EVALUATING SOLAR DISINFECTION FOR POINT-OF-USE WATER TREATMENT IN NON-TROPICAL CLIMATES

by

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ABSTRACT

SOlar DISinfection (SODIS) is a simple water treatment method using natural solar radiation to inactivate pathogens commonly found in drinking water. This technology involves simply filling transparent PET bottles with contaminated water and exposing the bottles to direct sunlight. SODIS inactivates microorganisms via three mechanisms: (1) DNA alterations by UV, (2) production of photo-oxidative species and (3) thermal inactivation. SODIS works best between 35^{o}S and 35^{o}N. Outside of these regions, SODIS works sub-optimally because of the limited availability of solar radiation and the colder climate.

In order to assess the applicability of SODIS to colder climates, this study investigated two possible methods of ensuring that SODIS is effective under the conditions of lower temperatures and sunlight intensity: 1) enhancing the heating capacity of the bottle with black paint and 2) increasing the amount of radiation incident on the system using a solar reflector. Additionally, a mathematical model for predicting the expected bottle water temperature of each exposure regime, based on the ambient air temperature, wind, and available solar radiation, was developed. Such a model will be useful in future studies for assessing which type of exposure regime will be most effective.

Field studies were conducted in two locations in Haiti: Barasa and Dumay, and in Boston, Massachusetts, between the months of January through March, 2002. Analysis of the data collected showed that clear and half-painted bottles were most effective for microbial inactivation in non-tropical climates (Barasa and Boston). In Dumay, however, significant microbial inactivation was achieved in all bottles because the bottle water temperatures reached were much higher. There was no statistical significance between the amount of inactivation achieved by bottle on a reflector or without a reflector. However, because of the limited amount of data, further studies on the use of solar reflectors are recommended to assess their actual effectiveness.

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1 The Need for Clean Water

Access to clean drinking water is one of the world's most daunting development challenges. The United Nations Development Program estimates that 1 billion people today lack access to a safe, adequate water supply (Reed *et al.*, 2000). Clean water is essential to maintaining human health because waterborne pathogens cause diseases such as cholera, typhoid fever, and diarrhea (Cadgil and Shown, 1995). These pathogens usually originate from an infected host (either human or animal) and are transmitted by contaminated water through the fecal-oral route (Maier, 2000). There are over 800 million cases of diarrhea reported each year, of which about 5 million result in death (Wegelin, 1994). Waterborne diseases kill more than 400 developing world children every hour (Cadgil, 1995).

Waterborne diseases can be successfully controlled through the protection and treatment of water supplies. However, in the absence of treated water, people draw water from contaminated sources that contain the disease-causing pathogens such as bacteria, viruses, protozoa, and helminthes. Centralized water treatment facilities are common in developed countries but are considered too capital-intensive to be implemented in many developing countries (Cadgil, 1995). In addition, when such infrastructure does exist in developing countries, it is usually limited to urban communities.

1.1 Clean Water in Haiti

Haiti is both the poorest and most densely populated country in the western hemisphere (US Dept of State, 1998), and one of the poorest countries in the world. Eighty percent of the population lives below the poverty line (CIA, 2002), and seventy percent lives in rural areas (US Dept of State, 1998). Haiti has been plagued by political unrest for most of its history, and as a result lacks the resources for adequate water and sanitation infrastructure. Diarrhea is the leading cause of mortality in children under five years of age, with an incidence of 47 percent in 6-11 month olds (Pan American Health

Org., 2002). As shown in Table 1.1, water related diseases are particularly common in rural areas where potable water is rare (USAID, 1985).

Table 1.1 Reported cases of water-related illnesses in 1980 (USAID, 1985)

		Diarrhea		Intestinal Infections		Typhoid	
Area	**Population**	**Cases**	**/1000**	**Cases**	**/1000**	**Cases**	**/1000**
Port-au-Prince	6,500,000	6608	10.2	4694	7.2	460	0.7
Gonaives	33,000	255	7.7	167	5.1	11	0.3
Port-de-Paix	15,000	455	30.3	2171	145	114	7.6
Hinche	10,000	694	69.4	738	74	100	10.0
St-Marc	23,000	851	37.0	314	13.7	266	11.6
Petit-Goave	7,000	294	42.0	1357	194	2	0.3
Belladere	25,000	875	350	272	109	68	27.2
Jacmel	13,000	320	24.6	152	11.7	87	6.7
North Dept.	560,000	3145	5.6	6819	12.2	141	0.3
South Dept.	500,000	1909	3.8	2380	4.8	462	0.9

1.1.1 Environment of Haiti

Haiti shares the island of Hispanola with the Dominican Republic, encompassing 27,750 square kilometers on the western one-third of the island (CIA, 2002). It is located roughly 600 miles south of Florida and 300 miles north of Venezuela, near the center of the West Indies, at 18° to 20° N latitude and 71° to 74° W longitude. It has two large peninsulas (Figure 1.1), called the northern and southern claws, which are separated by the Golfe de la Gonâve.

Figure 1.1 Map of Haiti (Lonely Planet, 2001)

The name Haiti comes from the Arawak word for 'mountainous land'. This name is more than fitting for Haiti, as 60 percent of all its terrain is on gradients of 20 percent or steeper (Lonely Planet, 2001). The main mountain ranges in Haiti include the Massif de la Hotte on the southern claw, the Massif de la Selle, running west to east just southeast of Port-au-Prince, and the Chaine du Bonnet in the north. Haiti also boasts astounding biodiversity, including 5,000 plant species and 25 endemic bird species. However, only two mammals native to the island still survive in Haiti: the Hispaniolan hutia (mole-like) and the solendon (long-nose rodent).

The climate of Haiti is generally hot and humid, with temperatures varying more over the course of a day than from season to season. Highs are generally around 30°C, while nighttime lows can reach 20°C. The summer in Haiti lasts from June to September, and can be slightly hotter than the winter (February to April), though temperatures drop markedly at higher elevations (Weil *et al*, 1985). Haiti also has a rainy season, which varies with region (in the north, October to May; and in the south, May to October), and a hurricane season, which usually lasts from June through September (Lonely Planet, 2001). Rainfall is usually from the North and East over the mountains. Thus there is more rain in the North and highlands (Weil *et al*, 1985).

One of the most detrimental environmental issues facing Haiti is that of deforestation. Ninety-eight percent of the original tropical forest in Haiti has been deforested for export crops and fuelwood (Lonely Planet, 2001). Deforestation also has detrimental impacts on water quality because of increased erosion of the now-barren hillsides. Erosion has also been the major cause of loss of rich topsoil to the sea, where it chokes the reefs and marine life. However, there are four national parks established in Haiti to preserve what is left of the remaining virgin forest: Forêt des Pins, in the southeast next to the Dominican border; Parc La Visite, with limestone caves and rainforests 40km southwest of Port-au-Prince; Parc Macaya, at the western end of Haiti's southern claw; and Parc Historique La Citadelle, in the center of the Massif du Nord, near Cap-Haïtien.

1.1.2 Assessment of water resources in Haiti

Only four percent of the governmental budget is allocated for potable water projects in Haiti, accounting for 15 percent of the total budget for such projects (USAID, 1985). The additional 85 percent of the funding for these projects comes from external assistance. There are two main organizations responsible for managing water resources in Haiti. The Centrale Metropolitaine d'Eau Potable (CAMEP) is responsible for supplying water in the metropolitan area and the Service National d'Eau Potable (SNEP) is responsible for rural water supply. Both organizations disinfect their water supply with chlorine, but this treatment is irregular and unreliable. CAMEP supplies water to approximately fifty percent of its potential customers and SNEP supplies approximately 39 percent (USAID, 1985). The rest of the population relies on private Haitian water vendors, whose water is from unprotected sources and rarely disinfected, or other local water resources such as wells and surface water.

The amount of water in Haiti, including surface water, groundwater, and springs, is believed to be sufficient supply for the entire population (USAID, 1985). However, these resources are limited by lack of access and proper treatment. Groundwater is believed to be abundant, particularly in the coastal plains where it is easy to access (Table 1.2). Groundwater is generally of better quality than surface water, for as water seeps through the soil to the water table, many microorganisms are removed (Lehr, 1980). Additionally, water quality often improves with storage in the aquifer because conditions are not favorable for bacterial survival. A properly constructed well (in addition to proper collection and storage methods) can ensure that the water remains clean and is safe for use.

Table 1.2 Groundwater potentials for selected areas in Haiti (USAID, 1985)

Region	Number of Project Area	Number of Project Aquifers	Potential No. of Aquifers for which flow was estimated	Water flow (t/sec)
North and North Western Region	7	13	7	500-685
Artibonite Region	2	2	-	-
Southeast Coastal Region	3	5	2	399-1114
South Coast Region	5	3	2	530+
Central Plains Region	5	6	1	15-45
Total	22	29	12	1444-1844

Springs (places where groundwater has come to the surface) and surface waters are much more susceptible to bacteriological contamination than groundwater. Therefore, surface water should only be used when groundwater sources are unavailable or inadequate (Lehr, 1980). Surface water flow in Haiti is irregular, with short torrential flows during the rainy season and long periods of dryness - very few rivers have permanent flow (USAID, 1985). However, because groundwater in Haiti is often difficult to access, surface water and springs are the main water source for the Haitian people.

1.2 Gift of Water, Inc.

The main religion in Haiti is Christianity, predominantly Roman Catholic (U.S. Department of State, 1998). In Haiti the church is the foundation of the community. The church often coordinates community infrastructure such as schools, government, and facilities. Therefore, the Haitian people have a very high respect for the church and work associated with them.

One U.S. based organization that works mainly through the churches in Haiti is Gift of Water, Incorporated (GWI). In 1995, the non-profit Industry for the Poor, Inc. (IPI), (now Gift of Water, Inc.) was created by Phil Warwick to investigate clean water options for the people of Haiti. After conducting epidemiological studies in conjunction with the Adopt-A-Village Medical Mission, they developed an in-home gravity water

filtration system (Figure 1.2) intended to reduce the presence of bacteria and volatile chemicals in the drinking water.

Figure 1.2 GWI gravity filtration system

The filter apparatus costs US$15.29, but is subsidized by the program so that each family must only pay approximately US$1.85 or even less (Anarchy, Inc., 2000). Operating expenses for each filter, including chlorination and granular activated carbon, amount to approximately US$0.42 per year. Since being approved by the Haitian Ministry of Health, filters have been placed in seven villages across Haiti (Lantagne, 2001), serving over 22,000 people (Anarchy, Inc., 2000). Because of their extensive contacts and knowledge of Haiti, GWI representatives assisted in choosing appropriate study locations, and making arrangements for travel and research necessary for this study.

1.3 Point-of-use water treatment options for Haiti

The estimated cost of providing worldwide water supply coverage in developing countries is US$150 billion (Wegelin, 1994). This cost cannot possibly be met by public funds, which are insufficient to even cover the costs of maintenance of the current infrastructure. An alternative to public water supply for people in developing countries is the use personal household water treatment systems, or point-of-use water treatment systems.

The most effective point-of-use water treatment usually consists of two stages: filtration and disinfection. In order to be most effective and appealing to it's users, a point-of-use water purification system should fulfill the following criteria (Lehr *et al.*, 1980; Shultz *et al*, 1984):

- Effective across a range of pathogens;
- Robust to changes in water quality;
- Effective in appropriate pH and temperature range;
- Should not make water toxic or unpalatable;
- Safe and easy to handle;
- Must provide residual protection against possible recontamination;
- Affordable;
- Adaptable to local conditions;
- Amenable to local production;
- Appropriate to local culture and customs;
- Comply with national sanitation standards;

Current household disinfection mechanisms include boiling water, filtration, and chlorination. However, boiling water requires energy in the form of fuelwood, which can be rare in rural areas of Haiti due to deforestation, and additionally exacerbate deforestation. The use of chlorine is often rejected by users because of the undesirable taste and odor associated with it, as well as because of its cost and unreliable supply and quality. Filtration techniques are also often unaffordable and such systems are subject to leaking and breakage. A more reliable and less expensive water disinfection technique is Solar Disinfection.

SOlar DISinfection (SODIS) is a simple water treatment method using natural solar radiation to inactivate pathogens commonly found in drinking water. This technology involves simply filling transparent PET bottles with contaminated water and exposing them to direct sunlight (Figure 1.3). SODIS utilizes the power of the sun to

inactivate microorganisms using UV-A radiation and increased temperature. Because this technology is so simple, both in concept and application, it is easily applicable in the developing world where safe water resources are scarce. However, the success of SODIS is dependent on a number of conditions, including climate and water clarity.

Figure 1.3 SOlar water DISinfection system

The pioneer of solar disinfection technology was Professor Aftim Acra, of the American University of Beruit (SANDEC, 2001). His work motivated the Integrated Rural Energy Systems Association (INRESA) to investigate the application of SODIS through a network project, which was reviewed at a workshop in 1988 organized by the Brace Institute of Montreal. In 1991 the Swiss Federal Institute for Environmental Science and Technology's (EAWAG) Department of Water Sanitation in Developing Countries (SANDEC) undertook extensive laboratory and field tests to analyze the effectiveness and social acceptability of SODIS as a low-cost water treatment method.

Currently SANDEC is promoting the use of SODIS by providing information, technical support, and advice on SODIS to institutions in developing countries worldwide (SANDEC, 2001). To date, successful SODIS studies have been completed in Columbia, Bolivia, Burkina Faso, Togo, Indonesia, Thailand, and China.

2 Application of SODIS

2.1 Mechanisms of Disinfection

The SODIS methodology utilizes both the infrared and ultraviolet spectra of radiation to disinfect water. The infrared spectrum is absorbed to generate heat and increase the bottle water temperature, and the ultraviolet spectrum directly inactivates microorganisms. The infrared spectrum is usually defined as electromagenetic radiation with wavelengths above 1000nm (10,000 Å), and the ultraviolet spectrum is radiation with wavelengths between 4 and 400 nm (40-4000 Å) (Koller, 1952), However, the atmosphere absorbs all radiation of wavelengths less than 200 nm (Parrish *et al*, 1978). Typically the remainder of the ultraviolet spectrum is divided into three portions: UV-C (200 to 290 nm); UV-B (290-320 nm); and UV-A (320-400 nm) (Figure 2.1). Of these, UV-A radiation is most abundant at the earth's surface.

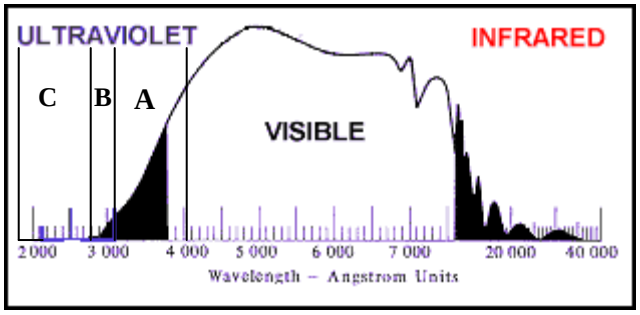

Figure 2.1 Electromagnetic Spectrum (Modified from PSU, 2001)

2.1.1 Thermal Inactivation

The first mechanism of disinfection utilized by SODIS is thermal inactivation of microorganisms. Microorganisms can only function within certain temperature ranges because of limitations of their metabolism. When these temperatures are exceeded, proteins and other macromolecules are denatured and the microorganism loses its ability to function properly (Madigan, 2000). It is possible to disinfect drinking water without

reaching boiling temperatures. This process, known as pasteurization, is different from sterilization in that sterilization inactivates all microorganisms, including heat-resistant spores. However, heat-resistant spores are harmless for humans to eat, and thus pasteurized water is sufficient for drinking purposes. For *E.coli*, a pathogen causing diarrhea, pasteurization occurs above 70^{o}C (Wegelin et al,1994).

Microbial inactivation is also possible at temperatures below pasteurization temperatures. Between 20 to 40^{o}C, the inactivation rate of fecal coliforms remains constant (Wegelin et al,1994). Above temperatures of 50^{o}C, microbial inactivation is enhanced through the synergistic effects of UV and temperature. At temperatures lower than 20^{o}C however, the thermal inactivation effects are negligible and therefore photobiologic effects (i.e. UV and photo-oxidative) are the main modes of disinfection.

The temperature of the SODIS system is increased by the absorbance of both long and short wave radiation by the bottle and the water, which then generates heat in the system. Some of this heat is re-emitted as back-radiation from the bottle into the atmosphere. Additionally, the system gains or looses heat through convective exchange with the air. The addition of wind can enhance convective exchange, thus increasing the rate of heating/cooling. In order to prevent rapid cooling, a wind-shield would be desirable to protect the bottles from heat loss, provided the shield does not shade the bottles. Additionally, uneven exposure can cause uneven heating, which causes a thermal gradient and induces circulation in the bottle (Wegelin *et al.*, 1994).

Because it is difficult to determine when water reaches pasteurization temperatures without thermometers, a device known as a Temperature Sensor has been developed for use in developing countries (SANDEC, 2001). This device contains soy wax, which melts just below pasteurization temperatures. When the wax melts it drops to the bottom of the indicator, so that even if the water cools again it is obvious that the threshold temperature was reached.

2.1.2 UV Induced DNA Alterations

Another inactivation mechanism of solar disinfection is the direct effects of UV induced DNA alterations. Ultraviolet radiation is more biologically active than visible light because it is made of higher energy photons (Parrish *et al*, 1978). When photons are absorbed, all of their energy is transferred to the absorbing atom or molecule, which brings it to an excited state. While in this excited state, changes may occur in the molecule such as rotation, vibration, or changes to the orbital shells. Ultimately, photochemical reactions may be induced if the energy of the absorbed photon is greater than or equal to the activation energy required for a reaction. The typical activation energy for most biological photochemical reactions is between 40 and 100 kcal/mol, making UV light highly effective in causing photobiologic effects because of the amount of energy it contains (Table 2.1).

Table 2.1 Energy associated with various ultraviolet wavelengths (Parrish, et al, 1978)

UV Band	Wavelength	Energy (kcal/mol)
UV-C	200	143
	250	114
UV-B	280	102
	300	95
UV-A	360	79
	420	72

The alteration of DNA molecules by UV radiation is the result of photochemical reactions within the cell. The peak amount of energy that can be absorbed by many bacteria corresponds to a wavelength of 260 nm, which is the maximum for absorbance by aromatic amino acid residues and their proteins (Parrish *et al,* 1978). Therefore, it appears that UV-C and UV-B radiation would be the most effective in the inactivation and killing of bacteria through photochemical alteration of cellular DNA. However, studies have shown that 10^4-10^5 times more UV-A radiation (either intensity or exposure time) can have the same inactivation effect as the lower wavelengths.

Because DNA has a maximum UV absorbance of approximately 260 nm, exposure to radiation of lower wavelengths causes mutagenesis, resulting in death of the cell (Raven and Johnson, 1996). UV light absorbed by microbial DNA causes the covalent bonding of adjacent bases (commonly thymine-thymine, cystosine-cystosine, and thymine-cystosine), which form pyrimidine dimers (Figure 2.2) (Parrish *et al,* 1978). DNA replication is prevented by this mutation because nucleotides either cannot properly pair with the thymine dimers, or the dimers are replaced with faulty base pairs. If these mutations are perpetuated they prevent protein synthesis, which blocks metabolism and causes the organism to die.

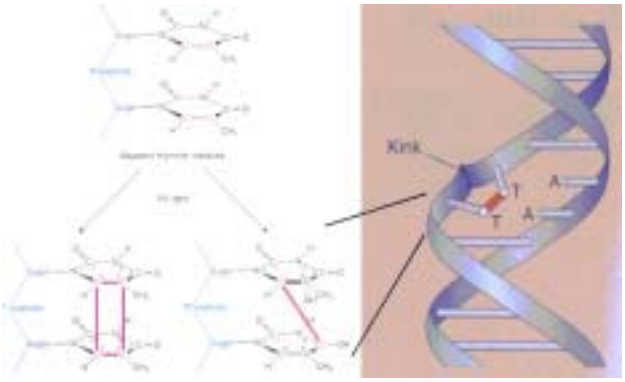

Figure 2.2 Formation of pyrimidine dimers in DNA

Additionally, hydrated pyrimidines, cross-linked DNA, DNA strand breakage, local disruption of hydrogen bonds, and changes to RNA can occur when cells are irradiated with UV (Parrish *et al,* 1978). All of these result in disrupted RNA synthesis and cell replication, likely resulting in death. Cell protein structure; and enzyme activity are also affected by UV irradiation, but in comparison to the effects of DNA disruption, they are negligible.

Some microorganisms have adapted to UV exposure by the production of repair enzymes and protective pigments. In most microbial populations the resistant fraction comprises only 0.01 percent, though some studies suggest it can be as high as 10 percent for certain species (Kowalski and Bahnfleth, 2000). In cases of massive exposure, damage is too extensive for these mechanisms to repair. UV-A radiation has also been

shown to damage these DNA repair mechanisms (Parrish *et al,* 1978). For example, the photoreactivating enzyme is both destroyed and activated by UV-A, and excision repair and single strand break repair mechanisms may be inhibited. Additionally, UV-A of about 365nm appears to alter active transport processes, proteins, and other enzyme activities.

According to SANDEC News, No. 3, total solar energy of 555 W/m^2 is necessary to induce these lethal UV effects at temperatures between 20-40^oC. This is equivalent to mid-latitude, midday summer sunshine (Wegelin, 1994). At temperatures of 50^oC, only one-third as much energy is required for equivalent disinfection. Therefore, exposure to sunlight of lower intensity for longer periods of time would provide the same amount of total energy as higher intensity sunlight for a shorter period of time. Therefore, for the application of SODIS, the less radiation that is available, the longer exposure time is necessary to achieve sufficient microbial inactivation.

Solar radiation also attenuates with depth through water. Therefore, shallower water parcels will be exposed to more intense radiation than deeper parcels. However, circulation induced by the thermal gradient would ensure that each water parcel is exposed to direct radiation (Wegelin *et al.*, 1994).

2.1.3 Photo-Oxidative Disinfection

A third mechanism of disinfection that is utilized by the SODIS system is photo-oxidative disinfection. Highly reactive forms of oxygen, including oxygen free radicals and hydrogen peroxides, are formed in well-oxygenated water when exposed to sunlight (SANDEC, 2001). These species are so reactive that they can cause serious damage to living cells if formed in significant amounts (McKee and McKee, 1999). These reactive forms of oxygen inactivate microorganisms by oxidizing microbial cellular components, such as nucleic acids, enzymes, and membrane lipids (Reed, 1996). This damage results in enzyme inactivation, polysaccharide depolymerization, DNA breakage, and membrane

destruction. These mechanisms either prevent proper cell replication or cause mutations, which are propagated through replication.

2.2 Required Conditions for SODIS

2.2.1 Weather and Climate

The optimal region for use of SODIS is between 15^{o} and 35^{o} N latitude (Figure 2.3), a region characterized by high solar radiation and limited cloud coverage (the second most optimal region for SODIS is between the equator and 15^{o}N latitude) (SANDEC, 2001). It should be noted that the majority of developing countries lie within this region. According to SANDEC, within this region and during optimal weather conditions (less than 50 percent cloudy), the contaminated water needs to be exposed for 6 hours to achieve total disinfection. If the sky is more than 50 percent cloudy, or the bottle water temperature does not exceed 42^{o}C (necessary to induce synergistic effects), the bottle should be exposed for two consecutive days.

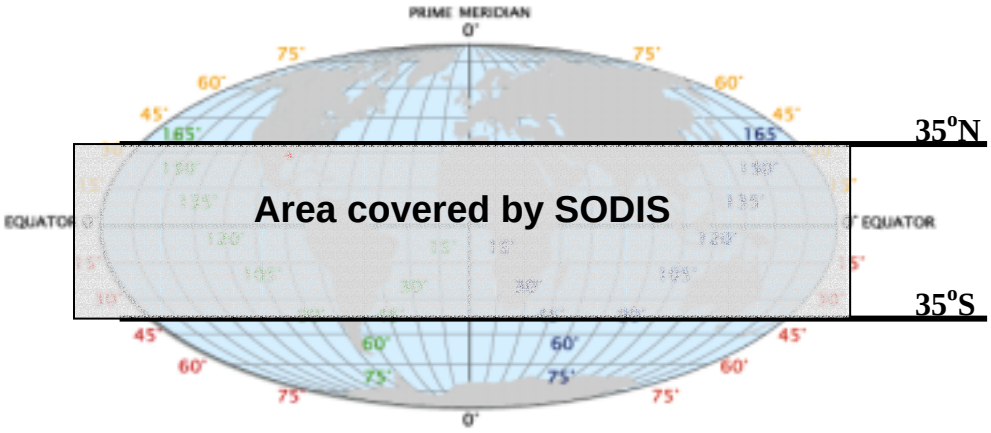

Figure 2.3 Effective area for SODIS application.

For practical application of SODIS in developing countries, where there is no accurate way of judging cloud cover or bottle water temperature, an exposure time of two days has been recommended as the standard SODIS procedure (Oates, 2001). Outside of the regions mentioned above, SODIS works sub-optimally because of the limited

availability of solar radiation and the colder climate. Often longer exposure can ensure the effectiveness of SODIS under these conditions, as the UV and photo-oxidative effects of the sunlight dominate the disinfection process, as opposed to thermal effects. However, the optimal length of exposure under different conditions has not been extensively investigated in the literature.

2.2.2 Turbidity

In order for SODIS to be effective, the water must be relatively clear (turbidity less than 30 NTU) (SANDEC, 2001). This is because suspended particles in the water can absorb solar radiation, thus reducing the depth to which solar radiation penetrates and protecting some microorganisms from radiation. Therefore, water with turbidity greater than 30 NTU would need to be filtered or bottle water temperature of 50^{o}C must be reached in order to achieve pasteurization.

In order to overcome the technical burden of exactly measuring turbidity, SANDEC has developed a simple method for determining whether or not water is suitable for SODIS. For this method, a full bottle is placed on top of the white SODIS logo in the shade. If the logo can be seen through the bottle, then the turbidity can be assumed to be less than 30 NTU. If the results are questionable, a higher turbidity should be assumed and the water treated accordingly (SANDEC, 2001). Such treatment may necessitate filtration, though usually allowing particles to settle and decanting the water off the top is sufficient.

2.2.3 Oxygen

In order to maximize the production of photo-oxidative species in the water, it is necessary to make sure the water is well aerated. In order to do this, one can shake the bottle when it is only half full, and then fill it completely (SANDEC, 2001). This technique should especially be applied to stagnant waters, such as from cisterns and wells. Reed (1997) recommends repeating this process hourly to ensure aeration is maintained. However, the effectiveness of this repeated agitation has been questioned by

Kehoe, et al. (2001). They found that repeated agitation had no effect on the amount of inactivation achieved.

2.2.4 Container Material and Design

The most common type of container used for SODIS are PET (PolyEthylene Terepthalate) bottles. These bottles are preferred because they are commonly available, more lightweight and durable than glass, and are more chemically stable than other plastics. However, glass bottles have higher transmittance than plastic bottles (75 percent for glass versus 70 percent for plastic), so some transmittance is lost in using plastic bottles. Plastic bags have an even higher transmittance (90 percent), but are significantly less durable than either glass or plastic bottles and are also difficult to use.

PET bottles can easily be distinguished from other bottles because of its clear appearance as compared to PVC, which has a bluish gleam. Additionally, PET burns more easily than PVC and the smell is sweeter than that of PVC. However, one significant drawback to the use of these bottles in comparison to glass is the rate at which they age due to mechanical scratches and the production of photoproducts, which leads to a reduction of UV transmittance (SANDEC, 2001). Because these bottles are commonly available in the developing world, this is not considered a significant problem because aged bottles can be easily replaced.

Another concern with the use of PET bottles is the possible formation of photoproducts on the plastic material as a result of UV-irradiation. These photoproducts are the result of the migration of additives out of the material, such as the UV stabilizers that are used to increase the plastics stability (SANDEC, 2001). However, in PET these additives are used less than in PVC (less than one percent of the PET components). Laboratory and field test addressing this concern have shown that these products are generated only on the outer surface of the bottles, and no migration into the water was observed.

In addition to the container material, one must also consider the size and shape of container most effective for SODIS. Because UV radiation attenuates with depth (50 percent attenuation at 10 cm with turbidity of 26 NTU), containers with a large exposed surface area to volume ratio are recommended. PET bottles used for SODIS have a sub-optimal shape because this ratio is small (SANDEC, 2001). With a water depth of 6-10cm, the water is not as evenly exposed to radiation as in a flatter container, such as a bag. However, this uneven exposure can cause uneven heating, which causes a thermal gradient and induces circulation in the bottle, which would ensure that each water parcel is exposed to direct radiation at some time (Wegelin *et al.*, 1994). Thus, although containers with a larger exposed area to volume ratio would be more efficient, in the developing world, one must learn to efficiently use whatever is available.

2.3 Limitations

Although SODIS seems to be the ideal solution for drinking water disinfection, as it requires no chemicals or technical expertise, it does have limitations. First, SODIS does not improve the chemical water quality, though studies are being undertaken to assess the effectiveness of UV-radiation in arsenic abatement, nor does it change the smell or taste of the water (SANDEC, 2001). The effectiveness of SODIS is also dependent on climate and certain water quality parameters, such as turbidity and dissolved oxygen, as discussed above. However, the user can easily adjust both of these parameters so that SODIS is effective (filtering/settling to reduce turbidity, mixing to increase oxygen). Additionally, SODIS offers only a very limited production capacity because of the limitations to bottle size/shape available, and therefore may not be a feasible solution for generating large quantities of clean water.

3 Research Goals

In order to assess the applicability of SODIS to colder climates, it is necessary to investigate possible ways of modifying the present system so as to make most efficient use of the available conditions. Though the area in which SODIS should be applicable based on the amount of available sunlight is very broad, some of the locations that fall within this region occasionally experience climate conditions not optimal for SODIS use due to elevation and seasonal variances. For example, the "winter" season has higher cloud cover associated with colder temperatures, during which SODIS may not be effective. Additionally, at higher altitudes, although sunlight intensity may be stronger, cloud cover is also much more common and temperatures much cooler.

Two possible methods to ensure that SODIS is effective under the conditions of lower temperatures and sunlight intensity are: 1) to enhance the heating capacity of the bottle or 2) to increase the amount of radiation incident on the system. The former can be achieved by painting the bottles with black paint, which absorbs solar radiation and converts it to heat energy. The later can be achieved through the use of solar reflectors to gather and focus UV onto the bottle. The purpose of this thesis was to investigate the effectiveness of both of these methods in sub-optimal climate conditions.

3.1 UV enhancement

Most metals are good reflectors for both visible and ultraviolet light (Koller, 1952). The efficiency of reflection depends on the cleanliness of the surface and absence of impurities. Aluminum is one of the most commonly used reflective metals because it is relatively inexpensive, easy to use, and resistant to corrosion. It is considered one of the most suitable for UV applications (Parrish, 1978). The shape of the reflector also influences the effectiveness of reflection. Parabolic reflectors are particularly good for focusing light on one point. However, their round shape would not efficiently focus light

on the elongated SODIS bottles. Flat reflectors on the other hand, are less efficient because they do not focus the light at all.

The reflector used in this study consists of two parallel "slings" of reflective material supported by rope (clothesline) hung between two wooden base pieces (Figure 3.1). One reflector was built using aluminum coated mylar and another was built using materials that would be available in a developing country (aluminum foil supported by a plain brown paper). Each "sling" held three bottles end-to-end (for a total of six bottles per reflector). The reflector should be oriented parallel to the path of the sun (approximately east to west) so as to minimize shadows (Figure 3.2).

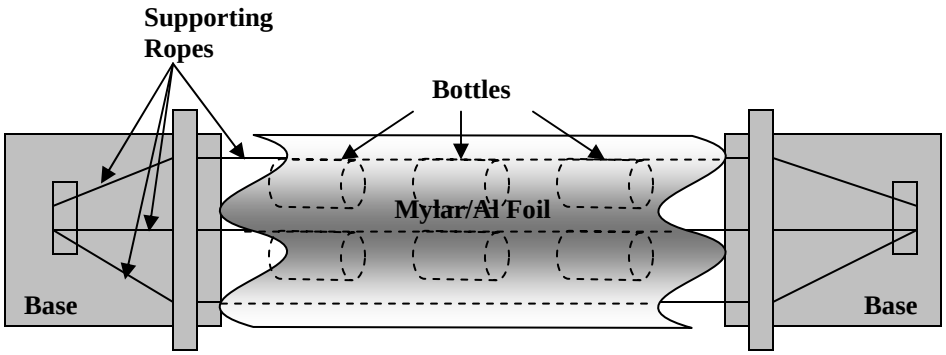

Figure 3.1 Top view of solar reflector used

Figure 3.2 Solar reflectors, Left: aluminum foil, Right: aluminum mylar

All reflectors use in this study were built at MIT and designed to be transportable, and so had to be light and compact. Therefore, these reflectors consisted of numerous

small parts, which were easy to reassemble (see assembly instructions in the research plan in Appendix I) The dimensions of such reflectors could be optimized based on the size of the bottles used, however, the bottle size for each location of this study was not known at the time the reflectors were built. Therefore they may not have been as effective as was possible, though it is estimated that no more than 20 percent effectiveness was lost.

3.2 Thermal enhancement

The recommended SODIS procedures call for painting bottles half black to enhance the heat absorbance capacity of the system (SANDEC, 2001). Theoretically, this increases the bottle water temperature by 5^{o}C by absorbing "extra" radiation. However, the amount of temperature increase is dependent on the available amount of radiation to be absorbed and the area and orientation of the surface painted black. This study investigated the thermal enhancing effects of painting bottles both half black and fully black to see if threshold temperatures could be reached despite low ambient air temperatures in areas where radiation is abundant. The bottles were painted using locally available flat black paint, following the procedure outlined in the research plan in Appendix I.

The purpose of painting the bottles half black is allow for both thermal enhancement as well as UV disinfection, whereas the fully painted bottle will rely on thermal inactivation alone. Therefore the fully painted bottles must reach the threshold temperature of 50^{o}C to achieve disinfection. These temperatures were not necessary in the clear and half painted bottles because UV disinfection would be active in these bottles.

The main mechanism of heat gain in the SODIS system is the absorbance of solar radiation. Additionally, if the ambient air temperature is greater than the bottle water temperature, some heat gain will be made through natural convection. However, because the amount of convection over two bottles of the same size would be equal, the difference

in temperature reached in the fully painted bottle versus the half-painted bottle is mainly dependent on the difference in the amount of radiation absorbed by the different systems. Therefore, it is also possible that the use of a solar collector/reflector could contribute to increased bottle water temperatures by increasing the amount of radiation incident on the bottles.

3.3 Bottle Water Temperature model

In addition to evaluating the above techniques for enhancing the effects of SODIS, this project also developed a mathematical model for the bottle water temperature under various conditions. Such a model would be useful for evaluating the suitability of SODIS in a particular locale and the techniques that should be used to enhance its effectiveness. The model is dependent on the local weather conditions over the appropriate period of time:

$T_a(t)$ = ambient air temperature [K]
$R(t)$ = total solar radiation [W/m^2]
$U(t)$ = wind speed [m/s]

In order to achieve an accurate model of the exact bottle water temperature under given conditions, these parameters must be monitored *in situ*. However, for the purposes of evaluating the effectiveness of SODIS, approximate weather conditions can be generated using a weather model or gathered from a local weather station to estimate best- and worst-case scenarios.

The model is also dependant on characteristics of the bottle and the water, including:

D = bottle diameter [m]
x = bottle thickness [m]
k_p = thermal conductivity of plastic [W/mK]
M = mass of water [g]

C_v = heat capacity of water [J/gK]

This model cannot substitute for *in situ* field tests to evaluate the actual effectiveness of SODIS. These tests are still necessary to make recommendations for factors that are more site specific, such as exposure time and necessary water pre-treatment. However, the results of the model can predict whether thermal enhancement measures would be effective or not.

There are four main heat flux components to this model: (1) heat generated by short-wave radiation absorbed by the system (Q_R), (2) heat gain through absorption of long-wave radiation (Q_L), (3) heat loss through long-wave radiation from the system ($-Q_b$), and (4) heat gain/loss by convection (Q_C). Therefore, at each time step the net heat flux into the system (Q_T) is the sum of these quantities:

$$Q_T = Q_R + Q_L + Q_C - Q_b \qquad \text{(Equation 1)}$$

The net heat flux can then be used to find the change in bottle water temperature over a single time step:

$$dT = \frac{Q_T}{C_v \cdot M}\, dt \qquad \text{(Equation 2)}$$

where dt is the length of the time step used, in seconds. It should be noted that in comparison to the mass of the water, the mass of the bottle, and thus the heat capacity of the bottle, is negligible.

3.3.1 Absorption of short-wave radiation

The main difference in the bottle water temperature in the painted versus un-painted bottles will be the amount of short-wave solar radiation absorbed (i.e. wavelengths shorter than 3000nm). Each regime will absorb a different amount of solar energy based on the amount of surface area painted black (Figure 3.3).

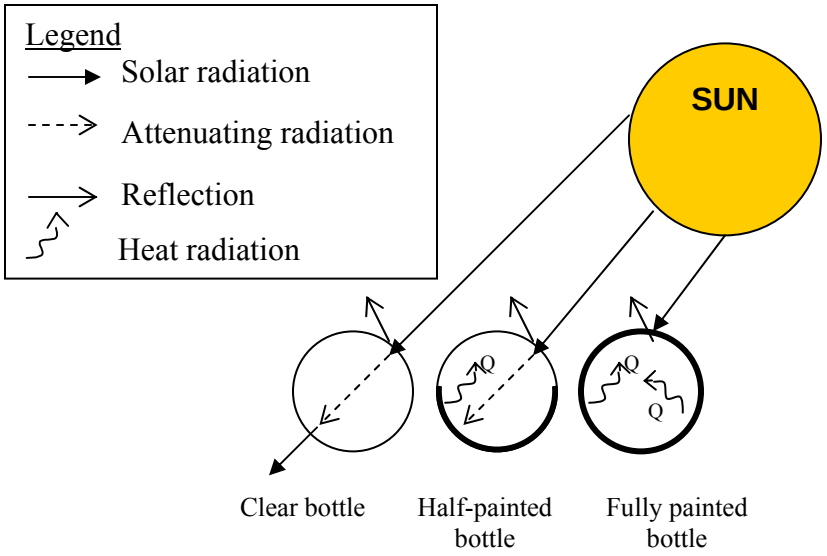

Figure 3.3 Diagram of short-wave solar radiation absorbed by the different bottle regimes

Ideally, the fully painted bottle will absorb all available radiation, and thus the heat flux into the bottle due to solar radiation would be equal to:

$$Q_R = R \cdot A_x \qquad \text{(Equation 3)}$$

where A_x is the cross-sectional area of the bottle, over which direct radiation is absorbed. In part this equation will underestimate the heat flux because it does not account for scattered radiation absorbed by the system. However, it is also an overestimate because it assumes 100 percent efficiency.

For the half painted bottle not all radiation is absorbed because some radiation is reflected off the unpainted surface. Therefore, for the half painted bottle, the amount of solar radiation absorbed is determined by:

$$Q_R = (1-\varepsilon) \cdot R \cdot A_x \qquad \text{(Equation 4)}$$

where ε is the percent of the total solar radiation reflected by the bottle.

The water in the clear bottle will also absorb some radiation, which is why the intensity of the radiation attenuates with depth as mentioned in Section 2.1.2. For the clear bottle, there will also be reflection off the clear surface. Therefore, the amount of radiation absorbed by the clear bottle system is calculated by:

$$Q_R = \eta \cdot (1-\varepsilon) \cdot R \cdot A_x \qquad \text{(Equation 5)}$$

where η is percent radiation attenuation.

3.3.2 Absorption and emission of long-wave radiation

In addition to short-wave radiation, long-wave radiation also has the potential affect the amount of heat in the system. The amount of radiation transmitted through the material is dependent on the properties of the material. All the radiation that is transmitted through the plastic will be absorbed by the water. This amount is determined by:

$$Q_L = \alpha \cdot \sigma \cdot T_a^4 \cdot A_s \qquad \text{(Equation 6)}$$

where α is the percent of long-wave radiation that is transmitted by the bottle, σ is the Stefan-Boltzman constant (5.67E-8), T_a is the ambient air temperature and A_s is the total surface area of the bottle through which radiation can be absorbed.

The amount of long-wave radiation lost by the system (often referred to as back radiation) is determined through a similar calculation:

$$Q_b = \varepsilon \cdot \sigma \cdot T_s^4 \cdot A_s \qquad \text{(Equation 7)}$$

Where ε is the bottle emissivity, and T_s is the bottle surface temperature.

3.3.3 Convection

The direction of heat flow due to convection is dependent on the thermal gradient across the bottle wall. If the air temperature is warmer than the bottle water temperature, than the direction will be into the bottle, but if the air is cooler than the water, heat flow will be out of the bottle. The rate of this heat flow is enhanced by wind flow over the bottle, which increases the number of parcels of air that come in contact with the bottle (Figure 3.4).

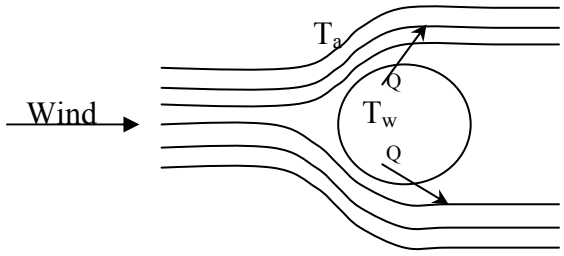

Figure 3.4. Diagram of convective heat exchange with wind

For an open water surface, this heat exchange would be governed by the equation for convective heat loss. However, because the plastic bottle acts as a resistor to heat flow, the equation for conductive heat loss is more applicable

$$Q_{cond} = \frac{(T_s - T_w) \cdot k_p \cdot A}{X} \qquad \text{(Equation 7)}$$

where T_s is the temperature on the outer surface of the bottle, T_w is the bottle water temperature, k_p is the thermal conductivity of the plastic, A_s is the surface area of the bottle and x is the thickness of the plastic. T_s can be found by equating conductive heat flow through the bottle to convective heat flow across the bottle surface (Figure 3.5):

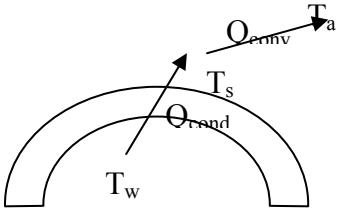

Figure 3.5 Diagram of convection and conduction

$$Q_{conv} = h \cdot A \cdot (T_a - T_s) \qquad \text{(Equation 8)}$$

$$Q_{cond} = Q_{conv} \qquad \text{(Equation 9)}$$

$$h \cdot A \cdot (T_a - T_s) = \frac{(T_s - T_w) \cdot k_p \cdot A}{X} \qquad \text{(Equation 10)}$$

where $h = Nu \cdot k_a / D$, Nu is the Nusselt number (as calculated in Appendix III), and D is the bottle diameter. Therefore,

$$T_s = \frac{\{((Nu \cdot k_a / D) \cdot T_a) + (k_p \cdot T_w / x)\}}{\{(k_p / x) + (Nu \cdot k_a / D)\}} \qquad \text{(Equation 11)}$$

The Nusselt number is dependent on the type of convection (free versus forced) and the shape of the surface over which convection is occurring. Convection over the end of the bottle will be different than convection over the cylinder. Therefore, different calculations must be made for convection over the end and convection over the cylinder, and then summed to find the total convection.

3.4 Summary of Research Goals

The main goal of this thesis was to evaluate SOLar DISinfection for use in non-tropical climates. Two methods for enhancing its effectiveness under such conditions were investigated: 1) use of black paint to enhance the thermal effectiveness of the system, and 2) use of solar reflectors to enhance the optical effectiveness of the system. In addition, a simple model for predicting the bottle water temperature was developed and evaluated to supplement *in situ* studies and pre-determine the type of exposure regime that would be most effective in a given climate.

4 Research Outline

4.1 Location, Climate and Water Supply

Experiments for this study were carried out during the months of January, February, and March 2002. The month of January was spent conducting studies in two locations in Haiti: the rural community of Barasa and the more urban center of Dumay. Follow-up studies were then conducted throughout February and March in Boston, Massachusetts, USA. All of Haiti falls within the optimal latitudes for application for SODIS, and so the locations in Haiti were chosen based on their disparate weather conditions, which are due mainly to differences in elevation.

The process for collecting water from the source and transferring it into the SODIS bottles varied with location and ease of access to the source. In some cases samples were taken directly from the source, but in others an intermediate storage container was used. In all cases, background samples for each run were collected at the same time and in the same manner as the filling of the bottles. Additionally, water turbidity measurements were taken before, during and after sample collection using a Hach® Pocket Turbidimeter (accurate to ±1 NTU) to ensure that the water was clear enough for effective SODIS application.

4.1.1 Barasa

Barasa is located in the southeastern part of Haiti, near the border of the Dominican Republic. The elevation in Barasa is approximately 1,400 feet. This is a mountainous region, characterized by cooler temperatures but more intense solar radiation than Dumay. The daily weather conditions observed usually consisted of approximately half a day of full sunshine (though it varied between morning and afternoon hours) and half a day of partly cloudy or fully overcast skies. The average daily ambient air temperature peaked at about 28^{o}C around 1pm, and radiation peaked at around 770 W/m^2 a 12:30pm (Figure 4.1).

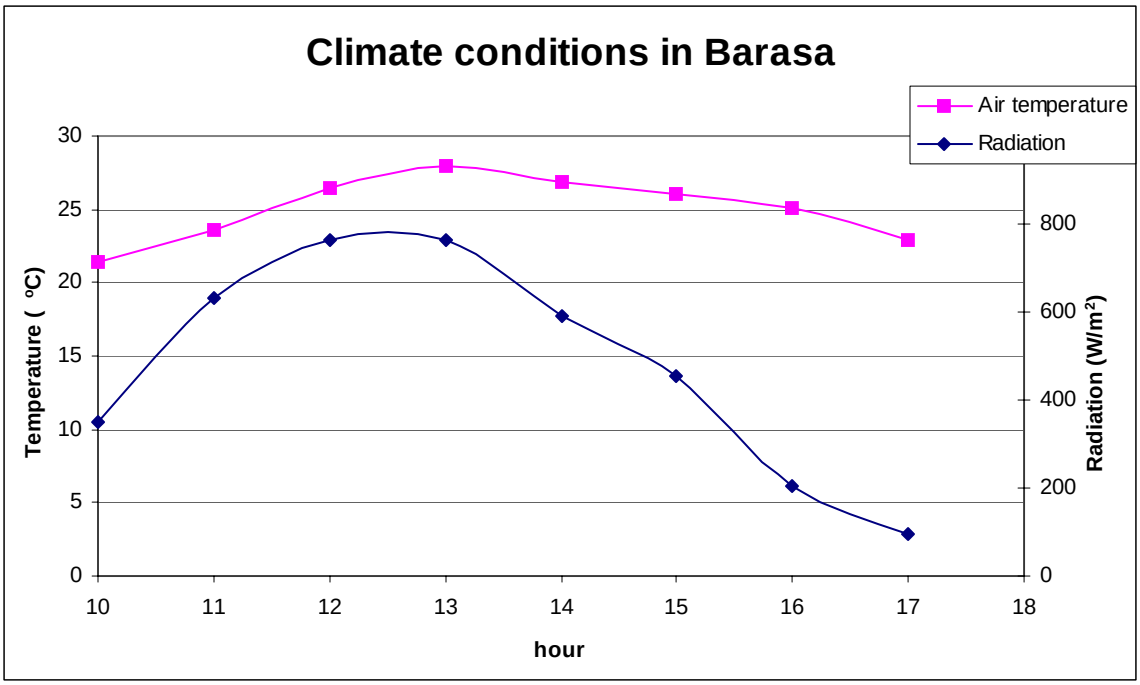

Figure 4.1 Average daily temperature and radiaiton profiles for Barasa

Barasa is located in a rural area where there is no access to running water or electricity. Therefore the people in Barasa do not have access to treated water, except for a few families with the Gift of Water, Inc. filtration system. Their main water supplies are cisterns or a nearby spring, Soos San Louis (Figure 4.2). This spring is difficult to access, not only because of its distance from the community, but also because it is located at the bottom of a steep ravine. The spring is highly contaminated, mainly from the fecal matter of pack animals used to transport water back to community members' homes.

Figure 4.2 Pictures of Barasa community water source

Experiments in Barasa were carried out on the roof of the local school so as to avoid disruption by animals or children. The water used for this study was a combination of water from the spring and a nearby cistern. It was collected in large quantities approximately three times throughout the study and stored in large plastic tubs in an empty classroom of the school (Figure 4.3). The SODIS bottles were then filled using a spigoted bucket, following the shaking procedure recommended in Section 2.2.3 to ensure aeration. The average turbidity of the water was 5.8 NTU (Table 4.1), well below the 30 NTU recommended for SODIS to be effective. However, the turbidity peaked at 16.6 NTU on the third day of sample collection, possibly due to agitation of the water which resuspended settled particles, and would otherwise have been only 3.6 NTU.

Figure 4.3 Temporary water storage for experiments in Barasa

Table 4.1 WaterTurbidity Data for Barasa

Run		1	2	3	Ave
1: 1/17	5-hour	3.5	3.5	4.1	3.7
1/18	1-&2-day	3.5	4.9	2.9	3.8
2: 1/20	5-hour	18.2	16.9	14.8	16.6
1/21	1-&2-day	3.6	6.4	4.5	4.8
3: 1/23	5-hour	0.6	0.3	8.6	3.2
1/24	1-&2-day	3.8	2.6	1.1	2.5
				Average:	5.8
				Average without data from 1/20:	3.6

4.1.2 Dumay

Dumay is located near the city of Port-au Prince, at the base of the "southern claw" of Haiti. Living conditions in Dumay are much better than in Barasa because of its proximity to the metropolis. Many homes have private wells or are connected to the public water supply. Additionally, treated water is released (on average three times) daily from public access facilities. Those who do not have access to these facilities collect water from local wells and streams.

Weather conditions are much hotter in Dumay because it is at a lower elevation (very near sea level) and does not benefit from the trade winds that cross the more mountainous regions. During the 5-hour duration of this experiment the sky was clear, there was little breeze, and sunlight was intense. The ambient air temperature peaked at 47^{o}C at 1pm (Figure 4.2). Radiation measurements from this location are not available due to equipment difficulties, but have been assumed to be on the same order of magnitude of daily radiation in Barasa. Experiments were carried out on the roof of Pastor Nathan Dieudonne's house.

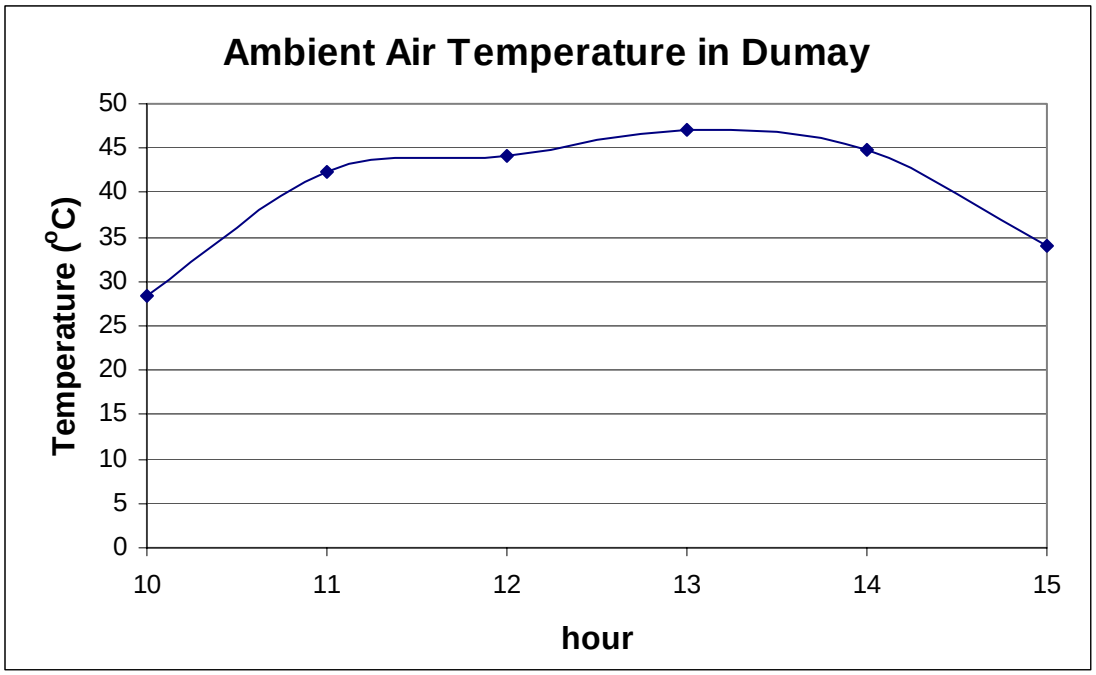

Figure 4.4 Ambient air temperature profile for Dumay

The water used for this study was collected directly from a local stream found running along the streets in a more rural section of the city. Downstream from the site of sample collection, women were found to be doing their laundry, implying that this is a common water source for the local community. Due to the number of poultry and other animals nearby, it can be inferred that fecal matter also contaminated the stream. The same aeration method as used in Barasa was applied during sample collection. The average turbidity of this source was 25.2 NTU, also below the 30 NTU threshold for effective SODIS application.

4.1.3 Boston

Boston is located at 42°N latitude, outside the recommended region for SODIS. Water supply and sanitation is not a problem in Boston, as it is an urban center of the developed world. Most residents have access to a reliable treated water supply or private wells. However, contamination is still a problem for area surface waters due to run off from streets, sewer overflows, and point sources. The source used for this experiment was the Charles River, which flows between the cities of Boston and Cambridge

Massachusetts, and past the MIT campus where the experiments were conducted. Turbidity measurements are not available for this source because the equipment was not available. However, all samples did pass the SODIS water clarity test, described in Section 2.2.2.

The weather in Boston during the time of this study was typical for the winter season in the northern hemisphere. Cold (near freezing) temperatures were observed, peaking at 12°C around 2:30pm, and overcast skies limited available radiation to less than 400 W/m^2. Because temperature and radiation measurements were taken less frequently than in Barasa, however, the exact peak radiation is not known (Figure 4.3). Additionally, because experiments were carried out on the roof of a four-story building, it was also subject to a constant breeze, which caused additional cooling of the bottles.

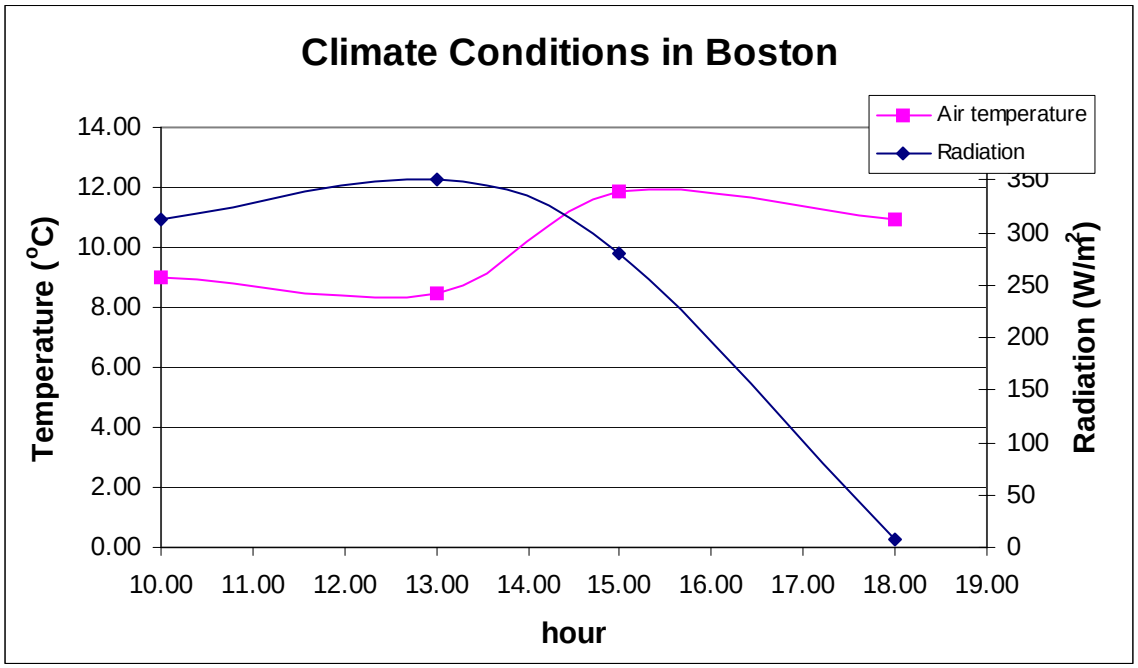

Figure 4.5 Average daily temperature and radiation profiles for Boston

4.2 Exposure and Monitoring

Nine different SODIS regimes (outlined in Table 4.2) were tested in Barasa. Duplicates were made of the bottles without a reflector and with the aluminum mylar reflector for quality control. Duplicates were not made of the bottles on the aluminum foil reflector due to lack of space. Each regime was tested over 5-hour, 1-day (7-8 hours), and 2-day (two 7-8 hour) exposure periods. Three complete sampling runs (including all regimes and exposure times) were completed, with the first day of the two-day exposure overlapping with the 1-day exposure (Figure 4.6).

Table 4.2 Overview of experimental SODIS regimes and their purposes

	Regime	Data label	Purpose
Without Reflector	Clear bottle ½ black paint Fully painted	C-a C-b C-c	UV UV and enhanced temperature Enhanced temperature
Reflector 1: Aluminum mylar	Clear bottle ½ black paint Fully painted	UV1-a UV1-b UV1-c	Enhanced UV Enhanced UV and temperature Enhanced temperature
Reflector 2: Aluminum foil	Clear bottle ½ black paint Fully painted	UV2-a UV2-b UV2-c	Enhanced UV Enhanced UV and temperature Enhanced temperature

January 2002						
Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**
15	**16**	**17**	**18**	**19** 5-hour	**20** 1-day 2-day (1) Run 1	**21** 2-day (2)
22 5-hour	**23** 1-day 2-day (1) Run 2	**24** 2-day (2)	**25** 5-hour	**26** 1-day 2-day (1) Run 3	**27** 2-day (2)	**28**

Figure 4.6 Calendar of research in Barasa

Only the aluminum foil reflector was used in Boston and Dumay because observations made in Barasa determined there was no significant difference between it and the mylar reflector. Therefore, only seven exposure regimes were tested in Dumay

and Boston. Additionally, duplicate bottles were not used, but duplicate microbial samples were taken instead. Only one 5-hour exposure regime was completed in Dumay. Two complete sampling runs, plus additional 1- and 2-day exposures were completed in Boston (Figure 4.7).

March 2002						
Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**
					1 5-hour 2-day (1)	**2** 1-day 2-day (2) Run 1
3	**4**	**5** 5-hour 2-day (1)	**6** 1-day 2-day (2) Run 2	**7** 1-day 2-day (1)	**8** 1-day 2-day (2) Run 3	**9**

Figure 4.7 Calendar of research in Boston

Temperature data was collected from every bottle hourly in Barasa and Dumay, and at least three times a day in Boston. A CheckTemp electronic thermometer from Hanna Instruments, which has an accuracy of ±0.3^{o}C between –20 to 90^{o}C, was used for making these measurements. In order to prevent cross contamination during this process, the thermometer was rinsed with boiled water between samples (see research plan in Appendix I.). Ambient air temperature was also recorded each time bottle water temperature measurements were taken.

Radiation data was collected hourly in Barasa using a Kipp & Zonen Solar Radiation Measurement System (Figure 4.8). This device measures total solar radiation between the wavelengths of 300 to 2800nm, which includes most UV-B, UV-A, visible, and some infrared radiation. The instrument detects both incoming direct solar radiation and reflected radiation. It works with a one percent accuracy between the temperatures of -40 to 80^{o}C. Radiation data was not collected in Dumay due to equipment malfunction, and was collected with the same frequency as temperature data in Boston.

Figure 4.8 Kipp & Zonen Solar Radiation Measurement System

4.2.1 Microbial Analysis

In order to evaluate the effectiveness of each exposure regime, it is necessary to determine the amount of microbial inactivation achieved. In order to do this, both treated and untreated water samples were analyzed using the membrane filtration test methodology (Figure 4.9). In this test, a measured amount of water is passed through a membrane filter (pore size 0.45 μm), which traps the bacteria contained in the sample on a paper filter (Maier, 2000). This filter is then placed on a thin absorbent pad in a petri dish saturated with a culture media specific to a desired indicator organism. The samples are then incubated at 35^{o}C for 18-24 hours to stimulate growth of microbial colonies present.

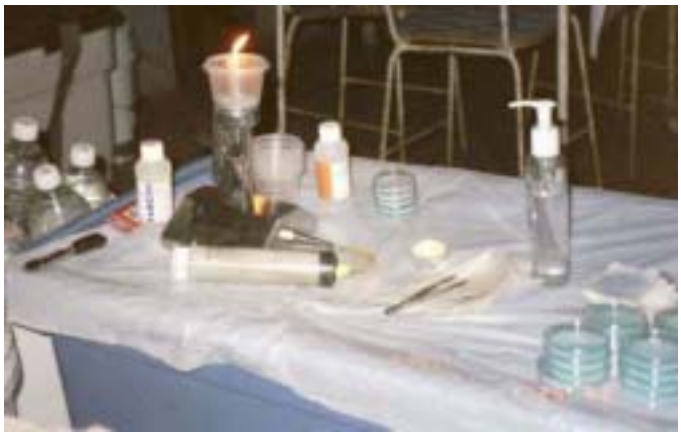

Figure 4.9 Microanalysis equipment

The indicator organisms used in this study were *E.coli* and Total Coliforms. These bacteria normally occur in the intestines of warm-blooded animals and are thus a commonly used indicator of fecal contamination (Maier, 2000). These organisms are also generally hardier than disease causing bacteria, and therefore their absence is a reliable indicator of the absence of other organisms of real concern. Previous extensive research has shown that the absence of these organisms from 100mL of drinking water ensures the prevention of bacterial waterborne disease outbreaks. The culture media used was m-coli blue broth from Millipore Corporation, on which *E.coli* colonies grow blue and Total Coliform colonies grow red.

The exact process for the membrane filtration technique used in this study is outlined in the research plan in Appendix I. It was necessary to dilute samples with boiled water so that the number of colonies that grew was countable by hand. In Barasa, the first 5-hour run was uncountable because the samples were not diluted and therefore the plates were overgrown by Total Coliforms. Because the need to dilute samples was not anticipated, proper measuring devices were not available. Therefore, the 10mL dilution used in Barasa was estimated as halfway to the 20mL mark on the filtration cup. In both Dumay and Boston, the 20mL mark on the sample filtration cup was used, and is therefore more accurate. However, it is not anticipated that any inaccuracies in dilution will have a large effect on calculations because of the order of magnitude differences between samples being compared.

Blanks were run for quality control purposes using sterile water and the boiled water used for dilution. The plates were incubated for 24 hours in a phase change incubator, provided by Amy Smith of the MIT Edgerton Center. This incubator does not require electricity, but instead maintains a constant temperature by taking advantage of the phase-change behavior of a material whose melting point is at the incubation temperature required. Once the material is melted, it keeps a constant temperature until it completely solidifies again (Smith, 2002). Therefore, the only energy input necessary to use this incubator was the heat necessary to initially melt the material – which was done by warming it in a pot of boiling water (see instructions for use in Appendix I). After 24

hours of incubation, the *E.coli* and Total Coliform colonies on each plate were counted and normalized to a 100mL sample by multiplying by the dilution factor. The membrane filtration technique gives a measure of the absolute number of bacteria present in the sample, so that the percent kill for each regime could then be calculated.

5 Results

5.1 Bottle Water Temperature

The bottle water temperature for the different regimes and different locations varied greatly because of the thermal enhancement techniques used and the local weather conditions. However, consistent trends with the time of day were observed within the same regime at the same location over different length exposure periods. Therefore, in order to provide a more representative profile of the average bottle water temperature, the data from all exposures (5-hour, 1-day, 2-day (day 1), and 2-day (day 2)) were combined. Individual daily data and data summaries are provided in Appendix II. Following are the resulting temperature profiles for each location in which the study was conducted.

5.1.1 Barasa

Bottle Water temperatures in Barasa did not ever exceed the threshold of 50^{o}C required for significant thermal disinfection. The temperatures of the bottles on either reflector were not significantly different (i.e. the standard deviation was less than the accuracy of the thermometer) from their counterparts without a reflector. Therefore, the temperature profiles of all three regimes (and duplicate bottles) were averaged in creating the average daily temperature profile (Figure 5.1).

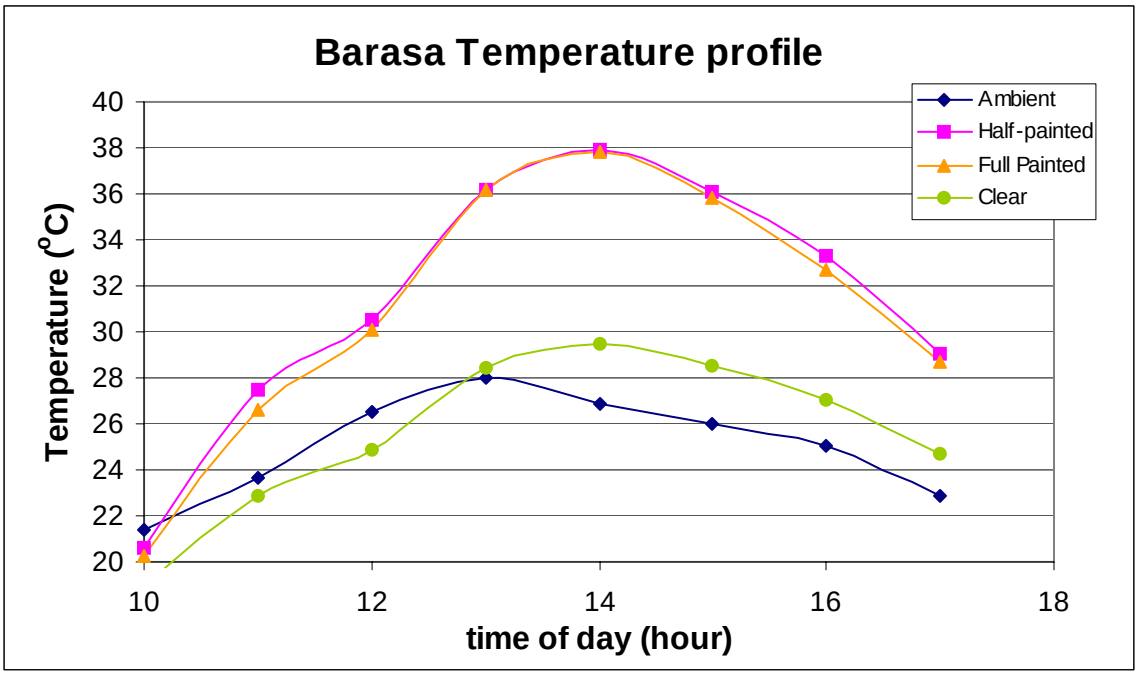

Figure 5.1 Bottle water temperature profile for Barasa

As illustrated in Figure 5.1, the temperature profile of the half-painted bottles was very similar to that of the fully painted bottles. The bottle water temperature in the clear bottle peaked at around 30°C, which is not significantly warmer than the ambient air temperature. The bottle water temperature of both the half-painted and fully painted bottles peaked around 38°C, approximately 10°C higher than the ambient air temperature. Therefore, a temperature increase of 8°C was achieved by painting the bottles – 3°C more than indicated in the literature. All of the bottles reached their peak temperatures approximately one hour later than the peak ambient air temperature and radiation.

5.1.2 Dumay

The SODIS experiments carried out in Dumay reached much higher temperatures than those in Barasa. This can be attributed to the much warmer and calmer weather conditions observed in Dumay. However, because only one 5-hour experiment was carried out in Dumay, the data is much less representative than that collected in Barasa. As in Barasa, the water temperature of bottles on the reflector were not significantly

different from their counterparts, and therefore these data were grouped in creating the temperature profile for each regime (Figure 5.2).

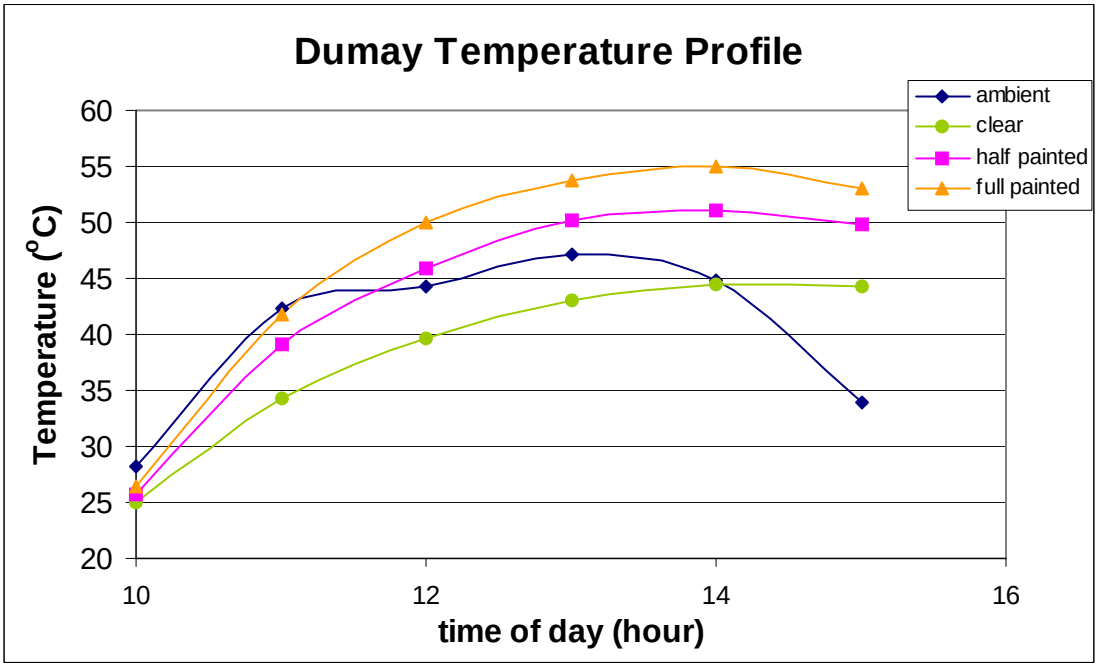

Figure 5.2 Bottle water temperature profile for Dumay

Unlike in Barasa, in Dumay both the painted and half-painted bottle water temperatures exceeded the threshold temperatures necessary for pasteurization for at least one hour. The peak temperature in the clear bottle was 44.5°C, also high enough to induce synergistic thermal effects. The peak temperature reached in the fully painted bottle was 55°C and in the half painted bottle it was 51°C. This is therefore an increase of approximately 10°C for the fully painted bottle and 6°C for the half painted bottle. Interestingly, the clear bottle water peak temperature was cooler than that of the ambient air temperature of 47°C. All peak bottle water temperatures were all reached approximately one hour later than the peak ambient air temperature.

5.1.3 Boston

Temperatures in Boston were significantly cooler than those in either Barasa or Dumay because of its northern latitude and the time of year. Additionally, temperature

was not monitored as regularly as at the other sites, and thus the profile is less defined. Again, there was no significant difference in temperature between the bottles on the reflector and those without and so these data were combined to create a more representative profile. The clear bottles appeared to peak at 11°C (Figure 5.3). As in Barasa, the painted and half-painted bottles had very similar temperature profiles, and both peaked at 14°C, three degrees warmer than the clear bottle, which is not a significant difference given the accuracy of the equipment.

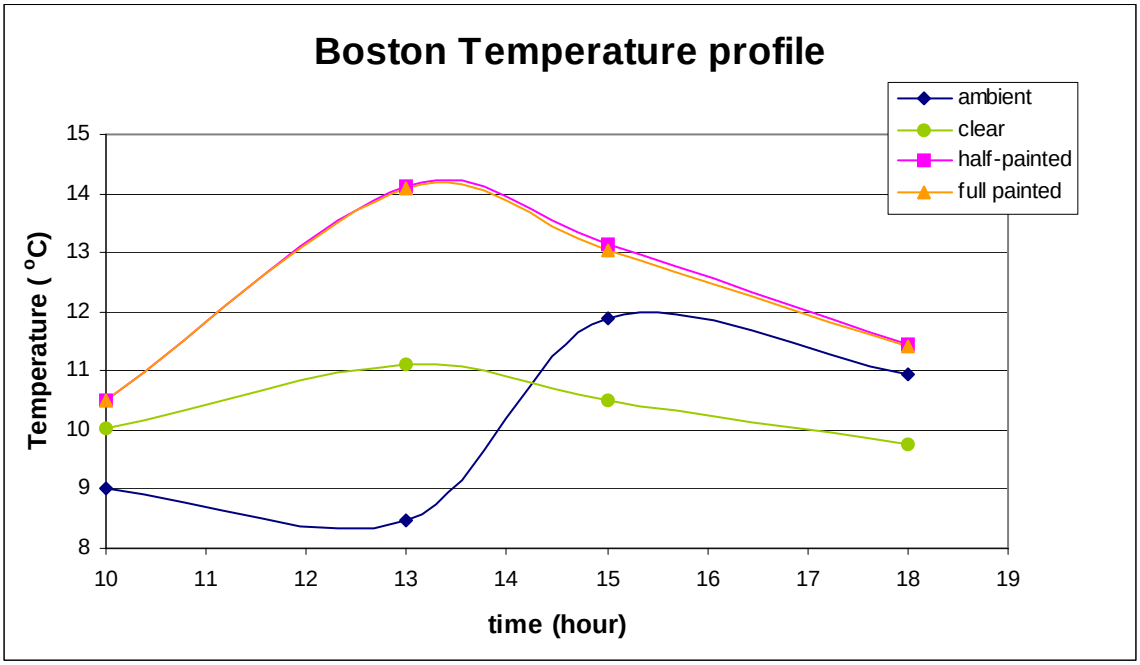

Figure 5.3 Bottle water temperature profile for Boston

5.1.4 Summary

Overall, given sufficient climate conditions, painting the bottles was effective for raising the bottle water temperature in this study. Additionally, the amount the temperature was raised as compared to the clear bottles was greater than was indicated in the literature (which is likely a conservative estimate). The results are inconclusive on the effectiveness of painting the bottles half black versus fully black, for in Dumay the

temperature increase was different between the two, whereas in Barasa they were very similar.

However, in Barasa the temperature increase in the half and fully painted bottles was not sufficient to induce either synergistic effects or pasteurization. The main difference in climate conditions between Barasa and Dumay was the ambient air temperature and wind speed. It can be assumed that the amount of available solar radiation was the same order of magnitude, though measurements for Dumay are not available. If anything, solar radiation would have been more abundant in Barasa because of its higher elevation. Additionally, the temperature profile for Dumay is less complete than that for Barasa, and thus less reliable.

5.2 Microbial inactivation

Unlike the bottle water temperature, the amount of microbial inactivation observed in each regime varied more with the amount of exposure than the location. Thus, data from the multiple runs of each exposure length in each location were grouped in order to provide a more representative data set. Individual data from each run, as well as data summaries, are provided in Appendix II along with the bottle water temperature data.

The amount of microbial kill (N_k) was calculated by subtracting the number of colonies present in the bottle sample (N_s) from the number in the background sample (N_b) collected at the same time (Equation 8). This number was the divided by the background number, and multiplied by 100 for the percent kill (P_k) (Equation 9).

$$N_k = N_b - N_s \qquad \text{(Equation 8)}$$

$$P_k = (N_k / N_b)*100 \qquad \text{(Equation 9)}$$

In some samples the plates were too overgrown to count individual colonies and were therefore labeled “Too Numerous to Count”. Therefore, in calculating the percent

kill for these samples, the largest number of colonies that was counted for a treated water sample during that run was used in substitution for N_s.

5.2.1 Barasa

The amount of microbial inactivation observed in Barasa varied not only with the exposure regime used, but also with the length of exposure. With 5 hours of exposure 100 percent kill was observed for *E.coli* in the clear bottle regimes on reflectors (UV1-a and UV2-a) (Figure 5.4). Additionally, 96 percent kill for *E.coli* was observed for the clear bottle not on a reflector (C-a). Significant kill was also observed for Total Coliforms in all clear bottle regimes. Additionally, some kill of Total Coliforms was observed in the half painted bottles (C-b, UV1-b and UV2-b). However, it appeared that there was growth of *E.coli* in these bottles, as indicated by negative percent kill, as well as all fully painted bottles (C-c, UV1-c and UV2-c).

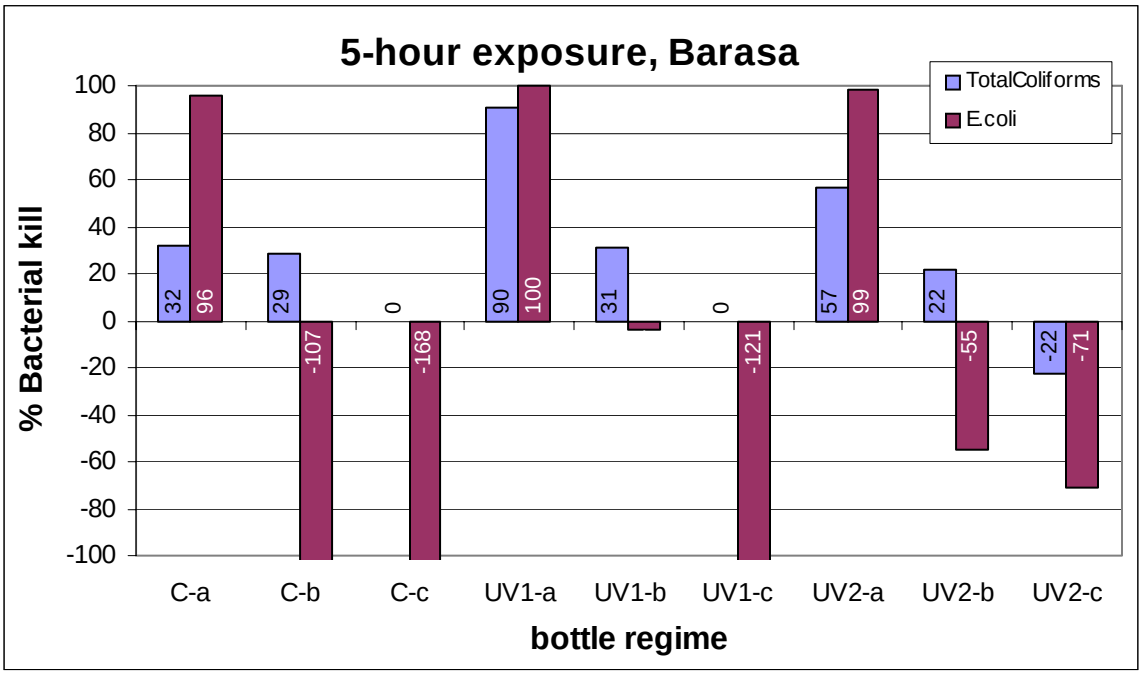

Figure 5.4 Percent bacteria kill after 5-hours exposure in Barasa

For 1-day of exposure, approximately 100 percent kill for *E.coli* was observed in all clear and half-painted bottle regimes (Figure 5.5). For Total Coliforms, almost 100 percent (approximately 96 percent) kill was observed in the clear bottles, and significant kill was observed in the half painted bottles. No siginificant kill was observed in the fully painted bottles, in fact *E.coli* growth was again apparent.

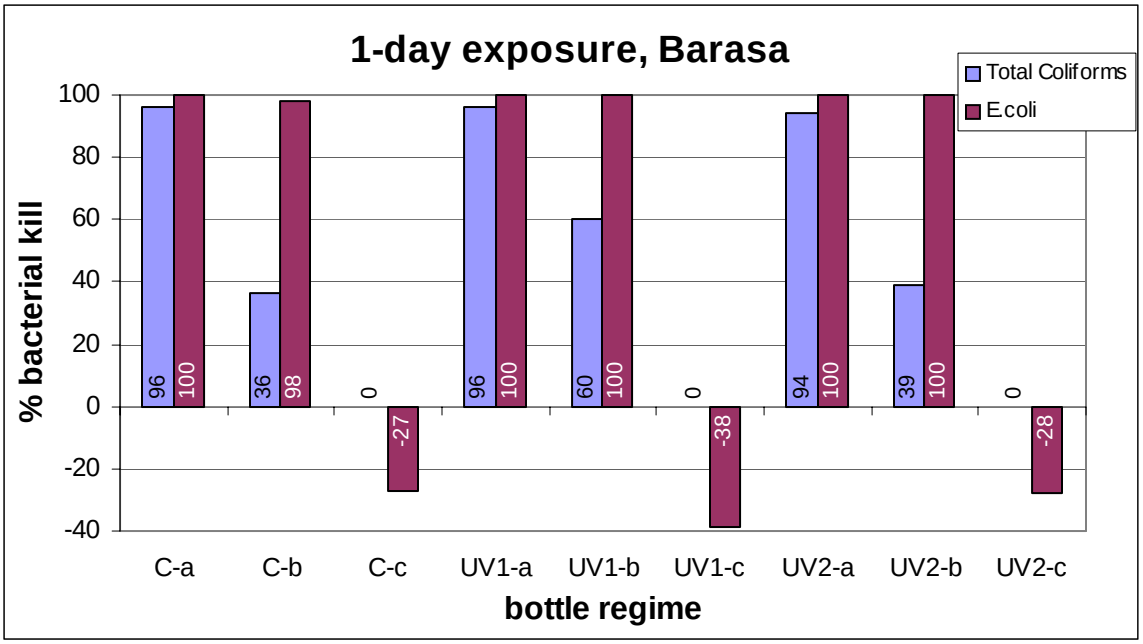

Figure 5.5 Percent bacteria kill after 1-day exposure in Barasa

With 2-days of exposure, 100 percent kill for *E.coli* was observed in all clear and half-painted bottles (Figure 5.6). Over 80 percent kill for Total Coliforms was also observed in all these bottles. While significant kill for *E.coli* was apparent in the fully painted bottles as well, it was much less significant than for Total Coliforms.

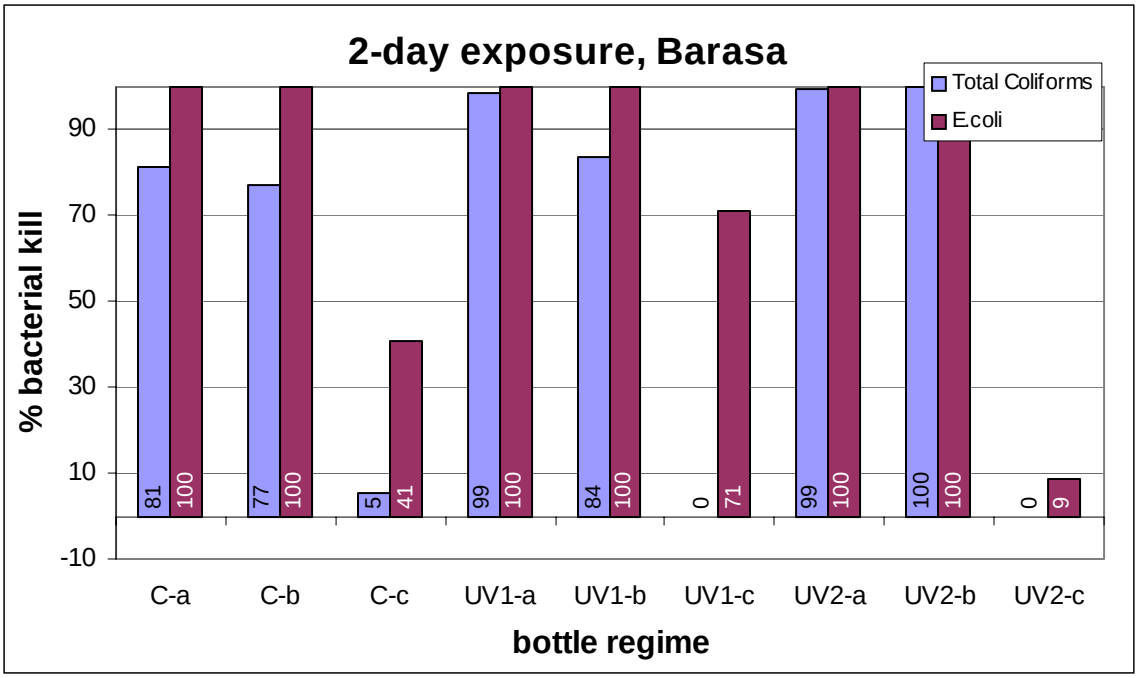

Figure 5.6 Percent bacteria kill after 2-days exposure in Barasa

5.2.2 Dumay

The amount of kill observed after 5-hours of exposure in Dumay was much higher than that observed in Barasa. Greater than 90 percent kill was observed for *E.coli* in all bottle regimes, reaching 100 percent in all bottles on the reflector and the half painted bottle not on the reflector (Figure 5.7). For Total Coliforms, kill greater than 80 percent was observed in the half painted and fully painted bottle not on the reflector and the half painted bottle on the reflector. Total Coliform kill was also observed in the clear and half painted bottles on the reflector. One and two day tests were not conducted in Dumay.

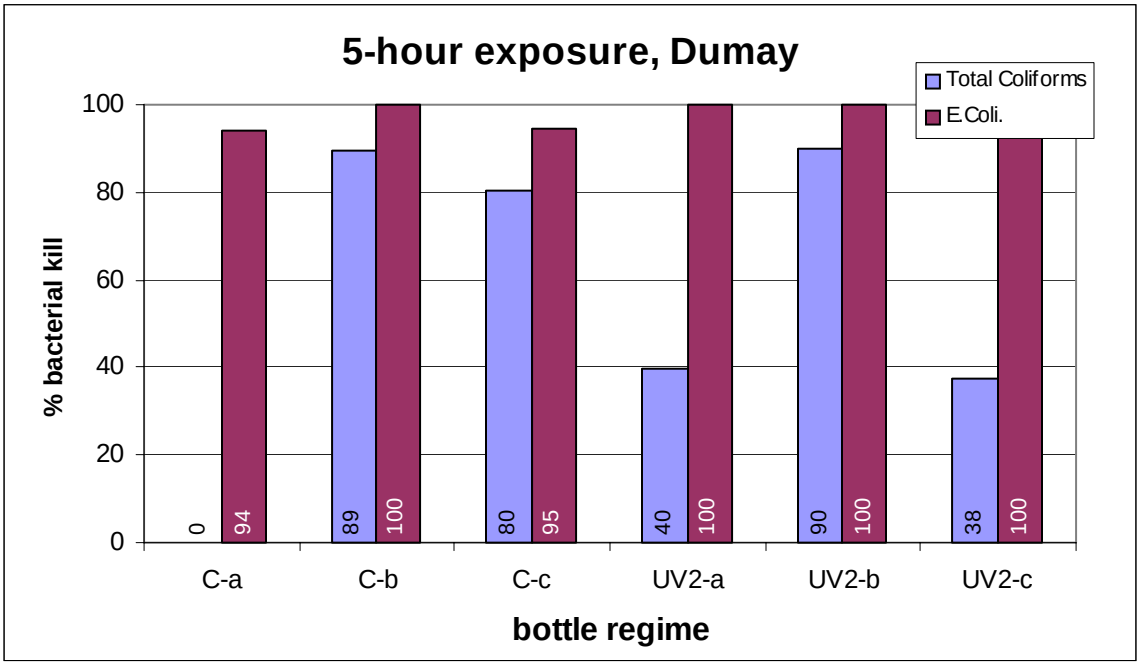

Figure 5.7 Percent bacteria kill after 5-hours exposure in Dumay

5.2.3 Boston

In Boston, 100 percent kill of *E.coli* was observed in all clear and half-painted bottles after the 5-hour exposure (Figure 5.8). Over 80 percent kill for Total Coliforms was also observed in these bottles. Significant kill was also apparent for *E.coli* in the fully painted bottles, but there actually appeared to be growth of Total Coliforms, the opposite of what was observed in Barasa.

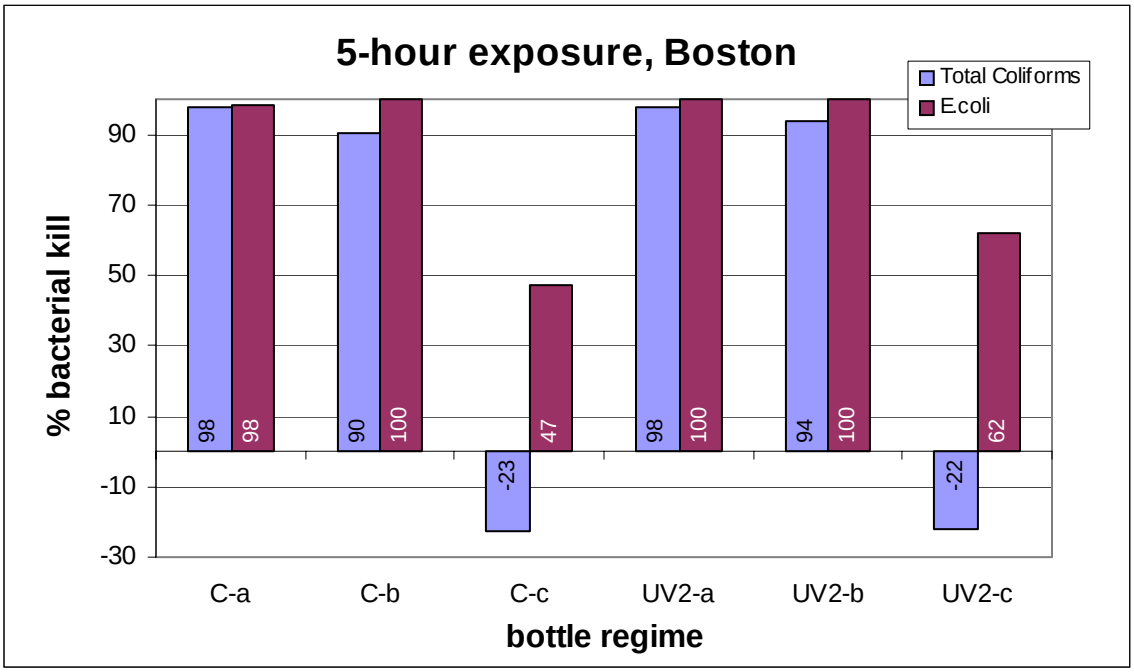

Figure 5.8 Percent bacteria kill after 5-hours exposure in Boston

After 1-day exposure, 100 percent *E.coli* kill was observed in both clear bottles and over 90 percent kill was observed in the half-painted bottles (Figure 5.9). For Total Coliforms, the percent kill in the clear bottles was 80 percent, and around 75 percent in the half-painted bottles. Significant *E.coli* kill was also observed in the fully painted bottles.

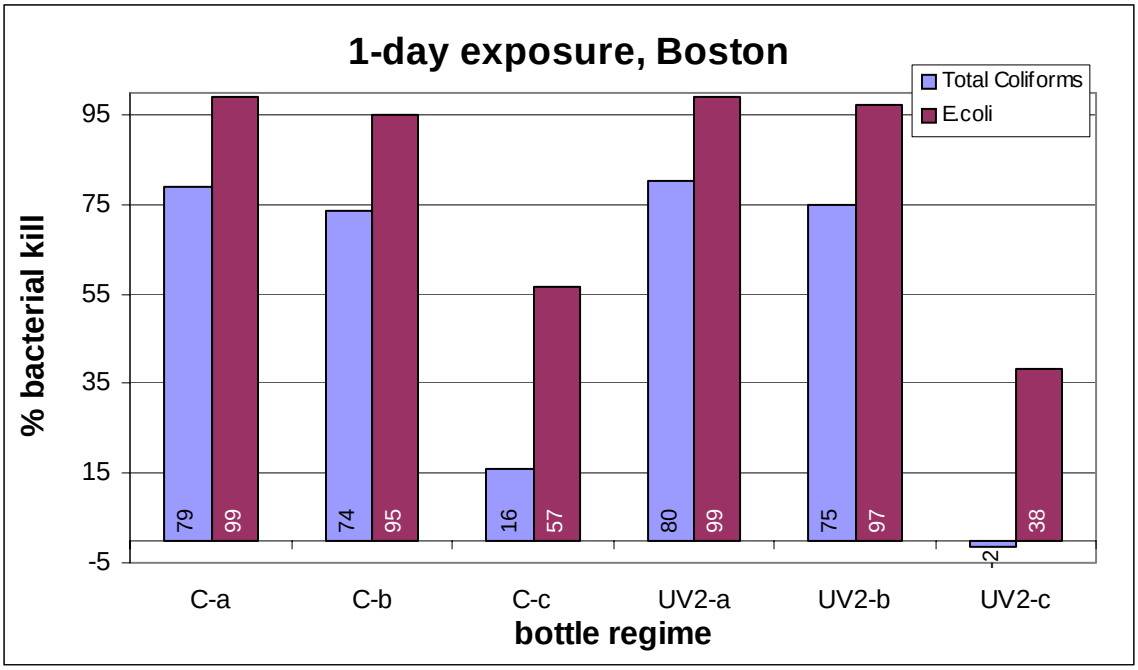

Figure 5.9 Percent bacteria kill after 1-day exposure in Boston

For 2-days of exposure, 100 percent kill was observed for *E.coli* in both the clear and half-painted bottles (Figure 5.10). Additionally, kill greater than 95 percent for Total Coliforms was also observed in these bottles. Significant kill was observed for *E.coli* in the fully painted bottle without a reflector, but growth of both *E.coli* and Total Coliforms was actually apparent in the fully painted bottle on the reflector.

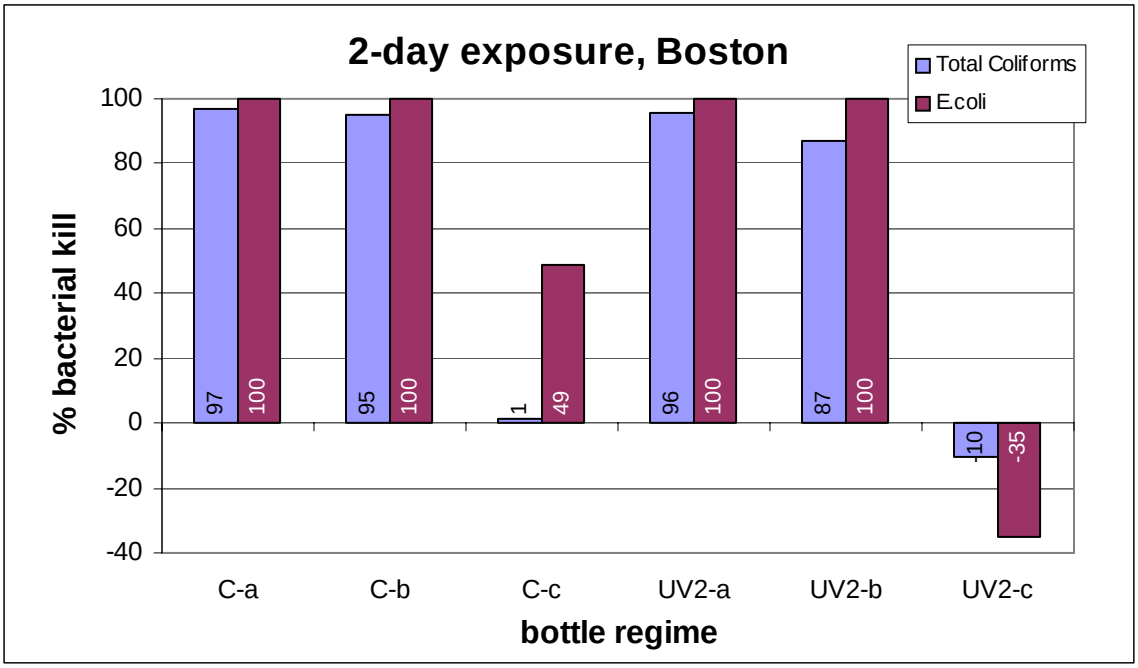

Figure 5.10 Percent bacteria kill after 2-day exposure in Boston

5.2.4 Summary

Overall, the effectiveness of each exposure regime was related to the length of the exposure time and location. The clear bottle regimes, both with and without a reflector, were most effective. Approximately 100 percent *E.coli* inactivation in all locations regardless of the duration of the exposure was seen in this regime. Additionally, the half painted bottle regimes consistently showed significant *E.coli* inactivation as well, though the percent inactivation increased with exposure time. The fully painted bottle regimes were generally not effective, except in Dumay.

5.3 Evaluation of Results

5.3.1 Barasa

The conditions observed in Barasa were sub-optimal for SODIS application because of cool climate conditions, but abundant solar radiation was available. None of the bottle water temperatures reached 50°C necessary for thermal disinfection (Figure 5.11). However, as shown in Figure 5.11, solar radiation was abundant in Barasa, and exceeded the necessary 500 W/m2 for effective UV-related microbial inactivation. This would therefore account for the differences in kill observed in the clear and half-painted bottles, which were exposed to UV radiation, versus the fully painted bottles, which were not exposed to UV radiation.

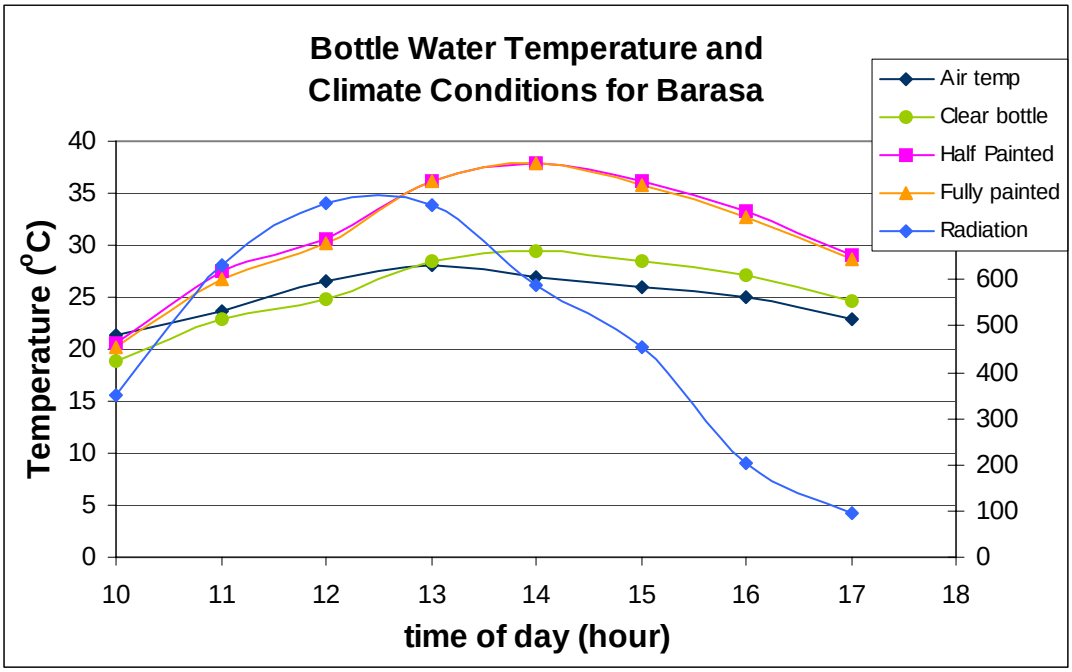

Figure 5.11 Bottle water temperature and climate conditions in Barasa

5.3.2 Dumay

The conditions in Dumay were ideal for the application of SODIS because not only was there abundant solar radiation, but the climate was warm as well. Both the half-

painted and fully painted bottles exceeded the threshold temperature of 50^{o}C for the one-hour required. It is therefore not surprising that significant kill was observed in both of these bottles. Additionally, it can be assumed that the amount of available solar radiation was high, therefore also effecting significant kill in the clear bottle as well.

5.3.3 Boston

The conditions in both Boston were again sub-optimal for SODIS application because of limited solar radiation and extremely cold temperatures. However, the trend in microbial inactivation was similar to that observed in Barasa. Significant kill was observed in the clear and half painted bottles, regardless of exposure time, implying that solar radiation was sufficient for bacterial deactivation, whereas there was no significant kill in the fully painted bottles.

5.4 Statistical analysis

In order to properly analyze the effectiveness of the different exposure regimes, two different statistical tests were used to detect trends in the data. The two tests used were the Mann-Whitney test and the 2-sample t-test. Both of these tests compute and compare the means of two sample sets and use the sample variances to determine whether or not they are statistically different within a given confidence interval. If the means of the two samples are statistically different, then it is assumed the two sample sets are statistically different within the same confidence interval.

Ideally these tests are applied to large sample sets, which are more representative of actual conditions. Unfortunately, the amount of data collected in this study was limited (only 2 data points for each exposure regime per run, therefore 6 total data points per location for each exposure regime). Because the conditions in Boston and Barasa were similar in that they did not exceed the threshold temperature, the two data sets were analyzed individually and grouped. No statistical analysis was conducted on the data collected in Dumay.

Statistical analysis was used to evaluate a number of different parameters and determine which regimes were worthy of further investigation. Each test compares two sample sets. The first analysis compared the background microbial concentrations to the concentrations in the treated water of each regime. The purpose of this analysis was to determine if the amount of bacterial kill in each regime was in fact significant, and thus the regime could be considered effective for water treatment. The second analysis compared the clear and half-painted bottle regimes on the two reflectors to their counterparts without a reflector. This analysis was used to determine whether or not the reflector was effective in enhancing microbial deactivation. Finally, the clear and half painted bottle regimes on the two different reflectors were compared in order to determine if there was a significant difference in their effectiveness.

5.4.1 Evaluating the Effectiveness of Each Regime

With 5-hours of exposure, only the microbial concentrations in the clear bottle regimes (both with and without the reflector) and the half-painted bottle regime on the aluminum foil reflector were statistically different from the background microbial concentration within a 95 percent confidence interval. Therefore, it can be assumed that these regimes were effective for microbial deactivation with only 5-hours of exposure. However, all of the other half-painted bottle regimes were statistically different from the background microbial concentrations within an 80 percent confidence interval, and thus could also be considered effective exposure regimes, though less so than the others mentioned. None of the fully painted bottle regimes in Boston or Barasa had statistically significant microbial deactivation.

Table 5.1 Statistically significant microbial kill after 5-hour exposure

	Statistically significant microbial kill?		
	Yes		**No**
	95% confidence interval	***80 % confidence interval***	
No reflector			
Clear bottle	✓		
Half-painted bottle		✓	
Painted bottle			✓
Al mylar reflector			
Clear bottle	✓		
Half-painted bottle		✓	
Painted bottle			✓
Al foil reflector			
Clear bottle	✓		
Half-painted bottle	✓		
Painted bottle			✓

With 1-day of exposure, both the clear bottle regimes (with and without the reflector) and the half-painted bottle regimes on either reflector were statistically different from the background microbial concentration within a 95 percent confidence interval. Thus, with 1-day of exposure these bottle regimes were effective for microbial deactivation. The half-painted bottle regime not on a reflector was also statistically different from the background microbial concentrations, but only within a 90 percent confidence interval, meaning it is also effective for microbial deactivation. Again, the fully painted bottles did not have statistically significant microbial deactivation.

Table 5.2 Statistically significant microbial kill after 1-day exposure

	Statistically significant microbial kill?	
	Yes ***(95% confidence interval)***	**No**
No reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓
Al mylar reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓
Al foil reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓

For 2-days of exposure, all clear and half-painted bottle regimes had statistically different microbial concentrations from the background samples, within a 95 percent confidence. Therefore, all these regimes were equally effective for microbial inactivation. The analysis determined that the microbial concentrations in the fully painted bottles were not statistically different form the background concentrations, and thus they were not effective for microbial inactivation.

Table 5.3 Statistically significant microbial kill after 2-day exposure

	Statistically significant microbial kill?	
	Yes ***(95% confidence interval)***	**No**
No reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓
Al mylar reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓
Al foil reflector		
Clear bottle	✓	
Half-painted bottle	✓	
Painted bottle		✓

Overall, only the clear bottle regimes were consistently effective for microbial inactivation, regardless of exposure time (within those investigated). However, the effectiveness of the half painted bottle regimes seems to increase with exposure time, and it also seems to be enhanced by use of the solar reflectors. Additionally, because the bottle water temperatures in Boston and Barasa did not reach those necessary to either induce synergistic effects or thermal inactivation, it is possible that the half painted bottle regimes would be more effective in only slightly warmer climates. The fully painted bottles were not effective in either Boston or Barasa because threshold temperature for thermal inactivation was not reached and no UV effects could penetrate the system.

5.4.2 Evaluating the Use of Solar Reflectors

Data was collected daily in Barasa to compare the amount of radiation incident on a bottle on and off a reflector. Calculations made from these measurements show that the aluminum mylar reflector increased the apparent sunlight intensity an average of 20 percent. According to the above evaluation, it appears that the reflectors do in fact enhance the effectiveness of microbial inactivation in the half painted bottles. However, statistical analysis shows that the microbial concentrations in the clear and half painted bottle regimes are not statistically different between the bottles on the reflector and not,

within a 95 percent confidence interval. This analysis was conducted for each of the 5-hour, 1-day, and 2-day exposure data sets within the grouped Boston and Barasa data, as well as the two individual location data. Additionally, no statistical difference was detected between the microbial concentrations in the bottles on the two different reflectors.

5.4.3 Summary

The validity of this statistical analysis is questionable because the sample set is small and may not be truly representative of the effectiveness of the bottle regimes. Additionally, the data that was collected contained many samples that had 100 percent kill. The presence of these "zeros" and the lack of a normal distribution of the data greatly skew the mean of the data set. Additional research is necessary to supplement this data for proper statistical analysis.

While few conclusions can be drawn from the data available about the effectiveness of the different exposure regimes, it is fairly clear which ones are worthy of further research. Because the bottle water temperatures of the fully painted bottles was not significantly different from that of the half painted bottles, and because there was no significant microbial inactivation in the fully painted bottles, they are not worth further research. The same temperature gains can be achieved in the half painted bottles, while still allowing for UV effects.

The clear and half-painted bottle regimes are worthy of further investigation specifically on their effectiveness in non-tropical climates. In particular, because the clear bottle regimes were consistently effective with only 5-hours of exposure, their effectiveness with shorter exposure times and/or less intense radiation should be investigated. Additionally, the same variable seemed to affect the effectiveness of the half-painted bottle regimes. However, because there is an abundance of data on the effectiveness of these two regimes in other locations already, more worthy of further study is the use of solar reflectors to enhance their effectiveness. In investigating the use

of these reflectors, not only should the conditions of this study be repeated, but also additional exposure times and sunlight intensities.

5.5 Bottle Water Temperature Model

The bottle water temperature model developed as a part of this study was created using a Microsoft Excel spreadsheet (presented in Appendix III). The average air temperature and radiation data collected in Barasa were used as the climatic inputs to the model, and so the outputs were compared to the actual bottle water temperature monitored in Barasa. However, the one-hour time step at which measurements were taken was found to be too large to achieve accurate calculations with the model, and so the data was interpolated at 10 minute time steps. Because the wind speed and direction was not monitored in Barasa, the speed was estimated to be approximately 3.8m/s from observations using the Beaufort scale (Table 5.1). It was assumed that the wind direction was perpendicular to the bottles, which would thus overestimate the amount of convection occurring.

Table 5.4 Beaufort Scale (Petterssen, 1969)

Beaufort #	General description	Specifications	Wind speed (m/s)
0	Calm	Smoke rises vertically	Under 0.6
1	Light air	Wind direction shown by smoke drift but not by vanes	0.6-1.7
2	Slight breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind	1.8-3.3
3	Gentle Breeze	Leaves and twigs in constant motion; wind extends light flag	3.4-5.2
4	Moderate Breeze	Dust, loose paper, and small branches are moved	5.3-7.4
5	Fresh breeze	Small trees in leaf begin to sway	7.5-9.8
6	Strong breeze	Large branches in motion; whistling in telephone wires	9.9-12.4
7	Moderate gale	Whole trees in motion	12.5-15.2
8	Fresh gale	Twigs broken off trees; progress generally impeded	15.3-18.2
9	Strong gale	Slight structural damage occurs; chimney pots removed	18.3-21.5
10	Whole gale	Trees uprooted; considerable structural damage	21.6-25.4
11	Storm	Widespread damage	25.5-29.0
12	Hurricane		Above 29.0

The short-wave transmissivity of the plastic was calculated from measurements taken in Barasa by placing the end of a plastic bottle around the pyranometer. The meter therefore gave a measure of the percent of radiation that was not reflected or absorbed by the bottle. The painted plastic was completely opaque, but the clear plastic transmitted approximately 90 percent of the radiation. Additionally, measurements were taken to calculate the percent attenuation of radiation through the bottle, which was found to be 80 percent of the total radiation (i.e. only 20 percent of the radiation was transmitted through the full bottle of water). The plastic's transmissivity/emissivity of long-wave radiation could not be calculated because there was no way to measure this radiation. The thermal conductivity of the plastic was found to be 0.2 W/mK (Matweb, 2002).

In general, convection was the limiting term to heat transfer in this model. Because convection is small, the surface temperature built up so that it was very close to the bottle water temperature, therefore limiting the rate of conduction, and creating an insulating effect. Additionally, because the long-wave properties of the plastic are

unknown, the model was run both with and without these components (Figures 5.12-14). Neglecting long-wave radiation creates a better fit for the clear bottle model, but has little effect on the fit of the half-painted and fully-painted bottle models.

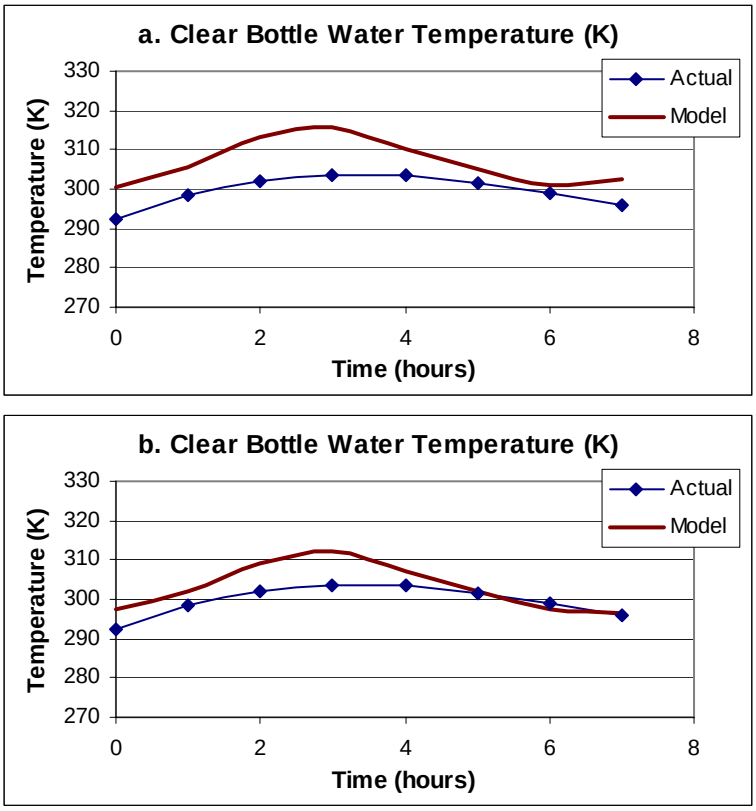

Figure 5. 12 Clear bottle water temperature model, a) with long-wave radiation, b) without radiation

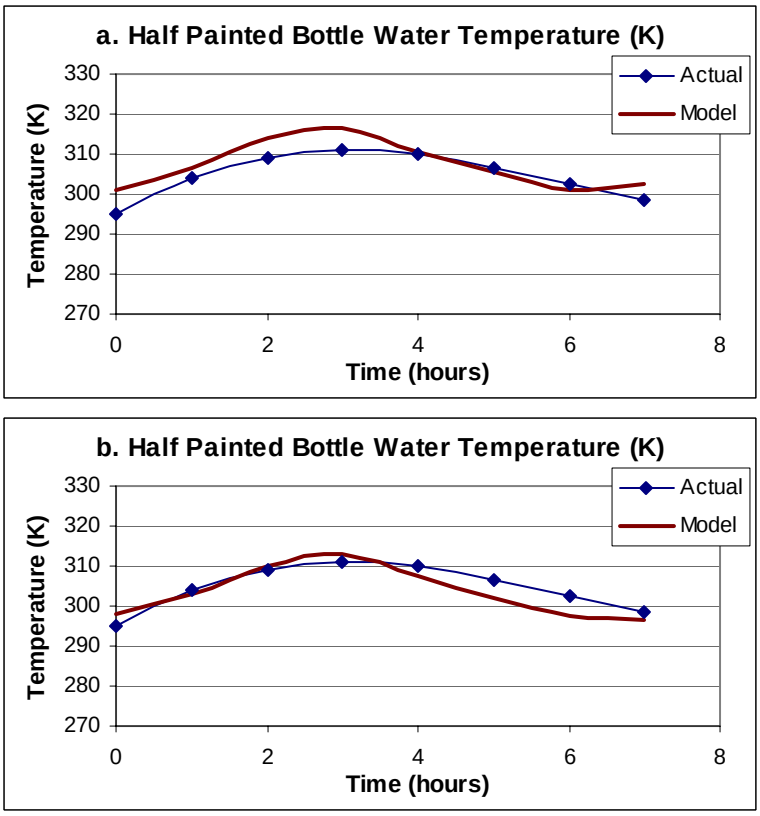

Figure 5.13 Half-painted bottle water temperature model,
a) with long-wave radiation, b) without long-wave radiation

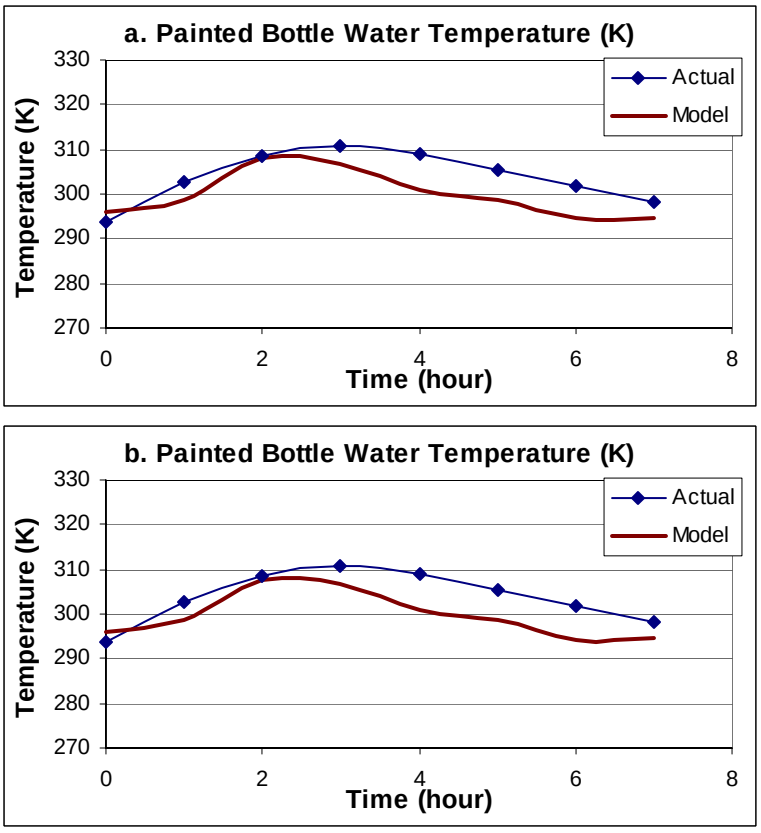

Figure 5.14 Painted bottle water temperature model,
a) with long-wave radiation, b) without long-wave radiation

As illustrated in Figures 5.12, the model consistently overestimates the temperature. However, an underestimate of the bottle water temperature would be more acceptable for SODIS application. Modifying the transmissivity factors for the clear bottle can greatly improve the fit, but it is consistently too high, even when all short-wave radiation is ignored. Additionally, there is no logical basis for this change. It is believed that theses discrepancies are more likely caused by inaccuracies of the material properties than by oversight of additional heat components. Therefore, more research is needed to assess the actual reflective, transmissive, and emissive properties of the plastic in order to make the model more accurate.

6 Conclusions

6.1 Thermal Enhancement

In order for thermal inactivation alone to be effective for microbial deactivation in the SODIS system, a bottle water temperature of 50^{o}C must be exceeded for at least one hour. Additionally, reaching this temperature also causes synergistic effects between UV and temperature to be enabled. It has been shown that painting the bottom half of the bottles black can raise the water temperature 5^{o}C, depending on the amount of radiation available. In order to test this technique under sub-optimal SODIS conditions, bottles in this study were painted half black so that UV inactivation of bacteria could also take place within the bottle. Additional bottles were fully painted in hopes of absorbing more radiation than the half painted bottles and thus raising the temperature more.

Under sub-optimal conditions, there was no significant difference in the amount the bottle water temperature was raised in the half-painted or fully painted bottles. The bottle water temperature of the clear bottles was the same as that of the ambient air temperature. In Barasa, the peak temperature difference between the clear and painted bottles was 8^{o}C – greater than that expected from the literature. However, this only achieved a peak bottle water temperature of 38^{o}C, well below the thresholds mentioned above. In Dumay however, which has similar amounts of available solar radiation, a temperature difference of almost 10^{o}C was achieved, and the threshold temperature of 50^{o}C was exceeded in both painted bottles. The difference in the peak temperature achieved can be mainly attributed to the difference in weather conditions, which were cooler and breezier in Barasa, which would cause cooler bottle water temperatures.

In order to assess whether or not a thermal enhancement technique would be effective in a specific region, the local weather conditions (air temperature, wind, available solar radiation) must be known. In general, if the ambient air temperature does not reach 45^{o}C, it can be assumed that the painted bottle water temperature will not reach 50^{o}C. Additionally, because there was little difference in temperature between the half-

painted and fully painted bottle, bottles should only be half painted in order to also allow for synergistic effects with UV.

6.2 UV enhancement

The second active disinfection mechanism of SODIS is UV induced DNA alterations, which inhibits proper cellular replication. According to SANDEC News, No. 3, a total sunlight intensity of 555 W/m^2 is necessary to induce these lethal UV effects. In order to increase the sunlight intensity in the system, a reflector was built to gather sunlight from a wider area and focused it on the SODIS bottles. This would not only enhance the UV intensity in the system, but also had the potential to additionally increase the bottle water temperature through increased radiation absorption. Two different reflective materials were used: aluminum mylar and aluminum foil. Aluminum mylar is sturdy and highly reflective, but aluminum foil has similar properties, and is also more commonly available in the developing world. The aluminum mylar reflector increased the apparent sunlight intensity an average of 20 percent. However, the amount of microbial kill observed in bottles on either reflector was not statistically different from that of their counterparts not on a reflector, nor was there a significant difference in bottle water temperature.

There are many reasons why the reflector may not have had a significant impact on microbial kill. First of all, the dimensions of the reflector were not optimized to the bottle size because the bottle size to be used in different locations was not known. Additionally, because of material lightness, it was easily misshapen by the wind, often causing partial shading of the bottles. Finally, the amount of ambient solar radiation may have been abundant enough that a 20 percent increase (i.e. 1100 W/m^2 versus 900 W/m^2) did not have significant effect. These results are not consistent with the findings of Kehoe, *et al* (2001), who observed a significant increase in solar intensities and water temperature, resulting in an increased inactivation rate. However, the efficiency of reflective backing may be higher than that of the reflectors used in this study, thus accounting for the difference in results. Additionally, the Kehoe, *et al* study was

conducted using laboratory simulated solar radiation, which would thus be more evenly distributed than natural sunlight.

Further studies are needed in order to properly evaluate the effective use of solar reflectors/reflective bottle backing. Possibly such enhancement techniques would be more obviously effective with shorter exposure times or lesser amounts of ambient solar radiation. In any case, the reflectors did not seem to inhibit microbial deactivation and when used properly can be used without concern of negative impacts on the system.

6.3 Summary

Proper assessment of the possible application of SODIS to a region is dependent on a number of factors. Therefore, it is strongly recommended that proper field studies be completed before SODIS is introduced as the primary point-of-use water treatment system in that area. However, in order to make most efficient use of field study time, the following should be noted about thermal enhancement using black paint:

1) There was no significant difference in the bottle water temperatures on the fully painted bottles versus the half painted bottles. Therefore, bottles should only be half painted (if at all) so as to allow for synergistic effects with UV as well.
2) In order for bottle water temperatures in a half painted bottles to reach temperatures of 50^{o}C necessary to activate synergistic effects, ambient air temperatures need to reach at least 45^{o}C.

If condition (2) is met, than only one hour of exposure is necessary. However, if (2) cannot be achieved, then the bottles should not be painted. In this case, a reflective surface (such as a reflector or reflective bottle backing) may be more effective in achieving increased deactivation by increasing sunlight intensity focused on the bottles.

This study evaluated a number of different exposure regimes in non-tropical climates in order to determine which were most effective and worthy of further research. In general, the fully painted bottle regimes were not significantly more effective for reaching the required temperatures than the half painted bottles. Additionally, there have been numerous studies already conducted on the use of the clear and half painted bottle regimes without a reflector. Therefore, it is recommended that the primary focus of future studies focus on the use of such reflectors with the clear and half painted bottle regimes in non-tropical climates.

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APPENDIX I: Research plan

SODIS Research Plan for Haiti, January 2002

Massachusetts Institute of Technology
Researcher: Julia Parsons
Advisor: Daniele Lantagne

Overview

One entire experiment should take 4 days, from initial sample collection to final microbial analysis. It will consist of 3 complete sample runs consisting of 17 bottles, 2 background samples and 2 blanks (21 samples total). The experiment will be run at least 3 times throughout our 15-day stay in Barasa.

Bottle Regimes:

Regime	Label	
No reflector	clear (2)	C-a1 and C-a2
	1/2 black (2)	C-b2 and C-b2
	all black (2)	C-c1 and C-c2
Al Mylar reflector:	clear (2)	UV1-a1 and UV1-a2
	½ black (2)	UV1-b1 and UV1-b2
	all black (2)	UV1-c1 and UV1-c2
Al foil reflector	clear (1)	UV2-a
	½ black (1)	UV2-b
	all black (1)	UV2-c

All supplies will be brought to Haiti from Boston, with the exception of bottles and paint. A detailed schedule, instructions for sample collection, exposure and membrane filtration follow.

The same procedures will be used for sampling done in Dumay and Boston as well.

Schedule

Day 1: Site selection, Bottle selection and preparation, Equipment preparation

Run #1
Day 2: SC1a
EXP1a (5 hours)
MF1a*, begin I1a*
Day 3: SC1b&c
EXP1b&c (1 day, 2 day - day1)
MF1b*, begin I1b*
continue I1a, CC1a*
Day 4: continue EXP1c (day 2)
MF1c*, begin I1c
continue I1b, CC1b*
Day 5: continue I1c, CC1c*

Run #2
Day 5: SC2a,
EXP2a (5 hours)
MF2a*, begin I2a*
Day 6: SC2b&c
EXP2b&c (1 day, 2 day - day1)
MF2b*, begin I2b*
continue I2a, CC2a*
Day 7: continue EXP2c (day 2)
MF2c*, begin I2c
continue I2b, CC2b*
Day 8: continue I2c, CC2c*

Run #3
Day 8: SC3a,
EXP3a (5 hours)
MF3a*, begin I3a*
Day 9: SC3b&c
EXP3b&c (1 day, 2 day - day1)
MF3b*, begin I3b*
continue I3a, CC3a*
Day 10: continue EXP3c (day 2),
MF3c*, begin I3c
continue I3b, CC3b*
Day 11: continue I3c, CC3c*

(SC = sample collection, EXP = exposure, MF = membrane filtration, I = incubation, CC = colony counting, a = 5 hr exposure, b = 1 day exposure, c = 2 day exposure)
* in evening

Bottle Selection and Preparation

Equipment:

Towel	Soap
Wash basin	Turpentine
Black paint	Paintbrush
Labeling marker	Aluminum foil and tape
Drying rack	Bottle Condition data sheet
Newspaper	Sponge and Bottlebrush

Preparation:

1) Collect Bottles that meet the following specifications:
   - 1 liter w/ lid, minimal scratches, dents and deformations

2) Make note of original condition on data sheet (ie. clear, minimal scratches, excessive scratches, deformation, discoloration). Expand on condition in "Notes" section at bottom of page if necessary.

3) Wash bottles using boiled water and non-disinfectant soap. Clean inside by vigorous shaking (use bottlebrush only if necessary – it scratches) and outside using soft sponge. Be careful not to scratch bottle or remove paint.

   NOTE: if new, unopened bottles are bought from a store, there is no need to wash them because them have been sterilized by the packaging process.

   ** DO NOT use chemically treated (ie. chlorinated) water or other kind of disinfectant on the bottles at ANY TIME. Using alcohol will increase kill and cause lower apparent microbial concentrations**

4) Dry outside with towel/paper towels and place on end in drying rack

5) Prepare bottles as follows:
   - 6 fully painted black, 6 ½ black, 6 clear

6) *Paint:* Line edges of surface to be painted with tape. Paint with paintbrush, being careful not to drip paint on surface that should not be painted. Allow paint to dry by placing on end in drying rack, over newspaper. Coat with additionally layers until opaque (test opaqueness by holding up to light).

7) Label lids as shown above.

(Bottle condition data sheet)

Collecting Water samples

Equipment:	Whirlpack bags	Bottles
	Labeling Marker	Turbidity/Radiation data sheet
	Thermometer	Bottle Condition data sheet
	Turbidimeter	Bottle Temperature data sheet

Procedure:

1) Note condition of each bottle for appropriate day on data sheet (ie. clear, minimal scratches, excessive scratches, deformation, discoloration). Expand on condition in "Notes" section at bottom of page if necessary.

2) Take all bottles (plus extra) and 4 whirlpack bags to source as early in the day as possible so as to maximize exposure time.

3) Take initial turbidity reading using turbidimeter. Record on Turbidity/Radiation data sheet.

4) Collect first background sample in a whirlpack bag: Label sample bag. Rip off top, open using tabs and be sure bottom is open. Fill to line and whirl closed. Wipe down outer surface and set aside.

5) Rinse inside of bottle with sample water by partially filling & shaking vigorously.

6) Fill first bottle 2/3 full, cap and shake vigorously to aerate. Fill completely (minimizing air space) and record temperature. Cap tightly and set aside.

7) Repeat (6) for rest of bottles. Be careful not to mix up lids.

8) Repeat (4) through (6) for second turbidity reading, background sample, and remaining bottles.

   ** NOTE: There is no need to be "sterile" during this procedure because all samples are coming from the same source and will therefore have the same initial microbial concentrations. However, it is necessary to take precautions not to contaminate samples with outside sources. **

Reflector Assembly

The reflector consists of two parallel "slings" of material (Aluminum coated Mylar or brown paper with Aluminum Foil) hung on rope. Both reflectors are constructed exactly the same way, but using different materials. Each "sling" holds three bottles end-to-end (total = 6 bottles). The reflector should be oriented parallel to the path of the sun (approx East – West) so as to minimize shadows. Samples not utilizing the reflector should be placed at a sufficient distance and orientation away from the reflector so as not to be affected by potential reflection.

Materials:	Al Mylar: 2' x 3'	Brown paper (same as Mylar)
	Wooden bases (2)	Nuts, Bolts, Washers
	Wooden "Arms" (6)	7' Rope (3)
	Duct Tape	Sand paper (to smooth rough edges)

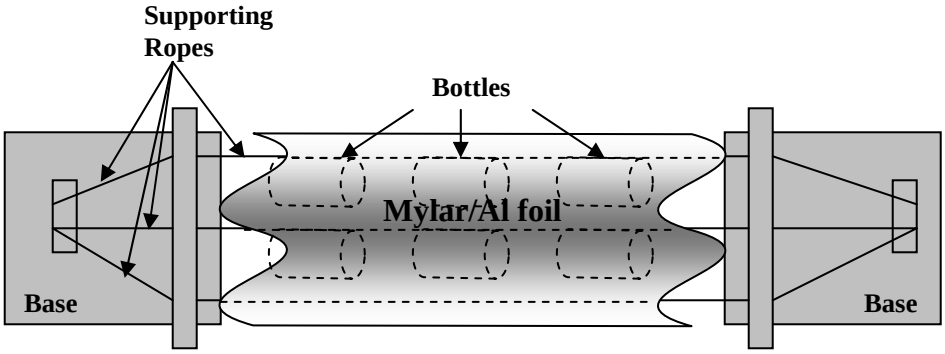

Figure 1. Top view

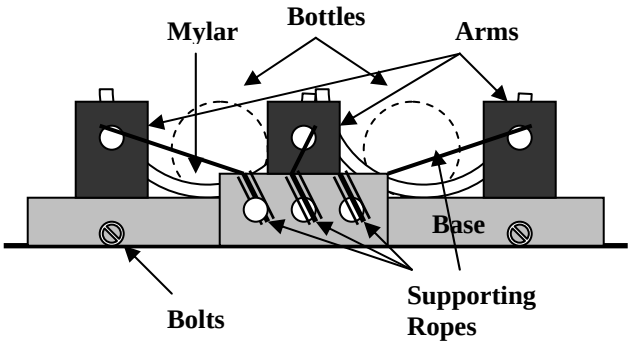

Figure 2. End view

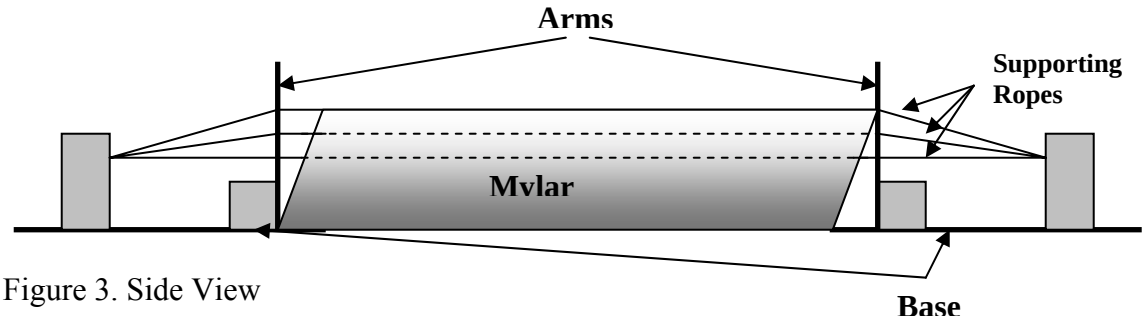

Figure 3. Side View

Assembly Instructions:

1) Choose a location free of shade (that will remain free of shade) and shielded from wind. If a wind shielded location is not available, you may have to rig up a wind block, as the wind affects bottle temperature and may also adversely affect the reflector.

2) Bolt arms to the inner side of the longer base piece with bolt heads facing outwards. This will allow the Mylar to rest on the ground without interference from the base or bolts. Three arms attach to each base.

3) Tape (using duct tape) one piece of rope to underside of Mylar down middle seam

4) Place the two bases approximately 3 feet apart. Flip over Mylar and position between the two bases.

5) Thread rope through middle arm on each side and through the back rope holes of the base and tie off. Be sure to pull the rope tight, but do not wrinkle Mylar.

6) Thread remaining two rope pieces through the side arms and attach to tie off on both sides as done above.

7) Tape outsides of Mylar to side ropes using duct tape.

8) Readjust ropes and Mylar to get rid of any slack or wrinkles.

9) If necessary, weight down the base with rocks to keep from flipping over.

Temperature Monitoring

Equipment: Checktemp electronic thermometer
Sterile or boiled water (for rinsing thermometers)
Squirt bottle
Bottle Temperature data sheet

** In order to keep thermometers sterile and avoid contaminating samples, they should be left in the sun during the day and rinsed well with boiled water between samples**

Procedure:

1) Take temperature in every bottle every hour (or as often as possible) as long as you are awake, starting at t=0 being when the bottles are first set in the sun.

2) Take ambient air temperature and note weather condition (ie. approximate wind speed) on temperature data sheet.

3) Take reading in first bottle and record on data sheet.

   ** Only open bottle when ready to take measurement and close immediately after. BE CAREFUL not to shade other bottles while taking temperature readings **

4) Rinse thermometer with sterile or boiled water. DO NOT wipe dry.

5) Repeat (2) and (3) for remaining bottles.

6) Make any necessary notes on data sheet.

(Temperature data sheet)

Microbial Analysis

** Remember to complete a blank with sterile water at the beginning and end of each sampling round. **

Equipment:

Filtration apparatus	Funnels
Petri dishes	Media packets
Filters	Tweezers
Sterile Water	Alcohol
Candle and matches	Incubator
Paper towels	Plastic trash bag
Labeling marker	Microbial Analysis data sheet

Procedure:

1) Pull back hair, don glasses, use gloves or wipe hands with alcohol

2) Prepare work surface: open plastic bag and wipe down with an alcohol soaked paper towel

3) Wash hands with alcohol

4) Set up filtration apparatus, set out equipment, wipe down outside of samples with alcohol, set out and light candle

5) ** BE CAREFUL not to get alcohol on the LIDS of the bottles but only wipe down the sides to avoid cross contamination **

6) Prepare media: snap open packet, pour entire packet into petri dish and cover immediately

7) ** PREPARE ALL petri dishes at once in order to minimize time filter is exposed to open air later. **

8) Sterilize tweezers in candle, pick up and sterilize carbon filter in candle using tweezers, replace in filtration apparatus and wet with sterile water

9) Wash hands with alcohol, sterilize tweezers.

10) Carefully open new filter package, pulling away package and paper, DO NOT touch filter with hands (if so, discard filter)

11) Pick up filter with tweezers and carefully center on filtration apparatus, place new funnel on top of filter. If filter rips – discard filter.

12) Carefully pour sample directly from bottle or whirl pack into the funnel, filling to the 100ml (or other appropriate) mark. DO NOT touch container to filter funnel. Close and set rest of sample aside in case it is needed later

13) Pull sample through filter, expelling wastewater into waste bucket or onto ground.

14) Sterilize tweezers

15) Remove filter funnel and pick up filter by edge with tweezers and place in petri dish (held in hand). Avoid air bubbles. Close petri dish immediately and label with sample, exposure and date.

16) Repeat from step 6 until all samples are completed.

17) Incubate samples for 24 hours, along with background and blanks.

18) When done, discard all used funnels, the garbage bag, paper towels and other trash. Empty bottles, wash with soap and boiled water and store under plastic sheet overnight (can also wash the next morning).

After 24 hours:
Count colonies formed (red = Total and blue = E.Coli) and record on data sheet.

Make note of any necessary details (from filtration or counting – e.g. spilled sample?) on data sheet.

(Microbial analysis data sheet)

Incubator Directions

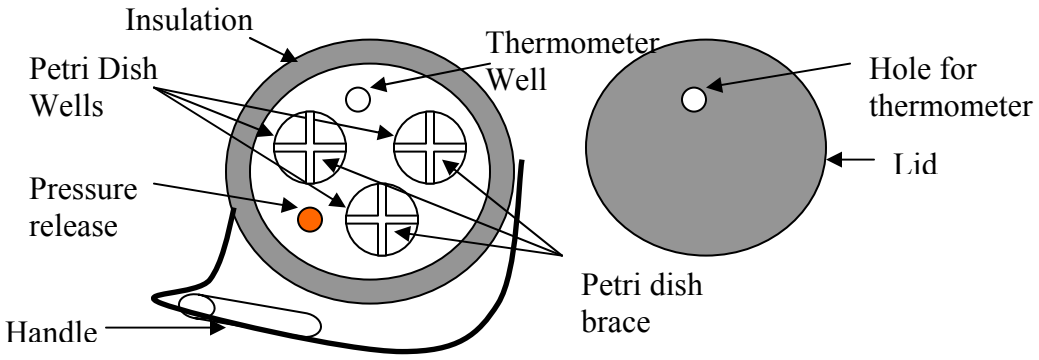

Figure 1. Top view of phase-change incubator

To heat:

1) Place incubator in pot, ensuring space between the incubator and the pot with rocks or other objects so that plastic does not melt.

2) Fill with water up to brim of incubator

3) Boil 15 – 20 minutes, or until contents of incubator has liquefied

* NOTE: occasionally lift and "swish" incubator to ensure even distribution of heat *

4) When ready, allow incubator to super cool and start crystallization before filling.

* Note: you can "jump start crystallization by touching the side of the incubator *

5) To release pressure from heating open valve and close again.

Alternative: Place incubator in direct sun to heat.

To use:

1) Place petri dishes inside brace and lower into wells (5 or 6 into each well). If not brace is available use string.

2) Place lid on top. If lid does not sit tightly, cover with a piece of cloth or stuff with extra insulation

3) Insert thermometer through lid and into the thermometer well.

4) Allow samples to incubate for 24 hours. Check temperature occasionally, when it drops below 35 degrees C, reheat.

Solar Energy Readings

Equipment: Pyranometer
Radiation data sheet
Bottle Temperature data sheet
Pencil
Black cloth cloak

Procedure:

1) Take normal radiation reading every hour and record on Bottle Temperature data sheet.

2) At peak time (approx. noon) each day take the following measurements:
   - on reflector
   - through plastic piece
   - through full bottle (cloaked in black cloth)
   - through full painted black bottle (cloaked in black cloth – should be 0)
   - through full foil wrapped bottle (cloaked in black cloth – should be 0)

3) Cover sides of bottle with black cloth.

4) Place full bottle covered in cloth over pyranometer, record reading on Radiation data sheet.

(Radiation data sheet)

APPENDIX II: Data Summary and Analysis

APPENDIX III: Bottle Water Temperature Model (with long-wave radiation component)