

SPIRASOL: IMPROVEMENTS TO SEMI-CONTINUOUS SOLAR DISINFECTION
WATER TREATMENT SYSTEMS

by

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ABSTRACT

An experimental study was carried out to determine the feasibility of an original point of use solar water disinfection system created by the author and named “Spirasol.” The study primarily focused on the comparison of microbial removal levels in the Spirasol system and the more traditional solar disinfection method called SODIS that uses a Polyethylene Terephthalate (PET) bottle. To address microbial removal capacity, the two systems were assembled and tested in Nairobi, Kenya and later in Cambridge, Massachusetts. The issue of economic feasibility and component availability were also addressed and factored in heavily during the design phase of the project.

The results suggest that the Spirasol system is equally as effective as the traditional SODIS system with respect to microbial inactivation. Analysis of the costs required for continuous and semi-continuous solar disinfection system implied that such systems were not a good match for sites of extreme urban poverty such as the Kibera slum in Nairobi, Kenya. However, the overall low cost among semi-continuous point of use treatment systems and the wide availability of the required pieces made them a sustainable technology for other areas in the developing world where available capital is marginally higher.

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For their undying love and support.

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I. INTRODUCTION

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1.1 The State of Water Quality in the Developing World

The concept of water being requisite for life may not come as obviously to those in highly developed countries like the United States, where safe, clean drinking water is as accessible as the nearest building. In other parts of the world, the reality of water's precious value may be recognized with each moment of the day. According to the World Health Organization, 1.1 billion people, about 17 percent of the global population, receive their water from an unimproved source, which includes streams such as rivers, springs, or open-air wells, but also considers those who rely on tanker trucks and other methods that must transport water from outside the community (WHO, 2004). Water-borne diseases such as diarrhea and dysentery are prevalent and common amongst these populations, and frequently lead to death among children.

While these susceptible populations exist around the world, most of them are concentrated in sub-Saharan Africa and Asia. About 66 percent of those with untreated water reside in Asia, while around 40 percent of the sub-Saharan Africa population has no access to improved water.

Many institutions – from community groups to international organizations – have worked to bring sustainable clean water access to those without. The Kenya Water for Health Organization, more commonly known as KWAHO, was founded in 1975 with the backing of the United Nations Children's Fund after the Women's Conference in Mexico City. Since then it has worked to make safe water readily available to the communities of Kenya while also working on related issues such as public health and sanitation. They have taught many successful training and hygiene importance classes throughout their 30-year history (Womensaid International, 2005). The IRC International Water and Sanitation Centre serves to coordinate and train numerous local groups that work on low-cost water supply and sanitation systems in the developing world. The center has established a number of networks, and brings together about 28 local or national organizations that work on water and sanitation (IRC, 2005). The United Nations claims that the actions of its partner organizations and itself during the first decade of water (1981-1990) reduced those who lack access to safe water by 1 billion and sanitation to 770 million (IRC "World Water Day", 2005). In 2004, the United Nations also declared that 2005 - 2015 be the decade of "Water for Life" which calls upon the organization and its bodies to deliver a coordinated response on the issue of water access (UN 58/217, 2004).

Despite the success of such programs in the past and promises for future improvement, the basic health concerns remain large and seemingly insurmountable, as those without proper facilities still number in the billions. The reasons that these challenges still face the world are numerous and up for debate. Many critics charge the bureaucracies of international organizations or the national governments that receive funding for infrastructure projects with gross ineptitude or corruption. The United Nations found that their initial decade of water was not as successful as initially conceived due to miscalculations of population growth, funding limitations, and inadequate maintenance of facilities and personnel. Most importantly, however, they identified a consistent reliance upon a "business as usual approach" that drew on traditional resources and technologies and relied upon established but ineffective policies (WHO, UNICEF, 1992).

1.2 Point of Use Treatment

In the past, many projects have focused on the improvement or expansion upon improved water sources, such as installing more pumps or piping a source of water to a closer location. Providing safe water to increasingly remote and dispersed populations of countries without significant capital has become a very burdensome task for governments, corporations, and donors alike. Likewise, from a sustainability point of view, the likelihood of such utilities continuing to work without outside maintenance is small, and the health benefits to the community (specifically, the change to an individual's water quality) is questionable. While many urban residents do have access to piped water or water vendors, access is frequently intermittent and the quality of the water is questionable. In many ways, these projects aimed at improving a region's development have not significantly improved the quality of life for the communities, and thus cannot bolster the area's development (Mintz et al., 2001).

Clean water itself has little effect on the rates of some important water-related infections whose primary mode of transmission is through food, food ware, and direct or indirect personal contact with the water. It should be noted that the areas plagued with diarrheal disease epidemics are areas where clean water tends to be available. The important factors needed to overcome water-borne illnesses in impoverished areas are, in order of importance, improved sanitation, increased water supply, and improved hygiene (Clasen and Cairncross, 2004). Thus, in order to curb diseases such as these, the amount of available clean water must be expanded to accommodate not just drinking needs, but hygiene and washing needs as well.

In the stead of these old large-scale programs has come the initiative of performing water purification on the site of its consumption. These small-scale individual systems, commonly termed point-of-use or POU treatment systems, have a number of advantages for developing countries. By treating water in individual houses just prior to consumption, post-transport contamination is virtually eliminated. Additionally, the increased amount of clean water coming into the house increases the likelihood of the water being used for hygienic purposes, POU water treatment systems are therefore more effective in reducing disease rates overall. Childhood diarrhea rates drop by 44 percent among communities with in-house systems, as opposed to 6 percent for a clean public water source (Brown, 2004).

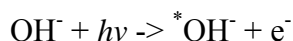
POU systems also bring along with them philosophical benefits that may help the cause of improving public health. The most distinct advantage of point-of-use treatment is the tendency of the systems to be low cost and self-sustaining. The capital required to purchase and maintain a household unit is more likely to be garnered than that needed for a large-scale treatment plant. POU technologies tailor themselves to each specific household's needs and capabilities, increasing the likelihood that the users will continue on with the technology after it is introduced. In addition, it ingrains the idea of clean water and hygiene being an individual's responsibility as opposed to it being a gift from others (typically, Americans and Europeans). The involvement of the population in the improvement of their health is almost guaranteed.

More and more, experts have called upon POU treatment to be given greater priority in international development campaigns (Mintz et al., 2001; Clasen and Cairncross, 2004).

1.3 Ultraviolet Irradiation as a Disinfection Method

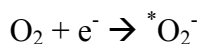
One of the more promising methods of water sterilization identified in the last few decades has been ultraviolet (UV) light disinfection. As the wavelength of light decreases, its potential to rupture molecular bonds increases, thus making it more ideal for disinfection. Electromagnetic wavelengths in the 100 – 400 nanometer spectrum are able to penetrate cellular walls and alter molecular compounds crucial to the cell's vital functions (Serway and Beichner, 2000).

In addition to a direct assault on microbes within the water, UV light is also known to create large concentrations of reactive oxygen species (ROS), which are short-lived compounds that are hazardous to living things. One of the most common reactions occurs with hydroxyl ions already present in the water to form hydroxyl radicals.



Hydroxyl radicals, though short-lived, are exceptionally reactive and will bond with or remove a naked hydrogen proton from almost any type of chemical. In the presence of organic material, they will frequently react with the fatty-acid chains of the membranes – cellular or other – of microorganisms. Done frequently enough and to the appropriate organelles, microbes will either be inactivated or die (Kimball, 2004).

Another common reaction involving ultraviolet irradiation is the creation of superoxide anions in oxygen rich water, which starts a sequence of reactions that aided by cellular enzymes that results in the further elimination of microbiota.



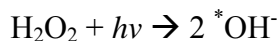
This reaction is catalyzed by ultraviolet radiation reacting with Advanced Glycosylation End products (AGEs) and will thus occur at a much faster rate in the presence of UV radiation.



The toxic superoxide anion can react in a similar way to the hydroxyl radical, or be adsorbed by the enzyme superoxide dismutase, endemic to most cellular pathways to spawn hydrogen peroxide and oxygen.



Finally, in the presence of ultraviolet radiation, hydrogen peroxide will decompose to two hydroxyl radicals, ultimately resulting in a greater concentration of bacterial inactivating chemicals.



These reactions will continue to spawn more free radicals or pass the unpaired electron on to another molecule until the radical molecule finds a free electron with which to bind, thus ending the cascade of reactions.

A high concentration of oxygen will not only facilitate the complex production of hydroxyl radicals, it will also abate the level of carbon dioxide. High concentrations of carbon dioxide will dramatically lower the pH (i.e. reduce the concentration of hydroxyl ions in the water), and thus hinder the production of hydroxyl radicals.

Temperature increases can also serve as a synergistic effect during solar irradiation. The energy carried by the light itself is in part transferred to the water molecules, thereby increasing the energy in the system and potentially raising it to a level intolerable for some forms of microorganisms.

The sun itself is a source of ultraviolet radiation, though one that first must pass through the Earth's own atmospheric layers. A majority of the wavelengths that exist outside the spectrum of visible light (400 nanometers to 700 nanometers) are either absorbed or scattered by particles surrounding the earth, as shown in Figures 1.1 and 1.2.

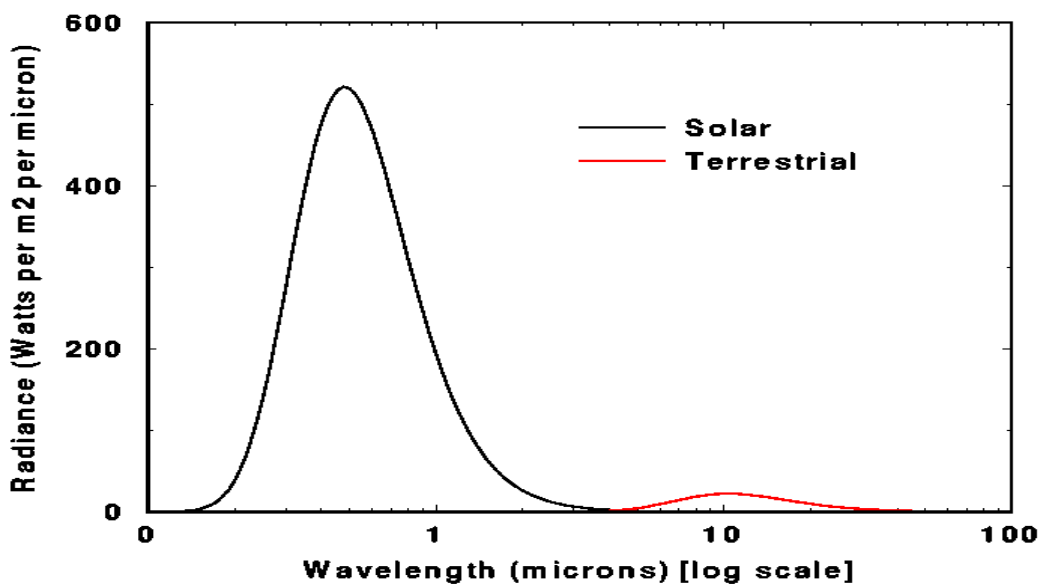


Figure 1.1: Solar and Terrestrial radiation spectra. (Grimes, 1999)

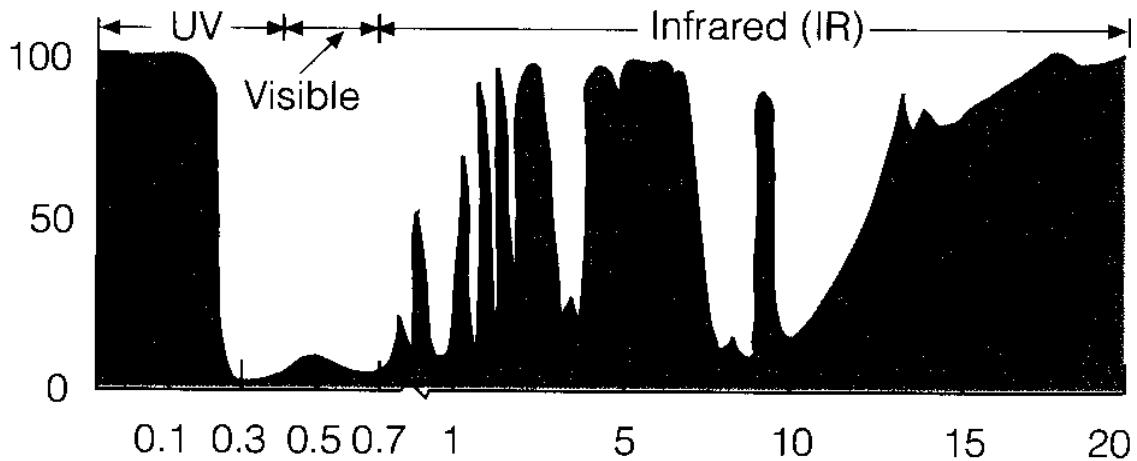


Figure 1.2: Radiation wavelength (in microns) plotted versus the percentage of radiation absorbed by the Earth's atmosphere. (Grimes, 1999)

The layer of ozone located approximately 20 kilometers above the surface of the Earth absorbs a majority of the ultraviolet radiation. The rest of the ultraviolet radiation – and including some small wavelengths of visible light (up to 500 nanometers) – is scattered by the lower atmosphere. It is this effect that is responsible for the sky appearing blue on a clear day (Grimes, 1999). While the intensity of the UV radiation is only a fraction of that of visible light and most of the wavelengths involved with solar disinfection (245 – 285 nanometers) get absorbed in the ozone layer, it is still a potent force that is capable of damaging biota (Sedway and Beichner, 2000).

Because of insufficient testing in the field for the elimination of viruses and its inability to provide residual disinfection for pipes, ultraviolet disinfection still remains an uncommon method for the treatment of drinking water in developed nations that could conceivably apply the technology (Veissman and Hammer, 2005). However, a number of underdeveloped countries have adopted the technology because the requisite materials (i.e. sunlight and a clear container) are easily available, and it has become quite popular among aid organizations.

As described below, solar disinfection of drinking water has provided mediocre to outstanding successes in various parts of the developing world. The most common application of this technology is found through the project SODIS, developed by a division of the Swiss Federal Institute for Environmental Science and Technology. The project encourages users to pour their contaminated water into clear polyethylene terephthalate (PET) plastic vessels with the volume of approximately 1 liter, shake the bottles vigorously to disperse the oxygen once the bottle is 2/3 full, and leave the bottles in direct sunlight for six hours or longer. In areas where sunlight is of consistently low intensity or on cloudy days, it is recommended to leave the bottles exposed for two days (EAWAG/SODIS, 1998).

While a successful process, the method does not allow consistent access to water throughout the day, and frequently becomes difficult to manage when more than a day's worth of residence time is necessary for adequate disinfection.

1.4 Intent of study

This study seeks to determine how continuous-flow solar disinfection systems can be an effective and feasible POU treatment option for developing countries, innovate on the current SODIS practices common to the developing world, and to begin to apply these new findings towards an optimal technology through field work in Nairobi, Kenya.

It is the belief of the author that a reluctance to innovate upon the original ideas and presumptions of the SODIS method – either by researchers or by local development groups – has potentially held back breakthroughs in a more successful solar water disinfection system. In relation to this study, **the hypothesis is that Spirasol, a continuous flow solar disinfection system designed by the author, is a low-cost and sustainable system that makes it a superior POU water purification technology to those systems presented in the past.**

The Spirasol project hopes to begin a movement away from the plastic bottles as the main conduit or vessel for solar disinfection and towards new innovative materials. Spirasol has the potential to become widely accepted for its aesthetic economic and technological value. As well, it has the potential to apply itself on larger scales if a building with a greater occupancy wishes to employ solar disinfection to treat their water.

This document briefly explains the history of solar disinfection as a practical tool for drinking water treatment in the developing world, and goes on to address the potential points of sterilization rate optimization for solar disinfection systems that remain to be addressed by researchers. Following that section are the studies and records pertaining to the author's work with the Spirasol project and other related solar disinfection systems during the authors' visits to Kenya and further experiments performed by the author at the Massachusetts Institute of Technology. Included after a discussion of the studies' findings are some recommendations for further studies and investigations on continuous flow solar disinfection systems and solar disinfection in general.

II. PREVIOUS STUDIES ON SOLAR DISINFECTION, THE METHODS EMPLOYED, AND ITS APPLICATIONS

II. PREVIOUS STUDIES ON SOLAR DISINFECTION, THE METHODS EMPLOYED, AND ITS APPLICATIONS

2.1 The Beginnings of Solar Disinfection

2.1.1 Acra's Inception of modern day Solar Disinfection

The practice of using the sun to sterilize media actually has its roots in early Indian civilization, when utensils and plates would be washed and placed in the sun in order to dry as well as clean the ware (Acra et al., 1984). Thanks to a growing interest in the problem of clean water scarcity and applicable solutions for impoverished areas, the technique has been given new life in recent decades.

The team led by Professor Aftim Acra at the American University of Beirut, Lebanon is credited for pioneering modern day research into the field of water disinfection through solar radiation. At the time, Acra was Chairman of the Department of Environmental Health of the university and was focusing specifically on water disinfection while considering the environmental and capital limitations of impoverished areas. The disadvantages and costs of traditional sterilization methods (such as boiling and introduction of chemical tablets) led the team to search for a more effective, affordable, and advantageous method of sterilizing water. Through a detailed understanding of the needs and available resources of impoverished areas, the team laid the groundwork for the solar treatment systems now in use today (Acra et al. 1984).

Acra's team carried out studies on the feasibility of solar disinfection on small quantities of water starting in June of 1979 and continued the studies for over two years. The study team took water of a uniform microbial contamination and placed it in transparent to semi-transparent containers such as plastic and glass with volumes ranging from one to three liters. The shape, thickness, and constituency of these containers were a controlled variable examined by the team. The team then exposed the containers to direct sunlight. The duration of contact with sunlight varied from 15 minutes to a few hours. Some control experiments were performed in the dark and others in standard lighting conditions.

The results of the studies consistently proved that "water from fecal sources" was susceptible to destruction via prolonged exposure to sunlight. For blue glass jugs, it took an average of 95 minutes to eliminate 99.9 percent of total coliform bacteria, and 300 minutes (5 hours) to eliminate 99.9 percent of all species of bacteria.

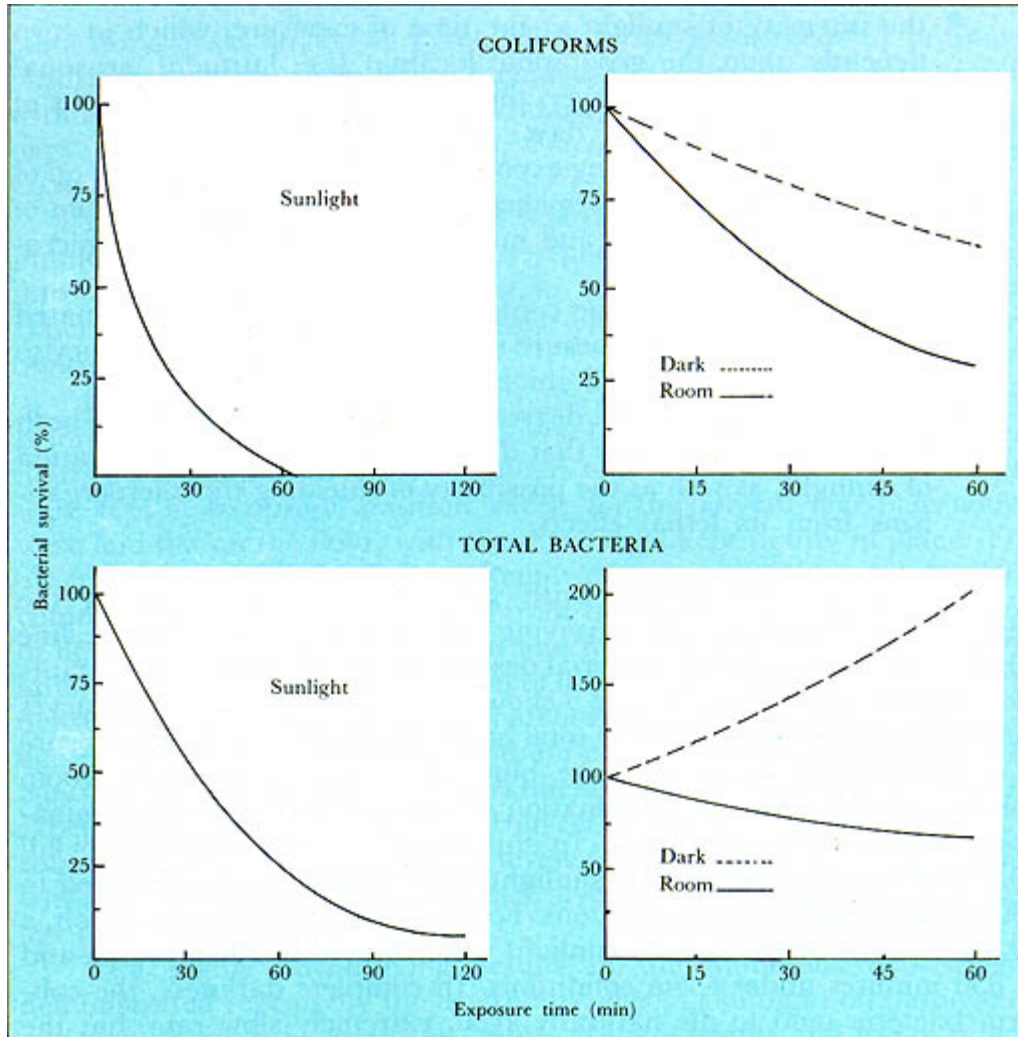


Figure 2.1: Germicidal effect of solar radiation on bacteria contaminating water held in blue glass containers. Identical samples of water kept in the dark and in a room served as controls for comparison. (Acra et al., 1984)

Acra et al. also determined some key factors in the effectiveness of the process of solar disinfection:

1. Container characteristics and quality, which included shape, color, thickness, and transparency to light. The study found that inappropriate bottles could vary the time for effective elimination of total coliform bacteria drastically, going as high as 1050 minutes (17.5 hours) for dark brown bottles. During the study, the team compared the effectiveness of each experiment by measuring the spectrum of light transmitted by each experiment's medium. From this data, the team constructed an "action spectrum" depicting which wavelengths of light were most effective in destroying microorganisms. It was found that wavelengths in the ultraviolet and near-ultraviolet band (400 nm and below) were the most effective. Considering how little UV light reaches the earth's surface because of atmospheric absorption and scattering (Serway and Beichner, 2000), it was concluded that

it was the UV-A band of light (between 290 nm and 400nm) was the most responsible for disinfection of the water.

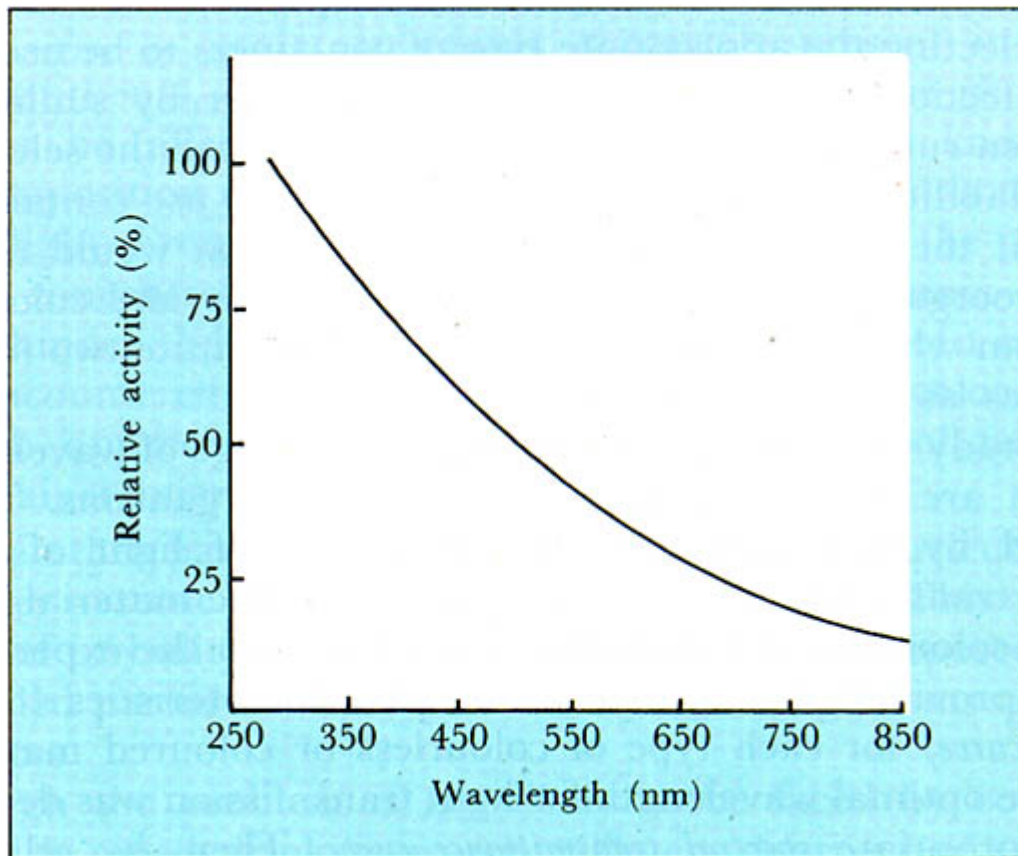


Figure 2.2: Action spectrum showing the relative germicidal effect of solar radiation on coliform bacteria as a function of wavelength (Acra et al., 1984).

2. Intensity of the sunlight. This parameter will depend upon latitude, cloud cover and atmospheric conditions, season, and time of day. The team concluded that purification would be best served by placing the bottles out early in the morning and retrieving them late in the afternoon so the water is exposed during peak hours of solar intensity. However, it was recognized that variations in intensity could drastically alter results.

3. The types of microorganisms present. For example, a pure culture of the common bacterium *E. coli* was completely eliminated in 75 minutes, while a pure culture of *P. aeruginosa* took only 15 minutes. Studies on mold and yeast cultures found that such organisms took longer to eliminate – usually on the scale of a few hours. *Penicillium* required six to eight hours for complete disinfection. Based on previous studies on UV irradiation, the team hypothesized that viruses too could be reduced in concentration given longer periods of exposure to sunlight. The team estimated that amoebic cysts would likely be killed through heat pasteurization rather than through solar irradiation, expecting the temperature inside the bottles in warmer climates would reach 50 °C. Further research would counter this last hypothesis.

4. Turbidity of the water. The team noticed that turbid waters would inhibit deep penetration of solar radiation and allow microorganisms to cling to particulate matter and potentially evade irradiation.

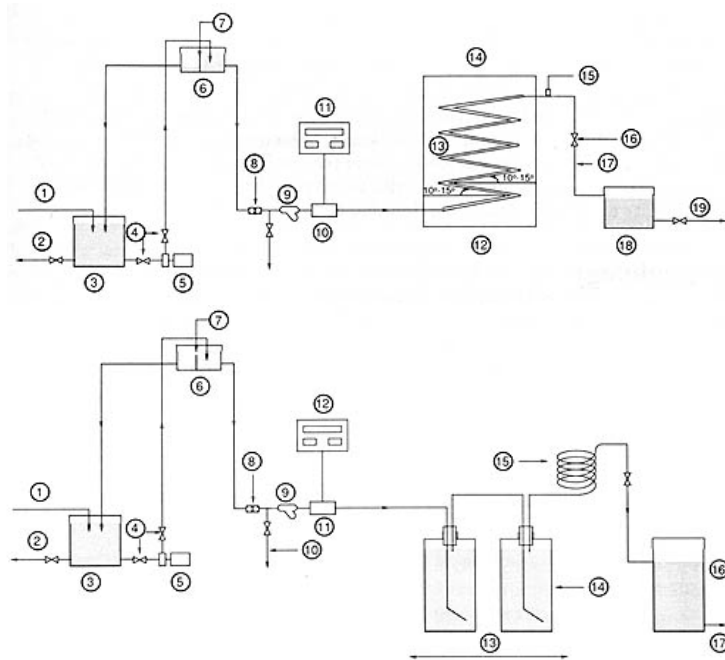
2.1.2 Continuous Disinfection System Research

In 1986, another team led by Acra conducted studies on the possibility of applying the same fundamental principles to a continuous flow system (Acra et al. 1990). The team created a uniform flow system in which solar UV-A intensity is uniform in all areas and presumed that inactivation would roughly comply with first-order kinetics.

$$N/N_0 = e^{-KIT} \quad (1)$$

where N is the bacterial density (in colony forming units per milliliter) at a given time, N_0 is the initial density, K is the inactivation rate constant to be resolved through the experiments, I is the intensity of the solar UV-A radiation (in microwatts per square centimeter), and t is the time of exposure (in minutes).

Two solar reactor systems were constructed, with the “type II” system attempting to maximize the number of transparent components utilized while type I relied primarily on one borosilicate glass tube located in the solar reactor (Figure 2.3a and 2.3b). Each facility had an “A” and “B” form, where dimensions and capacities were altered for comparison purposes. Type I used a serpentine Pyrex glass helical tube as its sterilization media, where type II applied Pyrex glass containers linked to the same type of helical tube. These curved figures were intended to minimize the formation of air gaps that would inhibit flow.



Figures 2.3a and 2.3b: Type I and II schematics of the solar reactor system. (Acra et al., 1990)

Prior to experimental testing, the 150-liter batch in the main storage container would be infected with 0.2-0.7% settled sewage from the university's main city sewer line to create a realistic concentration range of 50 to 5000 cells per milliliter. In some experimental runs, a pure culture of *E. coli* was used as a substitute for sewage. Studies were performed on bacteria that would indicate the presence of fecal contamination (*Streptococcus faecalis*, total coliforms, and *E. coli*) because of the high resistance these bacteria showed in previous tests. Certain tests considered water temperature, UV-A intensity, and flow rate as the independent variables to measure the dependant variable of bacterial density after treatment. The K values derived from equation 1 for the type IA and IB reactors were -2.5 to -3.2 m²/W-h. These exponential curves were fit with the data to examine how statistically significant the results were. The "P-value" – also called the "observed significance level" which indicates the probability that a data point would be off the curve fit – was less than 0.001. Typically, P-values below 0.05 are considered statistically significant (Devore, 2000), which indicates that Acra's results are very statistically significant and very likely to be an accurate representation of the disinfection rate. The team concluded that the performance of these two systems were "satisfactory" for the situation.

A constant head with low to moderate pressure was deemed necessary to create a system residence time sufficient for decontamination. The team mentioned that an increased water temperature would reduce the solubility of oxygen and thus force the gas to bubble out, and speculated that this had a detrimental effect on the experiments. Trial experiments also showed that high-density bacterial populations showed much less sensitivity to solar radiation than low to moderate density populations. As a result, the team discontinued studies above 10⁸ cells/mL. The team expected phytoplankton to grow on the sides of holding tanks and to ultimately reduce the solar penetration, yet there was no evidence of any such colonies forming. The team hypothesized that the lack of oxygen in the system created an unsuitable environment for phytoplankton growth.

2.2 The Idea Takes Root

2.2.1 Wegelin inspects the variables of Solar Disinfection

Building on the initial success of Acra's team, a team from the Swiss Federal Institute for Environmental Science and Technology (EAWAG) sought to better quantify the limitations of solar disinfection (Wegelin et al., 1994). Specifically, they sought to confirm the wavelengths responsible for microbial inactivation, the dose of solar radiation required for inactivation, the influence of temperature of the system's efficacy, the effect of organic matter on the process, and the effect of the photosensitizer methylene blue. Laboratory tests took place on a number of bacteria and viruses. Bacterial concentrations were analyzed through a membrane filtration process, while virus concentrations were analyzed through the rate of infection upon *E. coli* cells.

Results showed that UV-A and violet light (< 450 nanometers in wavelength) worked in tandem to destroy *E. coli*, whereas only UV-A affected *Streptococcus faecalis*. There was no change in *E. coli* inactivation rates between 20 °C and 40 °C, but rates began to rise above 50 °C. Species in the *Enterococcus* genus were only susceptible to

temperatures above 55 °C. While these temperatures were much higher than expected, they nonetheless proved that there is a strong synergistic effect between pasteurization and irradiation. The study found that low turbidities scarcely reduce the efficiency of solar radiation, though high turbidities can severely hinder it. The team concluded that turbidities below 25 NTU would have no problem undergoing solar disinfection. Finally a fluence of 555 W h/m² was deemed the minimum requisite for effective disinfection. The team equated this to about five hours of midday mid-latitude summer sunshine, which soon became a well known minimum for solar disinfection treatment projects.

2.2.2 Foundation of SODIS

Based on the impressive conclusions of their previous study, EAWAG's Department of Water and Sanitation in Developing Countries (SANDEC) went on to serve as a disseminator of the technology of Solar Disinfection, which was soon truncated to "SODIS." The program, now run by Martin Wegelin, continues to carry out further research.

Many experiments are performed outside the direct guidance of the program itself, though SODIS serves to catalog and disseminate the results of these experiments and create new benchmarks for the practice of Solar Disinfection if information warrants such action. SODIS has brought more researchers from other organizations under their umbrella as time has progressed, including Professor Robert H. Reed of Northumbria University.

2.3 MIT Nepal Project and Beyond

Starting in 1999, graduate students from the Civil and Environmental Engineering department have conducted research pertaining to water purification and sanitation solutions to developing countries under the auspices of Professor Donald Harleman and lecturer Susan Murcott. The project allows the students to test potential solutions in the countries themselves and work with partners integral in disseminating the solutions. In the past, teams have focused on the countries of Nepal, Haiti, Brazil, and Nicaragua. Research tends to factor in not only the scientific merit of the results, but the social, economic, and political feasibility of the solutions' integration into the society. Several of these thesis projects have focused either in part or completely upon various aspects of SODIS.

2.3.1 Amer Khayyat on Point of Use Solutions

Amer Khayyat was the first MIT student to examine the technique of solar disinfection in his Master of Engineering research (Khayyat, 2000). The study broadly focused on in-house disinfection techniques, examining chlorine disinfection, ultraviolet disinfection, and solar disinfection. Khayyat tested the three techniques and their viability in Katmandu Valley from mid to late January of 2000. He used three indicator organisms for microbial testing: total coliform, *E. Coli*, and H₂S producing bacteria. The HACH presence/absence test with MUG reagent was used for the two former and the HACH most probable number test was used for the latter. SODIS tests used locally available PET plastic and glass containers (varied for experimental purposes) which were thoroughly cleaned and dried before they were filled with raw tap water.

Unfortunately, logistical constraints did not allow for a sizable number of field tests to warrant any general conclusions. However, Khayyat found that the water temperatures inside the bottles never exceeded 28 °C, even among the bottles painted half-black, and thus no pasteurization effects boosted the rates of disinfection. Khayyat noted these results did conflict with earlier studies in a nearby region. In addition, the solar intensity did not always remain above 500 W/m² during the test period of 11 a.m. to 3 p.m, the intended period of maximum disinfection. Khayyat recommended that the disinfection period should be extended to two days instead of one for this environmental setting during the winter season.

In discussions with locals, Khayyat discovered that the process of placing household wares in the sun for cleansing purposes has been part of Nepalese tradition for centuries, thus increasing the likelihood of accepting SODIS practices as an updated tradition. In his preliminary surveys, he found that a majority of people greeted the general methodology with great enthusiasm.

2.3.2 Peter Oates on SODIS Feasibility in Haiti

In January of 2001, Master of Engineering student Peter Oates worked in Haiti specifically examining the feasibility of SODIS for that country (Oates 2001). Prior to travel, Oates developed a Fourier series to simulate the diurnal cycle of sunlight based on data obtained from NASA Langley Atmospheric Sciences Data Center, which provided ten-year averages, minima, and maxima for the total solar energy received on a 1°x1° plot of the world. This computer simulation was used to estimate the average intensity for the five peak hours of the day. Comparing the model to measured intensities from the data center, there was a 99% correlation between the two. This model was also used in Megan Smith's work in Nepal (see below).

Oates' microbial studies in Haiti focused on total coliform, *E. coli*, and H₂S producing bacteria. Standard SODIS procedure of filling the bottles 2/3 full, shaking, completely filling the bottles, then placing them on a dark surface was followed. HACH's Presence/Absence Broth test and the PathoScreen H₂S test were used to determine the concentrations of the indicator microbes. The study confirmed that under a variety of conditions, a residence time of two days was sufficient for total elimination of all three types of microorganisms. The more tropical climate of Haiti also was much more favorable to the one-day results as well; with only an unusually heavy storm system passing through on January 15 resulting in effective removal in an average of one in two tests. Oates advised that in order to maintain 100% efficiency and "the simplistic beauty of the technology," Haitians apply a two-day exposure period to the bottles regardless of that period's sunlight intensity. He concluded that the results as well as the characteristics of the Haitian environment (long periods of sunshine and a generally warm climate) showed that SODIS would be an effective solution.

2.3.3 Megan Smith on SODIS

Master of Engineering student Megan Smith continued research on point of use water treatment systems in her trip to Lumbini, Nepal in January of 2001 (Smith 2001). SODIS was one of two technologies being researched during her trip. Smith gathered

NASA data over ten years in duration to discern the insolation rates ($\text{W}/\text{m}^2/\text{day}$) in Nepal. Data confirmed that the winter months of December and January had the lowest average insolation rates of the year, expected not only because of the Earth's seasonal rotation but also because of the heavy cloud cover of the monsoon season. Her own measurements of the average insolation during those months found that the five-hour peak was only $170 \text{ W}/\text{m}^2$, far below the threshold level of $500 \text{ W}/\text{m}^2$. These results led her to conclude that SODIS would be "ineffective" for all but the warmest months of the year, and further echoed the concerns of Khayyat's study.

However, according to data collected by Smith's colleague Cathy Pham in Kathmandu in June and July of 2000 – the peak of the monsoon season for that region – there was still the presence of indicator bacteria after day-long attempts at solar disinfection. Pham's results demonstrated an almost certain infeasibility of SODIS systems with a residence time of only one day for the region. Through testing of both total coliform and H_2S producing bacteria, both students found that a residence time of two days was sufficient for near 100% removal of both respective classes of microorganisms. The results were cause for some concern as Smith found 92% removal after one day and Pham found only 54% removal after one day, when one might expect Pham to have found a faster rate of disinfection given the season.

Smith also conducted informal surveys among villagers to test their reaction to the system. Locals associated the terms "simple," "easy," and "inexpensive" with the technique. Villagers also found discomfort with the idea that the bottles were dirty since they were previously used and sometimes associated it with "stale water." Smith was the first to recognize and publish the idea that the SODIS technique was insufficient for treating a large enough volume of water to treat a family in the conditions inherent to Nepal, which would spur the work of Deborah Flores-Cervantes (see below).

2.3.4 Deborah Xanat Flores-Cervantes' SC-SODIS Revolution

After extensive research on previous SODIS projects, Masters of Engineering student Deborah Xanat Flores-Cervantes concluded that traditional use of small plastic bottles was insufficient to supply enough drinking and hygienic water to a large family (Flores-Cervantes, 2003). Cervantes decided to continue the research into continuous systems started by Acra (1990) and Wegelin (1994). Flores-Cervantes proposed a system she described as "Semi-Continuous SODIS (SC-SODIS)" which places multiple sets of PET bottles cut and glued back-to-back and then placed in parallel. The system would be connected to a source of microbially contaminated water and fed through the system at a slow enough rate that each parcel of water would obtain the equivalent of $500 \text{ W}/\text{m}^2$ for five hours. The user would need to turn the taps on in the beginning of the day and off at nightfall. Flores-Cervantes also chose to consider the social and economic feasibility of the system as well, and whether such a system could be replicated, maintained, and easy enough to use. The final cost of the system in Nepal was estimated to be approximately US \$0.50.

The study examined H_2S -producing bacteria using a presence/absence test and *E. coli* and total coliform using the membrane filtration technique. The flow rate was used as the independent variable. The studies found that flow rates as high as $100 \text{ mL}/\text{hr}$ were effective at eliminating *E. coli*, with rates between 100 and $175 \text{ mL}/\text{hr}$ being completely to

partially effective. Higher flow rates showed even less efficacy. Flow rates of 100 mL/hr or less were equivalent to placing the water in a batch system for ten days or more. The results were garnered among varying atmospheric conditions, allowing for a safe conclusion that the system would fare as well in almost all weather conditions. The studies showed that the system created an environment in which the microbial markers notably decreased in concentration and most particles settled out thanks to the long residence times.

Flores-Cervantes also found that an equivalent daily threshold of 2500 W/m² was infrequently reached over the period of one day in January for southern Nepal, but always reached in a span of two days. During initial examinations, Flores noticed that air bubbles tended to develop at the top of each bottle, which may potentially add oxygen to the incoming water or scatter the incoming sunlight. The air bubble is evidence of the fact that the water is losing some of its oxygen as it traverses the system. Overall, Flores-Cervantes concluded that the prototype system was effective at microbial inactivation, simple, and accessible to the communities it seeks to serve.

2.4 Characteristics of Disinfection Vessels

Conceivably, all that is requisite for an effective solar disinfection system is a closed vessel that does not fully block ultraviolet radiation. There are, however, a number of relevant vessel characteristics to be considered when choosing an appropriate container. Some examples are listed below:

- Retention of water and barrier to outside moisture
- Ultraviolet/Light transmission
- Oxygen transmission
- Heat transmission
- Strength
- Scratch and damage resistance
- Health risks from additive leaching
- Local availability
- Cost

There are still other variable characteristics that might be considered given the aspects of a certain solar disinfection project, such as flexibility, shape or form, and weight.

The bottle of choice for SODIS projects has been Polyethylene Terephthalate (PET), commonly designated as PETE #1 for recycling purposes. PET was chosen because of its overall efficacy in reducing microbial concentrations in previous tests and the perceived “availability” of the PET plastic bottle. SANDEC has also recommended glass bottles and PET bags were effective in reducing the concentration of microbes in the water, but have stressed that the disadvantages of low durability make a PET bottle a much more preferable choice (EAWAG/SODIS, 1998).

It should be noted that PET was not chosen for SODIS projects as the result of an exhaustive test of plastics, but rather a conclusion reached because of its availability and performance compared to tinted bottles, bags, and various glasses (Acra et al., 1984). After

his preliminary study, Acra performed further research using pyrex glass (Acra et al., 1990).

2.4.1 UV Light Transmittance

Solar disinfection studies have largely focused on the intensity of ultraviolet light that reaches the contaminated water. The first studies to vary containers loosely equated a container's UV transmission to efficiency of removal (Acra et al., 1984). In comparison with tinted bottles, plastic bags, and glassware, PET bottles were found to be the most efficient at reducing the concentrations of microbes in water, and – given that exposure to ultraviolet light was the only controlled variable in the experiment – had presumably transmitted the most ultraviolet light amongst the containers examined.

However, no studies that directly analyze the transmittance of the numerous types of plastics and other transparent media were found during the course of this study. In addition, Acra performed subsequent solar disinfection experiments regarding solar disinfection not with plastic, but with pyrex glass (Acra et al., 1990), implying that he was not adamant that PET plastic was the ideal material to use for solar disinfection.

PET loses its transmittance over time as exposure to the UV light breaks down the components of the plastic. A SODIS study in Thailand showed that a bottle used for six months loses 40% of its transmittance capacity between 300 and 400 nanometers (EAWAG/SODIS, 1998). The study also noted changes in the appearance of the bottles after six months of use in SODIS projects.

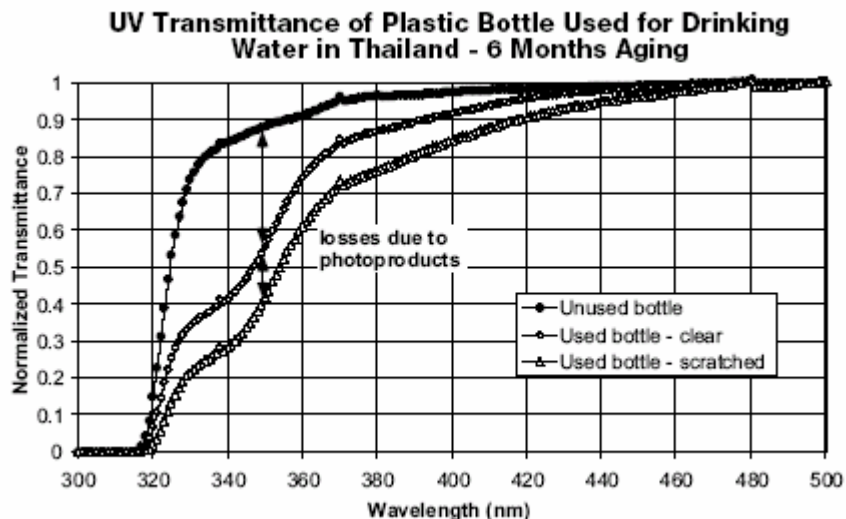


Figure 2.4: The loss of transmittance in a PET Bottle used for SODIS in Thailand. In the spectra relevant to solar disinfection, losses sometimes climbed to over 40 percent. (EAWAG/SODIS, 1998)

All plastics undergo a similar sort of degradation as the long polymer chains are broken apart by wear and strain. PVC, for example, undergoes “zip hydrochlorination” as its carbon chain backbone breaks apart which tends to result in discoloration (SpecialChem, 2005).

2.4.2 Health Effects through Leaching

One of the concerns for aging materials would be the leaching of plastic additives as the result of prolonged degradation. SODIS cites the frequent use of additives as a major reason for avoiding the use of PVC for SODIS systems (EAWAG/SODIS, 1997). There has been much debate over whether polycarbonate (not PET) plastics leach components such as bisphenol-A, an endocrine disrupting chemical into the fluid contained under certain circumstances (Biles, 1997; Consumer Products, 1999). While many have drawn the studies into question, polyethylene plastics (PET, HDPE, LDPE) have been regarded as much less of a long-term health risk than other plastics. EAWAG studies showed through mass spectrometry that the bottle interiors are not greatly altered by UV radiation, only the bottle exteriors as shown in Figure 2.5. For this reason, oxidized byproducts would not be a leaching concern (SODIS, 1998). A recent EAWAG test regarding degradation of PET byproducts such as di(2-ethylhexyl)adipate (DEHA) and di(2-ethylhexyl)phthalate (DEHP) were found to be in such small quantities that leaching was concluded to be of miniscule concern for SODIS projects (EMPA, 2003).

2.4.3 Thermal Resistance

The Achilles heel of PET would be its relatively low heat of deformation, at approximately 65 °C (SODIS, 1997). This prohibits a SODIS system that incorporates PET bottles from having a significant synergistic pasteurization effect. Along the spectrum of microorganisms, most organisms require heat pasteurization above 50 °C (Wegelin et al., 1994). The studies cited have found that the temperatures have not often reached a temperature near this threshold (Khayyat, 2000; Oates, 2001). However, thermoresistance studies have mostly focused on shorter time periods to pasteurize waters, whereas SODIS systems would look for time periods of three to five hours, corresponding to the peak hours of sunlight received. Thermoresistance studies on long term exposures to temperatures slightly above those of incubation may be warranted to fully understand how the temperature of the water affects the SODIS environment.

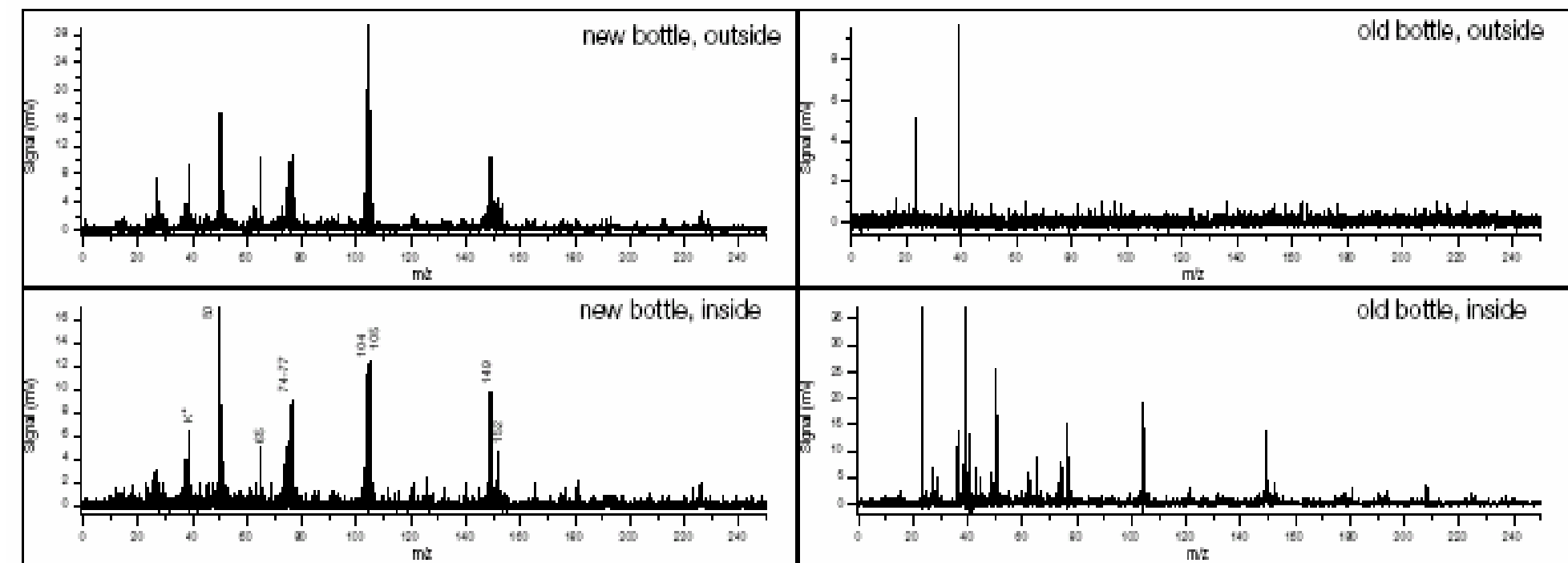


Figure 2.5: Mass Spectrometer analysis of the interior and exterior of a new PET bottle (left) and a PET bottle used for SODIS (right). While the exterior of the older bottle has significantly changed, the interior remains mostly the same.

Table 2.1: Time and temperatures required for the inactivation of certain microbial pathogens. (Wegelin et al., 1994; EAWAG/SODIS, 2004)

Thermoresistance of microorganisms			
<i>Microorganism</i>	<i>Time and Temperature for 100% destruction</i>		
	1 Min	6 Min	60 Min
Enteroviruses	-	-	62°C
Rotaviruses	63°C for 30 Min		
Faecal coliforms (E.coli)	80°C	-	-
Salmonellae	-	62°C	58°C
Shigella	-	61°C	54°C
Vibrio Cholerae	-	-	45°C
Entamoeba, Histolytica cysts	57°C	54°C	50°C
Giardia cysts	57°C	54°C	50°C
Hookworm eggs and larvae	-	62°C	51°C
Ascaris eggs	68°C	62°C	57°C
Schistosomas eggs	60°C	55°C	50°C
Taenia eggs	65°C	57°C	51°C

2.4.4 Best Choice of Plastic

Overall, PET and PVC appear to have the best combination of characteristics to serve in a SODIS system, as summarized in Table 2.2 (SKS, 2004). However, experiments run with plastics other than PET have not been found, and most preliminary projects tend to refer to plastic bottles not by the type, but simply as “plastic” (Khayyat, 2000). The best way to determine which plastics are most suitable for work in SODIS projects is through field studies and direct experimentation.

Table 2.2: Summary of the qualities of plastics that may be of import to solar disinfection. While PET was originally chosen for its availability, it generally has the highest overall ranking among the 6 types of recyclable plastics (SKS Bottle, 2004).

Plastic	Clarity	Moisture Barrier	Heat Barrier	Oxygen Barrier	Stiffness
PET (1)	Clear	B	D+	B	B+
HDPE	Hazy	B	B	D	C
PVC (3)	Clear	C	C	B	B+
LDPE	Hazy	A-	C	D	F
PP (5)	Semi	A-	B	D	B+
PS (6)	Clear	C	C	F	B+
Other	Vary	Vary	Vary	Vary	Vary

2.5 The Discovery of Oxygen's Role

While the general idea of SODIS took off, some studies questioned the successes of solar water disinfection. Some studies had found that fecal bacteria concentrations did not reduce significantly after prolonged exposure to sunlight (Miller, 1988). Studies such as these prompted researchers, largely led by Reed and described as "SOLAIR", to question whether there was some other factor that had resulted in the sterilization levels seen in earlier studies.

Reed, with a deep background in aquatic chemistry, questioned whether oxygen was this missing critical component seen in high sterilization results seen in the past (Reed 1997). Previous papers found that oxygen concentrations may have a role in the inactivation of UV-irradiated *E. coli* (Webb and Brown, 1979) and gamma-irradiated *Salmonella typhimurium* (Kim and Thayer, 1966). For Reed's study, centrifuged cell cultures of *E. coli* and *Ent. faecalis* were placed inside sterile 2-liter bottles of PET plastic and filled to the brim with deionized, distilled water to give a cell count of approximately 10^6 cfu/ml. Water samples were saturated with oxygen, prepared under anaerobic conditions, or were given an intermediate oxygen level by mixing the aerobic and anaerobic waters. The filled bottles were then placed either in a dark room or on the rooftop of Reed's laboratory free from shadow. Samples were then taken by syringes every 30 minutes.

Reed found that the fully aerobic and sunlit samples experienced log 6 removal for both species of microbes in less than 150 minutes (2.5 hours). The anaerobic samples, however, only experienced a removal of about log 1 over the same time period. The samples kept in darkness experienced little to no reductions over the three-hour time period.

Reed noted that the decrease in concentration of cfu/mL closely followed first-order decay models in the log-linear plots in all of the tests. Based on these results, he constructed a chart for decay constant k and its dependency upon the oxygen concentration of the water.

More broadly and more importantly, the test indicated that dissolved oxygen and its synergistic effects with solar irradiation are essential for rapid inactivation of *E. coli* and *Ent. faecalis* - two of the most common representatives for fecal contamination. From this, it is likely that many other bacteria to be found in areas of fecal contaminated water will be susceptible to the combined effects of oxygen-rich water and intense sunlight.

One of the variables left unexamined during Reed's experiment was temperature. Thus the potential for heat pasteurization to have had a key synergistic impact with sunlight and oxygen was a possibility.

After this information was disseminated, SODIS posted the results from the paper and began to advise users to fill the bottle half-full and shake vigorously before filling the bottle to the top in order to maximize oxygenation (SODIS, 1997; Reed, 1997). This process was coined as "photo-oxidative disinfection" in the paper. This concept was integrated into the teaching portion of the website, which describes the steps requisite for disinfecting a low turbidity sample of water.

SOLAIR study with opaque plastic

From Reed's studies and introduction of SOLAIR, Meyer and Reed sought to test the efficacy of the system for a rural South African village (Meyer and Reed, 2001). However, the vessels used for the experiments were white/opaque 25-liter jerry can frequently used by local villagers. All experimental vessels were filled with 20 liters of contaminated well water and then shaken every hour to ensure appropriate mixing. Control A was deoxygenated through nitrogen bubbling but placed in direct sunlight, while Control B was kept indoors away from the sun while its oxygen level was not reduced. The variable experiment was given full sunlight and retained its oxygen.

The average intensity of the sunlight over the 8-hour period of observation was around $43.1 \text{ W/m}^2/\text{h}$ measured by a quantum photo/radiometer. Even in the opaque container, fecal coliforms experienced log 3.2 removal within four hours and the total coliforms experienced log 3.5 removal in six hours in the container receiving both sunlight and oxygen. The controls in both instances reduced the fecal and total coliform levels only by about a factor of 10.

The team tested to see if the intensity of the UV-A radiation decreased as they passed through the opaque containers (Meyer, 2005). Using the same probe that determined the solar intensity, the team measured the differences between the intensity in daylight and the center of the container. Depending upon the thickness, the diameter, and the depth of the containers, UV-A intensity reductions decreased in the range of 5 percent to 35 percent.

The white/opaque plastic likely kept the temperature within the jerry cans low. Despite midday temperatures reaching around 34°C , the interior bottle temperatures in all experiments did not rise above 18°C (Meyer and Reed, 2001). As a result, the experiment also demonstrated that the combination of oxygen and UV-radiation were effective in eliminating bacteria without the aid of synergistic effects from heat pasteurization.

III. DESIGN CONSIDERATIONS

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3.1 Difficulties in Designing SC-SODIS

During preliminary concept and design phases of the study, the SC-SODIS system was considered as a template for design. Innovations were expected to take place on top of Flores-Cervantes' basic design of plastic bottles connected with PVC pipe. The SC-SODIS system was constructed during the concept phase in order to examine ways in which it could be improved.

Almost immediately, it was recognized that that the SC-SODIS system was a significant amount of effort and far more costly to create in the United States than originally considered by Flores-Cervantes. The requisite flow valves alone cost much more than the cost of \$1.00 estimated by Flores-Cervantes in her program. In addition, the requisite pipe connections, while approximately \$0.50 per piece, begin to add up when one is required for each bottle. But the most expensive concern comes with constructing the bottle-to-pipe connections. As PET bottle mouths are created to attach to threaded hose diameters and not pipe diameters, standard PVC pipes cannot fit over the bottle tops. Even when the bottle threads are whittled down, the seal created is not watertight even with liberal application of adhesives. One could consider other alternatives for the bottle-to-pipe connections, such as thinner pipes and lashings with watertight materials, but none of the lashing modifications tried during experimentation created a sufficiently watertight seal (though some did perform better than whittling the threads of bottle tops). The only tolerable solution found during design was to purchase 3/4" hose-to-pipe adapters, which are seldom found in plastic. The zinc adapters used for the experiments cost over \$3.00 each. The cost of all these pieces for SC-SODIS made the total price approximately \$50.

What also must be considered are the labor and parts difficulties that may arise. Hose-to-pipe adapter fittings are rather rare, even in the United States. Five generic hardware stores in the Boston area did not have the appropriate adapters. The adapters were purchased from a Home Depot superstore in Reston, Virginia. It is considerably unlikely that these pieces will be found in a local hardware store in a developing country. Indeed, the addition of every new part required for the construction of a SODIS system hinders the chances for replication on the site where the SODIS program is to be undertaken. Lastly, the proper assembly of the SC-SODIS system takes considerable effort and care. Any number of incorrect measurements when cutting the PVC pipes or bottles is possible, and just one could effectively force the designer to undo hours of work.

After the trials during the design phase, the goal of minimizing parts and labor for a continuous flow SODIS system was added to the project. With this goal in mind, the idea for Spirasol, a semi-continuous flow disinfection system with few parts and easy setup, was devised.

3.2 Design Guidelines for Spirasol



Figure 3.1: Constructed prototype of the Spirasol system. A) Three-quarter-inch faucet; B) Three-quarter-inch inner-diameter PVC tube; C) Three-quarter-inch PVC ball valve.

3.2.1 Construction

The ultimate purpose of the Spirasol system is to utilize an entirely UV-transmissive conduit whose flow valve ensures a long enough residence time. The simplest way to create this was to use a clear plastic tube coiled into a spiral with a flow valve at the end of the tube (Figure 3.1). The following guidelines were set as design experimentation continued.

Given that PVC is the most common type of flexible plastic tubing available, the diameters of PVC tubing available to consumers vary much more than any other type of plastic. The choice of diameter is largely related to the size of the outlet that will connect the raw water to the tube. Standard three-quarter-inch faucets were used throughout the experimentation and design phases, thus making the choice of a three-quarter-inch inner-diameter PVC tube an easy one.

Other considerations would be the “depth” of the water created by the tube and the tube thickness. The tube’s water depth would not be of significant concern if the diameter were below 10 centimeters, so most diameters selected for a single-family house would not be cause for concern. The smaller diameter does highlight one of the benefits of the tube: less reduction of UV radiation. Waters clear enough for the SODIS process, even tap water, rapidly scatters UV-light upon contact (EAWAG/SODIS, 1998). The efficacy of the process is usually suspect after 10 centimeters, the approximate diameter of a 2-liter soda

bottle. Figure 3.2 demonstrates how quickly the UV radiation intensity can diminish in water. Because this reduction occurs in depths of only centimeters, it is a sound idea to minimize the water depth if at all possible. In tubes under two inches in diameter, the loss of UV intensity would be minimized.

Industry standards for flexible PVC tube seem to dictate that the thickness of the tube wall increases with the tube. For three-quarter-inch inner-diameter tube, the wall thickness was one-quarter inch. To minimize thickness, one would need to select the smallest tube inner diameter available, but this would detract from the amount of water being treated and drastically increase the cost. There is the potential for the one-quarter-inch of PVC to block much more UV-light than the thinner PET plastic bottles that tend to measure less

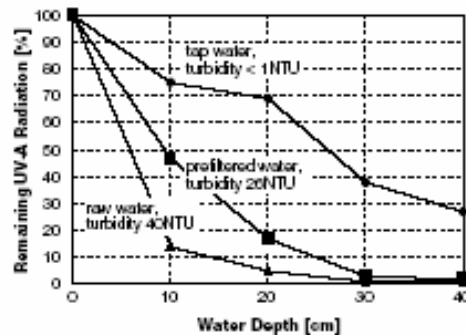


Figure 3.2: Dissipation of UV light in waters of various turbidity (EAWAG/SODIS, 1998)

than one millimeter in thickness. This could potentially offset the benefits gained by reducing the depth of the water, and would need to be tested through experimentation.

Having chosen the 3/4-inch diameter tube, the selection of sizes for a flow control valve and a faucet easily follows. Standard three-quarter-inch PVC ball valves most closely fit the circumference of the three-quarter-inch PVC tube, though the fit was not exact because of the different standards used for hoses and pipes. The excess space in the valve needs to be filled in order for the tube to hold and for the system to not leak. Plastic bags or thin cloth wrapped tightly around the tube may fill the void and create a watertight seal, though silicon sealant applied to the inside of the valve and then to the connection point of the tube and valve makes a more practical and consistent choice if available. The experiments in Nairobi used the latter option. The tube fits snugly over a three-quarter-inch faucet, but will not remain in place once the spigot is turned on. Both silicon and tightly wrapped bicycle tubing were used to attach the tube to the faucet.

3.2.2 Fluid Mechanics

In order to ensure proper treatment of the drinking water, it is crucial to understand how the water will act inside the treatment system. One of the benefits of the Spirasol tube is the likelihood of plug flow throughout the treatment process. With a small, uniform diameter and an unwavering path to travel, it is very likely that every parcel of water will receive an equal amount of treatment during the process. In contrast, if there were zones in a SODIS bottle that received less treatment (e.g. the bottom of a bottle with somewhat turbid water), parcels would not receive an equal amount of treatment because there is no advection. The absence of such “dead zones” is a serious advantage of the Spirasol system.

With the design parameters in place, the flow velocity in the Spirasol tube can now be calculated.

$$T_{\text{residence}} = \text{Residence time} = 6 \text{ hours}$$

$$D_{\text{inner}} = \text{Spirasol tube inner diameter} = \frac{3}{4} \text{ inches} = 1.905 \times 10^{-2} \text{ m}$$

$$A_{\text{inner}} = \text{Spirasol tube inner area} = 2.826 \times 10^{-4} \text{ m}^2$$

$$L = \text{Spirasol tube length} = 7 \text{ m}$$

$$V = \text{Spirasol tube volume} = 1.978 \times 10^{-3} \text{ m}^3 = 1.978 \text{ Liters}$$

$$Q = \text{Spirasol tube volumetric flux} = 2 \text{ Liters} / 6 \text{ hours} = 0.33 \text{ L/hr} = 5.5 \text{ mL/min}$$

$$U = \text{Mean velocity in tube} = Q/A = 1.17 \text{ m/hr} = 3.25 \times 10^{-4} \text{ m/s}$$

If we presume that the water in the Spirasol tube, though polluted, would still have the approximate densities and kinematic viscosities of pure water,

$$\begin{aligned} \text{Re} &= \text{Reynolds number} = \rho U D_{\text{inner}} / \mu \\ &= 1000 \text{ kg/m}^3 * 3.25 \times 10^{-4} \text{ m/s} * 1.905 \times 10^{-2} \text{ m} / 1 \times 10^{-3} \text{ N-s/m}^2 \\ &= 6.19 \end{aligned}$$

This low Reynolds number is far from the 2300 transitional range and indicates that the flow is laminar throughout the treatment system. The flow profile itself is likely to be parabolic and follow the characteristics of Poiseuille flow with slight variations that result from the curvature of the tube (Sabersky et al., 1999). This would make the maximum velocity at the center of the tube twice that of the mean velocity.

$$\text{Max velocity} = 2 \times \text{Mean velocity} = 6.5 \times 10^{-4} \text{ m/s.}$$

The question was then to treat the average parcel or the “worst case scenario” parcel that would travel at the midsection of the pipe throughout. To discern whether Brownian motion would play a role in the Spirasol system, a time scale analysis was performed. Treating non-motile bacteria as large particles with diameters of about one micron, the diffusion coefficient of bacteria D_{bac} would be $10^{-12} \text{ m}^2/\text{s}$ (Hemond and Fechner-Levy, 2000).

$$\text{Diffusion Time Scale} = D_{\text{inner}}^2 / 4 D_{\text{bac}} = \text{approximately } 2.9 \text{ years}$$

$$\text{Advection Time Scale} = L / U = \text{approximately } 6 \text{ hours}$$

Diffusion time scale \gg Advection time scale

Hence, bacteria would likely remain at one velocity throughout the system, and up to half of the water could potentially “short circuit” the system. It was questioned whether a system that will treat the water on an average of one day be given a residence time for two, and whether a four day residence time be even feasible. Given that the water would eventually mix with water that had been treated for periods even longer than six hours, and the chances that vertical mixing would likely arise in some small degree due to the following:

- Tube curvature and acceleration around curves
- Gravitational forces acting unevenly on the slanted tube
- Parcel mixing occurs at the flow valve as the flow opening contracts

the mean velocity was used in proceeding design calculations. The time scale analysis also serves to show that lateral mixing does not occur to any great degree and bacteria would not short circuit the system because of Brownian motion.

The slow velocity of the system will lead to a decent amount of particle settling. Suspended particulate matter settling velocities in low concentrations with diameters less than or equal to 200 microns are estimated to settle at a velocity of about 10^{-2} m/s (Metcalf and Eddy, 1991), which is two orders of magnitude greater than the operating velocity. This will likely lead to settling of particles at the bottom of the tube coils over a long period of time. It is likely that particle removal could be worked in to a routine cleaning process for the tube, where the system is flushed by turning the flow valve to fully open for a few minutes. After removing the particles, the tube would need to be filled once again before it is coiled and set up for operation.

Most motile bacteria can move at speeds of 50 $\mu\text{m}/\text{sec}$ (Tortora et al., 1995), whereas the fastest amongst them (the *Vibrio* genus) have been monitored to go at 200 $\mu\text{m}/\text{sec}$ (McGraw Hill, 1960). Average bacterium speeds are significantly slower than the intended flow rate of 3.25×10^{-4} m/s. In the worst case scenario, bacteria would be propelling themselves in the direction of the flow at all times, making the effective flow speed of these bacteria 3.75×10^{-4} m/s and reducing the residence time by approximately 40 minutes. Given the unlikelihood of this event (as bacteria may change direction many times and swim at an angle to the current), with a residence time as large as six hours, it is doubtful that the velocity of the bacteria will hinder disinfection. In Spirasol systems employing fast treatment – with low flow speeds such as the one of this experiment but significantly shorter residence times, bacterial velocities may become an issue. Should the Spirasol system specifically be treating a rapidly moving bacterium, such similarities in velocity should spark some concern, and design precautions should be taken to draw out the residence time.

In order to properly fill the tube, it must be done with a constant head gradient with an opening for air to escape. There are a number of ways to set up such a temporary system such as coiling the tube down around a cylinder or stretching the tube out completely. If this is not done, air bubbles in an upright coiled tube will have no means of escape without outside forces acting upon the system, and the top eighth of every coil will not fill up with water. Air bubbles greatly reduce the efficiency of the treatment, and in some cases can stop the flow of water altogether. In short circuit flow with air bubbles, the streamlines essentially stop at each coil and water is transported to the next coil drip by drip. No fluid model would truthfully hold in such a system. In general, air bubbles should be avoided to the best of the engineer's ability.

To ensure a flow of 3.25×10^{-4} m/s and velocities of that scale, the opening at the flow valve will constrict considerably from the area of the tube and the flow will be in drips and not a stream. For the small portion of the tube near the valve, the representation of flow in streamlines will not hold. As mentioned above, this will generally be good for mixing of the fast flow and slow flow portions of the tube, but will generally make the flow taxing to regulate. Small orifices will be optimal.

In short, the tube will ensure a laminar flow through the system and Brownian motion will not interfere with the residence time of the system. The flow will have a Pousille profile and a portion of the flow will have a residence time greater than the

average velocity, but small contributions to mixing throughout the system and near the valve should result in an effluent that has largely been treated for six hours.

3.3 Comparison of Costs

Upon examination, the Spirasol system costs approximately \$20 less than the SC-SODIS system overall (Table 3.1). While the cost of the PVC tube is rather large for one piece, it makes up almost the entire system. The numerous fittings of the SC-SODIS system, capped off by the hose-to-pipe adapters, ultimately make it cost more than Spirasol.

Table 3.1: Comparison of the Costs of the two continuous flow solar disinfection systems.

Cost Estimates			
Spirasol		SC-SODIS	
PVC Tube (20 ft.) x 1	\$21.50	PET Plastic Bottles x 8	Free
3/4" PVC Ball Valve x1	\$2.94	3/4" PVC Ball Valve x1	\$2.94
Silicon Caulk x 1 tube	\$2.99	3/4" PVC Pipe x 10 ft	\$7.50
		3/4" PVC 4-way fitting x 2	\$1.38
		3/4" PVC T fitting x 2	\$0.98
		3/4" PVC 90 degree bend x 4	\$1.56
		3/4" Zinc pipe-to-hose converter x 8	\$28.42
		Silicon Caulk x 1 tube	\$2.99
		Plumber's Tape x 1 roll	\$0.99
		Glue sticks x 1 Pack	\$0.99
TOTAL	\$27.43	TOTAL	\$47.75

While these prices will vary between countries (e.g. prices in Kenya are much lower for each piece), the ratios of the cost are likely to stay about the same. Therefore, it is equally as likely that a Spirasol system will not only be easier to purchase and assemble locally, but likely will cost about one half as much as the SC-SODIS system.

Some parts of each system were not considered in the total cost. Containers for both source water and collecting water were discounted, as they were separate from the treatment system itself. A faucet or spigot may be required to attach the raw water source to either system, which will likely add around \$10 to the cost of each system.

Parts of each system may not require adhesives, and could suffice on well-wrapped pieces of plastic, rubber, or other watertight materials. This does not guarantee the seal that one could get with a proper sealant, but it can suffice when adhesives cannot be easily found. The use of seal substitutes will bring down the cost of the Spirasol system only slightly, while it does have the potential to cut the cost of the SC-SODIS system in half, making it competitive with the Spirasol system.

It is important to note that while the Spirasol system is cheaper than the original estimate of SC-SODIS, it is not likely to be a revolutionary breakthrough for the developing world as the cost will still be inhibitive to many.

IV. RESULTS FROM NAIROBI

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4.1 Notes on SODIS Practices and Possibilities in Kibera

During the author's stay in Nairobi, the Kenya Water for Health Organization (KWAHO) offered to guide the author and other Master of Engineering students around the SODIS field office in Kibera, a 600-acre slum area just south of Nairobi. A number of problems with the application of traditional SODIS that could be remedied with the Spirasol system were noted, though it was overwhelmingly recognized that the state of poverty in which Kibera residents dwelled put a system like Spirasol out of their range of purchases.

The number of SODIS bottles used at each household in Kibera is remarkably low. Most households, which usually are composed of four or more people, tend to have no more than four 1 to 1.5-liter bottles in their home. The most frequent reason for this appears to be a lack of understanding about what bottles are appropriate for use. When asked why they did not have more, most replied that they didn't feel they needed any more bottles or that they were not given any more by the SODIS promoters, indicative of a lack of understanding about the technology. The grand idea of transforming an article of refuse into an invaluable tool has not really caught on in Kenya the way that the SODIS founders originally perceived. The bottles given out in Kibera by KWAHO are clear 1.5-liter bottles with square ridges that had never been filled. The bottles were industry surplus and are relatively unique in the Kenyan marketplace, as most other plastic containers have a distinctively different look.

In regards to the need, the SODIS water was looked as strictly for straight drinking purposes only. Many families placed the bottles somewhere cold so they could be drunk later. The water was not used for any type of washing, and most families did not consider the possibility of using the water for other means. The containers being drinking water bottles for many SODIS users implied that the water should be for drinking only; that SODIS was a poor man's way of creating bottled water. The introduction of a larger catchment container in a semi-continuous system would increase the chances of the disinfected water being used for hygienic purposes and not just consumption.

Another complication is the lack of prevalence of PET bottles in comparison to America. Soda is almost always bottled in glass containers that are returned to street vendors for refunds. Additionally, most drinking water containers are most commonly found in the 5-liter varieties, and those that are in the usual 1 to 1.5-liter range are rounded, tinted blue, and generally dissimilar to the bottles provided by KWAHO and other SODIS promoters. While potentially still viable as a disinfection media, they will only be used by locals through intense re-education efforts. If PVC tube appears to be as relatively available as PET plastic bottles in Nairobi, this makes Spirasol as applicable a solution as SODIS.

When the author asked families about their interest in a continuous system of water that may be able to supply them with a greater amount, they recognized that it may be helpful, but it was not seen as something revolutionary or a great unburdening. Because the Kenyan sunlight is usually so intense, SODIS only requires a bottle residence time of one day. Families that continue to partake in the SODIS program have easily added the placement and collection of bottles to their daily routine. Turning a system on in the

morning and off at night in addition to collecting raw would be about the same amount of work as before. The addition of more water was not looked upon as any great advantage because, as mentioned before, most thought that two or three bottles of clean water were adequate for a large family and the water was only used for drinking purposes.

The SODIS program itself also had a number of other characteristics which hindered the overall development and spread of the treatment technology. While many of the problems are beyond the scope of this paper, the author's critical observations upon the operation of the program are noted in Appendix A for future reference.

"Jerry cans" are the most common vessel used in transporting water from these stations to the homes of Kiberans. The cans – typically used detergent or gasoline containers that usually measure between 10 and 20 liters in size – strike a balance between satisfying a large enough fraction of a family's water need while still being easy to carry by hand. Every family interviewed had more than one jerry can for every member of the family. The cans tended to be made of high density polyethylene (HDPE, or #2 plastic), and were often colored and opaque, though a portion of light still penetrates the cans. With appropriate oxygenation, the vessels might still be able to sterilize water to some degree. The vessels could also be fitted with a spigot and serve as the raw water vessel for Spirasol, or serve as the disinfected catchment vessel for Spirasol without any structural change.



Figure 4.1: A queue for a water tap in Kibera, highlighting the likelihood of contamination at the spout. Note the use of "jerry cans" for containers.

The rooftops of Kibera are generally made of thick tin and can support a relatively large amount of weight. One family demonstrated that their son of about 13 years could easily walk about their roof. Placing jerry cans filled with water atop the roofs would be no concern structurally, though would be an issue for older residents with less mobility. The slants on the roofs vary significantly from house to house. Many have a gentle slope below 15 degrees, where as others have slopes above 45 degrees. In these instances, many SODIS users placed rocks or nailed wood to the roofs to stop bottles from sliding off. A large enough plank would be able to hold a jerry can and a Spirasol tube in place. Reflectance

also varied depending on the age of the tin, though SODIS was effective on roofs entirely covered with rust.

Overall, given the familiarity and foothold that SODIS has already acquired, Kibera does appear to be a decent candidate for later trial runs with a semi-continuous solar disinfection system.

4.2 Records from Nairobi Office Experiments

With the Spirasol tube system constructed, we sought to test the system against the traditional SODIS system of a PET plastic bottle and a modified SC-SODIS design which used clear flexible PVC tubing to connect bottle pairs in series.

4.2.1 Experimental Setup

During the stay in Nairobi, both KWAHO and the Kenyan Ministry of Water allowed the author to use their facilities (the central laboratories) in the city's industrial sector to conduct solar disinfection experiments.

A table was built with a 15-degree incline to receive the most intense solar radiation possible for near-equatorial regions. Atop the table was a large "space blanket" which reflects over 80% of incoming light and was used to maximize reflection off the tabletop (Figure 4.2). This table would hold the three solar disinfection systems that would be tested in Nairobi: the Spirasol tube, SC-SODIS bottle pairs connected in series by flexible PVC tubing as opposed to the traditional rigid pipe, and the traditional 1.5-liter PET plastic bottle. The three systems were tied down to the table and thus kept in place with thick nylon string. The string would insulate an insignificant fraction of the systems throughout the day, and was not considered a hindrance. The table was placed in a decently spacious yet out-of-the-way area that was not blocked by shadows save for a half-hour preceding sundown.

Abutting the rear of this table was a flat table on which rested two 16-liter buckets filled with diluted river water. Each bucket was fitted with a faucet that connected to one of the continuous flow systems. For every test, the bucket would be filled such that the head-induced flow would be as uniform for each test run as possible. The buckets were white-opaque in color and were selected in an attempt to minimize the amount of sterilization that occurred outside of the system itself. While disinfection had occurred in containers such as this before (Meyer and Reed, 2001), they were the best local option available for the experiment. A real system might seek to employ a container that transmits the maximum amount of ultraviolet light to improve sterilization results.

Two more 16-liter white-opaque buckets were placed below each treatment system to serve as the catchments for each system. The water heights in the bucket at one liter and two liters had been measured and marked on the side of the bucket, such that one could ascertain how much water had flowed through the treatment system over the course of the experiment. These readings were relied upon more regularly than the hourly milliliter-per-minute readings because the flow tended to change if left unattended.

KWAHO donated 1.5-liter PET plastic bottles (which were eventually intended for use in Kibera) to the author's experiments. The bottles were quadrilateral and ribbed along the sides, but these design characteristics were deemed unlikely to cause significant detrimental effects in the transmittance of ultraviolet light.

After setting up the two semi-continuous systems, the PVC tubes were connected to the appropriate bottles and ball valves. To assist in the attachment, the tubing was run under boiling water from the effluent of the central laboratories' distiller and then inserted into the bottleneck or valve casing. With the heat-induced flexibility, the tube can temporarily collapse itself to a smaller circumference before cooling. Once cooled, the seal is watertight and comes apart with the approximate force of 40 newtons (estimated as the weight of about four liters of water). This was not considered during the design phase of the experiment. One could potentially place a heated tube end onto a smaller ball valve (i.e. five-eighths inch) such that no additional care to the valve would be needed. However, given the materials already available to the designers, the three-quarter-inch PVC ball valves were still used in the experiment.

For the prototype system, the project was in some ways limited by the materials available in country. A seven-meter clear/blue-tinted plastic tube was purchased from the department store chain Allabi Sharrif in downtown Nairobi. Upon quick observation, it was presumed that the plastic was PVC given the feel and discoloration, but was never confirmed. The tube had an inner diameter of $\frac{3}{4}$ inches and an outer diameter of 1 inch as chosen by design.

During this phase, the prototype system with the bottle pairs fell apart between the tube and bottle joints because of the weight of the water. In addition, the system also demonstrated steady leakage in between the bottle pairs. Both of these flaws could conceivably be repaired with significant application of non-toxic adhesives. For this test, however, the experiment was much more concerned with the minimization of parts, labor, and failure rates, thus the modified SC-SODIS system was not tested after this initial failure.



Figure 4.2: The three solar disinfection systems assembled. The modified SC-SODIS (middle) was not broken at the time of this photograph, but was eventually discarded due to structural failure.

4.2.2 Experimental Design

The comparison of the two systems would be undertaken by examining the ratios of microbial concentration in the two systems both before and after exposure to the sun. It was hypothesized that the Spirasol system would perform about equally well as the PET plastic bottle.

Water was collected from the Nairobi River, located less than two blocks away from the central laboratories. The river was the most accessible source of microbe-contaminated water. And, given the constraints on travel and time, it was likely to be the only source the author and his colleagues could undoubtedly reach during the period of testing. It was quite apparent upon visual and olfactory examination that the river was largely untreated wastewater effluent. Total coliform counts were often on the scale of 1,000,000 colony forming units (CFUs) per 100 milliliters of water, but did vary by a factor of 10 as the likely result of rain from previous days.

Visual observation was enough to confirm that the water was far too contaminated to test undiluted. Unfortunately, appropriate dilution water was not plentifully available during the experiments. Tap water in Nairobi is treated with chlorine and has residual chlorine of approximately 2 mg/L (Central Water Testing Laboratories, 2004), and preliminary tests performed by the authors showed bacteria still present in the tap water. The central laboratories has a distiller which produces disinfected water at the rate of approximately 15 liters per day, and this was to be split amongst the entire laboratory team of 10 people. Additionally, distilled water does not have all the desired characteristics of Q-water to retain bacterial colonies. However, the distilled water was the most feasible option at the time and was used in conjunction with the source water throughout the majority of the experiments. Tap water was used for dilutions in one experiment when the amount of distilled water was not enough for experimentation. However, since that factor was carried through the experiment at all points of sampling and used in both the control and variable situations, it is unlikely to have drastically affected the results.

The source water was always diluted by a factor of 10 prior to experimentation. This was done in order to bring the turbidity levels below 30 NTUs, making the water non-turbid enough for solar disinfection.

4.2.3 Analysis Methods

Both systems would be tested for their concentrations of *E. coli* and total coliforms, common bacteria used as indicators of fecal contamination.

Samples from both systems were collected in sterile 100 mL whirl-pak sampling bags made by Nasco. The samples were then diluted with distilled water to reduce the microbial concentrations to readable levels. Estimations of the requisite dilution ratios were based on previous data in addition to a visual examination of the water. Bacteriological tests were performed less than 30 minutes after sampling occurred to minimize any outside effects such as temperature and natural decay on the colonies.

One hundred milliliters of the diluted sample were then filtered through a 0.45-micron membrane filter. A petri dish was then doused with 0.2 mL of m-ColiBlue24 broth, a lactose-based medium which allows for simultaneous colorimetric detection of both *E. coli* and total coliforms. The broth employs the enzyme beta-glucuronidase and BCIG (5-

bromo-4-chloro-3-indolyl-beta-D-glucuronide) to react with *E. coli* and turn the colonies blue. For non-*E. coli* species, the non-selective dye TTC (2,3,5-triphenoltetrazolium chloride) stains these colonies red (Hach Company, 1999).

The membrane filter was then transferred from the filtration unit to the saturated Petri dish and then incubated for approximately 24 hours at 35 degrees Celsius. For the incubation, the central laboratories' incubator was utilized. The incubator was accurate to within one-tenth of a degree Celsius, though was originally set to 37 degrees Celsius and thus incubated the first day's samples at a temperature between 35 and 37 Celsius for around 12 hours.

Once incubation was complete, the colony forming units were then counted by hand and then multiplied by the dilution factor to attain an appropriate estimate of the microbial concentration of the water.

Making the laboratory conditions sterile was of great concern for the author. Hand washing and the use of rubber gloves was not a routine among the workers at the central laboratories. In addition, windows were frequently left open in order to reduce the heat during the day. The author and laboratory assistants sought to remedy these problems during the author's stay. One work counter was set aside solely for the purpose of membrane filtration experiments and was cleaned with methanol after each day. Forceps were sterilized by flame before each use, and the membrane filtration units were doused with formaldehyde after each experiment. Assistants working without gloves (such as other lab workers curious about the membrane filtration technique) did not come into contact with the water or membrane at any time. All glassware was autoclaved after use in an experiment, and clean wares were not in short supply. While the risks of contamination through dust in the air and indirect contact with individuals' hands were still existent, overall risk of contamination was certainly minimized to the best of the team's ability.

Water turbidity was measured with a HACH digital turbidimeter. Following standard procedure for the device, ten milliliters were drawn from the source bucket using sterile gloves and a sterile container, then poured into the turbidimeter vial. At least three separate readings were taken each time to create an average reading. The turbidimeter was calibrated successfully before experimentation began.

4.2.4 Summary of Results

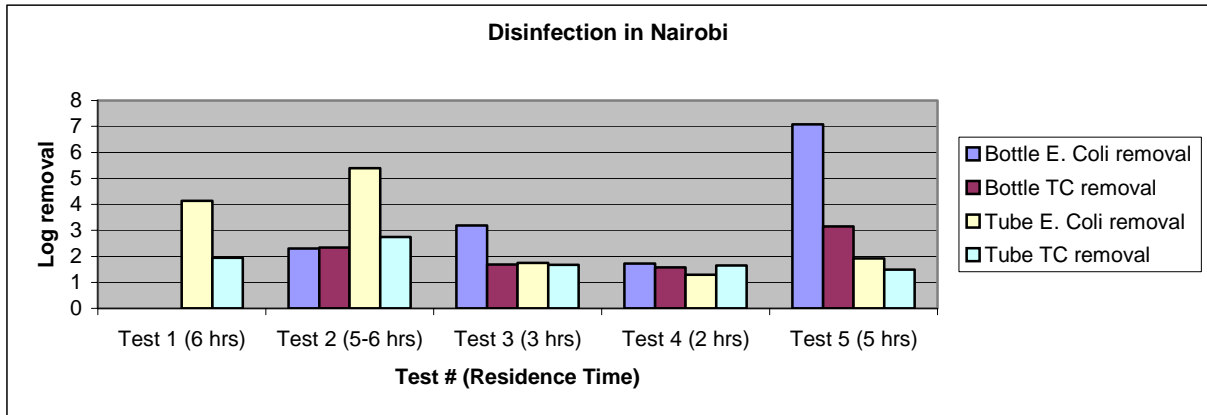


Figure 4.3: Results of the solar disinfection studies performed in the Central Laboratories of Nairobi. No trends in the data were identified and the data was generally disregarded as inconclusive.

Overall, the data showed such a significant amount of scatter in relation to both residence time and choice of vessel, that no trends could truly be detected in the data. The Spirasol tube appeared to be very successful in Tests 1 and 2 and even seemed to outperform the PET bottle. While that characteristic did not seem to hold up in the tests of shorter residence time, it did nonetheless appear that the disinfection rates were generally high enough for Spirasol to work as a disinfection system. The last test, however, made this conclusion completely invalid. Test 5 also showed an exceptionally fast rate of disinfection in the PET bottle that was not seen in any previous experiment, bringing the rate of disinfection of the “control” system into question. Given that neither previous studies (EAWAG/SODIS, 1998, Reed 1997) nor the past four tests did not reach rates this high, it is very likely that the bottle results from Test 5 are erroneous.

It almost appeared that after Tests 1 and 2, the tube was beginning to perform worse and worse, as if it is possibly deteriorating after each test. This was not entirely true, as the Spirasol tube’s results for the two-hour test (Test 4) are equal or better than the results for the Spirasol tube’s three-hour test (Test 3) performed earlier. In addition, the decrease in disinfection seen between the <3-hour tests (Tests 3 and 4) and the > 3-hour tests (Tests 1,2 and 5), while not fitting an exponential curve, are not all that unusual.

Detailed results of the Nairobi experiments are located in Appendix B.

4.2.5 Discussion

One of the things that must come out of the experiment is a reason for experimental failure. While there were a number of hypotheses formulated, no firm conclusion was reached before further work in Cambridge.

One thing to consider was the changes in dilution during the experiment. The original intent of conserving the amount of distilled water available for the lab may have resulted in more discrepancies than originally planned. The change between 1:100 and 1:10 dilutions (and subsequently a turbidity of about 2 to about 20 NTUs) is certainly a logical explanation for why the tube’s efficacy rates are not consistent with one another. It

does not, however, explain why one system performs better than the other. Additionally, there are striking differences between the PET bottle results of Test 5 and Tests 3 and 4 though all three tests used 1:10 dilutions.

Bacterial mobility was a concern as stated before, but it is not possible for the microbial diffusion to have overcome the advection in the tube and skew the results in the manner seen. Being a wastewater effluent stream, there is little reason to think that the water collected was in any way polluted with bacterial species known for rapid movement.

The faster flow speed of the central part of the tube was also a concern, but if short circuiting was consistently occurring, the results would have shown the Spirasol tube consistently underperforming the bottle. This was not the case, as Tests 1 and 2 showed very high removal rates for the tube and Tests 3, 4, and 5 showed poor removal rates for the tube. Given the oxygen concentration introduced to the system and the general intensity of the sun seen over the span of the five tests, a residence time of three hours was likely to have resulted in very high reductions in the microbial concentrations for both systems. Additionally as addressed before, a small amount of mixing was likely to occur and the effluent overall was expected to still have a residence time of six hours in the Spirasol tube.

The simplest explanation might be a problem arising from sun and shadow. While the most out-of-way and vacant area was selected for the experiment, it was still near buildings on two sides of the table. Being completely free of the shadows throughout the day was a practical impossibility. As mentioned before, the area was scouted previous to experimentation and no shadows were found to have reached the table with the exception of the 5 p.m. to 6 p.m. hour, after each experiment had ended. No data in regards to shadows were recorded during the experiment. It is unlikely the sun's trajectory significantly changed within the span of two weeks. The table did however draw attention for most of the days. Most visitors would stare at the two SODIS systems for spans of 15 minutes at a time. While traffic was sparse (usually only one to three people at a time), their shadows generated a random effect on both systems, and could therefore account for the discrepancies seen.

The tube's failures bring to question whether the system was working as intended or if some glitch had caused the scattered data. The residence time and flow of the tube performed appropriately as evidenced by the inflow and outflow gauge buckets exhibiting a net loss/gain of two liters, respectively. Therefore, no fluid mechanical error contributed to the inconclusive data seen.

Biofilms, a concern often associated with long term deterioration of pipes (Mayette 1992), may have arisen here in the two-week span of experimentations thanks to the high microbial concentrations, the high concentration of suspended solids, and creeping flow. As well, the PET bottle would not have had this problem since it was consistently "flushed" after every experiment, which would effectively remove a biofilm with the high rate of flow and sudden change in environment. Studies show that the rate of biofilm growth is irrelevant to the material of the pipe; only the measure of surface roughness, which helps the bacteria adhere to the pipe surface and spawn films, is important in determining the likelihood of biofilm accumulation (Pederson, 1990; Mayette, 1992). PVC has also been known to contribute organic carbon as a food supply for biofilms and form in small time periods such as one week (Edstrom Industries Inc., 2005). One would assume, however, that solar disinfection processes would still interact with these biofilms, even if it

were at a lesser rate. There was unfortunately not enough time to perform a test for the biofilms or examine the concentration of microbes inside the tube. While particles were noticed inside the tube, it was uncertain whether they were deeply engrained in the tube, settled particles from the water, or slime created from a concoction of microbes and sediment.

V. RESULTS FROM CAMBRIDGE, MASSACHUSETTS

V. RESULTS FROM CAMBRIDGE, MASSACHUSETTS

5.1 Preliminary Tests on Charles River Source Water

In order to better understand the scattered and inconclusive results obtained in Kenya, microbial concentration tests were performed again under more controlled conditions.

The intended source for the upcoming test was to be the Charles River water, a source known to be contaminated with *E. coli* as a result of sewer and storm runoffs often overflowing into the river after intense storms. It was clear at the outset that the intensity of the Cambridge sunlight and the microbial concentrations of the Charles River would not bring about the orders of magnitude seen in Nairobi. However, as we were interested primarily in the relative efficacies of a PET bottle and the Spirasol tube, this difference would not be a significant problem. It was desired to first understand the quality and microbial concentrations of the water.

The sampling site for all the experiments was the MIT Boathouse, adjacent to the Harvard Bridge, and near the facilities employed for the experiments. Samples were taken with washed, dried and sterilized 16-liter Home Depot PVC paint buckets. There had been no severe storms for at least two weeks when the sampling took place.

All of the tests followed the same analytical protocols as the Nairobi experiments (see Section 4.2.3). The MIT lab had many more amenities that aided in the sterilization of the lab space. The room was free from sunlight, dust, and outdoor air. There was a healthy supply of Q-water to use for all experiments, and there was a specific countertop prepared solely for membrane filtration studies. With the availability of lab time no longer an issue, the incubation time was consistently 24 hours. The early results of the source microbial concentration and turbidity readings resulted as follows:

**Table 5.1 Preliminary readings for the Charles River performed on March 20
Charles River Source Water**

Turbidity Readings (NTU):	2.33, 3.48, 3.2, 3.29, 2.86, 3.11
Average:	3.05

Dilution	<i>E. coli</i> (Blue)
Source (Blank)	0 colonies
Source (1:1)	58 colonies
Source (1:1)	72 colonies
Source (1:2)	24 colonies
Source (1:2)	19 colonies (watery)
Source (1:5)	7 colonies
Source (1:5)	13 colonies

Surprisingly, no total coliform colonies appeared in the results. It is highly unlikely that there are no other microbial species present. In a majority of the petri dishes, orange globules of predominantly water were present, though the intensities were light and often below 20. Because of their scarcity and appearance, they were not counted as total coliform colonies. Given that many tests on Charles River water samples before had shown the presence of total coliform bacteria, it is almost impossible that the species found in the Charles River are unculturable with M. Coli Blue-24. After discussing the issue with other

lab mates, it was concluded that the packet of broth (which was brought back from Kenya) used for this previous experiment had spoiled to the point where they should not be used in the future. New, unopened packets were used for the remaining experiments, and there were many fewer problems with these packets than with the packet from Kenya.

This did not mean that the results were completely invalid. As this was only a preliminary exercise to test the quality of the Charles River water at the testing site, it was decided that the concentrations and turbidity were low enough apparently to not require dilutions in the future. As the results show, there are just under below 100 colony-forming units in 100 mL of Charles River water. Given that a reading of 20 to 80 colonies per dish is the most appropriate reading for an M. Coli Blue-24 experiment (HACH Company, 1999), it was decided that no dilution was needed to carry out the experiments. The concentrations would, however, pose a problem in seeing if any reductions greater than log 2 took place.

Turbidity levels were comfortably low enough to ensure that solar disinfection would take place without hindrance, and were another argument against diluting the source water.

5.2 Design Setup

The solar testing area for the Cambridge-based tests was chosen as the 5th floor roof of building NW30. The patio area faces south and is not blocked from the sun for any period of the day. During the weeks of testing, the patio was off limits to residents, thus minimizing the likelihood of interference by outsiders.

Nearing the end of this experiment, management at NW30 expressed that they wanted to make the rooftop more accessible to the residents for outings and parties. This, along with maintenance to the roof, meant that access to the roof became much more limited. For the final experiment, the equipment was moved to the Baker House undergraduate dormitory, which also has an accessible roofdeck. This final experiment took place on a weekday, when traffic on the roof was light and interference was unlikely. In general, one can almost always find residents and partygoers for most of the day during weekends on the Baker roof deck, making an experiment attempt on a Friday, Saturday, or Sunday ill-advised.

Instead of a spigot for the top bucket, a 3/4-inch pipe flow valve attached to a small section of 3/4-inch PVC pipe was inserted into a bucket and sealed with silicon caulk. The improvisation worked as well as the previous design without the need to use additional sealants to ensure nothing leaked.

A 50-foot clear vinyl tube with 3/4-inches inner diameter and 1-inch outer diameter was purchased locally at Metropolitan Pipe in Cambridge, Massachusetts. Because a portion of the pipe was flattened and could not likely be expanded appropriately with the time constraints, ten feet of tubing was cut. A 3/4 inch pipe flow valve was attached to the end of the pipe with silicon caulk sealant. With the additional length, the flow through the pipe had to be increased to retain a six-hour residence time, and the flow was thus easier to regulate and maintain than the flow in Nairobi.

$T_r = 6 \text{ hours}$

$D_{\text{inner}} = 3/4 \text{ inches} = 1.905 \times 10^{-2} \text{ m}$

$$\begin{aligned}
A_{\text{inner}} &= 2.826 \times 10^{-4} \text{ m}^2 \\
L &= 40 \text{ ft} = 12.192 \text{ m} \\
V &= 3.45 \times 10^{-3} \text{ m}^3 = 3.45 \text{ Liters} \\
Q &= 3.45 \text{ Liters} / 6 \text{ hours} = 0.575 \text{ L/hr} = 9.6 \text{ mL/min} \\
\text{Mean velocity} &= U = Q/A = 2.03 \text{ m/hr} = 5.65 \times 10^{-4} \text{ m/s} \\
\text{Reynolds number} &= \rho U D_{\text{inner}} / \mu \\
&= 1000 \text{ kg/m}^3 * 5.65 \times 10^{-4} \text{ m/s} * 1.905 \times 10^{-2} \text{ m} / 1 \times 10^{-3} \text{ N-s/m}^2 \\
&= 10.76
\end{aligned}$$

Though the flow rate is approximately doubled from the prototype of the Nairobi experiments, the flow is still laminar.

While the sunlight at Cambridge's latitude is best intercepted at around 60 degrees to the normal, there was no table of this slant constructed. A table with a 15 degree slant designed for earlier trial runs was brought to the NW30 and Baker roof and used for this experiment..

Before experiments at each roof deck took place, the tube was primed using tap water (from either a hose or faucet) to remove all air bubbles, then source water was rapidly run through the tube to expunge any residential chlorine from the system. The priming was an easier task with the top of the tube not attached to a bucket or spigot. The top end of the tube can be hooked up to a proper faucet and the tube is much easier to manipulate without a bucket attached to it.

Attempts to coat the valves with silicon caulk and subsequently seal them with the silicon proved significantly more taxing and less effective than the first attempt in Kenya. The glue came undone much more frequently and remained malleable even after 48 hours of exposure. It is possible that the near-freezing temperatures in Boston adversely affected the seal and the material. Another consideration is that the tube was not appropriately heated enough to make the PVC sufficiently malleable once inserted inside the valve, causing fractures inside the coat. It is also possible, however, that the successful assembly in Kenya was primarily the result of luck. The failure of the system highlights the need to find a more appropriate (and potentially cheaper) implement that can be used as a valve with a tube. After these flaws were discovered, the leaks were held off through the application of lightweight plastic bags and duct tape wrapped around the spouts.

The bottle used for this set of experiments was a standard 2-liter PET plastic soda bottle made by the Coca-Cola Corporation.

With a myriad of tools and the Internet now easily accessible in comparison to the Nairobi experiments, extra care was taken to more accurately document the weather conditions for a given day. Between 2 p.m and 3 p.m. during every experiment, weather conditions for Boston at Logan Airport were taken from Weather.com and solar irradiation levels were measured with a laboratory pyranometer over a period of 15 minutes.

As the sunlight began peaking later in the day as spring wore on, the time of exposure was set for all experiments as 11 a.m. to 5 p.m.

5.3 The Silicon Glue Problem and Alteration

Test 1 brought about some interesting and unexpected results largely thanks to the earlier difficulties in drying the silicon caulk.

Once Test 1 had been initiated, still wet silicon glue that was expected to attach to the tube pipe to the bucket and the pipe valve to the tube broke off and flowed into the tube. This was visible as a plume emanating from around the sides of the ball valve and flowing through the tube in somewhat of a streamline. Flecks of the glue also flowed through the tube and began to settle out. In addition to the flakes inside the tube, the effluent in the first hour was noticed to have a much milkier color than any discharges noted from Kenya. At the six-hour mark, however, the clarity of the effluent water did not appear much different than that of the source water, though the milky tint was very apparent in the catchment bucket. Still, the differences noted earlier on prompted a measurement of the turbidity

Table 5.2: Turbidity readings before and after experimentation for Test 1
Turbidity in NTUs

	Readings	Average
Source	2.21, 2.00, 2.35	2.19
Tube after treatment	119, 123, 121	121

The treated water had a much higher turbidity than that with which it started. Given the circumstantial evidence against the silicon glue, it is concluded that the caulk raised the turbidity to such a high level.

As one might have expected, the increased turbidity hurt the disinfection results. While disinfection had taken place as noted in Appendix C, there was a stark contrast between the rate of total coliform disinfection in the PET bottle and the Spirasol tube. These differences were on the scale of the variations seen in the Nairobi tests.

In this instance, it is almost certain that solar disinfection was hindered by the extremely high turbidity readings, hence our high readings. SODIS recommends that water must be under 30 NTUs for sunlight to properly penetrate the water (EAWAG/SODIS, 1998).

It is possible that the silicon began to break apart and cloud the water during the later days of experimentation in Nairobi. However, turbidity levels for the Nairobi experiments were only taken before experimentation to assure that turbidity levels were low enough for disinfection to occur, not afterwards to see if turbidity had changed. Therefore, we cannot be certain that caulk leaching is primarily to blame for the variability of the Nairobi results. Though no visible turbidity changes were noted in Nairobi, it is alarmingly difficult to tell the difference between water of 10 NTUs and 30 NTUs. It is highly possible that the water being treated in Nairobi did become more turbid as a result of the glue seeping into the tube and was not recorded. The rate of glue seepage was likely to be inconsistent from day to day, and could have heavily influenced tube sterilization results one day and done little the next. These pieces of evidence point to the silicon caulk being the most likely cause for error in the experiments performed in Nairobi.

5.4 Design without Silicon Adhesives

Regardless of the glue's responsibility for the inconclusiveness in the Nairobi experiments, its dangers were clear and present enough to warrant a change. To remedy the problem, an entirely new source-to-tube transition was constructed. The PVC ball valve

was cast aside and in its place went a threaded plastic spigot intended for hose attachment. On the outside of the bucket, a rubber o-ring was placed around the spigot. Inside the bucket, a faucet-coupling nut with cap-thread gaskets was placed on the spigot's thread and wound tightly. Lastly, a hose clamp with Phillips-head screws was used to hold the tube in place on the spigot. The items used for the experiment are estimated to cost approximately \$14 in the United States and are generally less easy to find than other fittings.

Table 5.3: Additional costs of the source-to-tube connection

Fitting	Cost
Metal Spigot	\$3.49
Plastic hose coupler	\$2.29
$\frac{3}{4}$ x $\frac{1}{2}$ nylon bush	\$1.29
O-ring (x 2)	\$1.78
Cap gasket	\$2.29
Locknut faucet	\$2.69
TOTAL	\$13.83

5.5 Summary of Results

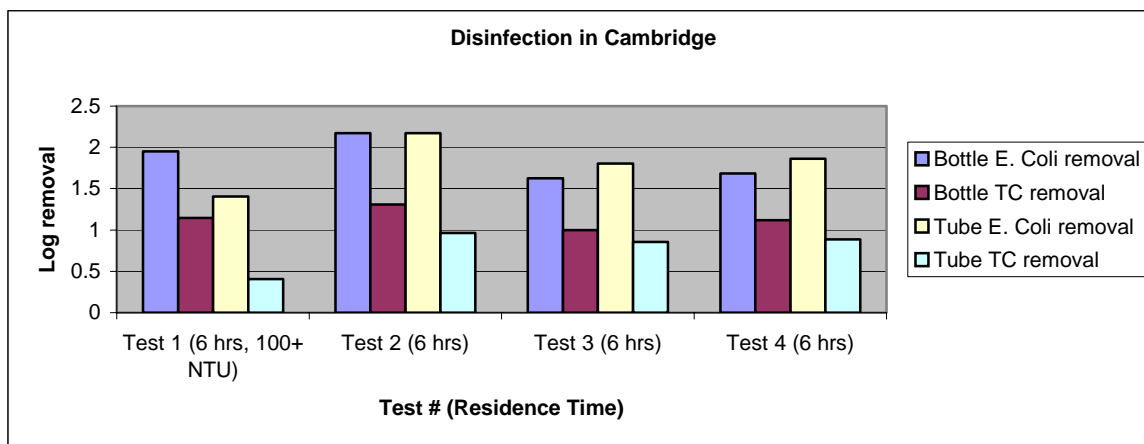


Figure 5.1: Results of the solar disinfection studies in Cambridge. The first study was performed with silicon caulk and noticeably altered the turbidity of the treated water. The other studies were performed in a system built without using adhesives.

After the change to a system without any silicon caulk, the results and consistency are striking. Test 1 was disregarded as an inaccurate representation of how the Spirasol tube fared. Tests 2 through 4 consistently showed *E. coli* removal rates around log 2 and total coliform removal rates around log 0.9 for the Spirasol tube. As no variables changed for the PET bottle setup, the results for the bottle from Tests 1 through 4 are all very consistent. The PET bottle constantly displayed an *E. coli* removal rate of around log 2 and a total coliform removal rate of around log 1.1 throughout the Cambridge tests. The Spirasol tube is around 12 percent more efficient at removing *E. coli* from the water than the tube, while it is only 85 percent as efficient as the bottle at removing total coliforms from the water.

5.6 Post-Experiment Observations on the PVC Tube

When the tube was drained and returned to the laboratory after the experiments were finished, an interesting change to the PVC tube was noticed. During the month of testing, the tube had turned from transparent to moderately opaque, as seen in Figure 5.2.



Figures 5.2 a and b: A comparison of the PVC tube used for Spirasol system experiments in Cambridge (left) and an unused PVC tube kept mostly in darkness (right). A) From afar, one can see the bluish tint beginning to develop. B) A close-up shot shows that the Spirasol tube has become rather opaque over the course of a month.

While the opacity of the tube is not enough to completely block light (one can still see through it), it appears milky enough to dissipate a sizable amount of solar intensity. The discoloration is almost certainly from the stresses of the oxygen and sunlight the tube encountered during testing, as the degradation of PVC and resultant discoloration is relatively well documented (SpecialChem, 2005). Most often, this process occurs in the presence of hydrochloric acid, high temperatures, and oxygen. Ultraviolet light would also be a likely candidate to cause the degradation.

What is curious is that the results of Tests 2 through 4 were so consistent even as the tube began to take on the tint. Additionally, the very tinted tube used in Nairobi was still able to achieve log 6 reductions on microbial concentrations for two tests. The discoloration seems to have very little effect on the UV transmittance. No papers were found to discuss the chemical properties of degraded PVC. The findings seem to refute the general findings of Meyers and Reed (2001) that UV intensity is not the most crucial element to disinfection; rather it is the combination of light and a high oxygen concentration.

5.7 Discussion

Given the consistency seen in the tests after the silicon caulk was removed from the system, it would be safe to say the PET bottle and the Spirasol tube are almost equally effective in disinfecting microbial contaminated waters. Tests consistently showed that the disinfection rates between the two systems differed by less than 15 percent, with the Spirasol tube being more effective at removing *E. coli* and the bottle more effective at removing total coliforms. It is likely that these estimates of efficiency ratios would change with more tests and with different parameters such as solar intensity and source

concentration. Still, the two systems consistently operating within 15 percent of each other is a confident indicator that the systems are very similar in their disinfection efficacy.

It is also likely that the use of silicon caulk was one of the main contributors for the fluctuating results for the Spirasol tube in Nairobi. Silicon and other opaque glues should be avoided if at all possible due to the high potential of seepage into the system.

Leaking and flow control are two crucial factors when it comes a point-of use water treatment system's overall success, and the use of any and all safe materials to reach those goals are certainly recommended. But the question remains whether the purchase of unique plumbing items would be a "first world solution" given the added cost. The purchase of nuts, spigots, and clamps will drive up the overall price of the Spirasol system, though the use of them would also be a sound practice for SC-SODIS and other continuous flow systems. An additional \$14 is significant for systems intending to fit budgets of \$2 a day, and some fittings (such as a hose-fitted gasket) might be a rarity in some countries. There is also the chance that local materials, such as lashing with plastic bags and rubber tubes as was the case in Kenya, would be able to perform the tasks of these plumbing items.

The ageing effects on the plastic tube combined with the lack of a noticeable effect on the tube's disinfection rates give one hope that a Spirasol system could endure for a very long time, potentially longer than a SODIS bottle.

VI. CONCLUSIONS

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6.1 Conclusive Findings

This study sought to determine whether there would be improvements in the SODIS method when employing a solar disinfection conduit other than the traditional PET plastic bottle. The major findings of the study to that effect were as follows:

- Removal efficiencies of *E. coli* for the Spirasol tube were between 100 and 112 percent of the efficiency of the standard PET Plastic bottle.
- Removal efficiencies of total coliform for the Spirasol tube were between 85 and 90 percent of the efficiency of the standard PET Plastic bottle.
- The requisite materials for the system were found easily in Kenya.
- The materials for the Spirasol tube purchased in the United States cost approximately \$20 less than the materials for SC-SODIS.

Based on this data, the Spirasol system can be preliminarily considered as an effective and cost-efficient point-of-use treatment system that performs on par with other solar disinfection treatment systems. The user can tailor the system's residence time to fit the constraints of an area's weather, the system is constructed of common and regularly available pieces of plumbing fittings, cheaper than semi-continuous flow alternatives, and proper use of the system can provide a steady flow of clean water to a household throughout the day.

Though largely dismissed in earlier literature in favor of PET, PVC should be considered as an effective medium for disinfection in future studies. As Meyer and Reed's 2001 study implied, the UV transmittance of the solar disinfection media may have very little effect on the overall disinfection rate. Thus, if a plastic is available in a unique vessel (such as PVC in tubular form), it should not be written off solely because it is not PET.

Based on the cost of the Spirasol system, it is currently not considered a sustainable technology for the Kibera slum in Nairobi. While Spirasol certainly solves a number of problems, the limited amount of funds available to the residents makes Spirasol not an ideal choice without the funding of an outside source.

The danger of using opaque glue is clear: leaching into the water system can increase the turbidity to levels intolerable for solar disinfection. On the upside, this folly did end up highlighting the value of other "trash" items such as plastic bags and rubber bike tubes, which can create an even tighter seal, are more readily available, and cost much less than a specialty adhesive. On the other hand, they are not likely to deliver consistent results, since the effectiveness will primarily rest on the system constructor's shoulders. Reliability is the key issue when choosing an adhesive or adhesive substitute. The choice between often-pricey plumbing fittings and questionable scrap fittings is often a difficult one, and should be made on a case-by-case basis.

6.2 Recommendations

This brief section is intended to give students and researchers information for future investigations into the Spirasol system and other solar disinfection systems based on

the work and general findings of the study. Many of these stem from the difficulties or frustrations encountered throughout the project.

Cost

While the author was very excited to have generally reduced the cost of a continuous flow system to between \$20 and \$30, the news was not greeted as warmly in a country where the average income is the equivalent of \$2 a day. One of the more surprising revelations uncovered during the study is the “real” cost of a continuous flow system, which is often outside the cost range of those who would benefit the most from the technology. In order to truly drive the costs down, finding local substitutes for one’s requisite materials will be the best way.

Flow Control

The experiments of both Flores-Cervantes and this author used a standard PVC ball valve for the unit to manage the outflow of the system. The device is generally intended to exist as an on/off switch, and not vary its flow significantly. Additionally, its operating velocities are intended for liters per minute, not milliliters per minute. The reasoning was solid: it is a cheap and universally common flow control unit. However, in order to develop a disinfection system that could feasibly be manufactured and sold to residents in developing countries, an appropriate flow control device needs to be found. Orifices and makeshift stop valves could serve to be a very simple and inexpensive solution to the problem, though the loss of the ability to vary the flow may become a problem for some systems.

Plastic research

The moderate success of a PVC plastic medium in a solar disinfection experiment brings to question again what plastics could effectively carry out solar disinfection. One of the more important characteristics to examine is UV transmittance for plastics of a uniform thickness. Such information would be an invaluable tool for solar disinfection innovators. However, as the results and previous studies have shown, strong UV transmittance is not a requisite for effective solar disinfection. The most effective comparison between plastics would be actual comparisons of microbial removal after a given time period. While such a test might be difficult to set up, it could truly revolutionize solar disinfection technology.

Water for washing

While a number of point of use systems have successfully taken root across the world, a number of people still assume the clean water to be only for drinking – as seen in Kibera. The real health revolution will come from decontaminating hands, food, and wares. A system that encourages the washing of hands and wares with uncontaminated water from a point-of-use system would be greatly valued. Such a task will likely delve into the social mores of each area in which one seeks to work, and will not be a simple or even accomplishable task.

Enlarging the system / First world treatment

The high cost of a PVC tube would often make it an investment of a number of families or a community. Such a scenario begs the question of whether or not the Spirasol system could be scaled-up to accommodate a complex of houses or a community center. One could conceivably use larger diameters of tube, different containers, and new tools for flow control. Dr. Shanahan has also suggested that the treatment process could also be feasible for an apartment complex's roof deck in a well-developed country. The residual treatment process could potentially take the place of chlorination and be construed as a novel amenity for a housing facility. The logistics and trial runs of this idea would need to be worked out before serious consideration.

All of these tasks and the manufacturing of Spirasol systems will likely require the help and guidance of a plastic manufacturer with a great understanding of industry standards and why they came to be. It is recommended that those interested in creating a point-of-use solar disinfection system be in close contact with such a person from the beginning of their project, as the system will undoubtedly be requiring some sort of plastic at some point in time.

VII. REFERENCES

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Acra, A., Z. Raffoul, and Y. Karahagopian (1984), *Solar Disinfection of Drinking Water and Oral Rehydration Solutions: Guidelines for Household Applications in Developing Countries*, Department of Environmental Health, Faculty of Health Science, American University of Beirut, Beirut, Lebanon.

Acra, A., M. Jurdi, H. Mu'Allem, Y. Karahagopian, and Z. Raffoul (1990), *Water Disinfection by Solar Radiation: Assessment and Applications*, International Development and Research Center, Ottawa, Ontario.

Afanzo Cosmeseuticals (2004), *What Causes Photo Aging?*, [<http://store.afanzo.com/photoaging.html>].

Brown, D. (2004), *Impact of Safe Water, Sanitation on World's Poor*, *The Washington Post*, November 22, 2004, Volume 127, Section A, p. 12.

Central Water Testing Laboratories (2004), *Physical/Chemical Water Analysis Report*, Kenyan Ministry of Water, Nairobi, Kenya.

Flores-Cervantes, D. X. (2003), *Feasibility of Semi-Continuous Solar Disinfection Systems for Developing Countries at a Household Level*, Master of Engineering Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts. May, 2003.

Clasen, T. F. and S. Cairncross, (2004) Editorial: Household water management: refining the dominant paradigm, *Tropical Medicine and International Health*, Volume 9, No. 2, pp. 187 – 191.

Consumer Products (1999), *Baby Alert: New Findings about Plastics*, [www.consumerreports.org].

Devore, Jay L. (2000) *Probability and Statistics for Engineering and the Sciences*, 5th edition, Duxbury, Pacific Grove, California.

EAWAG/SODIS (2004), [<http://www.sodis.ch>].

EAWAG/SODIS (1997), *Technical Note #2: Materials: Plastic vs. Glass Bottles*, [<http://www.sodis.ch/files/note2.pdf>].

EAWAG/SODIS (1998), *Technical Note #3 Material: Ageing effects on PET Bottles*, [<http://www.sodis.ch/files/note3.pdf>].

EAWAG/SODIS (1997), *Technical Note #8 Water Quality: Oxygen Concentration*, [<http://www.sodis.ch/files/note8.pdf>].

EAWAG/SODIS (1998) Technical Note #9 SODIS Efficiency: The Process, [<http://www.sodis.ch/files/note9.pdf>].

Edstrom Industries, Inc. (2005), Growth Factors, [http://www.edstrom.com/Resources.cfm?doc_id=146]

EMPA (2003), Migration of Organic Chemicals to Polyethylene Terephthalate to Water, [http://www.sodis.ch/files/Report_EMPA.pdf], EAWAD, Switzerland.

Grimes, D (1999), Artemis Project, [<http://www.met.rdg.ac.uk/~swsgrime/artemis/>], University of Reading, Reading, UK.

Hach Company (1999), Hach Method Specification Sheet: Total Coliforms and *E. coli*, [<http://www.hach.com/fmmimghach?/CODE:L81701501|1//true>], 2nd revision on August 17, 1999.

IRC International Water and Sanitation Centre (2005), Key Partnerships, [<http://www.irc.nl/page/7979>].

IRC International Water and Sanitation Centre (2005) World Water Day 2005, [<http://www.worldwaterday.org/page/130>].

Khayyat, A. M. (2000), Study of Point of Use Treatment Methods for the Disinfection of Drinking Water in Nepal, Master of Engineering Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts. May, 2000.

Kim, A.Y. and Thayer, D.W. (1966), Mechanism by which Gamma Irradiation Increases the Sensitivity of *Salmonella Typhimurium* ATCC 14028 to heat, *Applied and Environmental Microbiology*, Volume 62, pp.1759-1763.

Kimball, John W. (2004), Reactive Oxygen Species (ROS), [<http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/R/ROS.html>].

Mayette, D.C. (1992), The Existence And Significance Of Biofilms In Water, *WaterReview*, pp. 1-3.

Metcalf and Eddy (1991), *Wastewater Engineering Treatment, Disposal and Reuse*, 3rd Edition, McGraw Hill, Inc., Hightstown, New Jersey.

McGraw-Hill (1960), *McGraw-Hill Encyclopedia of Science and Technology*, McGraw Hill, Inc., New York, New York.

Meyer, V. (2005), Personal Communication.

Meyer, V. and Reed, R.H. (2001), SOLAIR disinfection of coliform bacteria in hand-drawn drinking water, *Water SA*, Vol. 27, No. 1, pp. 49-52.

Miller, R.L. (1988), Sunlight as Disinfectant, *The Lancet*, Vol. 2, pp. 912.

Mintz, Eric et al. (2001), Not Just a Drop in the Bucket: Expanding Access to Point-of-Use Water Treatment Systems, *American Journal of Public Health*, Vol. 91, No. 10, pp. 1565-1570.

NSF Solar Programs UV Monitoring Network (2005), Ultraviolet Radiation, [<http://www.biospherical.com/nsf/student/page3.html>], Biospherical Instruments, Inc.

Oates, P. M. (2001), Solar Disinfection for Point of Use Water Treatment in Haiti, Master of Engineering Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts. May, 2001.

OkSolar.com (2001), Angle of Orientation for Solar Panels & photovoltaic modules, [http://www.oksolar.com/technical/angle_orientation.html].

Reed, R. H. (1997), Sunshine and Fresh Air: A Practical Approach to Combating Water-Borne Diseases, *Waterlines*, Vol. 15, No. 4, pp. 27-29.

Sabersky, R., A. Acosta, E. Acosta, and E. Gates (1999), *Fluid Flow: A First Course in Fluid Mechanics*, 4th Edition. Simon and Schuster, New Jersey.

Serway, R. A. and R. Beichner (2000), *Physics For Scientists and Engineers with Modern Physics*, 5th Edition, Vol. 2, Saunders College Publishing, Philadelphia, Pennsylvania.

SKS Bottle & Packaging, Inc. (2004), [<http://www.sks-bottle.com>].

Smith, M. K. (2001), Microbial Contamination and Removal From Drinking Water in the Terai Region of Nepal, Master of Engineering Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts. May, 2001.

SpecialChem (2005), [<http://www.specialchem4polymers.com/tc/Tin-Stabilizers/index.aspx?id=2821>].

Thomson, E. A. (2001), Project Strives for Clean Drinking Water in Nepal. *Tech Talk*, Vol. 46, No. 14, December 5, 2001.

Tortora, G., B. Funke, and C. Case (1995), *Microbiology: An Introduction*, 8th edition, Benjamin Cumming, Redwood City, California.

United Nations (2004), International Decade for Action, “Water for Life”, 2005-2015, 58/217, 58th Session, Agenda Item 95.

Webb, R. B. and M. S. Brown (1979), Action Spectra for Oxygen Dependant and Independent Inactivation of *E. coli* WP2s from 254 to 460 nm, *Photochemistry and Photobiology*, Vol. 29, pp. 407-409.

Wegelin, M., S. Canonica, K. Mechsner, F. Mechsner, and A. Metzler (1994), Solar Disinfection: Scope of the Process and Analysis of Radiation Experiments, *J Water SRT-Aqua*, Vol. 43, No. 3, pp. 154-169.

Womenaid International (2005), Maji Safi – Clean Water, [<http://www.womenaid.org/press/info/development/pojectkenya.html>].

World Health Organization (2004), Water, Sanitation, and Hygiene Links to Health: Facts and Figures, [http://www.who.int/water_sanitation_health/en/factsfigures2005.pdf], Geneva, Switzerland.

World Health Organization (1992), Water Supply and Sanitation Sector Monitoring Report 1990, UNICEF, New York, New York.

APPENDIX A

Critique of Kibera SODIS Program

Problems with SODIS Program in Kibera Slum of Nairobi:

- Little to no communication between Nairobi (headquarters) office and Kibera field office.
- Twenty field agents attempting to serve city of 700,000.
 - KWAHO estimates 25% of Kibera has been canvassed by field agents
 - Agents estimate less than 50% of households canvassed have adopted the technology
 - Appeared to author that less than 10% of households adopted SODIS
- Agents insufficiently track households that employ SODIS then abandon it.
- Many residents “unconvinced” that SODIS water improves their health
- Applications of clean water for hygienic uses not mentioned.
- “Word of mouth” dissemination of SODIS not effective.
- Many KWAHO agents, including the heads of the system, do not fully grasp the science behind SODIS.
 - Leads to a “by the book” approach that forbids variations to the technology
 - Leads to confusion about how the system works.
 - Residents rely upon KWAHO to find bottles that work.

Author Recommendations:

- Better education of promoters and citizenry
 - Science of SODIS
 - Bacterial infection
 - Hygienic uses of water
 - Effective SODIS media and practices
- Broader health-related goals for Kibera office
- Discern why SODIS users do not spread the word
- Discern why some SODIS users abandon technology
- More aggressive SODIS sales pitch
- Better partnership with headquarters
- Better partnership with local doctors in Kibera

APPENDIX B

Results from Nairobi Experiments

Test 1

Day 1: January 13, 2005

Time: 6 hours (10 a.m. to 4 p.m.)

Other Variables: None

Source Dilution 1:100 (with tap)

Weather: Very Cloudy around 10 a.m. The clouds from the previous night's rainstorm began to disperse around 11 a.m. to 12 p.m., making the skies about 40 percent to 60 percent cloudy. The skies became very clear between 12 p.m. and 2 p.m., and the temperatures rose above 20 degrees C. The clouds intermittently returned around 3 p.m. and strongly returned at 4 p.m., but the temperatures remained above 20 degrees C.

Source		
Dilution	E. Coli (blue)	Total Coliform (red)
Blank	0 colonies	0 colonies
Blank	0 colonies	0 colonies
1:100,000	0 colonies	3 colonies
1:100,000	0 colonies	1 colony
1:10,000	141 colonies	134 colonies
1:10,000	129 colonies	96 colonies

Incubation Time: 24 hours		
Dilution	E. Coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:100,000)	0 colonies	0 colonies
Tube (1:10,000)	0 colonies	2 colonies
Tube (1:1,000)	0 colonies	8 colonies
Tube (1:100)	1 colony	23 colonies

Colleague Amber Franz noted that many of her tests that were left in the incubator longer than the standard incubation time of a day had grown more colonies, while her blank samples remained free of contamination. Outside contamination appeared highly doubtful. A similar test was conducted with the first day's samples.

Incubation Time: 48 hours		
Dilution	E. Coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:100,000)	0 colonies	18 colonies
Tube (1:10,000)	1 colony	2 colonies
Tube (1:1,000)	8 colonies	12 colonies
Tube (1:100)	1 colonies	40 colonies

HACH specifically states that the tests should be run for 24 hours (Hach Company, 1999), and these results were ultimately not factored into the final analysis. Still, the presence of other bacteria with longer incubation times warrants note.

Test 2

Day 2: January 14, 2005

Time: 6 hours (11 a.m. to 5 p.m.)
 Other Variables: None
 Source Dilution: 1:100 (with distilled)

Weather: Very cloudy during the first hour, but quickly disappearing by noon. The temperature remained very warm for the remaining hours. Clouds returned to make the sky approximately 10 percent cloudy, but scarcely diminished the amount of sunlight hitting the test apparatus.

Source (Brian Loux results)

Dilution	E. coli (blue)	Total Coliform (red)
Blank	0 colonies	0 colonies
Blank	0 colonies	0 colonies
1:100,000	3 colonies	20 colonies
1:100,000	2 colonies	21 colonies
1:10,000	TNTC	TNTC
1:10,000	TNTC	TNTC
1:1,000	TNTC	TNTC
1:1,000	TNTC	TNTC

Source (Amber Franz results)

Dilution	E. coli (blue)	Total Coliform (red)
Blank	0 colonies	0 colonies
Blank	0 colonies	0 colonies
1:10,000	23 colonies	57 colonies
1:10,000	24 colonies	51 colonies
1:1,000	TNTC	TNTC
1:1,000	TNTC	TNTC

Incubation Time: 14 hours

Dilution	E. coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:10,000)	0 colonies	0 colonies
Tube (1:1,000)	0 colonies	5 colonies
Tube (1:100)	0 colonies	20 colonies
Bottle (Blank)	0 colonies	0 colonies
Bottle (1:10,000)	0 colonies	0 colonies
Bottle (1:1,000)	1 colony	3 colonies
Bottle (1:1,000)*	3 colonies	15 colonies
Bottle (1:100)	8 colonies	56 colonies

A 24-hour incubation was impossible due to the weekend hours of the lab. When the samples were examined upon Monday's return (circa 70 hours), all of the samples were far too infested with bacteria colonies to be of any value. As such, the Saturday morning results (after 14 hours incubation) were considered more valuable.

In addition to inadequate incubation time, inadequate flow regulation also added to the likelihood of error for the tube treatment. During final collection, the flow valve was turned on too fast, and the liter that likely received six hours of sterilization drained into the gauge bucket. Much of the water was the fourth liter to flow through treatment, and likely received only between four and five hours of proper tube sterilization.

The bottle test for the 1:1,000 dilutions was discarded and rerun because it was filtered after an experiment with a lesser dilution, potentially contaminating the filter. The rerun test is indicated with an asterisk in the table and is more in line with the rest of the data.

While no colonies were detectable, there were small flecks of red visible in the SODIS samples, likely indicating that these colonies had not yet matured due to the low incubation time.

Test 3

Day 3: January 17, 2005

Time: 3 Hours (10:30 a.m. to 1:30 p.m.)

Other Variables: None

Source Dilution: 1:10 (with distilled)

Weather: Nearly optimal conditions for solar disinfection. Cloudless morning with a negligible amount of small white clouds moving in around 11 a.m. Less than 10 percent cloudiness for the rest of the experiment. It is likely that cloudiness played no part in hindering the disinfection process.

Source

Dilution	E. coli (blue)	Total Coliform (red)
Blank	0 colonies	0 colonies
Blank	0 colonies	0 colonies
1:100,000	64 colonies	106 colonies
1:100,000	58 colonies	93 colonies

Incubation Time: 22 hours

Dilution	E. coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:1,000)	91 colonies	192 colonies
Tube (1:1,000)	130 colonies	231 colonies
Tube (1:100)	TNTC	TNTC
Tube (1:100)	TNTC	TNTC
Bottle (Blank)	0 colonies	0 colonies
Bottle (1:1,000)	3 colonies	213 colonies
Bottle (1:1,000)	5 colonies	197 colonies
Bottle (1:100)	TNTC	TNTC
Bottle (1:100)	TNTC	TNTC

Test 4

Day 3: January 17, 2005

Time: 2 Hours (2:00 p.m. to 4:00 p.m.)

Other Variables: None

Source Dilution: 1:10 (with distilled)

Weather: Still nearly optimal conditions for solar disinfection. Sky remained cloudless to 10 percent cloudy with small white clouds seldom covering the sun.

As the untreated source water had remained in a darkened room for the duration of the first test, the same source readings from the earlier days tests were to be used.

Incubation Time: 20 hours

Dilution	E. coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:1,000)	327 colonies	283 colonies
Tube (1:1,000)	290 colonies	167 colonies
Tube (1:100)	TNTC	TNTC
Tube (1:100)	TNTC	TNTC
Bottle (Blank)	0 colonies	0 colonies
Bottle (1:1,000)	97 colonies	298 colonies
Bottle (1:1,000)	137 colonies	233 colonies
Bottle (1:100)	TNTC	TNTC
Bottle (1:100)	TNTC	TNTC

An errant dilution at the beginning of the tests (1:10 instead of 1:100) that was not appropriately marked unfortunately led to half of the incubation results being too numerous to count. What was even more frustrating was the change in efficacy between the traditional bottle and the tube system. While the earlier tests had the efficiency of the tube three times that of the bottle, the short residence time tests of the third day found the bottle to be anywhere from 1.5 to 10 times as efficient as the tube. It is unlikely that the stronger dilution used on this day would be responsible for this change.

Test 5

Day 4: January 18, 2005

Time: 5 hours (11 a.m. to 4 p.m.)

Other Variables: Coils spaced apart

Source Dilution: 1:10 (with distilled)

Weather: Nearly optimal conditions similar to the previous day. Occasional hazy clouds near the end of the day, but cloud cover was less than 10 percent of the sky.

Source

Dilution	E. coli (blue)	Total Coliform (red)
Blank	0 colonies	0 colonies
Blank	0 colonies	0 colonies
1:100,000	111 colonies	123 colonies
1:100,000	131 colonies	147 colonies

Incubation Time: 20 hours

Dilution	E. coli (blue)	Total Coliform (red)
Tube (Blank)	0 colonies	0 colonies
Tube (1:10,000)	27 colonies	84 colonies
Tube (1:10,000)	8 colonies	36 colonies
Tube (1:1,000)	86 colonies	115 colonies
Tube (1:1,000)	TNTC	TNTC
Bottle (Blank)	0 colonies	0 colonies

Bottle (1:10,000)	0 colonies	1 colony
Bottle (1:10,000)	0 colonies	1 colony
Bottle (1:1,000)	0 colonies	7 colonies
Bottle (1:1,000)	0 colonies	11 colonies

	Source (<i>E. coli</i>)	Source (total coliform)	Bottle (<i>E. coli</i>)	Bottle (total coliform)	Log removal <i>E.coli</i>	Log removal total coliform	Tube (<i>E. coli</i>)	Tube (total coliform)	Log removal <i>E. coli</i>	Log removal total coliform
		300,000						0		
		100,000						20,000		
	1,410,000	1,340,000						8,000		
6 hrs	1290000	960,000					100	2,300		
AVERAGE	1350000	675000					100	7,575	4.13E+00	1.95E+00
	300,000	2,000,000	0	0			0			
	200,000	2,100,000	1,000	3,000			0	0		
	230,000	570,000	3,000	15,000			0	5,000		
5-6 hrs	240,000	510,000	800	5,600			0	2,000		
AVERAGE	242,500	1,295,000	1,200	5,900	2.31E+00	2.34E+00	1	2,333.33	5.38E+00	2.74E+00
	6,400,000	10,600,000	3,000	213,000			91,000	192,000		
3 hrs	5,800,000	9,300,000	5,000	197,000			130,000	231,000		
AVERAGE	6,100,000	9,950,000	4,000	205,000	3.18E+00	1.69E+00	110,500	211,500	1.74E+00	1.67E+00
	6,400,000	10,600,000	97,000	298,000			327,000	283,000		
2 hrs	5,800,000	9,300,000	137,000	233,000			290,000	167,000		
AVERAGE	6,100,000	9,950,000	117,000	265,500	1.72E+00	1.57E+00	308,500	225,000	1.30E+00	1.65E+00
			0	10,000						
			0	10,000			270,000	840,000		
	11,100,000	12,300,000	0	7,000			80,000	360,000		
5 hrs	13,100,000	14,700,000	0	11,000			86,000	115,000		
AVERAGE	12,100,000	13,500,000	1	9,500	7.08E+00	3.15E+00	145333.33	438333.33	1.92E+00	1.49E+00

APPENDIX C

Results from Cambridge Experiments

Test 1

Date: March 26, 2005
 Partly cloudy
 High 52 F, Low 41 F
 UV Index: 5 Moderate
 Visibility: 10.0 miles
 High Intensity 883 W/m²
 Low Intensity 396 W/m²
 Steady around 806 W/ m²

Source

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Source (1:1)	89 colonies	101 colonies
Source (1:1)	89 colonies	123 colonies

Incubation time: 24 hours

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Bottle (1:1)	0 colonies	4 colonies
Bottle (1:1)	1 colony	12 colonies
Tube (1:1)	4 colonies	51 colonies
Tube (1:1)	3 colonies	37 colonies

While monitoring the experiment, it was noted that a plume of white viscous liquid was leaching into the tube around the point of the spigot. This was almost certainly the silicon caulk used to adhere the PVC tube to the flow valve. Afterwards, the catchment bucket for the Spirasol tube had noticeably white-opaque water with the texture of the silicon caulk used in the construction of the experiment. Turbidity tests were performed to determine how drastic the change was to the water.

Turbidity in NTUs

	Readings	Average
Source	2.21, 2.00, 2.35	2.19
Tube after treatment	119, 123, 121	121

As solar disinfection is recommended to only take place at NTUs of 30 and below (EAWAG/SODIS, 1998), the poor tube results were attributed to the silicon caulk leaching. The Spirasol system was temporarily disassembled such that a new tube-to-spigot connection apparatus with fittings that did not require the use of adhesives could replace the faulty system.

Test 2

Date: April 12, 2005

Mostly cloudy (dark storm clouds interspersed)
 High 48 F, Low 39 F
 UV Index: 2 Low
 Visibility: 10.0 miles
 Peak intensity: 967 W/m²
 Minimum intensity: 406 W/m²
 Steady intensity: 913 W/m²

A visual examination of the water made it appear more yellow than the previous experiment, which implied a higher turbidity reading was to be expected.

Turbidity in NTUs

	Readings	Average
Source	4.02, 4.21, 4.19	4.14

Table 5.4: Turbidity readings from April 12

The higher turbidity readings also seemed to hint that the microbial concentrations would also be higher. As such, the source readings were diluted by one-half to counter the doubling of the turbidity.

Source

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Source (1:2)	68 colonies	254 colonies
Source (1:2)	92 colonies	218 colonies
Source (1:2)	63 colonies	304 colonies

Incubation time: 24 hours

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Bottle (1:1)	0 colonies	34 colonies
Bottle (1:1)	0 colonies	17 colonies
Tube (1:1)	1 colony	65 colonies
Tube (1:1)	0 colonies	48 colonies

Test 3

Date: April 14, 2005
 Partly cloudy and windy (mostly white cirrus)
 High 51 F, Low 39 F
 UV Index: 4 Moderate
 Visibility: 10.0 miles
 Peak intensity: 973 W/m²
 Minimum intensity: 613 W/m²
 Steady intensity: 949 W/m²

With the turbidities returning to normal levels this time, no dilution was used.

Source

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Source (1:1)	67 colonies	203 colonies
Source (1:1)	60 colonies	236 colonies

Incubation time: 24 hours

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Bottle (1:1)	0 colonies	15 colonies
Bottle (1:1)	3 colonies	29 colonies
Tube (1:1)	0 colonies	40 colonies
Tube (1:1)	0 colonies	21 colonies

Test 4

Date: April 22, 2005

Partly cloudy (remnants of a small storm from the previous day)

High 61 F, Low 39 F

UV: 2 low

Visibility: 10.0 miles

Peak intensity: 992 W/m²

Minimum intensity: 536 W/m²

Steady intensity: 927 W/m²

As the turbidity once again was in between the 2 NTU to 4 NTU range, no dilution for the source water was used during membrane filtration.

Source

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Source (1:1)	78 colonies	228 colonies
Source (1:1)	67 colonies	217 colonies

Incubation time: 24 hours

Reading	E. coli (Blue)	Total Coliform (Red)
Blank	0 colonies	0 colonies
Bottle (1:1)	2 colonies	20 colonies
Bottle (1:1)	1 colony	14 colonies
Tube (1:1)	0 colonies	32 colonies
Tube (1:1)	1 colony	36 colonies

	Source (<i>E. coli</i>)	Source (total coliform)	Bottle (<i>E. coli</i>)	Bottle (total)	Log removal <i>E. coli</i>	Log removal total coliform	Tube (<i>E. coli</i>)	Tube (total coliform)	Log removal <i>E. coli</i>	Log removal total coliform
6 hrs / Turbidity	89	101	0	4			4	51		
	89	123	1	12			3	37		
AVERAGE	89	112	1	8	1.95E+00	1.15E+00	3.5	44	1.41E+00	4.06E-01
	136	508								
6 hrs	184	436	0	34			1	65		
	126	608	0	17			0	48		
AVERAGE	148.67	517.33	1	25.5	2.17E+00	1.31E+00	1	56.5	2.17E+00	9.62E-01
	67	203	0	15			0	40		
6 hrs	60	236	3	29			0	21		
AVERAGE	63.5	219.5	1.5	22	1.63E+00	9.99E-01	1	30.5	1.80E+00	8.57E-01
	78	228	1	14			0	32		
6 hrs	67	217	2	20			1	26		
AVERAGE	72.5	222.5	1.5	17	1.68E+00	1.12E+00	1	29	1.86E+00	8.85E-01