relatively small, it may be that the stirring assumption is not a very significant source of error in SODIS dose calculation. Figure 18 depicts a case in which mixing was found to be important; however, this experiment used 50% wastewater, which is about five times more absorptive of radiation than the water qualities typically used in SODIS treatment. It would be reasonable to expect that for better water quality, the mixing assumption may be more valid than it was in the experiment described in Section 4.3. This could be because convection alone generates enough mixing in the reaction vessel to satisfy the missing assumption. If this is the case, optimizing the Layer Method would not be able to improve the dose calculation to a very great extent. Furthermore, application of the Layer Method is a lot more involved than simply applying an equation, because the experimenter must conduct a bioassay to determine the kinetics in one layer, and then use a series of calculations to apply this rate to the other layers before averaging the calculated final concentrations together and back-calculating an effective dose. This is experimentally intensive, and the extra effort may not be worthwhile considering the small improvement that it seems to generate.

The benefit of a perfect dose calculation method would be that it would make most testing unnecessary, because all the desired information could be calculated based on a few key inputs (the container's and water's transmittance spectra, the radiation's intensity and duration, and the water layer depth). This is currently the case for UV-Disinfection, but not for SODIS.

It is important to note that, besides the experiments that are specifically comparing alternate methods of calculating dose, the inactivation curves presented in the current research are plotted against time instead of dose. The study compares several dose calculation methods and finds that they all have significant drawbacks and weaknesses, so it was decided that the results should be reported in units of time instead.

8 Other Practical Considerations

Besides the primary conclusions regarding the relative treatment efficiencies of SODIS bottles and bags, there is an interesting secondary significance of the results depicted in Figure 20 and Table 2. The SODIS bags reached fairly high temperatures and exhibited accelerated treatment efficiency, and the control reached the same temperature as the SODIS bags, yet it did not show any reduction in concentration. This suggests that the increased treatment efficiency that has been observed when the temperature crosses the 45^{o}C threshold is a truly synergistic phenomenon. It would be reasonable to suspect that the increased efficiency is just a result of the beginning of a pasteurization effect at these elevated temperatures. However, if this were the case, the control (which also reached these elevated temperatures) should have shown a decrease in concentration. The fact that the exposed samples exhibited increased treatment efficiency at elevated temperatures but the unexposed control did not show any bacterial die-off suggests that the SODIS + heat phenomenon is truly synergistic, rather than just being the additive combination of SODIS and low-temperature pasteurization. This means that SODIS treatment with concurrent heating above 45^{o}C is more effective than if these two components took place separately.

However, the control was just a single sample, and no attempt was made to repeat this outcome. But the conclusion is logical because fecal coliform's incubation temperature is 44.5^{o}C, which is barely below the SODIS acceleration threshold. This suggests that temperatures around 46^{o}C and 47^{o}C should not be able kill fecal coliform from the heat alone.

Furthermore, pasteurization, which is a heat denaturization process, is conducted at much higher temperatures at or above 72 °C.

With reference to Figure 23, it is interesting to note that the profiles for lying bottle and lying bag follow the same general shape, with the effective surface area increasing during the first half of the treatment period, and decreasing during the second half. This is because the sunlight's angle of incidence increases as it rises higher in the sky, and decreases after reaching its zenith. As the sun's angle increases and then decreases, the projected area of the SODIS bottles and bags increases and decreases as a result. This is one reason why, for conventional SODIS in lying bottles, it is recommended to center the period of SODIS exposure around noon. However, unlike the lying samples, as the sun passes its zenith the projected surface areas of the hanging bags reach a local minimum. The hanging bags are in a vertical orientation, so a higher solar altitude means the hanging bags have a smaller projected area, and they intercept less direct radiation. For this reason, for hanging SODIS bags may be less important to center the exposure period around mid-day, because mid-day does not necessarily offer the most favorable condition for SODIS treatment. More extended tests could show which part of the day offers the best conditions for treatment with hanging SODIS bags. However, effective surface area is not the only relevant parameter; the sun is also the most intense in the middle of the day, when the high solar altitude minimized the amount of atmosphere that the sun's rays must penetrate to reach earth, thereby decreasing atmospheric radiation absorption. The optimal exposure time must account for both of these crucial parameters. This is an excellent example of a case where a dose calculation that accounts for all of the relevant factors would be a powerful tool.

Another interesting subject to consider is the actual SODIS bag design; the perforated tear-off bags with slide locks for closure. The slide locks were found to seal the bags reasonably effectively, but not perfectly. The sealed bags withstand pressure very well. This is presumably because pressurizing the bag causes the rod and sheath to squeeze together more tightly, forming a self-pressurizing seal similar in principle to a bathtub plug. For this reason, no amount of squeezing was able to cause the sealed bags to leak, short of damaging the bags themselves, which proved to be very difficult.

However, when the bags were filled with water and left alone for extended periods, in some cases a small amount of leakage occurred. It was hypothesized that in this un-pressurized state the rounded edges of the bags where the plastic folded over on itself were not quite squeezed together tightly enough to form a full seal, so a little bit of water was able to gradually bead out of the corners.

This problem may be overcome by optimizing the design of the slide locks based on the bags' wall thickness. A slide locks' annular space (the space between the sheath and the rod) determines how tightly it squeezes the bag's walls together, so these leaks could possibly be corrected by using slide locks with a slightly smaller gap between the sheath and rod.

9 Implications

9.1 Comparison of SODIS Efficiency in Lying Bottles, Lying Bags, and Hanging Bags

The SODIS bags showed much faster treatment rates than the conventional SODIS bottles. It is believed that this was because the bags reached higher temperatures during treatment and have a greater effective surface area. It is likely that the temperature played the largest role in the bags' accelerated treatment rates, because former research has showed that crossing the threshold of 45^{o}C leads to faster treatment (K G McGuigan et al. 1998), and because the treatment rate accelerated after the first 40 minutes, once the water had a chance to warm up.

However, it cannot be assumed that SODIS bags will always yield such favorable results. These experiments were conducted in low wind conditions, and increased wind would increase convective cooling, which may cause the bags' temperature to remain below the 45^{o}C threshold. However, even at lower temperatures it is likely that SODIS bags would exhibit higher treatment rates than SODIS bottles because of their increased surface area relative to bottles. All of the samples were at ambient temperature at the beginning of the experiments, but the SODIS bags showed significantly faster treatment than the bottles right from the beginning.

More experiments under a variety of treatment conditions would be helpful to further understand how SODIS bags compare to SODIS bottles. In particular, conditions that keep the temperatures well below the 45°C threshold would shed light on the nature of SODIS bag treatment.

However, the current results show that SODIS bags can lead to significantly higher apparent inactivation constant than SODIS bottles. They can be used in practice with confidence that the water is being treated as well or better than in conventional SODIS bottles.

These experiments suggest that water treated with hanging SODIS bags is not disinfected as rapidly as it is in SODIS bottles lying down. Because the hanging bags' decrease in direct radiation and increase in scattered radiation approximately cancel each other out, the effective surface area is similar in magnitude to lying SODIS bags. However, under the conditions of these tests the hanging bags did not achieve elevated temperatures as the lying bags did. The hanging bags do not cross the 45°C threshold that enables accelerated treatment.

However, the reason that SODIS bags are of interest is that the decreased physical wear realized by avoiding lying the bags on a hard surface may extend the bags' useful life, thus decreasing cost for the SODIS user. The purpose of these efficiency experiments was simply to determine whether there is any efficiency cost associated with using hanging SODIS bags instead of lying SODIS bottles. It was found that the apparent inactivation constant achieved in hanging bags is still slightly better than in conventional SODIS bottles. For SODIS implementers considering a switch to hanging SODIS bags, the most important consideration is that SODIS bags work at least as well as conventional SODIS bottles.

9.2 Effect of Various Parameters on Degradation of SODIS Bags

The results of these combinatorial experiments regarding the impacts of material thickness, bag orientation, type of use, and duration suggest the following conclusions about SODIS bag degradation:

- Thick bags are more susceptible to optical degradation than thin bags.
- Thick and thin bags are equally susceptible to physical degradation.
- Orientation has only a small impact on the rate of optical degradation of SODIS bags.
- Lying SODIS bags undergo physical degradation at a rate more than double that of hanging SODIS bags.
- Sun exposure causes significantly more optical degradation than physical use does.
- Sun exposure and physical use are of comparable importance in causing physical degradation.
- The impacts of the sun exposure and physical use are simply additive. There is no evidence of interactions between the two causes of degradation.
- Optical degradation does not proceed linearly with time; it slows as time progresses.
- The percent decrease of tensile strength with time is approximately linear.

9.3 Effect of Water Layer Depth on Treatment Efficiency and Calculation of Dose

9.3.1 Effect of Water Layer Depth on Treatment Efficiency

As expected, it was found that increased water layer depth results in decreased apparent inactivation constant, with respect to both time and to the Surface Dose Method of calculating dose. While it was not the intent of the current study to fully model the relationship between water layer depth and dose response, the specific dose response values determined herein will allow interpolations and modest extrapolations for determining the approximate dose response that can be expected with different water layer depths, under similar water qualities and treatment conditions. This is a useful tool because determining water layer depth is a crucial design parameter for SODIS bags.

Further study should focus on increasing the number of data points so that a full model can be developed to correlate apparent inactivation constant and water layer depth. It would also be of value to independently confirm the results found herein, because of the importance of water layer depth as a design decision for SODIS bags.

9.3.2 Effect of the Stirring Assumption on the Calculation of Dose

The three dose calculation methods that are explored in the current study were found to each have benefits and drawbacks, and the choice of which is most appropriate to use in a given context will be situation-specific.

The proposed Layer Method yields the closest to ideal results, meaning that the dose response is more consistent under varying treatment conditions than the other methods considered herein. An ideal dose calculation method would give perfectly consistent results regardless of the treatment conditions, so the Layer Method is a step in the right direction. This is because the Layer Method accounts for both the water's transmittance spectrum and the partial-stirring that occurs during SODIS treatment.

The Layer Method of calculating dose is much more complex than simply applying an equation with known values, because it requires that the experimenter determine the kinetics for one layer, and then apply the result to a series of subsequent calculations. This added complexity will make it impractical under many conditions of field research.

While the Layer Method described herein represents a meaningful improvement for the reasons discussed, it is still far from perfect, and is in fact a relatively small step toward the ideal case. It may be that the remaining non-ideality can be addressed by determining the action spectrum of the SODIS process, so that the current assumption that this action spectrum is flat might no longer be necessary. This would be a significant undertaking, but it would be an important achievement for SODIS research, because it might enable a greatly improved means of calculating SODIS dose.

It also may be worthwhile to further improve the Layer Method by varying the layer thickness, whereas the present study simply assumed a value of 5 mm and made no attempt toward optimization. It may be that optimizing the layer thickness (which could also require different layer thicknesses under different treatment conditions) could improve the consistency of the results. This would be the case if the stirring assumption is the major source of error in applying the conventional UV-Disinfection method of calculating dose to SODIS.

The benefit of a perfect dose calculation method would be that it would make most testing unnecessary, because all the desired information could be calculated based on a few key inputs (the container’s and water’s transmittance spectra, the radiation’s intensity and duration, and the water layer depth). This is currently the case for UV-Disinfection, but not for SODIS.

It is important to note that, besides the experiments that are specifically comparing alternate methods of calculating dose, the reduction curves presented in the current research are plotted against time instead of dose. The study compares several dose calculation methods and finds that they all have significant drawbacks and weaknesses, so it was decided that the results should be reported in units of time instead.

10 Conclusions

The goal of this research was to develop an understanding certain key technical considerations of SODIS bags and their application, to inform upcoming decisions regarding their potential application. As a result of the research described herein, the following conclusions were reached:

- Lying SODIS bags exhibit as much as 74% higher treatment efficiencies than the conventional lying SODIS bottles, possibly because of increased surface area and because lying bags can reach temperatures above 45^{o}C, which have been shown to accelerate the SODIS treatment process.
- Hanging SODIS bags yield treatment efficiencies 25% greater than those of SODIS bottles. This may be because, while comparable in effective surface area, the hanging bags are less likely to achieve temperatures exceeding 45^{o}C. However, both lying and hanging SODIS bags can be used in practice with confidence that the water is being treated as well or better than in conventional SODIS bottles.
- Thick bags are more susceptible to optical degradation than thin bags, but thick and thin bags are equally susceptible to physical degradation. Orientation has only a small impact on the rate of optical degradation of SODIS bags, but lying SODIS bags undergo physical degradation at a rate more than double that of hanging SODIS bags. Sun exposure causes significantly more optical degradation than physical use does, but sun exposure and physical use are of comparable importance in causing physical

degradation. There is no evidence of interactions between the two causes of degradation.

- As expected, it was found that increased water layer depth results in decreased efficiency. A relationship between water layer depth and treatment efficiency was generated.
- A new method of calculating SODIS dose, the Layer Method, was developed, which attempts to account for the partially stirred nature of SODIS treatment. The Layer Method yields the closest to ideal results, meaning that the dose response is more consistent under varying treatment conditions than the conventional methods of calculating dose. However, due to the increased complexity of its application relative to conventional methods, the Layer Method may or may not be practical to implement on a wider scale.

11 Recommendations

More experiments under a variety of treatment conditions would be helpful to further understand how lying and hanging SODIS bags compare to SODIS bottles. In particular, conditions that keep the temperatures well below the 45^{o}C threshold would shed light on the nature of SODIS bag treatment.

The tests of SODIS bag degradation would benefit from a controlled field implementation in a real SODIS-using community, to determine the actual average lifetime of the bags under real use conditions.

Regarding the effect of water layer depth on SODIS treatment efficiency, it may be of value for further study to focus on increasing the number of data points so that a full model can be developed to correlate efficiency and water layer depth. It would also be of value to independently confirm the results found herein, because of the importance of water layer depth as a design decision for SODIS bags. Furthermore, varying water quality could add a valuable element to the research.

The need for a dose calculation method that is optimized for SODIS could be addressed by determining the action spectrum if the treatment process, so it can be properly incorporated into the UV-Disinfection dose calculation. This may be more valuable than attempting to further refine the labor-intensive Layer Method described herein.

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Appendix A – Results for Laboratory Experiments Using Natural Sunlight

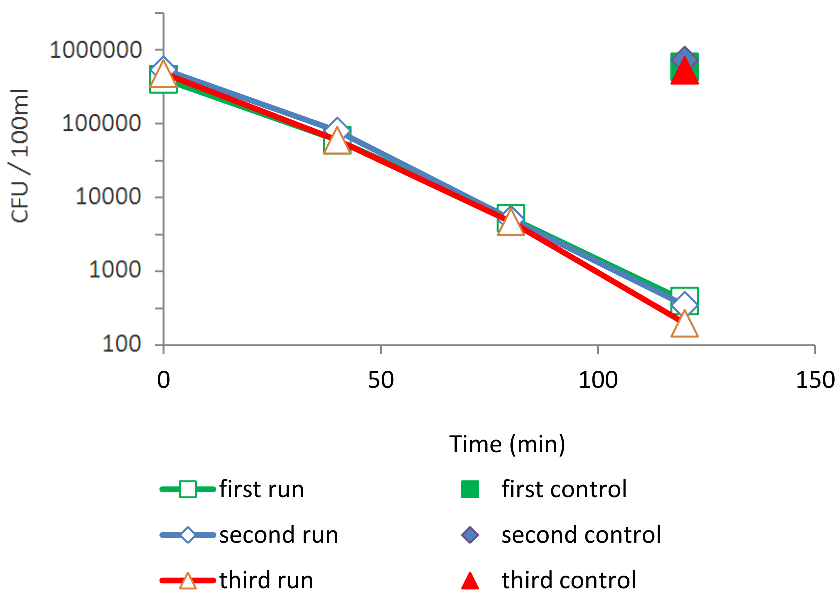

FIGURE 32 INACTIVATION CURVES FOR BOTTLES

TABLE 6 RESULTS FOR BOTTLES

first run		*input*		*output*
sample	time (min)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	40000	400000	5.60
2	40	6000	60000	4.78
3	80	530	5300	3.72
4	120	40	400	2.60
first control	120	59000	590000	5.77
second run				
0	0	54000	540000	5.73
1	40	8000	80000	4.90
2	80	510	5100	3.71
3	120	35	350	2.54
second control	120	73000	730000	5.86
third run				
0	0	48000	480000	5.68
1	40	6000	60000	4.78
2	80	470	4700	3.67
3	120	20	200	2.30
third control	120	53000	530000	5.72
bottle, average of three runs				
0	0			5.67
1	40			4.82
2	80			3.70
3	120			2.48
bottle, average contro	120			5.79

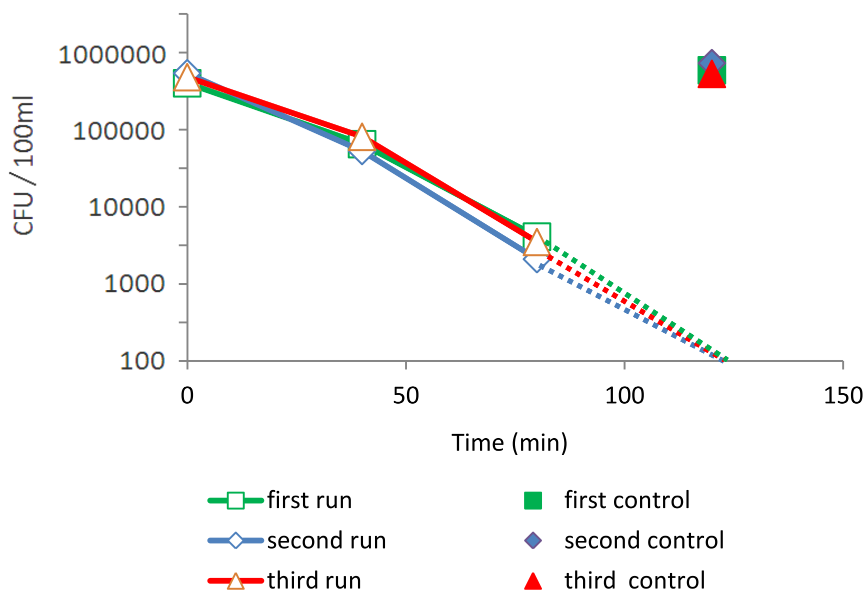

FIGURE 33 INACTIVATION CURVES FOR HANGING BAGS

TABLE 7 RESULTS FOR HANGING BAGS

first run		*input*		*output*
sample	time (min)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	40000	400000	5.60
2	40	6500	65000	4.81
3	80	410	4100	3.61
4	120	9	90	1.95
first control	120	59000	590000	5.77
second run				
0	0	54000	540000	5.73
1	40	5300	53000	4.72
2	80	210	2100	3.32
3	120	1	10	1.00
second control	120	73000	730000	5.86
third run				
0	0	48000	480000	5.68
1	40	8100	81000	4.91
2	80	350	3500	3.54
3	120	5	50	1.70
third control	120	53000	530000	5.72
hanging bag, average of three runs				
0	0			5.67
1	40			4.82
2	80			3.49
3	120			1.55
hanging bag, average c	120			5.79

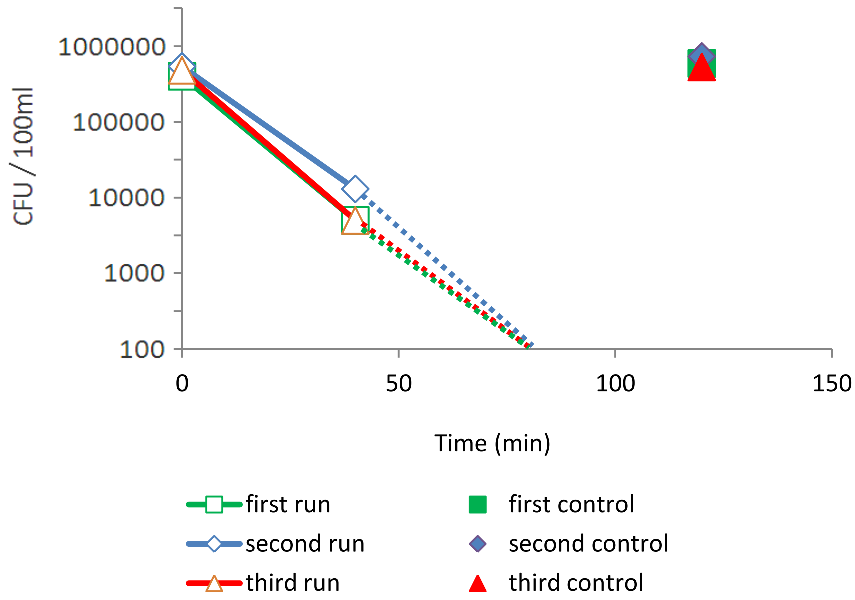

FIGURE 34 INACTIVATION CURVES FOR LYING BAGS

TABLE 8 RESULTS FOR LYING BAGS

first run		*input*		*output*
sample	time (min)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	40000	400000	5.60
2	40	500	5000	3.70
3	80	0	0	0.00
4	120	0	0	0.00
first control	120	59000	590000	5.77
second run				
0	0	54000	540000	5.73
1	40	1300	13000	4.11
2	80	0	0	0.00
3	120	0	0	0.00
second control	120	73000	730000	5.86
third run				
0	0	48000	480000	5.68
1	40	500	5000	3.70
2	80	0	0	0.00
3	120	0	0	0.00
third control	120	53000	530000	5.72
lying bag, average of three runs				
0	0			5.67
1	40			3.84
2	80			0.00
3	120			0.00
lying bag, average con	120			5.79

Appendix B – Results for Lab Experiments Using Simulated Sunlight

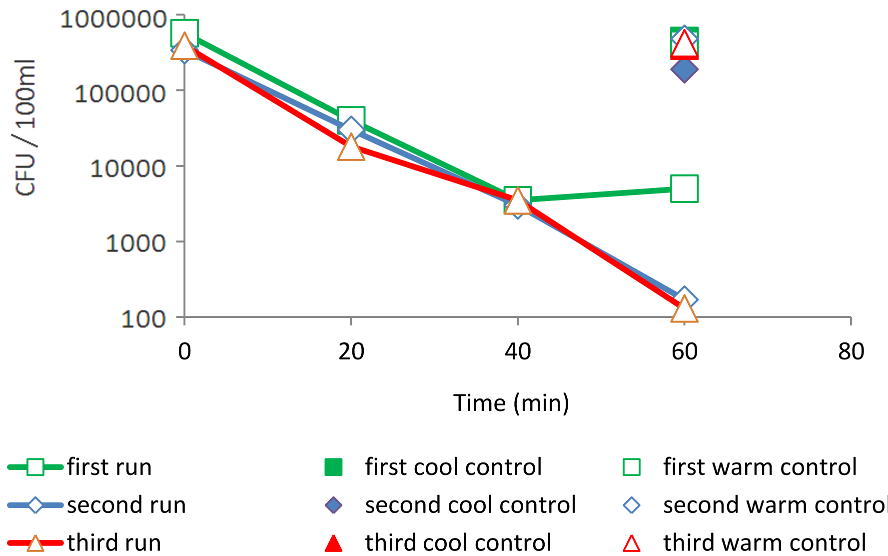

FIGURE 35 INACTIVATION CURVES FOR 0.5 CM SAMPLES

TABLE 9 RESULTS FOR 0.5 CM SAMPLES

first run					*input*		*output*
sample	time (min)	dose (incident)	dose (UV-dis)	dose (new)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	0		0	57000	570000	5.76
2	20	40	27	27	4000	40000	4.60
3	40	80	54	54	350	3500	3.54
4	60	119	80	80	500	5000	3.70
first cool control	60	119	80	80	45000	450000	5.65
first warm control	60	119	80	80	40000	400000	5.60
second run							
0	0	0	0	0	34000	340000	5.53
1	20	40	27	27	3000	30000	4.48
2	40	80	54	54	300	3000	3.48
3	60	119	80	80	17	170	2.23
second cool control	60	119	80	80	19000	190000	5.28
second warm control	60	119	80	80	48000	480000	5.68
third run							
0	0	0	0	0	39000	390000	5.59
1	20	40	27	27	1800	18000	4.26
2	40	80	54	54	350	3500	3.54
3	60	119	80	80	13	130	2.11
third cool control	60	119	80	80	39000	390000	5.59
third warm control	60	119	80	80	42000	420000	5.62
0.5cm, average of three runs							
0	0	0	0	0			5.63
1	20	40	27	27			4.44
2	40	80	54	54			3.52
3	60	119	80	80			2.68
0.5cm, average cool co	60	119	80	80			5.51
0.5cm, average warm c	60	119	80	80			5.64

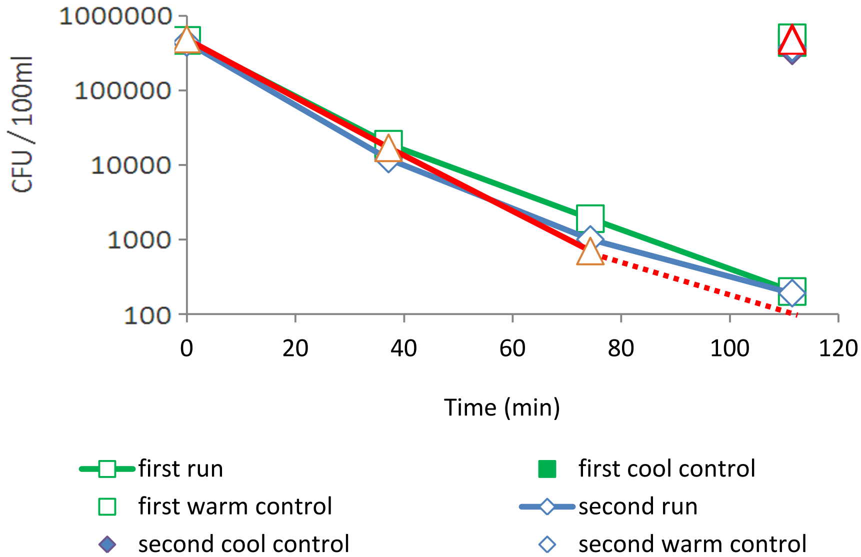

FIGURE 36 INACTIVATION CURVES FOR 2 CM SAMPLES

TABLE 10 RESULTS FOR 2 CM SAMPLES

					input		*output*
first run							
sample	time (min)	dose (incident)	dose (UV-dis)	dose (new)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	0		0	47000	470000	5.67
2	37	74	49	48	1900	19000	4.28
3	74	148	97	95	190	1900	3.28
4	112	222	146	143	20	200	2.30
first cool control	112	222	146	143	44000	440000	5.64
first warm control	112	222	146	143	51000	510000	5.71
second run							
0	0	0	0	0	44000	440000	5.64
1	37	74	49	48	1200	12000	4.08
2	74	148	97	95	100	1000	3.00
3	112	222	146	143	19	190	2.28
second cool control	112	222	146	143	34000	340000	5.53
second warm control	112	222	146	143	38000	380000	5.58
third run							
0	0	0	0	0	49000	490000	5.69
1	37	74	49	48	1700	17000	4.23
2	74	148	97	95	70	700	2.85
3	112	222	146	143	5	50	1.70
third cool control	112	222	146	143	51000	510000	5.71
third warm control	112	222	146	143	47000	470000	5.67
2cm, average of three runs							
0	0	0	0	0			5.67
1	37	74	49	48			4.20
2	74	148	97	95			3.04
3	112	222	146	143			2.09
2cm, average cool cont	112	222	146	143			5.63
2cm, average warm co	112	222	146	143			5.65

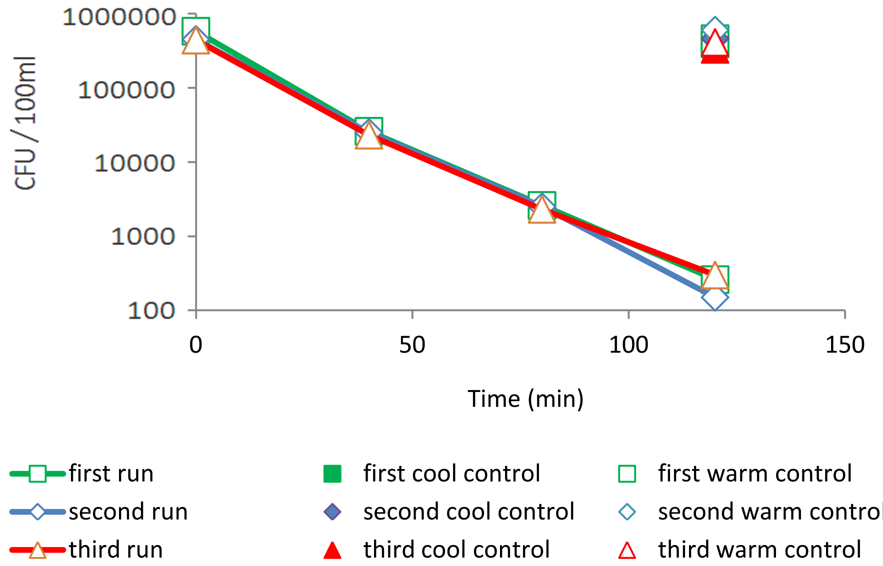

FIGURE 37 INACTIVATION CURVES FOR 4 CM SAMPLES

TABLE 11 RESULTS FOR 4 CM SAMPLES

first run					input		output
sample	time (min)	dose (incident)	dose (UV-dis)	dose (new)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	0		0	58000	580000	5.76
2	40	80	51	48	2600	26000	4.41
3	80	159	101	96	260	2600	3.41
4	120	239	152	144	26	260	2.41
first cool control	120	239	152	144	39000	390000	5.59
first warm control	120	239	152	144	46000	460000	5.66
second run							
0	0	0	0	0	45000	450000	5.65
1	40	80	51	48	2500	25000	4.40
2	80	159	101	96	250	2500	3.40
3	120	239	152	144	15	150	2.18
second cool control	120	239	152	144	46000	460000	5.66
second warm control	120	239	152	144	60000	600000	5.78
third run							
0	0	0	0	0	44000	440000	5.64
1	40	80	51	48	2300	23000	4.36
2	80	159	101	96	230	2300	3.36
3	120	239	152	144	30	300	2.48
third cool control	120	239	152	144	33000	330000	5.52
third warm control	120	239	152	144	41000	410000	5.61
4cm, average of three runs							
0	0	0	0	0			5.69
1	40	80	51	48			4.39
2	80	159	101	96			3.39
3	120	239	152	144			2.36
4cm, average cool cont	120	239	152	144			5.59
4cm, average warm co	120	239	152	144			5.68

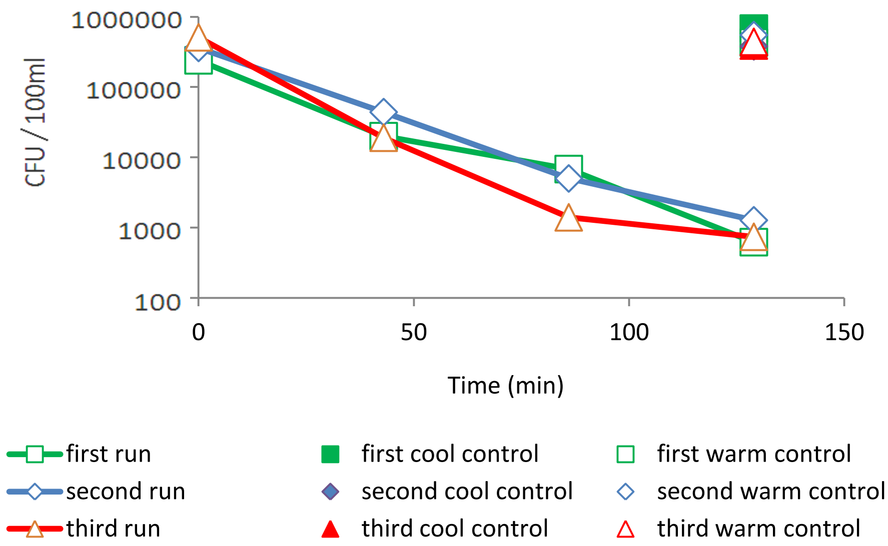

FIGURE 38 INACTIVATION CURVES FOR 6 CM SAMPLES

TABLE 12 RESULTS FOR 6 CM SAMPLES

first run					*input*		*output*
sample	time (min)	dose (incident)	dose (UV-dis)	dose (new)	CFU/10mL	CFU/100mL	log CFU / 100ml
1	0	0		0	24000	240000	5.38
2	43	86	53	48	2000	20000	4.30
3	86	171	105	96	680	6800	3.83
4	129	257	158	145	62	620	2.79
first cool control	129	257	158	145	68000	680000	5.83
first warm control	129	257	158	145	43000	430000	5.63
second run							
0	0	0	0	0	36000	360000	5.56
1	43	86	53	48	4400	44000	4.64
2	86	171	105	96	500	5000	3.70
3	129	257	158	145	127	1270	3.10
second cool control	129	257	158	145	38000	380000	5.58
second warm control	129	257	158	145	55000	550000	5.74
third run							
0	0	0	0	0	51000	510000	5.71
1	43	86	53	48	1900	19000	4.28
2	86	171	105	96	140	1400	3.15
3	129	257	158	145	74	740	2.87
third cool control	129	257	158	145	39000	390000	5.59
third warm control	129	257	158	145	44000	440000	5.64
6cm, average of three runs							
0	0	0	0	0			5.55
1	43	86	53	48			4.41
2	86	171	105	96			3.56
3	129	257	158	145			2.92
6cm, average cool cont	129	257	158	145			5.67
6cm, average warm co	129	257	158	145			5.67