HIGH DENSITY POLYETHYLENE (HDPE) CONTAINERS AS AN ALTERNATIVE TO POLYETHYLENE TEREPHTHALATE (PET) BOTTLES FOR SOLAR DISINFECTION OF DRINKING WATER IN NORTHERN REGION, GHANA

by

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BSc Civil Engineering
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Submitted to the Department of Civil and Environmental Engineering
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Abstract

The purpose of this study is to investigate the technical feasibility of high density polyethylene (HDPE) containers as an alternative to polyethylene terephthalate (PET) bottles for the solar disinfection of drinking water in the Northern Region of Ghana, in a process know as SOLAIR. This study is in line with the intention of Pure Home Water, a registered non-profit organization in Ghana, to offer a variety of low-cost household water treatment and safe storage (HWTS) products as it continues to grow, including the possibility of offering a solar disinfection product in the future. If successful, SOLAIR is practically advantageous over SODIS, which uses smaller PET bottles, chiefly due to the ability to use a larger water container (2-25L), and one that is more likely to be available in a rural setting, given the widespread use of HDPE jerry cans as water collection and storage vessels in many developing countries.

The main idea behind the SOLAIR system is to keep high dissolved oxygen (DO) levels in the water which, in turn, enhances disinfection. A study done by Meyer et al. (2000), in South Africa, showed that regular shaking of the water-filled HDPE container keeps DO at sufficiently high levels to augment disinfection.

The SOLAIR results, using 10L translucent HDPE containers, obtained in Tamale, Ghana over the month of January, 2007, show that complete solar disinfection of water over the course of 7 consecutive hours of solar exposure, did **not** take place. It is believed that the primary reason for the low degree of disinfection is the scattering and absorption of UV radiation by the aerosol particles present in the seasonal Harmattan (Sahara dust) haze, which thereby reduces the amount of UV light that reaches the earth's surface.

Using radiation measurements, obtained in Tamale, a model relating the solar radiation intensity versus NASA's OMI Aerosol Index (AI), which is a measure of the amount of particulates in the atmosphere, was derived.

Another key conclusion suggested by this study is that shaking does **not** increase the DO concentration in the SOLAIR water to sufficient levels, if at all, to augment photo-oxidative disinfection, due to the fact that the oxygen level of the sample water was already near saturation. Laboratory tests performed substantiate this claim.

In brief, this solar disinfection process, using translucent 10L HDPE containers, in January in Northern Region, Ghana, does not produce a safe drinking water.

Thesis Supervisor: Susan Murcott
Title: Senior Lecturer of Civil and Environmental Engineering

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To God, for **everything**.

To my mother for her love and guidance from the spiritual realm.

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List of Abbreviations

µm	Micrometre
AI	Aerosol Index
Alum	Aluminium Sulphate
CFU	Colony Forming Units
DO	Dissolved Oxygen
EAWAG	Swiss Federal Institute for Environmental Science and Technology
E. coli	Escherichia Coli
EC	Escherichia Coli
FC	Faecal Coliform
GWEP	Guinea Worm Eradication Program
H_2S P/A	Hydrogen Sulphide Presence/Absence
HDPE	High Density Polyethylene
L	Litre
MDG	Millennium Development Goal
MF	Membrane Filtration
MIT	Massachusetts Institute of Technology
mL	Millilitre
NASA	National Aeronautics and Space Administration
nm	Nanometre
NTU	Nephelometric Turbidity Units
OMI	Ozone Monitoring Instrument
ORT	Oral Rehydration Therapy
PET	Polyethylene Terephthalate
PHW	Pure Home Water
SANDEC	Department of Water and Sanitation in Developing Countries
SODIS	Solar Disinfection (with PET bottles)
SOLAIR	Solar Disinfection (with HDPE containers)
TC	Total Coliform
TOMS	Total Ozone Mapping Spectrometer
UNICEF	United Nations Children's Fund
UV	Ultra-Violet
WHO	World Health Organization
W/m^2	Watts per metre^2
$W.hr/m^2$	Watt hours per metre^2

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SECTION I – INTRODUCTION & BACKGROUND

1. Introduction

1.1 The Global Need for Improved Water & Sanitation

According to the World Health Organization (WHO), 1.1 billion people did not have access to an improved water supply in 2002, and 2.3 billion people suffered from diseases caused by contaminated water. Each year 1.8 million people die from diarrhoeal diseases, and 90% of these deaths are of children under 5. The figure below shows the per-capita deaths per million related to water and sanitation in each country in 2000 (*Figure 1.1*). Besides causing death, water-related diseases also prevent people from working and leading active lives (WHO/UNICEF 2004).

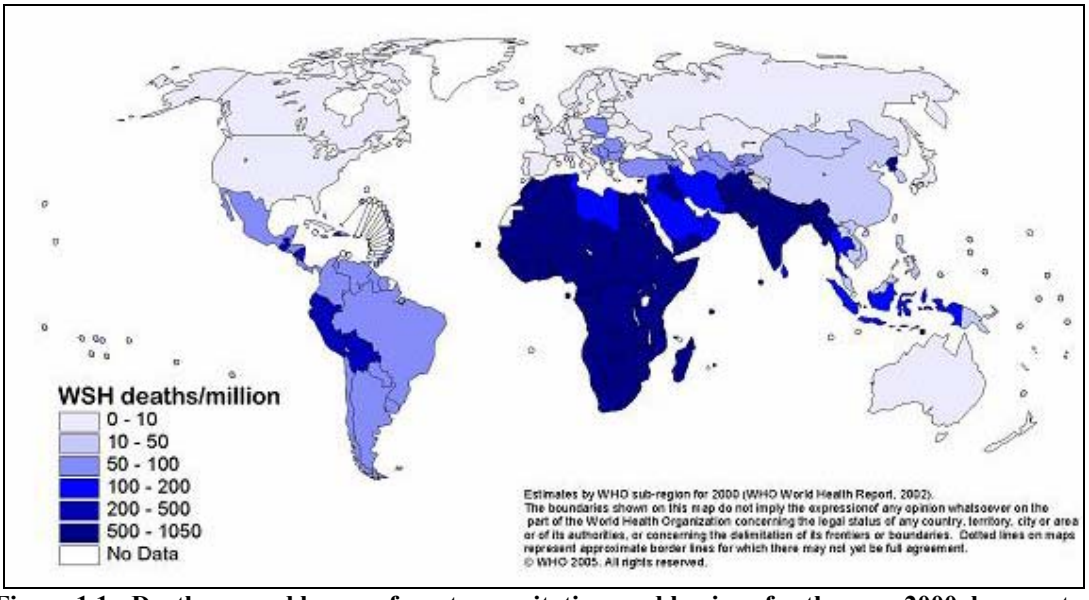

Figure 1.1 - Deaths caused by unsafe water, sanitation, and hygiene for the year 2000, by country (WHO 2002)

In 2000, 189 nations adopted the United Nations Millennium Declaration, and from that the Millennium Development Goals (MDGs) were derived. The MDGs include 8 main goals, 18 targets, and more than 40 indicators. Their purpose is to focus efforts, promote study, raise awareness, and encourage strong alliances. Goal 7 addresses environmental sustainability, and Target 10 is to "halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation" (UN-NGLS 2006). According to the United Nations report, 80% of the world's population used an improved drinking water source in 2004, up from 71% in 1990. Although improvement has been made, there will be challenges as populations increase. There are still a large number of people who will not even be covered by Target 10, and, significantly, an improved water supply is not necessarily a safe water supply.

1.2 Guidelines for Drinking Water Quality

In recent years, the WHO has moved away from defining *set* values for microbiological water quality levels, to providing *recommendations* using a more realistic risk-based approach. *Table 1.1*[1] shows the levels of *E. coli*[2] in drinking water, and respective risk levels from the WHO 3rd Edition Guidelines for drinking water quality:

Table 1.1 – Categorization of drinking water systems based on compliance with performance and safety targets (WHO 2004)

	Proportion (%) of samples negative for *E. coli*		
	Population size:		
Quality of water system	**<5000**	**5000–100 000**	**>100 000**
Excellent	90	95	99
Good	80	90	95
Fair	70	85	90
Poor	60	80	85

The 3rd Edition Guidelines, *Table 1.2*[3], for the verification of microbial quality indicates that "*E. coli* or thermotolerant coliform bacteria must not be detectable in any 100mL sample" but goes on to say that "individual values should not be used directly from the Guideline tables." The guideline value should be used and interpreted with the information contained within the Guidelines (WHO 2004). In many cases, particularly in the developing world, it is difficult to achieve zero *E. coli* per 100mL sample, making the risk-based framework depicted in *Table 1.1* particularly useful.

Table 1.2 – Guideline values for verification of microbial quality[a] (WHO 2004)

Organisms	Guideline value
All water directly intended for drinking	
E. coli or thermotolerant coliform bacteria[b,c]	Must not be detectable in any 100-ml sample
Treated water entering the distribution system	
E. coli or thermotolerant coliform bacteria[b]	Must not be detectable in any 100-ml sample
Treated water in the distribution system	
E. coli or thermotolerant coliform bacteria[b]	Must not be detectable in any 100-ml sample

[a] Immediate investigative action must be taken if *E. coli* are detected.
[b] Although *E. coli* is the more precise indicator of faecal pollution, the count of thermotolerant coliform bacteria is an acceptable alternative. If necessary, proper confirmatory tests must be carried out. Total coliform bacteria are not acceptable indicators of the sanitary quality of water supplies, particularly in tropical areas, where many bacteria of no sanitary significance occur in almost all untreated supplies.
[c] It is recognized that in the great majority of rural water supplies, especially in developing countries, faecal contamination is widespread. Especially under these conditions, medium-term targets for the progressive improvement of water supplies should be set.

[1] WHO 3rd Edition Guidelines (2004) p. 97, Table 5.2.
[2] *E. coli* is a microbial indicator of faecal contamination in water, which is discussed in subsequent chapters of this thesis.
[3] WHO 3rd Edition Guidelines (2004) pp. 142-143, Table 7.7.

1.3 Ghana Background

Ghana is located in West Africa (*Figure 1.2*) and has a total area of about 240,000km^2 and a population of approximately 22.5 million. The climate is tropical in the south near the coast, and semi-arid towards the north. Although the official language of Ghana is English, more than 70 other local languages are spoken (Ethnologue 2007). 63% of the population is Christian, 16% are Muslim (mostly in the Northern region) and 23% follow traditional indigenous beliefs (CIA 2006).

Figure 1.2 - Map of Ghana (CIA 2006)

The current environmental concerns in Ghana include soil erosion due to deforestation and overgrazing, recurring drought in the north which affects farming, and inadequate supplies of potable water (CIA 2006).

The major diseases prevalent in Ghana are malaria, yellow fever, schistosomiasis (bilharzia), typhoid fever, guinea worm and diarrhoea. Diarrhoea is of particular concern since this has been identified as the second most common disease treated at clinics and one of the major contributors to infant mortality (Gyimah 2003), which currently stands at about 55 deaths per 1,000 live births (CIA 2006). Furthermore, the under-five childhood mortality rate is significantly higher in the Northern Region of Ghana, at 154 deaths per 1,000 live births (GSS 2004). The major cause of diarrhoeal disease is lack of safe and sufficient drinking water, hygiene, and adequate sanitation. After Sudan, Ghana has the highest incidence of dracunculiasis (guinea worm disease) in the world. 75% of these cases have been reported in Ghana's Northern Region (WHO 2006).

1.4 Pure Home Water

Pure Home Water (PHW) is a registered non-profit organization established in 2005 to promote household drinking water and safe storage (HWTS) products to low income customers in the Northern Region of Ghana (*Figure 1.3*). Currently, PHW's main focus is on the promotion and sale of ceramic pot filters, although there is hope to make a variety of HWTS products available, in the future.

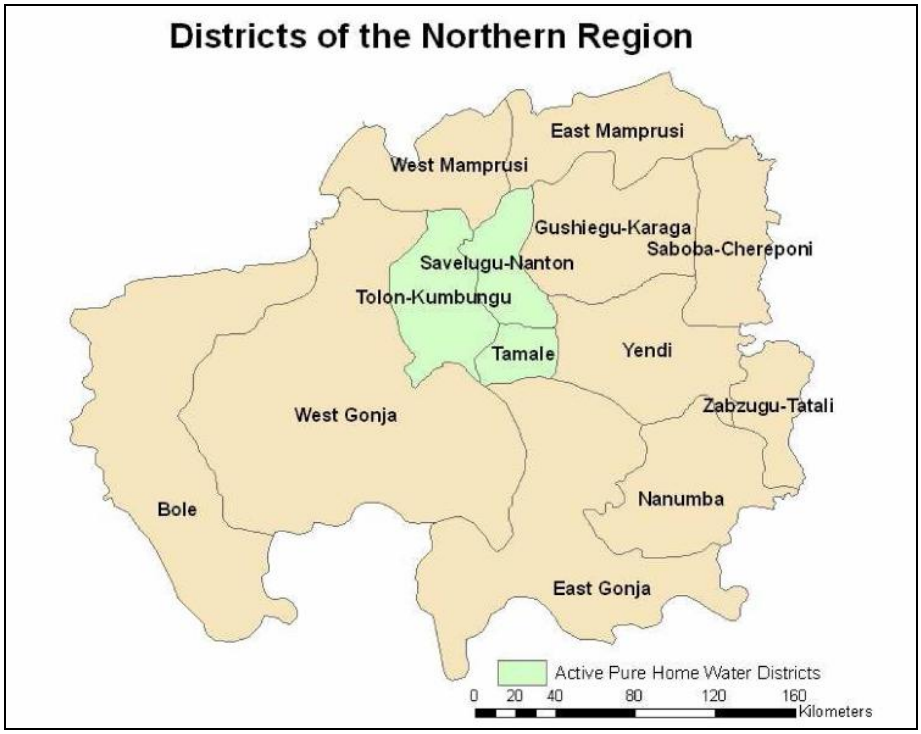

Figure 1.3 - Target Region of Pure Home Water in Northern Ghana (VanCalcar 2006).

1.5 Research Objectives

The objective of this thesis is to determine the technical feasibility of the SOLAIR method of solar disinfection of drinking water in the Northern Region of Ghana. Previously, SOLAIR had been tested in only one location (South Africa). This thesis sought to repeat the SOLAIR procedure under different solar radiation and meteorological conditions in West Africa.

This topic of research is in line with PHW's intention to offer a variety of HWTS products as it continues to grow, including the possibility of offering a solar disinfection product as a viable HWTS system, in the future. In particular, the use of larger (2-25L) high density polyethylene (HDPE) containers (SOLAIR) as an alternative to smaller (0.5-2L) polyethylene terephthalate (PET) bottles (SODIS) for solar disinfection of drinking water will be investigated.

2. Major Water-Related Diseases in Ghana

A few of the major water-related diseases prevalent in Ghana will now be discussed. Diarrhoeal diseases, guinea worm, typhoid fever and schistosomiasis can be significantly reduced if drinking water is treated to a level which is safe prior to consumption. Households that use Pure Home Water's ceramic filter, the *Kosim* filter, have been shown to have significantly lower rates of diarrhoea than households without the filter (Peletz 2006; Johnson 2007).

In addition to dissemination of ceramic water filters, PHW provides training in improved water supply, sanitation and hygiene. These initiatives help prevent other water-related diseases, namely guinea worm disease, typhoid fever and schistosomiasis, also common in PHW's project area. Brief overviews of each disease follow.

2.1 Diarrhoea

Each year 1.8 million people die from diarrhoeal diseases, and 90% of these deaths are of children under the age of five (WHO/UNICEF 2004). Diarrhoea is associated with loose, watery stool, dehydration and lowered resistance to other infections. *Figure 2.1* shows the percentage of children under the age of five with diarrhoea in Ghana, based on data from the Ghana Statistical Service, 2003:

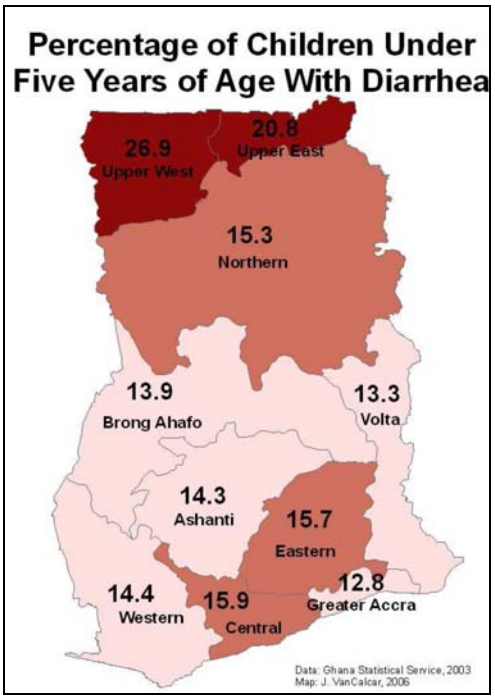

Figure 2.1 – Percentage of children under five with diarrhoea in Ghana (VanCalcar 2006)

Diarrhoea is often a symptom of diseases such as cholera or dysentery. All these diseases are faecal-oral in their transmission route, meaning that the pathogen passes from faeces and is subsequently ingested. Numerous studies have shown that diarrhoeal diseases

decrease with an increase in the quantity of water used, with an improvement in water quality, with improved sanitation and with improved hygiene (Cairncross 2003). Oral rehydration therapy (ORT) is an effective method for the control of diarrhoeal diseases. This is the oral administration of a solution consisting of sodium, a carbohydrate and water. A *simple* oral rehydration solution consists of salt, sugar and water. The aim of ORT is to minimize dehydration, which is one of the symptoms of diarrhoea that can lead to death (Victora 2000).

2.2 Guinea Worm Disease

Guinea worm disease, which is formally known as dracunculiasis, is a severely debilitating condition caused by the parasite *Dracunculus medinensis.* The disease is transferred to humans through contaminated drinking water containing cyclops (also known as *copepods* or *water-fleas*) that are the intermediate hosts of the larvae of the parasite. Once ingested the larvae grow into worms, of up to 1 metre in length, inside the human carrier's body before emerging from the skin about a year later; from the legs in most cases. The disease is rarely fatal but is extremely painful and severely debilitating (Hopkins 2005).

2.2.1 Current Status Worldwide

The Global Programme to Eradicate Dracunculiasis has continued to make great strides, reducing the number of endemic countries from 11 in 2004 to 9 in 2005. *Figure 2.2* shows a near exponential decrease in the number of dracunculiasis over the past 15 years or so:

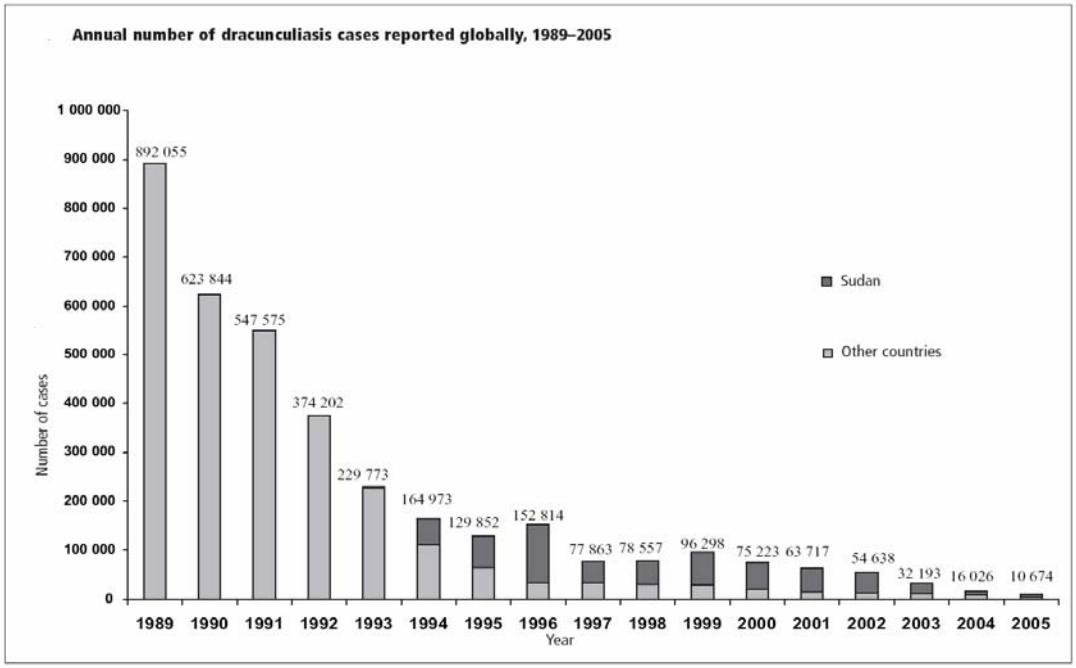

Figure 2.2 – Distribution of dracunculiasis cases reported monthly by country in 2005 (WHO 2006)

Over the course of the year in 2005, Sudan reported the most number of cases at about 5500, followed by Ghana at around 4000. Other countries where cases were reported include Burkino Faso, Ethiopia, Togo, Nigeria and Mali. No cases have been reported from outside of Africa. *Figure 2.3* shows areas in West Africa with the highest infection rates. The Northern Region in Ghana reported about 75% of the overall Ghanaian cases (WHO 2006). The most recent data shows that the total number of cases in 2006 was 4,132 from 605 communities, a 4% increase from the 3,981 cases in Ghana in 2005 (CDC 2007).

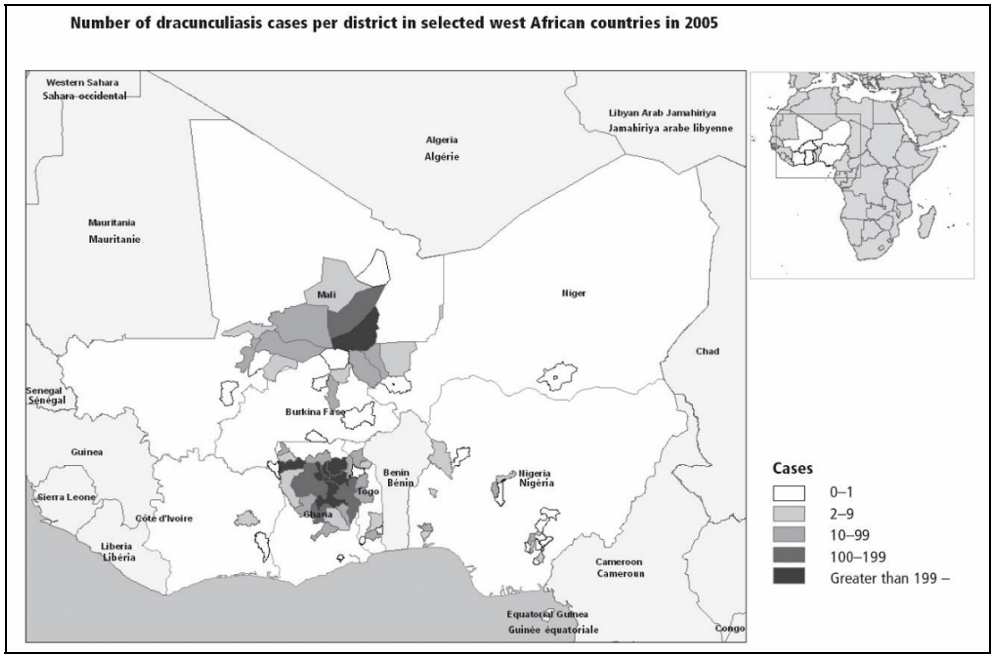

Figure 2.3 – No. of dracunculiasis cases in West Africa in 2005 (WHO 2006)

2.2.2 The Cyclops Vector

2.2.2.1 Biology

Cyclops (0.5 – 2mm in size) have a distinct "jerky" mode of swimming (*Figure 2.4*). Their natural habitat is in ponds and other pools of stagnant water, and their density is highest during the dry season when rivers and streams form shallow pools. Although cyclops live primarily in water, one observation suggests that they are able to survive out of water for at least 30 minutes. Copepod eggs are dispersed from place to place by humans, animals or floods (Rozendaal 1997).

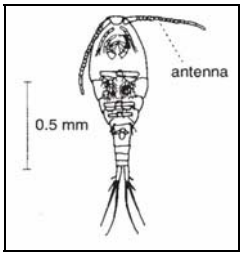

Figure 2.4 – Cyclops (Rozendaal 1997)

2.2.2.2 Transmission & Life Cycle

Figure 2.5 illustrates the various stages in the life cycle of a guinea worm. It is important to note that guinea worm larvae are released into the water once the worm emerges from the carrier's skin. This contact with the water usually occurs when the infected person is bathing, or has gone to collect water from the source.

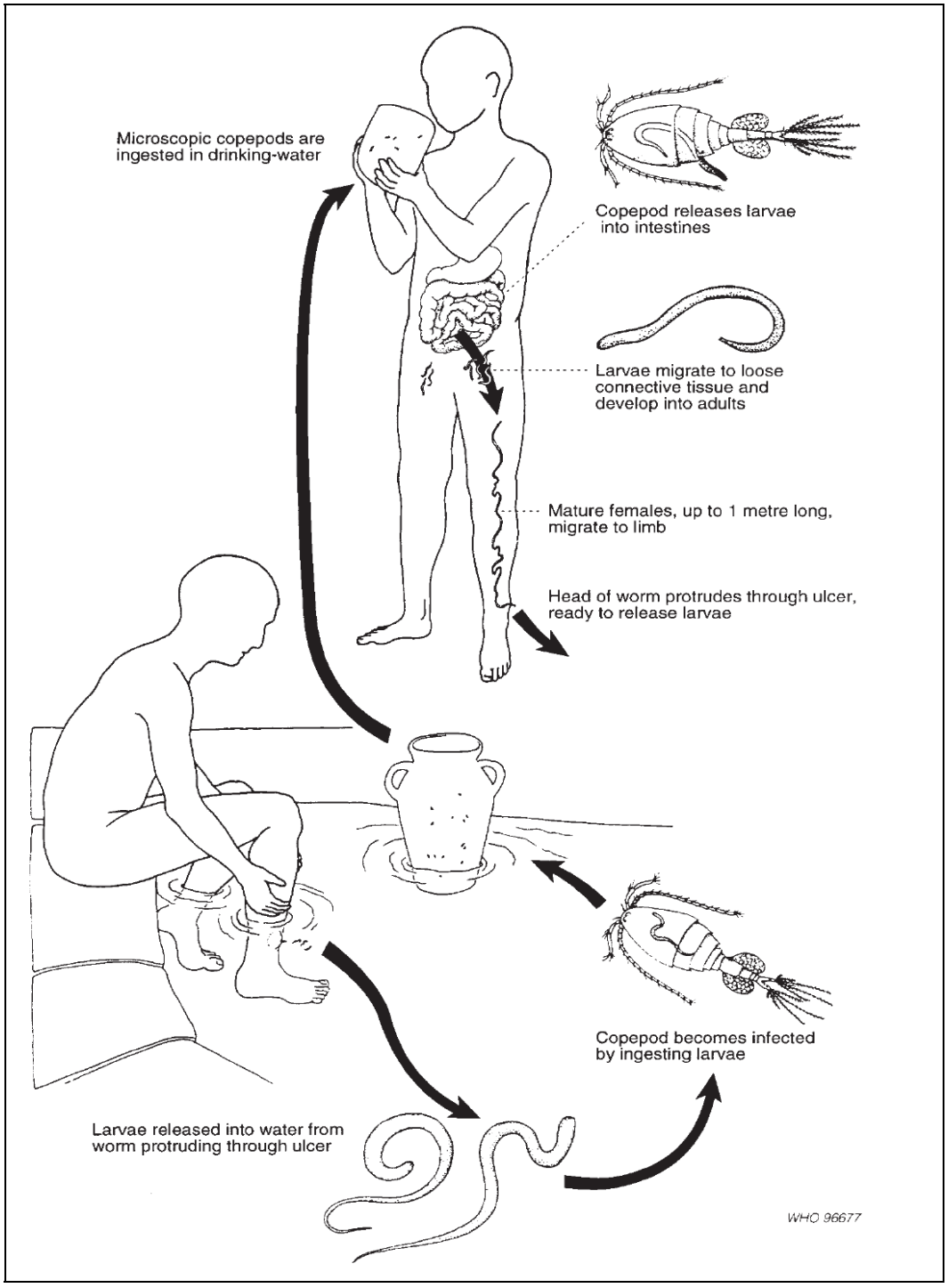

Figure 2.5 – Guinea worm life cycle (Rozendaal 1997)

Transmission of the disease will be greatest at accumulations of water where:

- the water is used regularly as drinking water
- the water is stagnant and contains copepods
- infected people enter the water

A typical example is a dug-out water source in West Africa (*Figure 2.6*). In West Africa, transmission is prevalent in the dry season since it is at this time when drinking water is found at fewer dug-outs or ponds, so the chance of infection increases (Rozendaal 1997).

Figure 2.6 – A typical dug-out water hole scenario (Rozendaal 1997)

2.2.3 Measurement of Cyclops Density in Water

A quick and practical measurement technique, as put forward by the U.S Centers for Disease Control and Prevention (CDC), for the estimation of the density of copepods, is described in *Appendix A* (CDC 2004).

2.2.4 Control Measures

Since guinea worm disease is contracted by drinking unsafe water, it can be eradicated entirely if populations living in endemic areas were provided with, and used, safe drinking water (Diamenu 1998). Vector control methods can also break the life cycle of the disease-carrying copepods.

2.2.4.1 Treatment

There are no effective drugs or vaccines against the disease itself and there is no natural immunity against it. Treatment of guinea worm disease is limited to the control of secondary infections, including abscesses, tetanus, and arthritis. Once the worm has emerged from the skin, it can be pulled out very carefully, over the course of several weeks, ensuring that the worm does not tear. Surgical removal of the worm is also possible, but this method is not readily accessible in regions where the disease is prevalent; regions which are mainly rural (Rozendaal 1997).

2.2.4.2 Prevention & Control

Guinea worm disease can be kept in check by either controlling the number of copepods in the drinking water sources, or by providing safe drinking water to the population. Methods of achieving this will now be discussed.

Filters

Filtration remains the best technology-based treatment method of preventing guinea worm transmission. The filters hold back all the copepods when water is poured through. Filters should have a pore size smaller than or equal to 0.15mm. The most common filter materials are cotton cloth and monofilament nylon or polyester. 100-120 micron (0.10-0.12mm) pore size nylon filters[4] (*Figures 2.7 & 2.8*) have been widely distributed, free of charge, throughout endemic areas by donors supporting the Guinea Worm Eradication Programme (GWEP)(CDC 2000).

The biggest disadvantage of the cotton cloth filter is that turbidity particles, such as clay and silt, quickly clog up the pores. The material is then difficult to wash out. The monofilament materials, however, do not become clogged and are easier to clean (Rozendaal 1997).

In 1997 a study done by Olsen et al., in the Northern Region of Ghana, compared the acceptability and effectiveness of the nylon and polyester monofilament filters. The reason for this study is that the polyester material was half the cost of nylon. 100 micron (0.1mm) woven nylon filters and "a knitted polyester cloth with an irregular mesh, whose size is not specified" (Olsen 1997) were the materials used. It was found that both filters completely retained the stages of copepods that are responsible for transmitting dracunculiasis. Furthermore, community pilot projects and surveys showed that the majority of the respondents found that the polyester filter was stronger, easier to clean out, and had a quicker filtering time, compared with the nylon filter (Olsen 1997).

[4] The nylon filter cloth distributed by GWEP is manufactured by Vestergaard-Frandsen. Price of the cloth filter is US$0.40-0.90 (Mortensen 2007). URL: www.vestergard-frandsen.com .

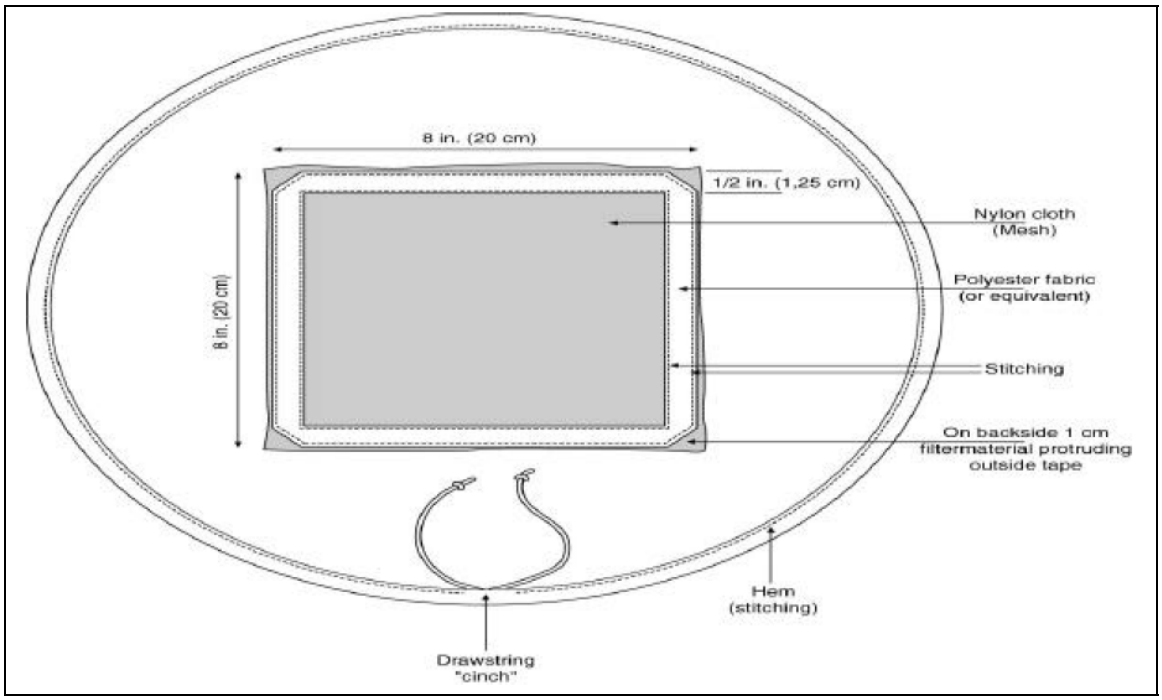

Figure 2.7 – Nylon cloth filter distributed by GWEP in Ghana (Mortensen 2007)

Boiling

Boiling the drinking-water will effectively kill the cyclops in the water. However, this is time consuming and, in most of the guinea worm endemic areas (rural), firewood is needed, which may be scarce (Rozendaal 1997).

Chemical

Temephos (Abate®) is an insecticide which can be used to kill cyclops. It is safe to use in drinking water, under a certain limit. This control method, however, is expensive and requires trained personnel. It is, therefore, usually reserved for use on small water bodies, and by special eradication programmes (Rozendaal 1997).

2.2.4.3 Guinea Worm Eradication Program

The global Guinea Worm Eradication Program (GWEP), run by the Carter Centre, has been instrumental in eradicating guinea worm disease from numerous countries. Currently, in Ghana, GWEP has a five part eradication strategy (CDC 2007):

1. Treatment of the source with Abate® larvicide.
2. Free treatment of patients done by surgically removing the worm.
3. Distribution of free monofilament nylon filters (*Figures 2.7 & 2.8*).
4. Conducting education campaigns.
5. Providing improved water supplies to endemic regions.

Figure 2.8 – Cloth filter distributed by the Guinea Worm Eradication Program

2.2.5 Current Status and Future Directions

Momentum is gaining towards the complete eradication of dracunculiasis thanks to the leadership of the Carter Centre and the support, dedication and services of numerous donor agencies. In light of the most recent data which shows that the total number of cases in 2006 was 4,132 from 605 communities, a 4% increase from the 3,981 cases in Ghana in 2005 (CDC 2007), it is clear, however, that the job is not yet complete[5].

2.3 Typhoid Fever

Typhoid fever is a disease caused by the *Salmonella Typhi* bacterium and is picked up by eating or drinking contaminated foods/beverages. As with diarrhoea, typhoid fever is transmitted via the faecal-oral route. Carriers shed *S. Typhi* in their stool before handling food/beverages, which in turn may become contaminated with the bacteria. Therefore, typhoid is most common in regions of the world where water supply is inadequate, handwashing is less frequent and water has a higher chance of being contaminated with sewage.

Typhoid fever is characterized by high fever, stomach pains, weakness, headache, chills and malaise. In extreme cases, delirium, intestinal perforation and death may occur.

Typhoid can be prevented by avoiding risky foods/beverages or by getting vaccinated against typhoid fever (CDC 2005). In the long term, however, areas which are provided

[5] "The rule of the final inch . . . The work has been almost completed, the goal almost attained . . . In that moment of fatigue and self-satisfaction it is especially tempting to leave the work without having attained the apex of quality . . . In fact, the rule of the Final Inch consists in this: not to shirk this crucial work. Not to postpone it . . . And not to mind the time spent on it, knowing that one's purpose lies . . . in the attainment of perfection." (Solzhenitsyn 1968).

with an improved water supply coupled with hygiene education programmes are likely to see a reduction in incidences of typhoid fever.

2.4 Schistosomiasis

Schistosomiasis, also known as bilharzia, is caused by parasitic flatworms (*Schistosoma* sp.). The intermediate hosts of the parasite are certain types of freshwater snails which prefer slow moving waters. *Figure 2.9* depicts the life cycle of schistosomiasis. Freshwater becomes contaminated with *Schistosoma* eggs when infected people defecate or urinate in the water. The eggs then hatch into larvae which infect the appropriate snails, in which the parasite grows (for ~1 month). The parasite then leaves the host and enters the water where it can survive for up to 2 days, during which time they can penetrate the skin of humans who are swimming, wading, washing or bathing in the contaminated water. Parasites then grows into worms, over several weeks duration, within the blood vessels of the body. These worms, in turn, produce eggs which are passed into the urine or faeces of the infected person, and the cycle continues.

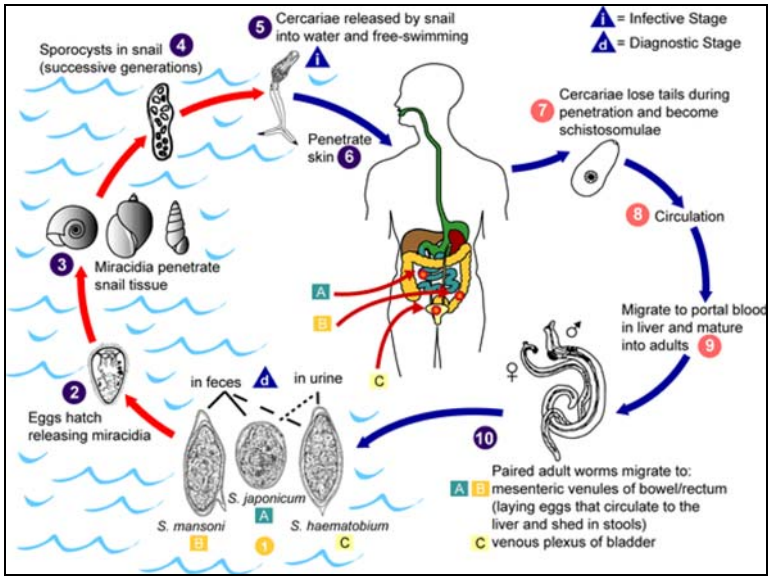

Figure 2.9 – Life cycle of schistosomiasis (CDC 2001)

Symptoms of schistosomiasis, which begin 1-2 months from the time of infection, include chills, fever, coughing and muscle aches. Repeated infection, occurring over many years, can damage the liver, intestines, lungs and bladder. Effective drugs are available to treat schistosomiasis.

The disease can be controlled by:

- Reducing snail populations – use molluscicides, change habitat (eg. minimize aquatic vegetation).

- Limiting human contact with contaminated water – provide safe water for consumption and washing, provide improved sanitation facilities, site development away from infected areas.

(CDC(2) 2004)

3. Solar Disinfection of Water

Solar water disinfection uses the sun's (solar) energy, which is an abundantly available and renewable resource, to kill pathogenic microorganisms that are present in raw water. It is a simple, low-cost and environmentally sustainable water treatment solution, particularly at the household level (EAWAG 2002).

3.1 History & Background

In 1984 Aftim Acra of the American University of Beirut in Lebanon first presented the idea of solar water disinfection, in a booklet published by the United Nations International Children's Emergency Fund (UNICEF)(Acra 1984). The birth of this novel technique of water purification led to extensive research being carried out by the Swiss Federal Institute for Environmental Science and Technology (EAWAG) in collaboration with EAWAG's Department of Water and Sanitation in Developing Countries (SANDEC), from 1991 onwards. Several field and laboratory tests have been conducted by these two departments, which has led to the adoption of solar water disinfection as an effective purification solution in several countries (EAWAG 2002). Numerous other organizations and universities have also conducted solar disinfection studies, including those done by Khayyat (2000), Oates (2001), Parsons (2002) and Flores-Cervantes (2003), at the Massachusetts Institute of Technology.

3.2 Theory behind Solar Water Disinfection

3.2.1 Solar Radiation

The sun continuously emits large amounts of solar radiation, or energy. This solar radiation can be broken down into sub-sections of energy radiated at different wavelengths. The diagram below depicts this energy band:

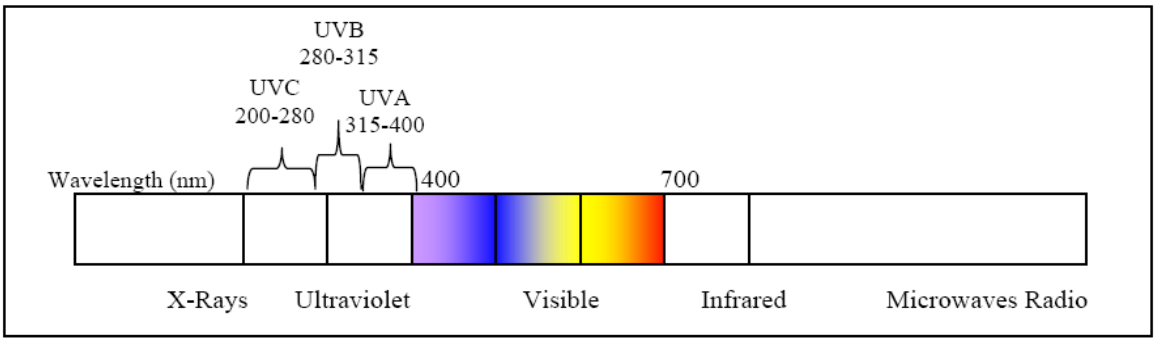

Figure 3.1 – Radiation bands vs. wavelengths (Flores-Cervantes 2003)

The UV band can be broken down into UV-A, UV-B and UV-C. Most of the UV-B and UV-C light is absorbed by the ozone (O_3) layer in the earth's upper atmosphere and, hence, very little reaches the surface of the earth. UV-A rays, however, reach the earth's surface, and it is this range of light that has been shown to have a lethal effect on many of the pathogens present in water.

In addition, the infrared range of light is absorbed by water, which raises its temperature, thereby creating a "pasteurization" effect in the water (EAWAG 2002). This pasteurization effect takes place at temperatures above 50°C (Wegelin 1994).

The location on earth will affect the favourability of solar disinfection (*Figure 3.2*). The most-favourable zone lies between the 15° and 35° parallels of latitude. This is because these regions are frequently semi-arid and have limited cloud coverage, thus allowing the most amount of direct radiation to reach the surface.
The next most favourable zone lies between the equator and 15° latitude. Incoming solar radiation is reduced since this zone is more humid, which leads to greater cloud formation. Nevertheless, solar radiation is still high in these regions (Acra, Karahagopian et al. 1984). It is pertinent to note that the Northern Region of Ghana lies within the most-to-moderately favourable zone.

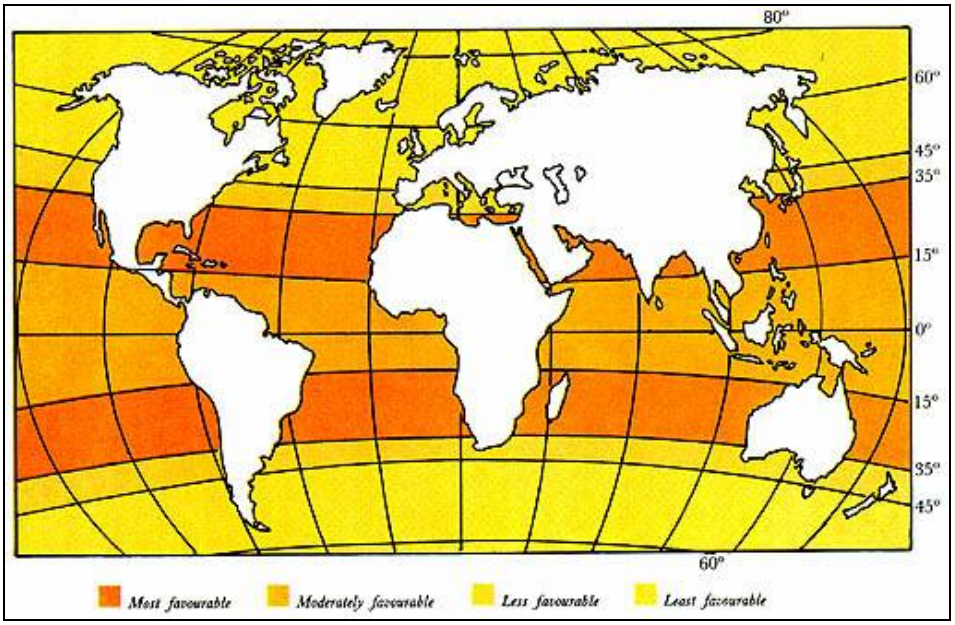

Figure 3.2 – Feasibility of solar disinfection based on worldwide location (Acra, Karahagopian et al. 1984)

The effect of clouds on incoming radiation available for solar disinfection is simply illustrated in the *Figure 3.3*, where the shaded bars represent the % of UV-A radiation reaching the earth's surface and the unshaded bars show the % of radiation in the visible spectrum reaching the ground. These bars are plotted against varying degrees of cloudiness:

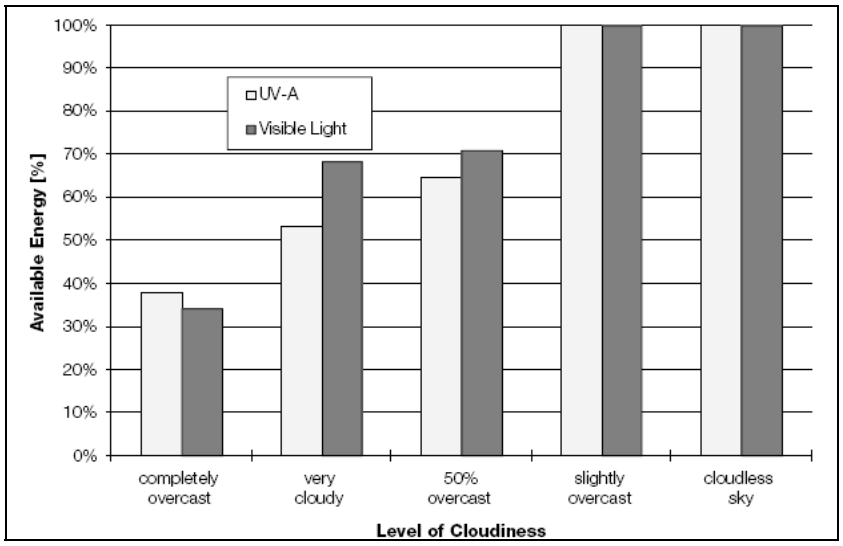

Figure 3.3 – Effect of cloudy skies on available solar energy (EAWAG 2003)

3.2.2 The Disinfection Process

There are 2 main forms of disinfection that are caused by exposure of water to solar radiation. Inactivation of pathogens is caused by:

1) **UV-A radiation**
    a. Direct alteration and mutation of pathogen cell deoxyribonucleic acid (DNA).
    b. Indirect breakdown of pathogen cells due to the photo-oxidative effect.

2) **Infrared radiation**
    a. High temperatures (>50^{o}C) eliminates some sensitive microorganisms.

A detailed description of each process follows.

3.2.2.1 DNA Alteration due to UV-A

This primary disinfection process is due to the UV-A radiation, which directly affects the DNA structure of several of pathogens found in water. The radiation causes cells to mutate which ultimately results in cellular death. Any repair mechanism that the cells may have are overpowered at a threshold of 500W/m^2 total[6] solar radiation, applied for approximately 6 hours (EAWAG 2002). The disinfection of the following list of microorganisms has been documented (EAWAG 2002):

[6] *Total* radiation is the radiation emitted by *all* spectrums of light.

Table 3.1 – Microorganisms inactivated by UV-A radiation (EAWAG 2002)

Type of Microorganism		Disease(s) Caused
Bacteria	• Escherichia coli (*E. coli*) • Vibrio cholerae • Streptococcus faecalis • Pseudomonas aerugenosa • Shigella flexneri • Salmonella typhii • Salmonella enteritidis • Salmonella paratyphi [13A/15/16]	➢ Enteritis ➢ Cholera ➢ Dysentery
Viruses	• Bacteriophage f2 • Rotavirus • Encephalomyocarditis virus [15]	➢ Diarrhoea, Dysentery
Yeast & Mould	• Aspergillus niger • Aspergillus flavus • Candida • Geotrichum [13A]	
Protozoa	• Giardia spp.* • Cryptosporidium spp.*	➢ Giardiasis ➢ Cryptosporidiasis

*"*Found under a UV lamp measured in the UV-C range. Although UV-C is not found in sunlight, it suggests these organisms would be sensitive to the UV-A portion of sunlight" (Oates 2001).*

It should be pointed out that solar disinfection does not *sterilize* the water. Organisms that are not harmful to human health, algae for example, may still remain in the water (EAWAG 2002).

3.2.2.2 Photo-Oxidative Disinfection & Effect of Dissolved Oxygen Concentration

UV-A radiation can lead to the formation of reactive oxygen free radicals and hydrogen peroxides if there is sufficient dissolved oxygen (DO) in the water (Miller 1998). These radicals then oxidize cellular components of the pathogens, such as enzymes, nucleic acids and membrane lipids, which kills the microorganisms (Reed 1997). Although this process is secondary to the direct destruction of the pathogens by UV-A, it will nevertheless augment the disinfection process. Therefore, the presence of dissolved oxygen plays an important role in destroying the microorganisms. *Figure 3.4* graphically compares the inactivation of bacteria, *E. coli* in this case, under both aerobic and anaerobic conditions:

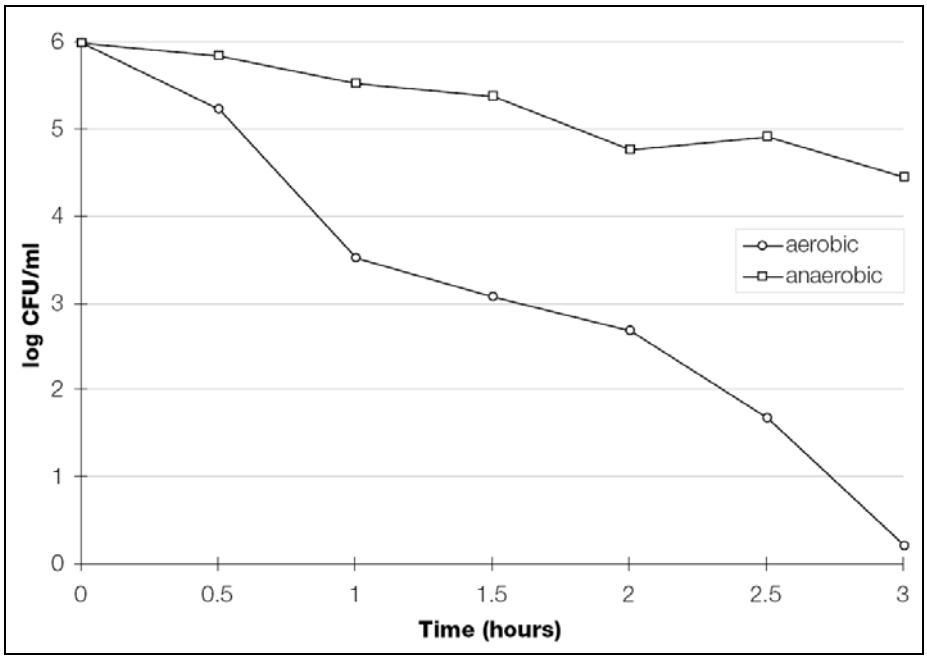

Figure 3.4 – Inactivation of *E. coli* under aerobic and anaerobic conditions (EAWAG 2003)

3.2.2.3 Thermal Inactivation & Effect of Temperature

Infrared radiation is absorbed by water, causing the water to heat up. Heating water to between 50°C and 60°C for one hour has the same effect as boiling the water, which would kill 99.9% of microorganisms (EAWAG 2003). Thus, the temperature of water plays a large role in increasing the rate of disinfection. *Figure 3.5* depicts the combined effect of both UV-A disinfection and thermal inactivation:

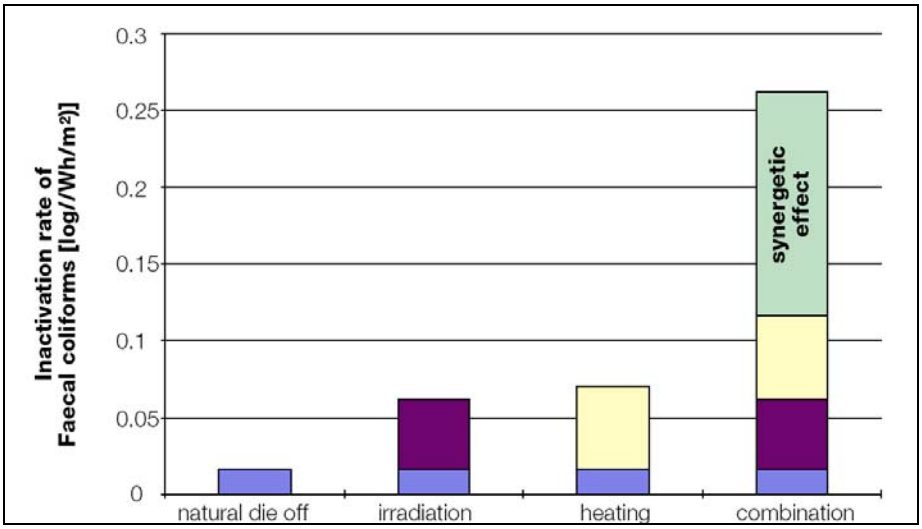

Figure 3.5 – Combined effect of UV-A and thermal radiation on solar disinfection (EAWAG 2003)

To explicate the effect of temperature on the disinfection process, EAWAG states that at a temperature of 30°C, 6 hours of mid-latitude midday sunshine (radiation fluence of 555W.hr/m^2 in the 350-450nm UV-A wavelength spectrum ≡ 3000W.hr/m^2 in the entire

wavelength spectrum) is required to achieve a 3-log reduction of harmful bacteria (faecal coliforms). At a temperature of 50°C, however, this reduction is seen at an equivalent exposure time of just 1 hour (or 140W.hr/m^2 of UV-A radiation for 6 hours) (EAWAG 2002).

3.2.2.4 Effect of Turbidity & Water Depth

Turbidity is the "decrease in the transparency of a solution due to the presence of suspended and some dissolved substances, which causes incident light to be scattered, reflected, and attenuated rather than transmitted in straight lines; the higher the intensity of the scattered or attenuated light, the higher the value of turbidity" (Ziegler 2002). Turbidity can be measured in Nephelometric Turbidity Units (NTU). Tests have shown that turbid water reduces the effectiveness of solar disinfection, since the suspended particles scatter the radiation by deflecting it in all directions. An increase in water depth also reduces the amount of radiation able to pass through the entire water column. *Figure 3.6* shows the % of UV-A radiation remaining in the water column at a certain depth of water, given varying turbidities:

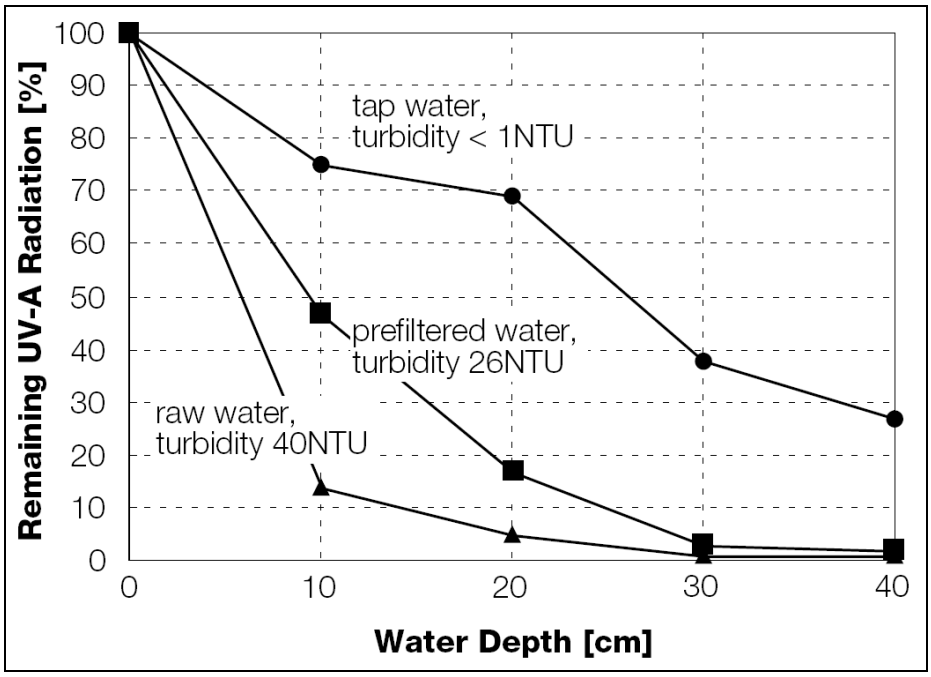

Figure 3.6 – Effect of turbidity & water depth on solar disinfection (EAWAG 2003)

Turbidity reduces the intensity of the solar radiation, protects microorganisms from being irradiated by concealing them, and hence, reduces the overall disinfection efficiency. It is, therefore, highly recommended that the turbidity of the water measure no more than 30NTU. If turbidity is >30NTU, it is necessary for a pre-disinfection turbidity removal step to be implemented (EAWAG 2002). Methods of turbidity removal will be discussed in greater detail in sections to follow, as this will be of great importance due to the high turbidity of some surface waters in Northern Ghana (Foran 2006).

3.2.2.5 Effect of Reflective Material & Painted Surfaces

A container with a foil or reflective backing may increase the rate of disinfection. Tests conducted in Dublin, Ireland by Kehoe et al. (2000) (*Figure 3.7*), using a water container with a foil backing, showed this increased rate, which is due to the higher effective UV-A radiation passing through the water (back and forth), and also due to the slightly higher temperatures achieved in the disinfection vessel (Kehoe 2000).

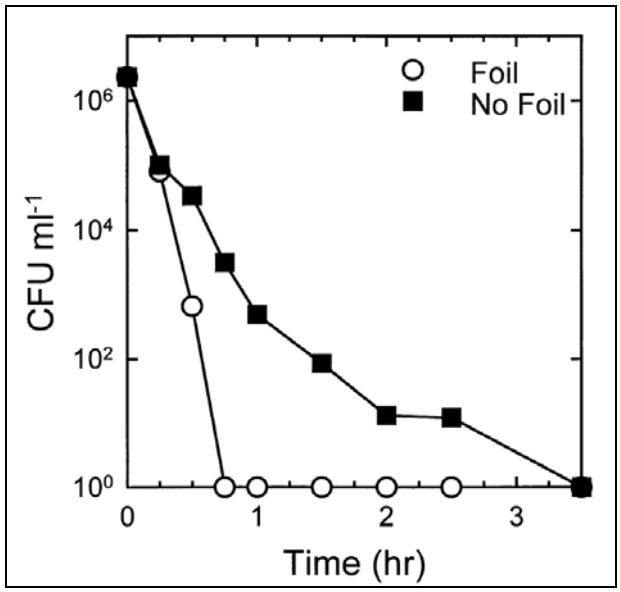

Figure 3.7 – Effect of reflective surfaces on solar disinfection (Kehoe 2000)

Painting the half of the container black whose face is not exposed to the sun, will result in a higher temperature, which will, in turn, lead to greater thermal inactivation of the microorganisms (EAWAG 2002). However, if the solar radiation is not sufficient to raise the water temperature to between 50°C and 60°C, at the site where solar disinfection is being undertaken, painting the lower face of the water container black may be of no use, as was found by Khayyat (2000) in Nepal.

3.2.3 Microbial Indicators

In order to test the efficiency of solar disinfection systems, EAWAG and SANDEC, along with most other SODIS researchers, have used indicator organisms. An ideal indicator organism meets these criteria:

- Present in high number in human faeces,
- Detectable by simple methods,
- Does not grow in natural waters,
- Persistent in water and similar to other water-borne pathogens.

It was, therefore, found that the *E. coli* faecal coliform suitably matched these criteria thereby making it a good indicator organism for verifying the quality of solar disinfected water. One particular advantage of measuring *E. coli* is that it is possible to do this with

portable field equipment under the difficult conditions that exist in some developing countries.

Total coliform bacteria and *total bacterial* counts cannot be used as an index of faecal contamination. However, they can be used as an indicator of treatment effectiveness (WHO 2004). Therefore, total coliform is used as an indicator by the MIT MEng teams, for technology testing, since frequently one finds no *E. coli* in influent water, leading to effluent values that show no improvement.

3.3 Solar Disinfection Systems

3.3.1 SODIS

The acronym SODIS has become synonymous with solar disinfection. However, solar disinfection of drinking water can take many forms, for example solar cookers are being used to disinfect drinking water in Kenya and elsewhere, and SOLAIR is yet another example. In this thesis, SODIS is defined as the technology that entails the solar disinfection of small quantities of water in transparent plastic bottles or bags.

The SODIS technology considers all the solar disinfection variables, as discussed previously, and combines them in order to provide a safe, disinfected product. SODIS comprises numerous stages which will now be discussed at greater length.

3.3.1.1 Choice of Characteristic Vessel

The two main types of vessel recommended for SODIS are plastic polyethylene terephthalate (PET) *bottles* and thick, clear, plastic polyethylene *bags*, since both are good transmitters of UV-A light. Polyvinylchloride (PVC) bottles are also effective light transmitters but are not recommended since they contain a high number of artificial additives which may harm human health. Some types of glass bottle can also be used. The type of glass to be chosen largely depends on the concentration of iron oxide in the glass (EAWAG 2002). The following table provides a comparison between the various vessel types:

Table 3.2 – SODIS vessel comparison

	Advantages	Disadvantages
PET bottles	❑ Low weight ❑ Chemically stable ❑ Durable ❑ Neutral in taste ❑ Low cost	❑ Treats small quantities ❑ Limited heat resistance ❑ Ageing effects (eg. scratches) ❑ Plastic is an environmental problem
Glass bottles (Corex,Pyrex,Vycor)	❑ Ageing resistant ❑ Limited ageing	❑ Treats small quantities ❑ High cost ❑ Heavy ❑ Easily smashed
Polyethylene bags	❑ Low weight ❑ Small bulk ❑ Fast & efficient disinfection	❑ Treats small quantities ❑ Limited heat resistance ❑ Ageing effects (eg. scratches) ❑ Plastic is an environmental problem ❑ Treated water smells of plastic ❑ Not durable

In order to optimize solar disinfection efficiency it is recommended that the vessel have a volume of less than 2L and that the depth of the water column facing the sun is less than 10cm. SODIS efficiency will also be augmented if the vessel is placed on a reflective surface (to increase effective UV-A radiation) (Kehoe 2000) or if the bottle is placed on a dark surface (to increase temperature and, hence, thermal inactivation) (EAWAG 2002).

Usually, the choice of characteristic vessel is determined by local availability.

3.3.1.2 SODIS Method

As previously stated, the water to be disinfected should have a turbidity of <30NTU. If the original turbidity is higher than this value, the water needs to be pre-filtered or coagulated.

The SODIS procedure, as recommended by EAWAG/SANDEC (2002), is as follows:

> *Water is poured into the selected vessel up to the half way point of the container. The receptacle is shaken vigourously for up to 1 minute to increase the dissolved oxygen concentration in the water. This will increase the rate of photo-oxidative disinfection occurring in the water. The vessel is then filled to the top with water. It is important to fill the container to the brim, in order to avoid the formation of air bubbles which can reduce radiation penetration*[7].
>
> *The bottle is now exposed to the sun for a duration ranging from 3 hours to 2 days (duration is dependent on location, altitude, cloud cover, time of day etc.).*

[7] This procedure can be found at http://www.sodis.ch/Text2002/T-Howdoesitwork.htm & http://www.sodis.ch/Text2002/T-FAQ.htm .

The exact exposure time needs to be properly verified before solar disinfection is undertaken.

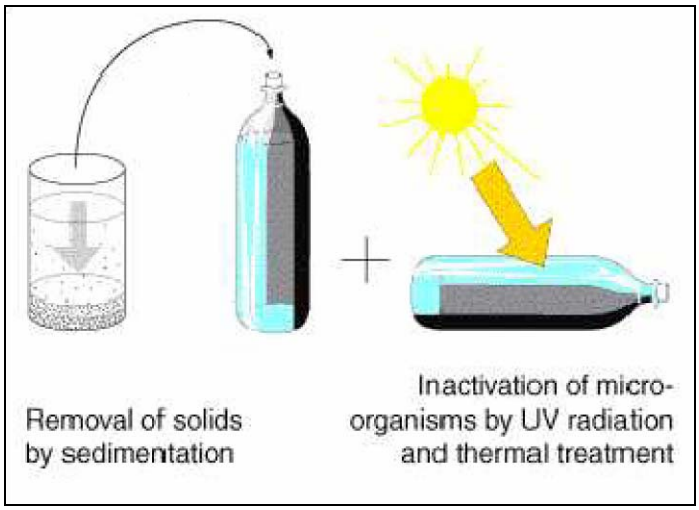

Figure 3.8 – SODIS put simply (Flores-Cervantes 2003)

Assuming such verification has occurred and proper procedures have been followed, the resultant water is now ready for safe consumption. Great care should be taken to prevent recontamination of the water by practicing effective safe storage methods of the treated water and by cleaning the bottles before re-use.

3.3.2 SOLAIR

SOLAIR is a modification of the SODIS technology which substitutes the typical SODIS vessel types (PET or glass bottles, polyethylene bags) with larger HDPE containers. Whereas SODIS vessels are 0.5-2L, SOLAIR containers are typically 2-25L. SOLAIR is a solar disinfection system on which **particular emphasis** is placed on the inactivation of pathogens by the **photo-oxidative process**. SOLAIR uses both UV radiation and oxygen to purify water. In essence, SOLAIR is a variation of the SODIS system, modified to make it more applicable and practical, especially in a rural context. SOLAIR was developed by Meyer et al. (1999, 2000, 2001) whose research was conducted in rural South Africa.

3.3.2.1 Choice of Characteristic Vessel

Meyer et al. (2000) wished to use a container that is representative of those commonly used in rural South African communities. The UV intensities inside HDPE plastic containers of various colours (translucent, white, red, blue, yellow, black) were measured:

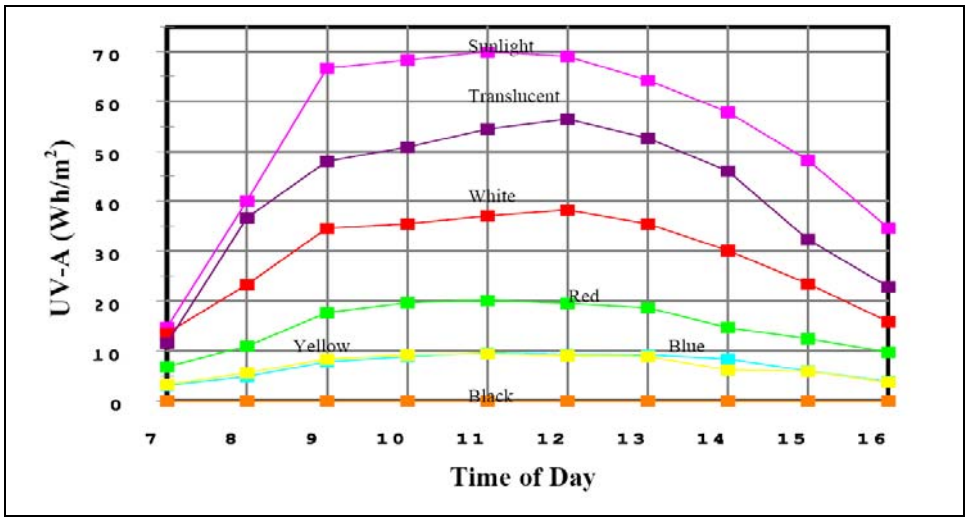

Figure 3.9 – UV-A radiation in different coloured containers (Meyer 2001)

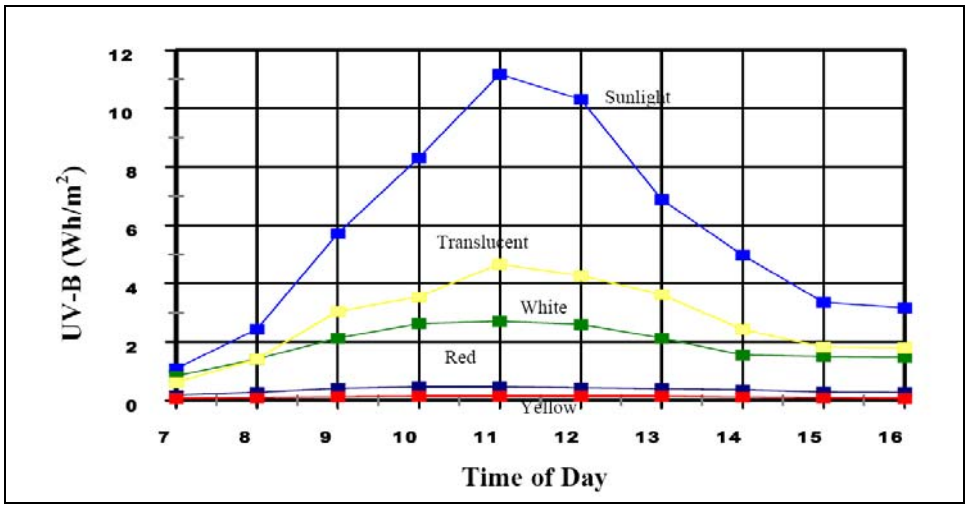

Figure 3.10 – UV-B radiation in different coloured containers (Meyer 2001)

Meyer (2001) determined that the translucent or white containers would be the most suitable for SOLAIR as these let through the most UV light. The white containers, which allow the second highest amount of UV radiation through, were chosen for the Meyer (1999, 2000, 2001) field tests as this type of container would be more readily available in the local communities.

The volume of the container will also affect the efficiency of the disinfection process:

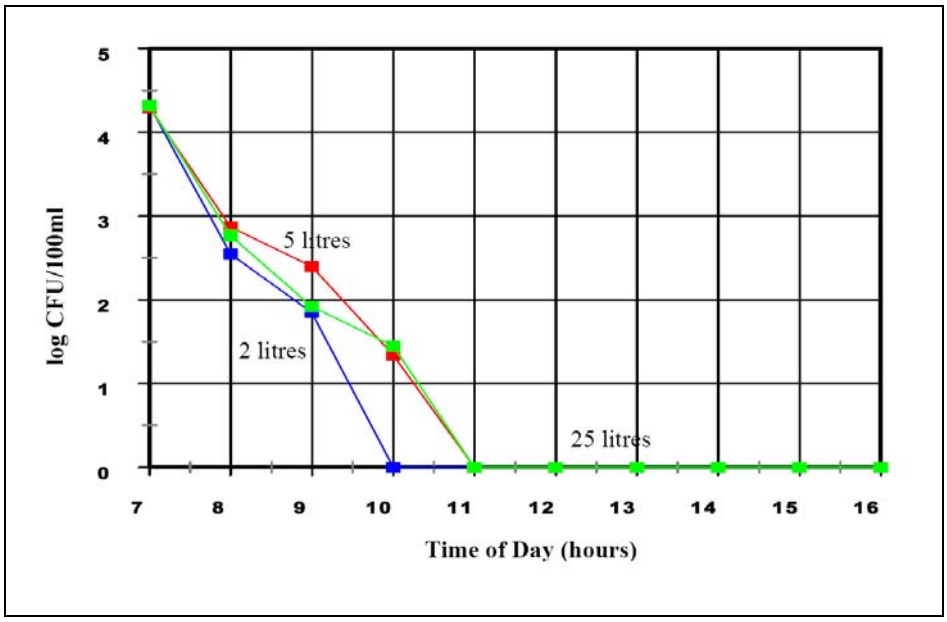

Figure 3.11 – Effect of volume of container on SOLAIR *E. coli* reduction efficiency (Meyer 2001)

It can be seen from Meyer's data shown in *Figure 3.11* that the 2L volume showed a complete reduction in *E. coli* over 3 hours whilst the 5L and 25L showed this complete reduction in 4 hours. It is interesting to note that despite the inherently large difference in volume between the 5L and 25L containers, both containers display the same disinfection efficiency.

3.3.2.2 SOLAIR Method used in Field Tests in South Africa

As with SODIS, so too in SOLAIR, the turbidity of the water should be reduced to below 30NTU before solar disinfection occurs.

Furthermore, "intermittent vigorous shaking is important to dissolve and distribute the oxygen throughout the whole volume of water and to ensure the contact of all organisms in the water with the absorbed ultraviolet light"[8] (Meyer 1999).

[8] With regard to SODIS, EAWAG (2003) states that "aeration can be achieved by stirring the raw water vigorously before filling the SODIS containers or by shaking the half-filled containers thoroughly and filling them completely before sunlight exposure. Especially stagnant water drawn from ponds, cisterns and possibly wells should be aerated to enhance the inactivation of microorganisms by SODIS".

The SOLAIR method used in field testing by Meyer (1999) is as follows:

> *The container is first filled with water, up to the about the ¾ mark of the container. The vessel should then be closed and shaken vigorously for 5 minutes, in order to increase the amount of dissolved oxygen (DO) concentration in the water. As with SODIS, the purpose of increasing the DO concentration in the water is to ensure there is enough oxygen that can be converted into free radicals by the UV light. These free radicals will then destroy the microorganisms.*
>
> *The container is then placed in direct sunlight and shaken every hour thereafter. As previously stated, the shaking not only aides the dissolution and distribution of oxygen in the water, but also re-distributes the pathogen population to various parts of the water column, which brings them in contact with the varying radiation intensities in the container (Meyer 1999).*

3.3.2.3 Field Test Results

Field tests were performed by Meyer et al. (2000) at one site in rural South Africa. A 25L white receptacle was used in the tests. The following coliform reduction results were obtained for the SOLAIR system, compared with 2 experimental control set-ups:

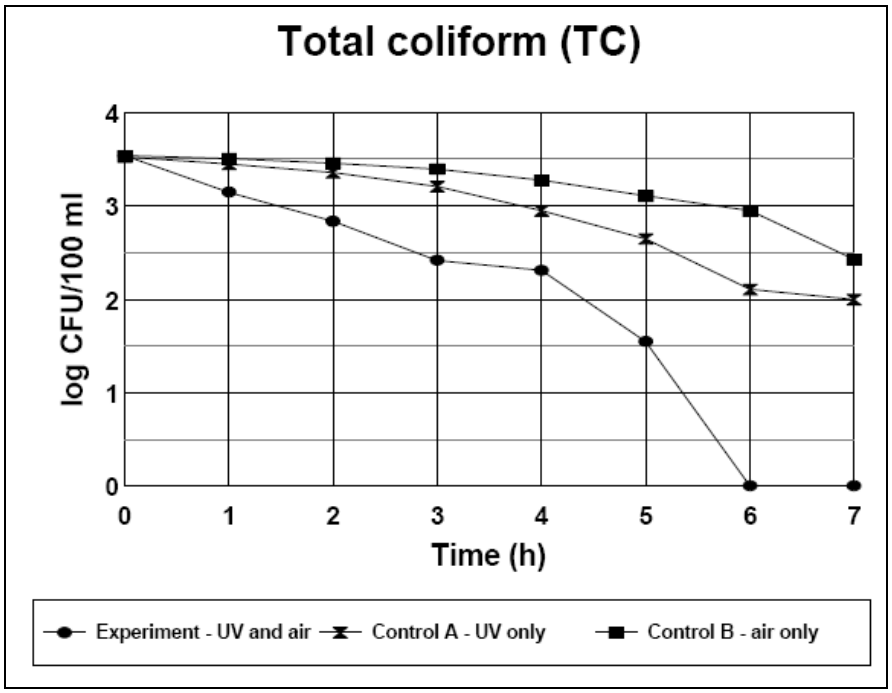

Figure 3.12 – Total coliform concentrations over SOLAIR experimental duration (Meyer 2000).
-Control A was de-oxygenated, by bubbling nitrogen through it, and placed in direct sunlight.
-Control B was kept in a dark room (Meyer 2000).

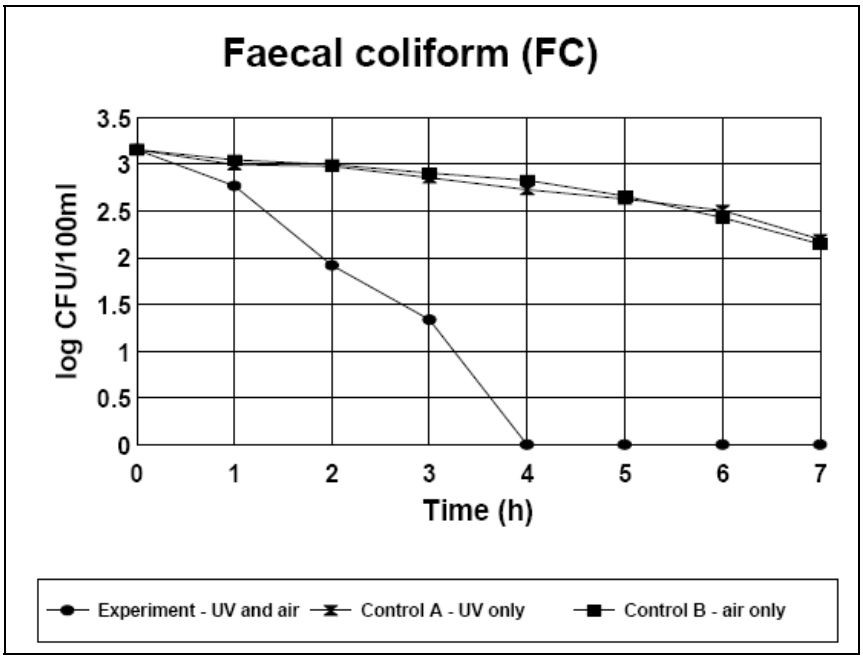

Figure 3.13 – Faecal coliform concentrations over SOLAIR experimental duration (Meyer 2000)

After a 24 hour lag period following the successful completion of these SOLAIR tests, no re-growth of bacteria was observed indicating that these cells were irreversibly damaged or killed by the disinfection process (Meyer 2000).

It is important to note that Control A was an *anaerobic* system, whilst SOLAIR is aerobic. No comparison between two *aerobic* systems (one with shaking and one with no shaking) was done in Meyer's study. Therefore, the ability to increase the DO concentration, which translates into a potential increase in photo-oxidative disinfection, in a natural source (aerobic) water, by shaking, was not investigated.

In a separate experiment, Meyer (2001) showed SOLAIR achieving complete disinfection over 8 hours, using water with a turbidity of 280NTU. The turbidity was *artificially* increased to 280NTU using calcium carbonate.

3.3.2.4 Conclusions

Meyer et al. (2001) drew the following conclusions:

- SOLAIR is applicable and effective in volumes of water between 2L and 25L, based on results obtained in South Africa.
- White/translucent HDPE containers are reasonable transmitters of UV light, and can be used.
- Visible turbidity (say, <30NTU) should be removed before performing SOLAIR disinfection.

- The containers should be kept closed, with a lid, and must be exposed to full and direct sunlight at all times.
- Intermittent vigorous shaking is very important during the disinfection process. This dissolves and disperses the diffused (some oxygen enters the vessel by diffusion through the container) and dissolved oxygen throughout the entire water column and ensures contact of all microorganisms in the water with the UV light entering the receptacle.
- A minimum of 4 hours irradiation is required for effective faecal coliform disinfection in sub-tropical latitudes. Exposure time is dependent on the various factors, as discussed in previous sections of this chapter.
- Unlike chlorination or other chemical disinfection processes, no residual disinfectant is available after the SOLAIR process. Therefore, secondary contamination of the water should be prevented through the practice of safe storage and good hygienic practices.

3.3.3 System Comparison

The table below compares the advantages and disadvantages of the SODIS and SOLAIR systems:

Table 3.3 – Comparison of SODIS and SOLAIR

	Advantages	Disadvantages
SODIS	❑ Low cost ❑ Simple ❑ Widely known & studied; practiced in 34 countries (Murcott 2007) ❑ Proven through health impact studies (Conroy 1996; Rose 2006)	❑ Treats small quantities (<2L) ❑ Requires many small, transparent bottles or bags, which can be impractical and laborious and may not readily provide sufficient quantities of safe water, depending on family size and need ❑ Bottles and bags could pose an environmental problem ❑ Containers are less durable and need frequent replacement ❑ Inadequate user knowledge and implementation can lead to poor use of system so *education is key*
SOLAIR	❑ Low cost ❑ Can use containers that are representative of those commonly used by many local communities world-wide (eg. white jerry can-type containers). ❑ Treats larger quantities (2-25L), making it more practical and less laborious ❑ Containers are more resilient ❑ Simpler and more practical in a rural context	❑ Requires intermittent shaking [according to Meyer (1999, 2000, 2001)] of container which may be laborious ❑ Not widely studied ❑ Inadequate user knowledge and implementation can lead to poor use of system so *education is key*

Considering the aforementioned advantages and disadvantages, it can be seen that SOLAIR has potential benefits that could make it a more feasible and practical method of solar disinfection than SODIS. This is chiefly due to the ability to use a larger water container, and one that is more likely to be available in a rural setting (translucent/white jerry can-type container).

4. Turbidity Removal Alternatives

As stated previously, for solar disinfection to be effective, the turbidity of the water should be <30NTU. There are various methods of reducing the amount of particulate matter in highly turbid waters, the simplest of which include sedimentation, coagulation, flocculation, and filtration.

4.1 Sedimentation

Sedimentation is a process of solid-liquid separation that allows suspended particulates to settle to the bottom of the water vessel or tank. A common method of sedimentation is to simply store and allow the water to settle. After several hours or more, the supernatant can then be poured off from the top of the container. Settling for one day can lead to a substantial reduction in turbidity and >50% reduction in bacteria due to natural die-off (WELL 1999), since conditions within the container are generally not conducive to their survival. In waters where the suspended particulate is very fine (clay particles), sedimentation may not occur even after allowing the water to stand for several days (WELL 1999).

4.2 Filtration

For hundreds of years, various types of filters have been used to separate particulate matter from water. The basis of filtration is to physically strain, or capture, particles that are larger than the effective pore size of the filter.

4.2.1 Cloth & Monofilament Materials

These filters are simply pieces of material which, when water is poured through them, strain out particles larger than the pore size of the material. Two common sets of fabrics used are cotton cloth and monofilament materials.

Cotton cloth is generally a poor filter material, especially when dealing with very turbid waters. They are not easy to clean and get clogged up easily (Rozendaal 1997).

A more effective alternative to the cotton cloth material is the monofilament filter. These filters are generally made from synthetic materials such as nylon (which come in varying pore sizes) (Decotex Inc. 2006) or polyester. Synthetic materials are advantageous in that they are easier to clean than cotton cloth filters.

4.2.2 BioSand

The BioSand filter (BSF) is an intermittent, household-scale slow sand filter. These filters are mainly used in individual households, with the most common type of BSF being a concrete or plastic container approximately 1m high with 0.3m sides. Water is then poured and allowed to trickle through the sand-filled container with the resulting filtered water available via an outlet pipe. The top layer of sand is particularly crucial in

that a bioactive layer grows here. This layer helps to reduce disease-causing organisms. A perforated plate is usually placed on top of the sand to prevent disruption of the bioactive layer when water is poured through. The BSF has a flow rate of up to 60L/hr, depending on the size of the unit.

Tests have shown that the filter removes a large amount of the turbidity, as well as between 80% and 100% of the bacteria and protozoa if it is properly used and maintained. Less than 90% of the indicator viruses are also removed. The disadvantages of this system are that it is relatively expensive, bulky and requires a certain level of technical knowledge and maintenance, in order for the system to run efficiently (CAWST 2007).

4.2.3 Ceramic

The most common form of ceramic filter is the *candle filter* (0.2 to 1 micron pore size). This type of filter is usually made up of a cast hollow porous ceramic tube (candle), which is mounted between an upper layer, where untreated water is poured, and a lower layer, where filtered water collects. This filtration process removes most bacteria and protozoa but little of the virus population (modifications can remove virus removal).

Although the cost of purchasing the initial system (including container) poses a potential challenge to low income groups, replacement candles are relatively inexpensive. The cheaper candles, however, can sometimes be of poor manufacturing quality (Franz 2005).

Another type of ceramic filter is the *pot filter* (0.2 to 1 micron pore size) (Lantagne 2006; van Halem 2006), also referred to as the "Filtron" or the Potters for Peace (PFP) filter. This system consists of a porous clay pot (~10L) fitted over a collection vessel (usually plastic, holding 20-30L). As with the candle filter, most protozoa and bacteria are removed, with little virus removal.

The clay pot filter is available in the Northern Region of Ghana, as part of the Pure Home Water initiative. It has a substantially lower flow rate (1-3L/hr) compared to the BSF and is susceptible to breakage. Furthermore, highly turbid waters will rapidly clog up the system.

4.3 Coagulation

Coagulation is the electrochemical process of aggregating the suspended and colloidal particles in water. These aggregates are called "flocs", which are heavier and settle out at a faster rate due to the increased gravitational effect.

In order to optimize coagulation, there are 3 mixing regimes which should be adhered to. These are:

- *Rapid Mix* – once the coagulant has been added, the water is mixed rapidly in order to distribute the coagulant evenly amongst the suspended particles.

- *Gentle Mix* – after rapid mixing the water, a more gentle mix regime should be adopted. This promotes particles to aggregate (without breaking up) in a process called flocculation. If the duration of gentle mixing is insufficient, then poor agglomeration of particles results.
- *Settling* – after flocculation, the water is left to stand, giving time for the flocs to settle (Luu 2000).

Once the particles have settled, the supernatant water can be decanted or filtered. The following table shows the factors which generally affect coagulation:

Table 4.1 – Factors affecting coagulation (Luu 2000)

Coagulant Characteristics	Physical Characteristics	Raw Water Characteristics
• Coagulant type • Coagulant dose • Proper solution makeup and dilution • Proper coagulant age	• Settling time • Mixing intensity • Mixing time • Coagulant addition point • Proper coagulant feed	• Suspended solids • Temperature • pH • Alkalinity • Presence of microorganisms and other colloidal species • Ionic constituents (sulfate, fluoride, sodium, etc.)

4.3.1 Aluminium Sulphate (Alum)

Aluminium sulphate, or *alum* as it is usually called, is the most commonly used coagulant world-wide. It is found as a white to off-white lump or powder (ChemicalLand21.com 2006). Iron salts such as ferric chloride and ferrous sulphate are widely used coagulants.

In Northern Ghana alum is locally available in the form of alum balls at a cost of US$0.03 per ball (Foran 2006). One economic consideration in trying to reduce the cost of the alum per litre of water treated, is to determine more precisely the number of "uses" each alum ball is able to provide.

4.3.2 Procter & Gamble PuR Packets

The Procter & Gamble Company (P&G) has developed a system which incorporates both the coagulation step and the disinfection step of treating raw water. This product is called the *PuR* water-purifying sachet. Each one of these small packets contains a coagulant (ferrous sulphate) and a disinfectant (calcium hypochlorite) and is able to purify 10L of water.

Once the contents of the sachet are added to water, the solids are allowed to settle, before the water is then filtered through a cloth into a second container where it is left to stand for 20 minutes; enough time for the calcium hypochlorite to inactivate the microorganisms. This dual coagulation and disinfection process results in high removal

rates of bacteria, viruses and protozoa, even in highly turbid waters. Heavy metals, such as arsenic, can also be removed by this process.

P&G's distribution of its PuR packets is focused in two areas; for emergency relief and to local Non-Governmental Organizations (NGOs). The distribution of the product is done in a break-even, non-profit model manner (P&G 2006).

4.3.3 Moringa Oleifera Seeds

Moringa Oleifera (Moringaceae) is a tree which is grown and cultivated in many tropical and sub-tropical regions in the world, including in Ghana. The seeds of this tree have coagulation properties. The most widespread use is at the household level. The seeds are first crushed then added to a small quantity of water to create a stock solution. The solution is then added to water following which the normal coagulation mixing regime is followed. One major advantage of the Moringa seeds is that they, unlike alum, are effective regardless of the pH of the water. Furthermore, it does not change the natural alkalinity of the water (Katayon 2005).

Studies have shown that Moringa seeds show turbidity reduction efficiencies of greater than 80% (Dorea 2006), with this percentage higher in waters with a higher initial turbidity:

Sample	*Moringa oleifera* concentration ($mg\ l^{-1}$)	Turbidity (NTU)		Turbidity removal (%)
		Initial	Final	
Medium turbidity	160	87.8 ± 2.1	21.3 ± 1.7	79 ± 2.0
High turbidity	300	194 ± 3.8	22.0 ± 2.2	89 ± 3.2
Very high turbidity	400	390 ± 4.5	23.6 ± 3.6	94 ± 4.1

Figure 4.1 – Optimum dosage of Moringa Oleifera for waters of differing turbidity (Katayon 2005)

Studies have shown that Moringa seeds are capable of reducing turbidity as effectively as coagulant chemicals such as alum (Dorea 2006). However, this turbidity removal method is dependent on the local presence of Moringa trees. If these trees are present, the use of its seeds by households can be realized at a very low to nil cost.

4.4 Comparison of Turbidity Removal Methods

The following table compares the turbidity removal methods:

Table 4.2 – Comparison of turbidity removal methods

Removal Method		Advantages	Disadvantages	Annual Cost[9]
SEDIMENTATION	Settling	• Easy technique • Cheap; only cost is in purchase of storage vessel(s)	• Can be slow • May not remove fine clay particulates	<US$1
FILTRATION	Cloth Material	• Easy to use • Widely available	• May not lower turbidity to <30NTU (required for solar disinfection)	<US$1
	BioSand	• Long life • Removes large amount of turbidity, bacteria & protozoa	• Bulky • Difficult to transport • Requires some technical knowledge • Requires regular maintenance	<US$1
	Ceramic	• Long life • Removes large amount of turbidity, bacteria & protozoa • Easy to use	• Cheap candle filters are often poor quality • Pots difficult to transport • Susceptible to cracking and breakage • Low flow rate	<US$1
	Alum	• Very effective in removing particles • Widely available • Treats large amounts of water	• Complex mixing regime and dosing	US$10-20[10]
COAGULATION	PuR	• Easy to use • Quick • Residual disinfection • Treats relatively large amounts (10L) of water	• Packets may pose an environmental problem • Many steps • Much equipment required • Virus removal	US$50-100[11]
	Moringa	• As effective as most chemical coagulants	• Not available in all locations • Effective regardless of pH • Does not change alkalinity of water	US$1-5

[9] Estimates based on annual quantity of water used by a typical household (Murcott 2006)

[10] Assumes $0.01/coagulant dose treating 10L, requiring four treatments per day per family x 365 days per year = $14.60. In practice, the amount used would likely be lower (Murcott 2006). Coagulant price may vary depending on location.

[11] Assumes $0.05/ sachet treating 10L, requiring four sachets per day per family x 365 days per year = $73. In practice, the amount used would likely be lower (Murcott 2006).

4.5 Summary – Turbidity Removal Alternatives

The main aim of selecting one of the aforementioned particle removal methods is to lower the turbidity to <30NTU, which is the allowable range for solar disinfection. All of the processes also remove a large percentage of the bacteria and protozoa populations, which attach to particles in water. All these approaches add an additional treatment step and, therefore, increase the complexity, labour and, in most cases, the financial cost of treating the water. It would therefore be most appropriate to select a system which removes the most turbidity at the lowest cost, and, to select a system that is available in the target location.

SECTION II – SOLAR DISINFECTION IN NORTHERN REGION, GHANA

5. Methodology of Testing

5.1 Experimental Setup

5.1.1 SOLAIR

The SOLAIR experiments were carried out using two 10L translucent HDPE containers, whose original use was to store cooking oil, purchased from the market in Tamale, Ghana. One was used for SOLAIR (sunlight & shaking), whilst the other was used as a control (sunlight & no shaking):

5.1.1.1 Apparatus

- Two 10L translucent HDPE containers
- 100 micron monofilament nylon filter[12]

Figure 5.1 – SOLAIR experimental set-up

5.1.1.2 Procedure

1. Clean the containers thoroughly with detergent and rinse several times.
2. Fill each container up to ~3/4 mark with raw water, passing water through the nylon cloth filter in order to remove the guinea worm copepods.
3. The "SOLAIR" container is shaken vigourously for 5 minutes prior to the start of the experiment, as per the method of Meyer (1999). This is intended to increase the dissolved oxygen concentration in the water. The "control" container is not to be shaken.

[12] Cloth obtained from Decotex, Inc. 63 East Main Street, Pawling, NY 12564, URL: http://decotexinc.com/mono.htm .

4. Place both containers, upright, in direct sunlight for 7 hours.
5. Shake the SOLAIR container vigourously for 1 minute every hour, for 7 hours, as done by Meyer (1999).
6. Collect 100ml water samples from both containers on an hourly basis. These samples are tested for *E. coli* and total coliform using the Membrane Filtration and 3M Petrifilm™ methods, which are described below in *section 5.2*. Ensure that the water in each container is well mixed prior to removing hourly samples, so that particulate settling does not skew results and that representative samples are extracted.

5.1.2 SODIS

The SODIS experiment was carried out as follows:

5.1.2.1 Apparatus

- 2L transparent (with slight blue tint) PET bottle

5.1.2.2 Procedure

1. Clean the bottle thoroughly.
2. Half-fill the bottle with the water to be disinfected and shake vigourously for about a minute. Top up the container with the water.
3. Place the bottle in direct sunlight, with the bottle lying on its longest side.
4. Test for *E. coli* and total coliform at 0, 3 and 6 hours after the start of the experiment.

5.2 Microbial Testing

The three microbial tests used were the Membrane Filtration and 3M Petrifilm™ tests to detect coliform, and the Hydrogen Sulphide Presence/Absence test to detect hydrogen sulphide producing bacteria

In order to ascertain the levels of microbial contamination in a sample of water, *E. coli* counts were performed since this, as previously mentioned, is an indicator of faecal contamination in the water. In addition, total coliform (TC) counts were done. A coliform is a gram-negative rod-shaped bacteria which ferments lactose with the production of acid and gas when incubated at 35^{o}C (Standard Methods 1999). TC describes *all* coliform bacteria present in the water, including *E. coli*. The levels of *both E. coli* and TC are important in determining into which "risk-category" the water falls, as set out in the WHO guidelines for drinking water (WHO 2004).

5.2.1 Membrane Filtration Test

Membrane Filtration (MF) is one technique that can be used to determine the number of *E. coli* and total coliform in a water sample. It is a method that is recommended by the United States Environmental Protection Agency (EPA) (MILLIPORE 1992), providing results 24 hours after testing. The MF test works on the principle that coliform, given suitable conditions such as an appropriate temperature and availability of a nutrient medium, grow over the course of approximately 1 day. These colonies formed can then be counted.

Although MF is the costliest of the three types of microbial test performed, at US$2.52 per test (Okioga 2007), it is also the most accurate. Within the context of this thesis, the MF test results will be used as the primary input for the analysis of the effectiveness of SOLAIR, whilst the H_2S Presence/Absence and 3M test results provide additional data to reinforce the conclusions made.

5.2.1.1 Apparatus

- Millipore MF field unit
- mColiBlue24® broth ampule (nutrient medium)
- Petri dish
- Absorbent pad
- 0.45µm filter paper
- Sterile water (distilled/bottled)
- 100ml sterile Whirl-Pak© bag
- Tweezers
- Rubbing alcohol
- Methanol
- Handheld magnifying glass

Figure 5.2 – Membrane Filtration apparatus (Mattelet 2006)

5.2.1.2 Procedure

1. *Collect* the sample:
    - Using a Whirl-Pak© bag, collect a 100ml sample of the water to be tested (from either the SOLAIR container or the control container).
    - To minimize error, the final TC count should lie between 20 and 200. In order to achieve this, dilute accordingly (Standard Methods 1999).

2. *Sterilize* the lab bench and immediate surroundings using rubbing alcohol.

3. *Sterilize* the Millipore MF filter holder:
    - Flame-sterilize by soaking the cloth rim of the filter holder with methanol, before igniting the methanol and tightly placing the filter cup over the funnel. Sterilization is accomplished by formaldehyde, which is a product of the incomplete combustion of methanol. Leave the cup on for 15 minutes then remove and rinse the funnel thoroughly with sterile water (Standard Methods 1999).

4. *Prepare* the *Petri dish*:
    - Carefully place an absorbent pad onto a sterile Petri dish using flame-sterilized tweezers.
    - Pour 1 plastic mColiBlue24® broth ampule onto the pad, ensuring the pad is evenly soaked. Pour off excess broth, leaving approximately one drop behind.

5. Begin *Membrane Filtration*:
    - Using the tweezers, place 0.45µm filter paper over the filter and clamp in funnel.
    - Pour and vacuum through, using the hand pump, the 100ml sample of water.
    - Rinse the walls of the funnel with sterile water a few times to ensure complete flushing of the sample.

6. *Remove* the filter paper and *incubate*:
    - Remove the filter paper and place this onto the absorbent pad that has been soaked with the mColiBlue24® broth. Ensure there are no air bubbles between the filter paper and the pad.
    - Close the lid of the Petri dish and invert.
    - Incubate the sample for 24 hours at 35°C (95°F).

7. *Count* results:
    - Remove the Petri dish and count the number of blue and red colonies (*Figure 5.3*) formed with the aid of a handheld magnifying glass (10x magnification). The blue colonies represent *E. coli* whilst the sum of the red and blue gives the total coliform in the sample. The results are

reported as Colony Forming Units (CFU/100ml) and can be calculated using the following equation:

$$\frac{\textit{Number of Indicator Organisms Counted}}{\textit{Millilitres of Sample}} \times 100 = \textit{No. of Indicator Organisms per 100ml}$$

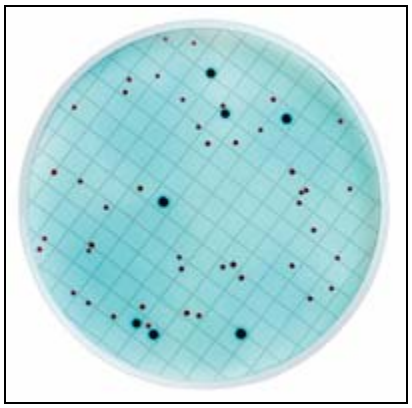

Figure 5.3 – A typical Membrane Filtration test (MILLIPORE 2007)

5.2.2 3M Petrifilm™ *E. coli*/Coliform Count Test

The 3M Petrifilm™ *E. coli*/Coliform Count test is a relatively cheap (US$1.48) (Okioga 2007), quick-and-easy method of coliform enumeration. Each Petrifilm™ plate contains a Violet Red Bile nutrient medium and a colony enumeration indicator, set in a gelling agent. Approximately 95% of *E. coli* produces gas, since they are lactose fermenting coliforms. This gas becomes trapped in the Petrifilm™ plate, surrounding blue colonies (*E. coli*). Other coliform, which also produce gas, are visible as red colonies surrounded by gas (3M Microbiology 2001).

A disadvantage of this test method is that only a 1mL sample can be tested, which is not always representative of the entire water body. This makes it reasonably accurate at high levels of coliform contamination but less sensitive, and hence, less accurate, at low levels of contamination (Mattelet 2006).

5.2.2.1 Apparatus

- 3M Petrifilm™ plate
- 1-5mL pipette
- Sterile pipette tip
- 3M spreader/press

5.2.2.2 Procedure

1. *Sterilize* the lab bench and immediate surroundings using rubbing alcohol.

2. *Inoculate* the 3M Petrifilm™ plate with the sample:
   - Place the plate on a flat surface and lift top cover.
   - Pipette a 1mL sample onto the centre of the plate.
   - Carefully roll down the top cover, ensuring there are no air bubbles.
   - Gently press down on the plate with the spreader (flat side down).
   - Lift spreader and wait at least 1 minute for gel to solidify.

3. *Incubate* the plate:
   - Incubate the plates at 35°C±1°C for 24±2 hours, with the clear side up, in stacks of no more than 20.

4. *Count* results:
   - Blue colonies surrounded by gas bubbles represent *E. coli* whilst total coliform is the summation of both red and blue colonies (*Figure 5.4*) surrounded by gas bubbles. *Figure 5.5* shows the various patterns associated with gas forming colonies. All these examples numbered 1-10 in *Figure 5.5* should be counted. Red colonies without surrounding gas bubbles are non-coliform bacteria and should not be counted (3M Microbiology 2001).

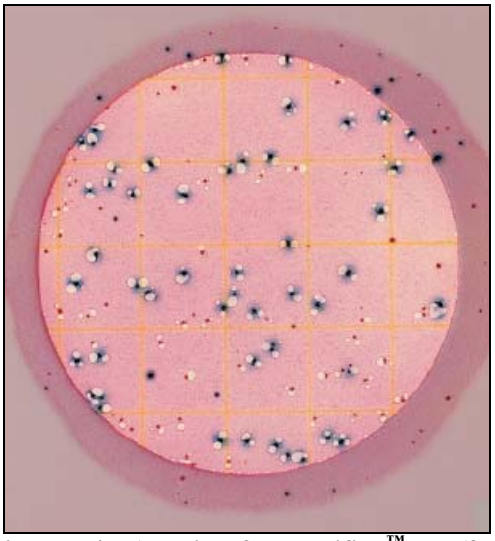

Figure 5.4 – A typical 3M Petrifilm™ test (3M Microbiology 2001)

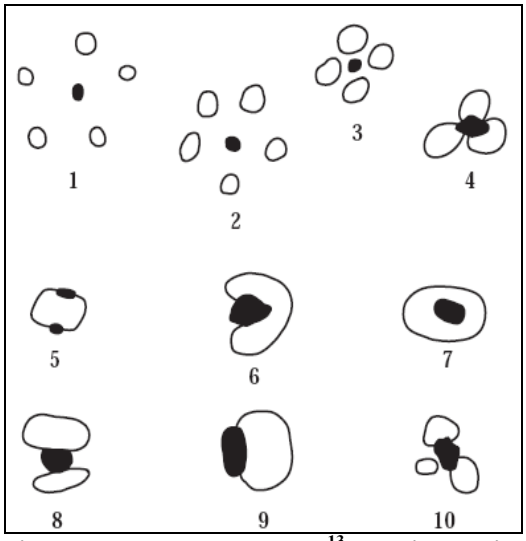

Figure 5.5 – Bubble patterns[13] associated with gas forming colonies (3M Microbiology 2001)

[13] The shaded shapes represent the colonies whilst the unshaded shapes represent the gas bubbles formed by the colonies.

5.2.3 Hydrogen Sulphide Presence/Absence Test

Faecal contamination in water can be determined by testing for the presence of suitable indicator organisms, such as hydrogen sulphide producing bacteria. This category of bacteria includes the Salmonella, Citrobacter, Proteus and Edwardsiella species (HACH 2003). The Hydrogen Sulphide (H_2S) Presence/Absence (P/A) test is a simple alternative to testing for *E. coli*.

A positive result is obtained if H_2S producing bacteria are present in the sample, leading to the formation of a black iron sulphide precipitate. The P/A test is not recommended as the *only* method in testing for faecal contamination due to the tendency for false positive and false negative results to occur. These false results can be caused by a source of H_2S in the sample, other than from the aforementioned bacteria (Peletz 2006). Manja et al. (1982) conclude that H_2S producing bacteria are consistently associated with the presence of coliform in water. This is backed up by tests done by Grant et al. (1996) which show that there is a 85-95% agreement between faecal coliform detection using the Membrane Filtration method, and the P/A test. They also showed that, for total coliform, the agreement between the two tests ranged from 93-99%. This relatively inexpensive (US$0.27) (Okioga 2007), convenient and simple test method provides a reasonably reliable indication of faecal contamination in the water.

5.2.3.1 Apparatus

- 20ml glass bottle
- HACH PathoScreen™ Medium powder pillow for 20mL sample
- Rubbing alcohol to sterilize immediate surroundings

5.2.3.2 Procedure

1. Sterilize the glass bottles and caps by placing in boiling water.
2. Add a 20mL sample to the bottle.
3. Add the contents of one PathoScreen™ Medium powder pillow to the sample.
4. Immediately cap the bottle and shake thoroughly.
5. Place the bottle in a location with a constant temperature within the range 25-35°C (77-95°F) for 24 to 48 hours. Ambient conditions may be used in warm climates.
6. Evaluate the reaction after 24 hours. If the colour has changed from yellow to black the result is **positive** (*Figure 5.6*). A positive result indicates the presence of hydrogen sulphide reducing bacteria. If sample is still yellow, incubate for a further 24 hours and re-evaluate. If there is no colour change the result is **negative** (HACH 2003).

Figure 5.6 - H_2S Presence/Absence test showing negative (yellow) and positive (black) results (Peletz 2006)

5.2.4 Cost of Microbial Tests

The cost of each test is given in *Table 5.1*:

Table 5.1 – Cost of microbial tests (Okioga 2007)

Test Type	Approximate Cost per Single Test (US$)
Membrane Filtration	2.52
3M Petrifilm™	1.48
Hydrogen Sulphide (20mL sample size)	0.27

5.3 Solar Radiation

Solar radiation measurements were taken using a Kipp & Zonen Solrad pyranometer (*Figure 5.7*):

Figure 5.7 - Solar radiation measurement apparatus (Oates 2001)

The pyranometer works on the principle of converting the light energy it receives into heat energy which is in turn converted into an electrical signal that is proportional to the intensity of the solar radiation (W/m^2) (Oates 2001).

5.4 Turbidity

Turbidity levels can be measured using an electronic detector called a *nephelometer* or by more simple visual methods, such as using a *secchi disk*, where a disk is lowered into the water and the depth at which it can no longer been seen is measured (this depth is a measure of the turbidity of the water), or by using a *turbidity tube*.

In Ghana, turbidity readings were obtained using a portable HACH 2100P turbidimeter (*Figure 5.8*):

Figure 5.8 – Turbidimeter

The water sample was placed in a 30mL glass vial, placed in the turbidimeter and a reading was taken.

5.5 Temperature & pH

The temperature of the water was measured using an alcohol-filled thermometer whilst pH was measured using pH indicator strips, the readings of which could be interpolated to the nearest 0.25.

6. Results & Discussion

6.1 Prevailing Meteorological Conditions

The winter months (November to February) in Ghana generally see a dry and dusty wind blowing through the country, from the direction of the Sahara desert south-west towards the Gulf of Guinea. This is known as the *Harmattan* wind. As a result, a thick haze of dust forms in the atmosphere, thereby limiting visibility. The heavy amounts of fine dust particles in the air interact with sunlight by *scattering* radiation back to space, as well as *absorbing* radiation (Sokolik 1996; Colarco 2002). Since winter is the dry season in Northern Ghana, the sky is cloudless for the most part.

The percentage UV absorbed by the dust, and, hence, not able to reach the earth's surface, is difficult to accurately quantify due to the differing shapes and sizes of dust particles (Colarco 2002). The Ozone Monitoring Instrument (OMI) Aerosol Index (AI), which is provided by the Total Ozone Mapping Spectrometer (TOMS) unit of the United States National Aeronautics and Space Administration (NASA), is a scale depicting the amount of aerosol particulate in the atmosphere (*Figure 6.1*). It is formally defined as "how much the wavelength dependence of backscattered UV radiation (360nm wavelength) from an atmosphere containing aerosols (Mie scattering[14], Rayleigh scattering[15], and absorption) differs from that of a pure molecular atmosphere (pure Rayleigh scattering)" (NASA 2005). In simpler terms, the AI provides a *qualitative* measure of the amount of UV absorbing aerosol particles in the earth's atmosphere.

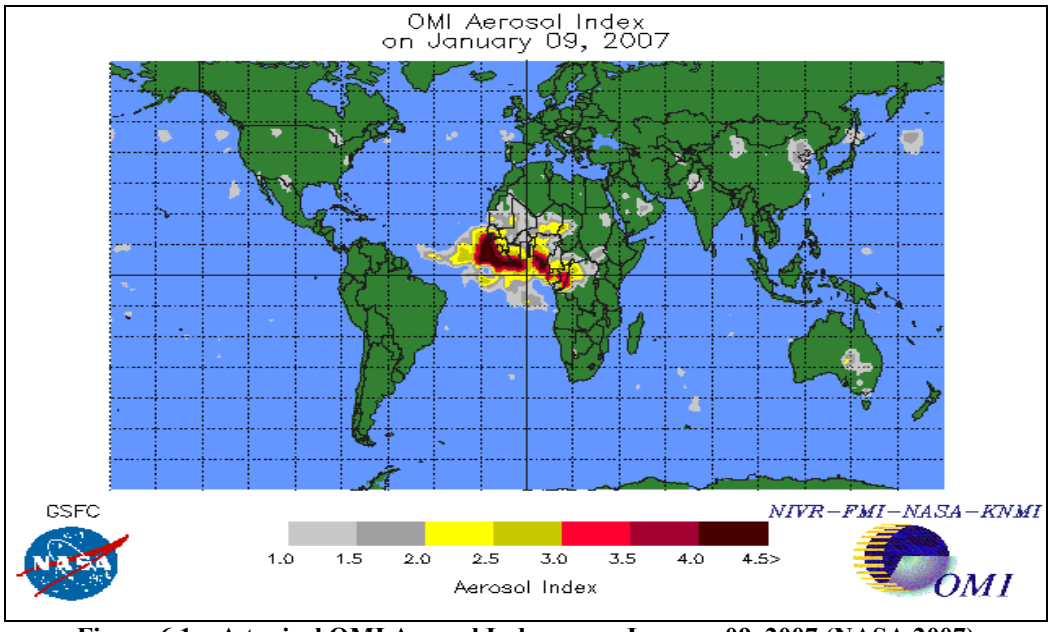

Figure 6.1 – A typical OMI Aerosol Index map: January 09, 2007 (NASA 2007)

[14] "Scattering of light by particles small enough to render the effect selective so that different colours are deflected through different angles" (Encyclopaedia Britannica 2007).

[15] "Any scattering produced by spherical particles whose diameters are greater than 1/10 the wavelength of the scattered radiation" (NOAA 2007).

6.2 Radiation

6.2.1 Peaks, Averages & Trends

Hourly radiation measurements were taken on different days in Tamale, Northern Region, Ghana (*Figure 6.2*). Average and peak radiation intensity values, as well as approximate OMI AI values (*based on OMI AI maps in Appendix B*) are presented in *Table 6.1*.

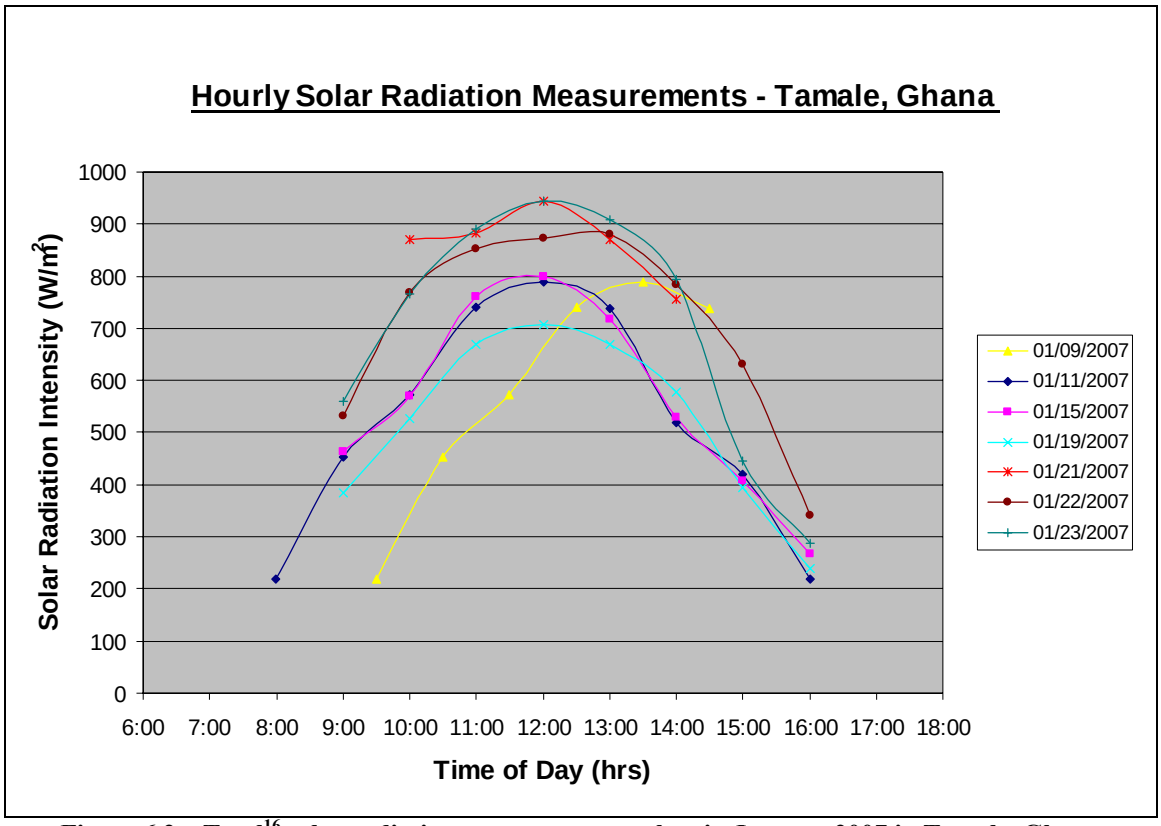

Figure 6.2 – Total[16] solar radiation measurements taken in January 2007 in Tamale, Ghana

Table 6.1 – Average, peak daily radiation and OMI Aerosol Index Values – Tamale, Ghana

Date	Average Intensity (W/m^2)	Peak Intensity (W/m^2)	~ OMI Aerosol Index (for Tamale, Ghana)
01/09/2007	607	788	2.00
01/11/2007	557	788	3.00
01/15/2007	593	799	3.00
01/19/2007	551	707	4.00
01/21/2007	878	945	1.75
01/22/2007	746	881	2.00
01/23/2007	739	944	2.00
Mean	**667**	**836**	**2.50**

[16] *Total* radiation is the radiation emitted by *all* spectrums of light.

The high variability ($p<0.0001$)[17] of the radiation measurements on a day-to-day basis is indicative of the fickle nature of the dust haze. A model can be derived to quantify the radiation intensities in terms of the OMI AI (*Figure 6.3*), despite the AI being a ratio of absorption of UV light (360nm) *only*, as mentioned previously.

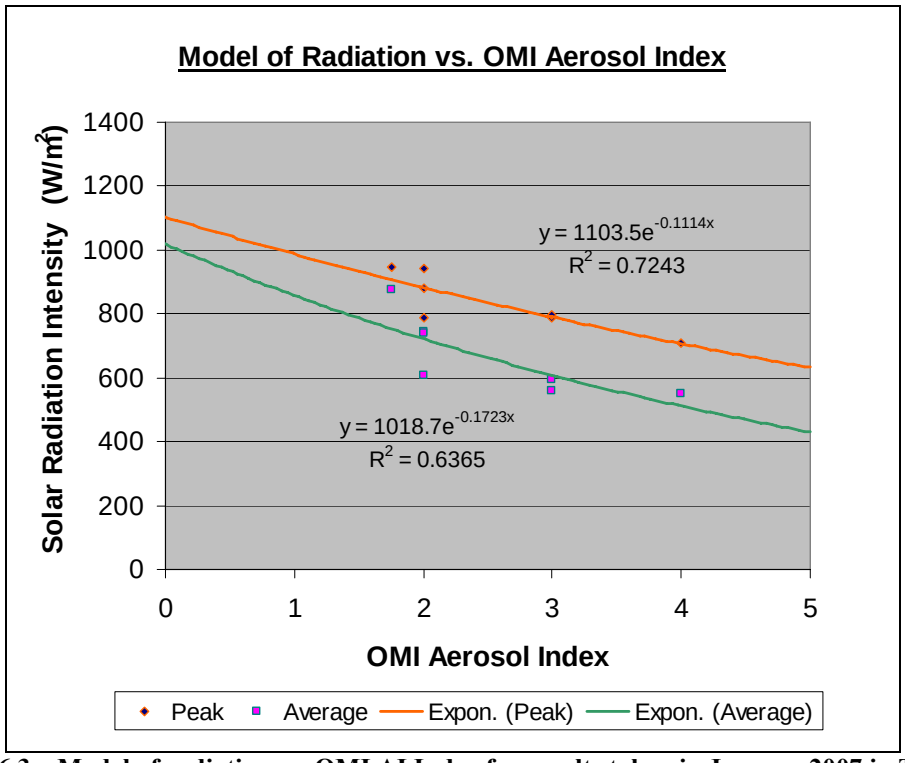

Figure 6.3 – Model of radiation vs. OMI AI Index for results taken in January 2007 in Tamale, Ghana

The peak potential radiation in Tamale, at noon on a cloudless mid-January day, was calculated as 1164W/m^2 (*Appendix C*). The equation derived for the peak radiation is:

$$\mathbf{I_p \approx 1100e^{-0.11AI}}$$

where $\mathbf{I_p}$ *is peak radiation intensity (W/m^2)*
AI *is OMI Aerosol Index (0<AI<5.0)*

For an AI of zero, the above equation yields I_p = 1100W/m^2, a value which is comparable to the peak potential radiation. The average radiation can then be represented as follows:

$$\mathbf{I_{avg} \approx 1000e^{-0.17AI}}$$

where $\mathbf{I_{avg}}$ *is average radiation intensity (W/m^2)*
AI *is OMI Aerosol Index (0<AI<5.0)*

[17] Probability calculated using a one sample *t* test which compares the mean of the peak radiation values with the expected peak value of 1164W/m^2.

These models are comparable to the relationship proposed by Krotkov et al. (2002):

$$\mathbf{F_{aerosol} = F_{clear} e^{-g(H)AI}}$$

where $\mathbf{F_{clear}}$ *is UV irradiance at the earth's surface under clear sky conditions (W/m^2)*
$\mathbf{F_{aerosol}}$ *is UV irradiance at the earth's surface under the presence of aerosols in the atmosphere (W/m^2)*
H *is aerosol height*
g *is a conversion factor (function of* **H***)*
AI *is OMI Aerosol Index*

6.2.2 Inside HDPE Container

In order to determine the amount of radiation inside an HDPE container, the pyranometer was placed at the bottom of an upright, translucent 10L HDPE receptacle and radiation measurements were taken (*Figure 6.4*). An average (average "% Penetration" experienced over the day) of 53% of the incoming radiation, as shown by the dark horizontal line in *Figure 6.4,* penetrates the container. Interestingly, radiation penetration varies non-linearly with incoming radiation. It was noticed that % penetration was lowest when radiation was at a peak. This could be because less surface area of the container is exposed to the sun's face when the sun is at its zenith. Based on this prediction, a recommendation would be for future experiments to be conducted with the largest surface of the container exposed at a correct angle to the sun for the specific latitude.

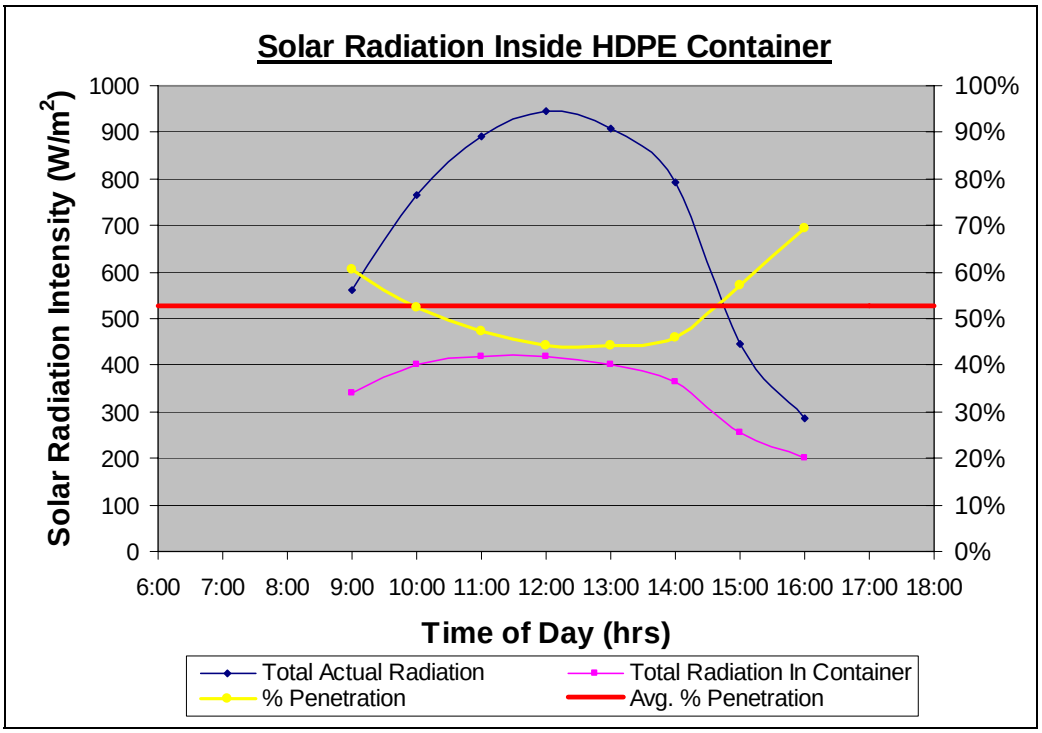

Figure 6.4 – Total solar radiation measurements taken inside a 10L translucent HDPE container in January 2007 in Tamale, Ghana

A radiation penetration of about 90% through a 1.5L PET (SODIS) bottle was observed (*Appendix E.7*).

6.3 Turbidity

In the Northern Region of Ghana the surface waters, which are used as drinking water by some of the population, have turbidity levels ranging from around 20NTU to more than 2000NTU. Turbidity values recorded by Foran (2006) in June-July 2006 during the rainy season, and by the author in January 2007 during the dry season, from various drinking water sources in Northern Region, Ghana, and which were collected and used experimentally by the MIT teams, are presented in *Table 6.2 & Table 6.3* respectively:

Table 6.2 – Turbidity, *E. coli*, total coliform readings of surface waters in June-July 2006 in Northern Region, Ghana (Foran 2006)

Location	Pre-Alum			Post Alum		
	Turbidity [TU]	TC /100ml	EC /100ml	Turbidity [TU]	TC /100ml	EC /100ml
Ghanasco Muali Dam	~1600	6621	169	<5	6	0
Kaleriga Dam	>2000	13475	754	<5	26	4
Bipelar Dam	38	21667	100	~6	10.5	4.5
St. Mary's Dam	>2000	52110	1650	<5	7.5	6
Dungu Dam	400	4540	133	<5	108	0
Libga Dam	75	500	0	<5	3	0
Bunglung Dam	300	5117	200	<5	.5	0
Diare Dam	23	3417	0	<5	2.5	0
Libga Dam	50	1408	50	<5	0	0
Gbanyami Dam	~1000	19150	367	<5	0	0
Vitting Dam	~125	12767	1400	<5	0	0

Table 6.3 – Turbidity of source waters in January 2007 in Northern Region, Ghana

Location	Turbidity [NTU]
Ghanasco Muali Dam	817
Libga Dam	23
Datoyili Dam	115
Unprotected Well (Shishegu)	12.5

The results by Foran (2006) in *Table 6.2* show that a large percentage of the coliform in dam waters in the Northern Region of Ghana is attached to the particulates, thereby inferring that the majority of the coliform will be shielded from UV disinfection.

6.4 SOLAIR

6.4.1 SOLAIR Results with High Turbidity Water

Meyer (2001) showed that at a turbidity of 280NTU, using SOLAIR, complete *E. coli* removal was achieved after 6 hours exposure to sunlight, which is only 1 hour longer than 100% *E. coli* removal from a low turbidity water (1.5NTU). The author's SOLAIR experiments in Ghana were conducted on water collected from Datoyili dam. The water had a high initial turbidity (136NTU for the experiment and 108NTU for the control) due to the presence of a large amount of suspended fine clay particulates. *Table 6.4* provides a summary of the key physical experimental conditions for water tested from Datoyili dam, namely the total radiation fluence the containers were exposed to and the temperature, pH and turbidity of the water:

Table 6.4 – Physical properties of experiments: water from Datoyili Dam (01/11/2007)

		Experiment (UV & Shaking)	Control A (UV & No Shaking)
Total Fluence ($W.hr/m^2$)		4453	4453
Avg. Intensity (W/m^2)		557	557
Temperature (^oC)	**Avg.**	36.0	36.0
	Max.	42.0	42.0
Turbidity (NTU)	**Start**	136	108
	End	--	--
pH	**Start**	5.75	5.75
	End	--	--

The maximum temperature attained was less than the threshold temperature of 50^{o}C at which the synergetic disinfection caused by both cell breakdown due to UV, and pasteurization due to temperature, is most prominent (Wegelin 1994; Sommer 1997). Therefore, one can assume that disinfection due to pasteurization was negligible compared to disinfection due to direct UV and photo-oxidative disinfection. The water had an initial turbidity of >100NTU.

Figures 6.5 & 6.6 plot hourly log CFU/100mL (Colony Forming Units) counts for total coliform (TC) and *E. coli* (EC), respectively, for one day. Log CFU/100mL values at the start of the experiments are on the order of 4.0 TC and 3.5 EC. Both the experiment (SOLAIR) and the control (no shaking) showed <1.0 log reduction of TC and EC over 7 hours using the Membrane Filtration method. The 3M Petrifilm™ and H_2S tests confirm

these results (*Appendix E.2*). Comparing the SOLAIR and control results (p=0.26)[18], there is no significant difference with regard to the *degree* of disinfection.

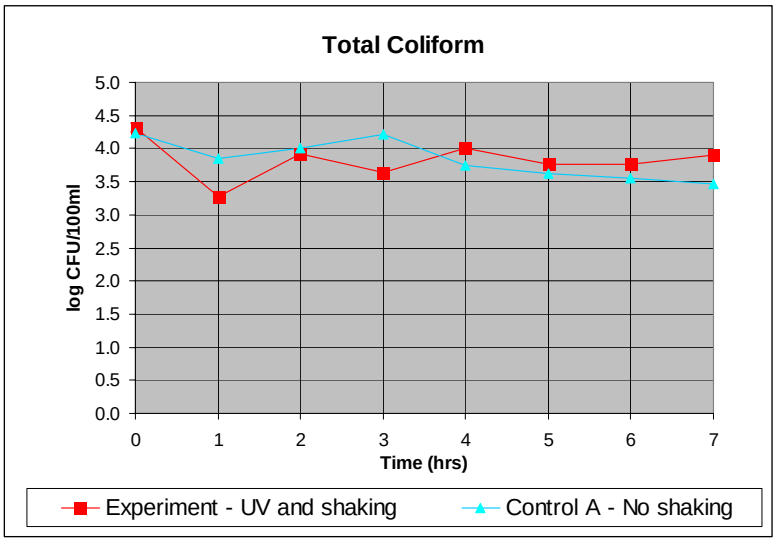

Figure 6.5 – Graph of log CFU/100mL (TC) vs. time for water with turbidity >100NTU

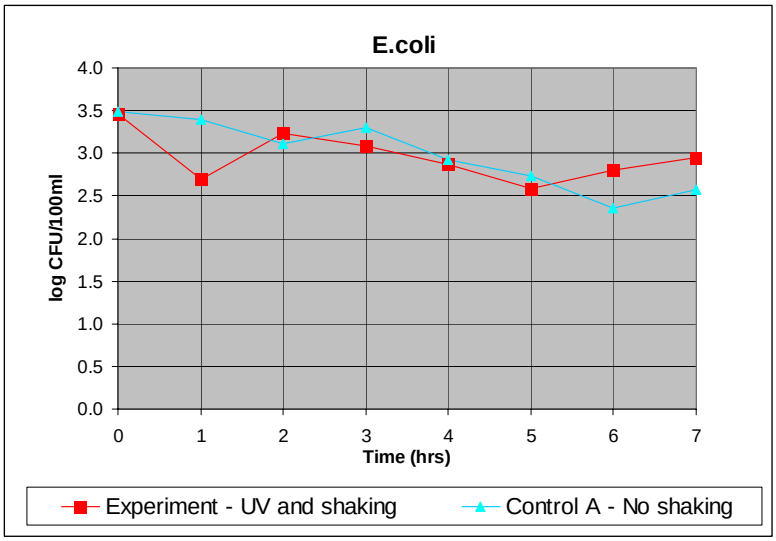

Figure 6.6 – Graph of log CFU/100mL (EC) vs. time for water with turbidity >100NTU

[18] Probabilities comparing disinfection were calculated using the paired *t* test. For each group, both the reduction in the number of TC and the number of EC were included in order to have sufficient data to perform the test.

6.4.1.1 Discussion

The results show a low rate of coliform reduction of <1.0 log. The relatively low average radiation intensity of 577W/m^2 (compared to a potential peak radiation of about 100W/m^2) coupled with the high turbidity most likely accounts for this.

It is highly probable that a large percentage of incoming UV radiation was absorbed and scattered by the Harmattan haze, as is evinced by the average recorded radiation on the day (01/11/2007, *Table 6.4*) being half of the potential maximum radiation on a clear day. Furthermore, only half of this radiation is able to penetrate the walls of the container, as shown in *Figure 6.4*.

High levels of particulates in water, measured as turbidity, limit radiation penetration through the water. Furthermore, bacteria are attached to particles and are shielded from radiation. As mentioned in *section 6.3*, a large percentage of the coliform in dam waters in the Northern Region of Ghana is attached to the particulates, thereby inferring that the majority of the coliform will be shielded from UV disinfection (Foran 2006). Despite the turbidity concentration, it would still be expected that a greater degree of disinfection be observed in the SOLAIR container, compared with Control A, due to shaking the container which keeps dissolved oxygen (DO) levels raised, based on the Meyer et al. (2000) results which assume an increase in photo-oxidative disinfection. However, the results show that this is not the case, and that the SOLAIR and Control A display similar disinfection. An explanation for this is that there is enough air above the air-water interface in the container that the water is *almost saturated* with DO even without shaking and, hence, shaking can only make a marginal improvement. Lab tests performed by the author back at the Massachusetts Institute of Technology, in April 2007, support this claim (*Appendix F*), which is depicted in *Figure 6.7*:

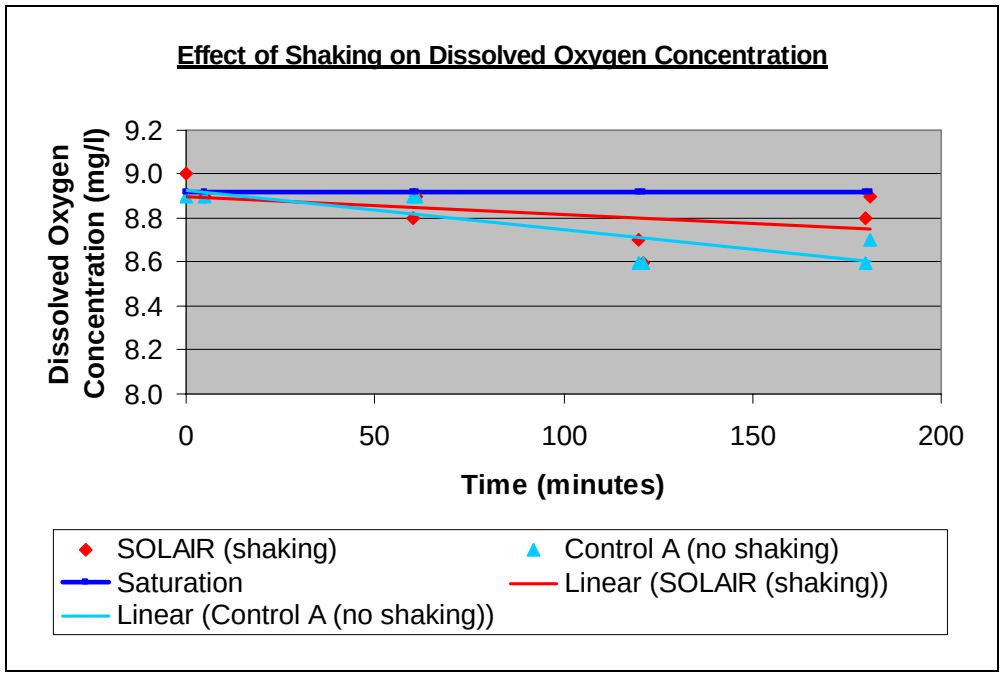

Figure 6.7 – Effect of shaking on dissolved oxygen concentration in water

The most likely reason for the slight reduction in coliform is, therefore, disinfection by direct UV cellular breakdown, closest to the walls of the container.

Although Meyer (2001) showed successful results at a turbidity of 280NTU, the turbidity was *artificially* increased using calcium carbonate in those experiments. Since the turbidity introduced was artificial, it is possible that the coliform were not attached to the particulates. Therefore, the coliform were not shielded by the calcium carbonate particles which could explain the high rate of disinfection in the case of the artificially adjusted water.

6.4.2 SOLAIR Results with Low Turbidity Water

Water measuring approximately 12NTU turbidity (*Table 6.5*) was collected from an unprotected well at Shishegu, Tamale. The lowest average radiation (551W/m^2) of those measured during January was experienced on this day. Again, pasteurization will be negligible due to the relatively low maximum temperature (38^oC) of the water in the containers.

Table 6.5 – Physical properties of experiments: water from unprotected well at Shishegu (01/19/2007)

		Experiment (UV & shaking)	Control A (UV & No shaking)
Total Fluence (W.hr/m^2)		3855	3855
Avg. Intensity (W/m^2)		551	551
Temperature (^oC)	**Avg.**	33.0	33.0
	Max.	38.0	38.0
Turbidity (NTU)	**Start**	12.5	12.5
	End	11.5	12.7
pH	**Start**	5.25	5.25
	End	5.25	5.25

Log CFU/100mL values at the start of the experiments are on the order of approximately 5.0 TC and 3.0 EC (*Figures 6.8 & 6.9*). Both the SOLAIR and Control A showed ~1.0 log reduction of TC over 7 hours. Log EC reduction was ~1.0 for SOLAIR and ~1.5 for the control. Again, it can be seen that complete disinfection was not achieved and that SOLAIR did not display a statistically significant increase in the degree of disinfection compared with the control (p=0.57). This general trend is confirmed via Membrane Filtration performed on 01/15/2007 using another low turbidity source water collected from Libga dam (<20NTU), as well as by the 3M Petrifilm™ and H_2S test results (*Appendix E.4*).

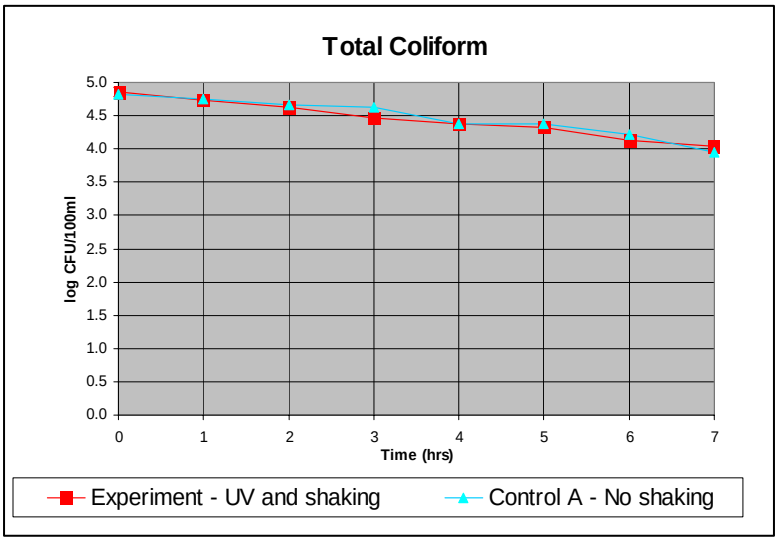

Figure 6.8 – Graph of log CFU/100mL (TC) vs. time for water with turbidity <20NTU (at 551W/m^2)

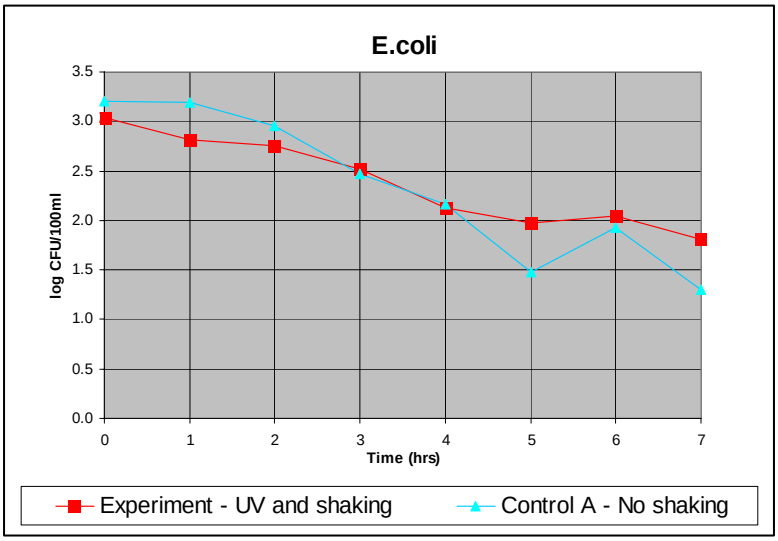

Figure 6.9 – Graph of log CFU/100mL (EC) vs. time for water with turbidity <20NTU (at 551W/m^2)

Experiments using water with a similar turbidity of <20NTU, using a mix of various source waters, were also conducted, on a separate day, with exposure to an average radiation which was higher at 746W/m^2:

Table 6.6 – Physical properties of experiments: mix of various source waters (01/22/2007)

		Experiment (UV & Shaking)	Control A (UV & No Shaking)
Total Fluence ($W.hr/m^2$)		5224	5224
Avg. Intensity (W/m^2)		746	746
Temperature (°C)	Avg.	37.5	37.5
	Max.	43.0	43.0
Turbidity (NTU)	Start	16.1	16
	End	19.5	17.6
pH	Start	5.25	5.25
	End	5.25	5.25

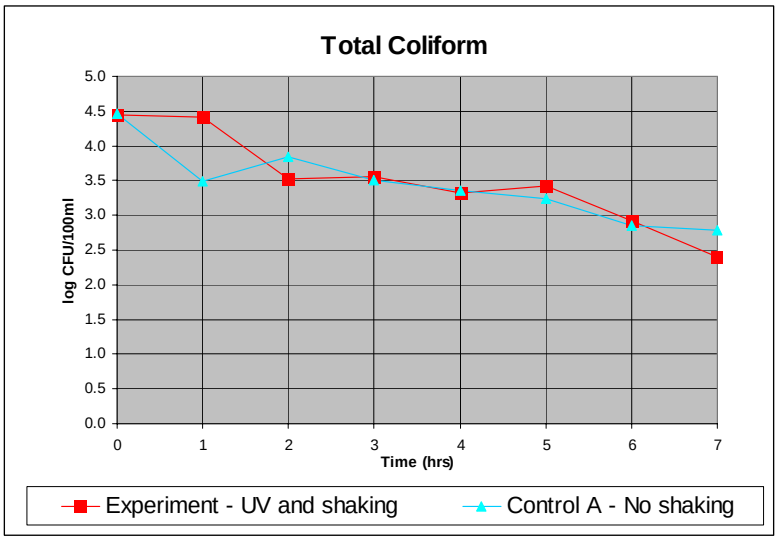

Figure 6.10 – Graph of log CFU/100mL (TC) vs. time for water with turbidity <20NTU (at 746W/m^2)

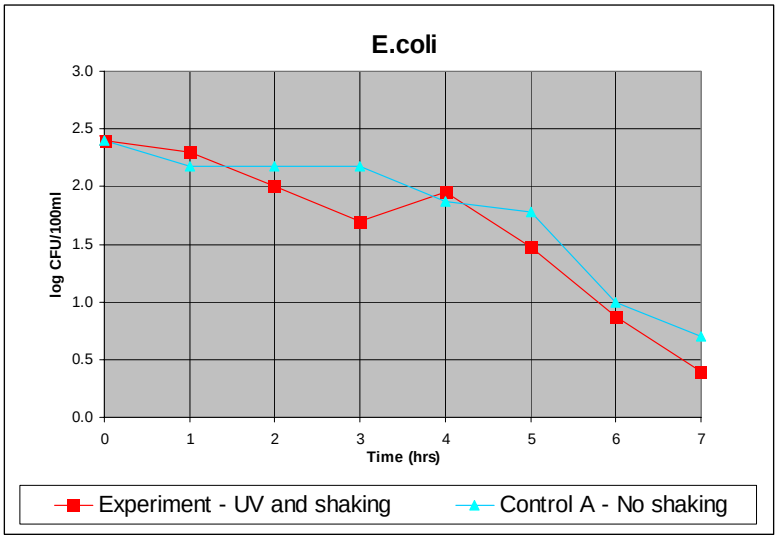

Figure 6.11 – Graph of log CFU/100mL (EC) vs. time for water with turbidity <20NTU (at 746W/m^2)

This set of experiments (*Appendix E.6)*, which corresponded to one of the highest recorded average radiations of 746W/m^2, also showed the highest rate of disinfection out of all the experiments conducted. A 2.0 log reduction in both TC and EC was observed for both SOLAIR and the control. However, it can be seen that *complete* disinfection was not achieved. Furthermore, as before, the rate of disinfection for SOLAIR is *not* significantly different (p=0.50) from that of Control A.

6.4.2.1 Discussion

The two sets of experiments conducted using water with turbidity <20NTU can be compared side-by-side. Results show that on the day with a higher level of radiation (01/22/2007), a statistically significant increase in the disinfection rate was not observed (p=0.16).

Very little, if any, increase in disinfection was noticed with shaking. As before, it is likely that the limiting factor in the photo-oxidative reaction is the DO concentration (or lack thereof), in the water. If the disinfection due to temperature is assumed to be negligible, then the results lead to the conclusion that disinfection occurs mainly by cellular breakdown due to the direct effect of UV radiation, with some photo-oxidative disinfection occurring, aided by the **initial** DO present in both containers.

6.5 SODIS

Having observed the poor performance of SOLAIR, with respect to disinfection efficiency, under the solar and meteorological conditions of Northern Region, Ghana in January, it was decided to test the hypothesis that this was mainly because of *low levels of UV-A radiation* reaching the surface of the earth, as a result of the dust haze. Ideally, a UV radiation sensor would have provided concrete results (only a *total* radiation pyranometer was available); the unavailability of which led to a less sophisticated method for proving this, via a SODIS experiment.

The SODIS experiment was conducted (*Appendix E.7)*, as per the methodology section of this thesis. SODIS is *known* to show a 3.0 log reduction in TC for a water with turbidity <30NTU, exposed to a total radiation of 500W/m^2 for about 5 hours (EAWAG 2002). The lack of effectiveness of a SODIS experiment would support the conclusion that the dust haze was causing the low UV-radiation efficacy.

Table 6.7– Physical properties of SODIS experiment: mix of various waters (01/23/2007)

		SODIS
Total Fluence (W.hr/m^2)		4805
Avg. Intensity (W/m^2)		739
Temperature (^oC)	**Avg.**	43.5
	Max.	53.0
Turbidity (NTU)	**Start**	13.4
	End	12.6
pH	**Start**	5.25
	End	5.25

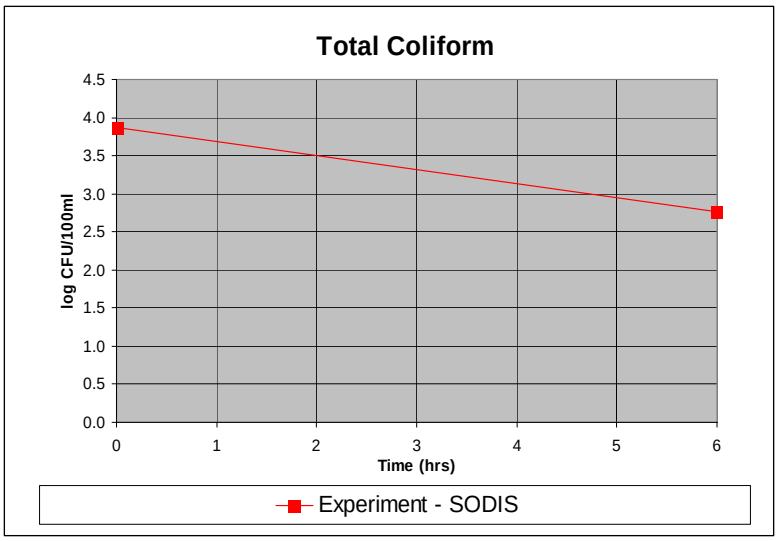

Figure 6.12 – Graph of log CFU/100mL (TC) vs. time for SODIS experiment

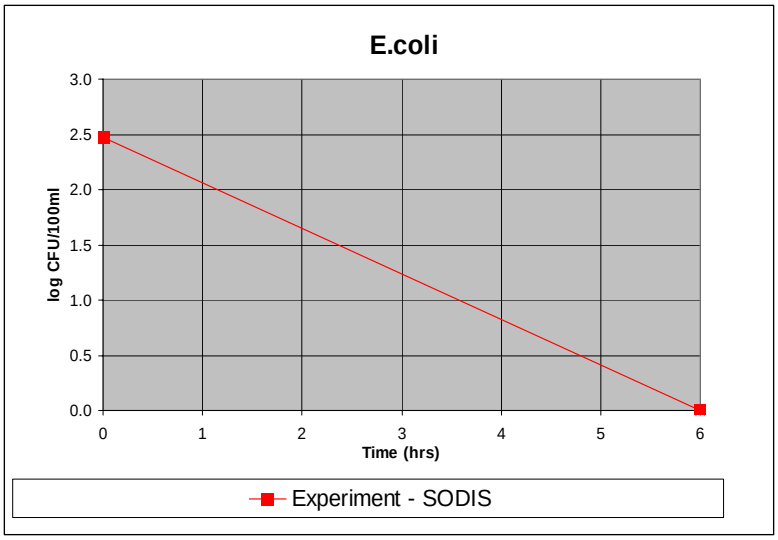

Figure 6.13 – Graph of log CFU/100mL (EC) vs. time for SODIS experiment

The water in the SODIS bottle reached a maximum temperature of 53^{o}C, with an average temperature of 43.5^{o}C. Therefore, it is expected that synergetic disinfection occurred for a portion of the experiment. The water was exposed to an average total radiation of about 800W/m^2 for 6 hours, well above the minimum limits required for a 3 log reduction in total coliform. Results show that, although *E. coli* was completely removed, there was only a ~1.0 log reduction in TC. Calculations show that there is an approximate loss of UV, in the wavelength range between 350nm and 450nm, of 80% (*Appendix D*) due to scattering and absorption by the dust in the haze. This loss is approximate and only applicable to the prevalent meteorological conditions on the day of the SODIS

experiment. However, under the assumption that AI is directly proportional to UV, days with lower average radiation values experience a higher loss in UV radiation.

6.6 Discussion & Comparisons

Comparing the results for a water with turbidity >100NTU with water that has turbidity <20NTU, it is clear that there is higher total coliform and *E. coli* reduction in the latter case, both experiments having been exposed to similar radiation fluences.

The SODIS experiment showed that, although the recommended *total* radiation conditions for a 3.0 log reduction of total coliform (EAWAG 2002) had been met, a high percentage of the UV radiation was prevented from reaching the earth's surface by the Harmattan dust haze. Hence, this is likely a major reason that SOLAIR did not show complete reduction in TC or EC.

A key conclusion of this study is that there was no significant difference between SOLAIR and Control A (no shaking) (p=0.82). As mentioned previously, shaking does not increase the DO concentration in the water to sufficient levels, if at all, to augment photo-oxidative disinfection. An explanation for this is that there is enough air above the air-water interface in the container that the water is *almost saturated* with DO even without shaking and, hence, shaking can only make a marginal improvement. Meyer et al. (2000) showed that SOLAIR shows a significantly higher degree of disinfection compared with an **anaerobic** system (*see section 3.3.2.3*). However, there is no comparison between two **aerobic** containers (one with shaking and one with no shaking) as given in this study. Therefore, because the author's experimental conditions varied from Meyers' on these key parameters (meteorological conditions, control experiments used) an exact side-by-side comparison of results is not possible.

Another conclusion is that similar coliform reduction displayed by both SOLAIR and the control, therefore, indicates that disinfection was chiefly as a result of *direct cellular breakdown* by UV radiation, assuming disinfection by pasteurization was negligible, with some photo-oxidative disinfection occurring, aided by the **initial** DO present in both containers.

SECTION III – CONCLUSION & RECOMMENDATIONS

7. Conclusion

The SOLAIR results obtained in Tamale, Ghana over the month of January show that complete solar disinfection of water over the course of 7 consecutive hours of solar exposure, did **not** take place in SOLAIR or SODIS containers. This is true for both high turbidity (>100NTU) and low turbidity (<20NTU) waters.

It is believed that the primary reason for the low degree of disinfection is the scattering and absorption of UV radiation by the aerosol particles present in the seasonal Harmattan (Sahara dust) haze, which thereby reduces the amount of UV light that reaches the earth's surface. Calculations showed that the amount of UV reaching the surface of the earth was approximately 20% of the peak potential expected on a clear (cloudless and hazeless) day.

Using radiation measurements, a model relating the peak total radiation intensity versus the OMI Aerosol Index (AI) was derived:

$$\mathbf{I_p \approx 1100e^{-0.11AI}}$$

where $\mathbf{I_p}$ *is peak radiation intensity* (W/m^2)
AI *is OMI Aerosol Index (0<AI<5.0)*

The average total radiation can then be represented as follows:

$$\mathbf{I_{avg} \approx 1000e^{-0.17AI}}$$

where $\mathbf{I_{avg}}$ *is average radiation intensity* (W/m^2)
AI *is OMI Aerosol Index (0<AI<5.0)*

Incomplete SOLAIR disinfection of the water did take place. Recapping, the main forms of disinfection that are caused by exposure of the water to solar radiation are due to:

1) **UV-A radiation**
   a. Direct alteration and mutation of pathogen cell deoxyribonucleic acid (DNA).
   b. Indirect breakdown of pathogen cells due to the photo-oxidative effect.

2) **Infrared radiation**
   a. High temperatures (>50^{o}C) eliminates some sensitive microorganisms.

The maximum temperature attained in all SOLAIR experiments performed in Ghana was less than the threshold temperature of 50^{o}C at which the synergetic disinfection caused by both cell breakdown due to UV, and pasteurization due to temperature, occurs. Therefore, one can assume that disinfection due to pasteurization was negligible compared to that due to direct UV and photo-oxidative disinfection.

Furthermore, there was no distinct difference between SOLAIR (radiation & hourly shaking) and the control experiment (radiation & no shaking). Shaking does not increase the DO concentration in the water to sufficient levels, if at all, to augment photo-oxidative disinfection. Laboratory tests performed substantiate this claim. An explanation for this is that there is enough air above the air-water interface in the container that the water is *almost saturated* with DO even without shaking and, hence, shaking can only make a marginal improvement. Similar coliform reduction displayed by both SOLAIR and the control, therefore, indicates that the 1.0-2.0 log reduction that did take place was chiefly as a result of *direct cellular breakdown* by UV radiation, assuming disinfection by pasteurization was negligible, with some photo-oxidative disinfection occurring, aided by the **initial** DO present in both containers.

Although some disinfection did take place, the *recommended* WHO guideline of an *E. coli* count of zero colony forming units (CFU) per 100ml water was not met by SOLAIR (*Table 1.2*). It can be concluded, therefore, that this solar disinfection process, using translucent 10L HDPE containers, in January in the Northern Region of Ghana, does not produce a safe drinking water and should not be pursued in this context.

8. Recommendations

The hazeless conditions in summer (between the months of April to September) in Northern Region, Ghana may be more conducive to the success of SOLAIR. It is, therefore, recommended that further technical studies, if any, be conducted, in the absence of the Harmattan haze. Furthermore, containers should be placed parallel, not perpendicular to, the surface, or at a correct angle to solar radiation ($\sim 10^{o}$). Subsequent results obtained will then, more likely, be comparable to those given by Meyer et. al (2000). Since it has been shown that an increase in photo-oxidative disinfection is not likely with shaking, research into augmenting pasteurization could be looked into. This may be possible by using darker coloured containers, in order to raise the temperature of the water being held.

Should future studies on SOLAIR or an associated system prove *technically* successful, the *social* acceptance of the treatment system in this region of Ghana would need to be considered. Furthermore, use of the system would have to be limited to hazeless months, which adds another hurdle in the way of this "simple" process.

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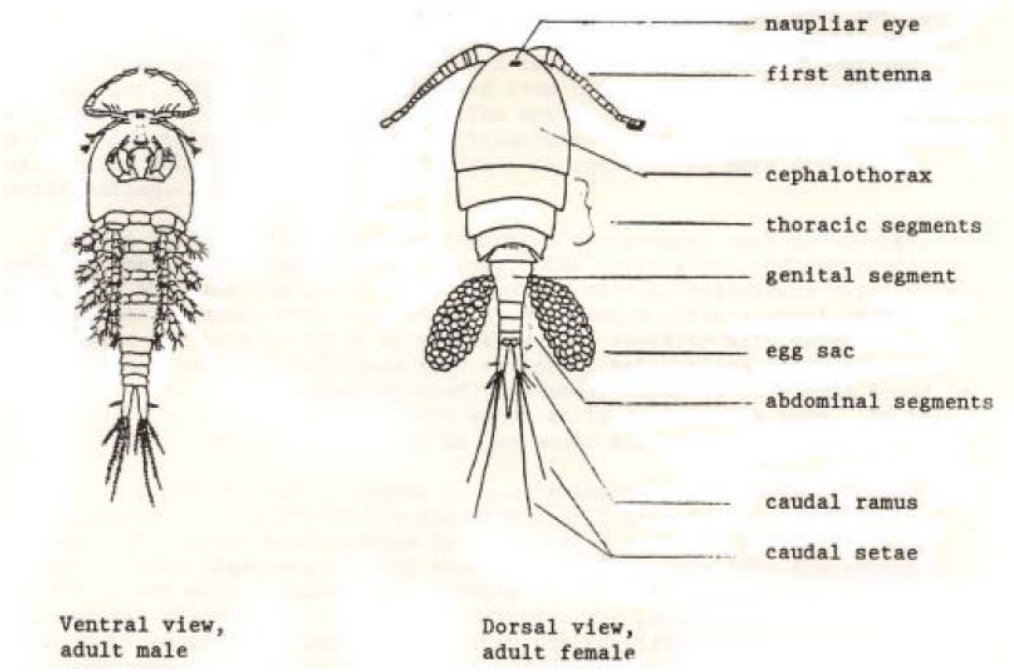
Appendix A - Assessing the density of cyclopoid copepods



"1. Sampling of water should be preferably done when the cyclopoid copepods move to the surface (morning or evening).

2. 25 liters of water should be sampled. Five samples of water, each containing a volume of 5 liters should be collected, 4 from around the edges of the pond (but not scraping the bottom), e.g., 2 samples from one side and 2 from the opposite side of the pond, and if possible one sample from the around the center of the pond. The container used to collect the sample should be allowed to sink to the bottom and then pulled up out of the water.

3. The container used can be a plastic or metal bucket open at the top and hanged with a rope connected to the handle or to four points on the top edge of the bucket. Do not use small mouth containers.

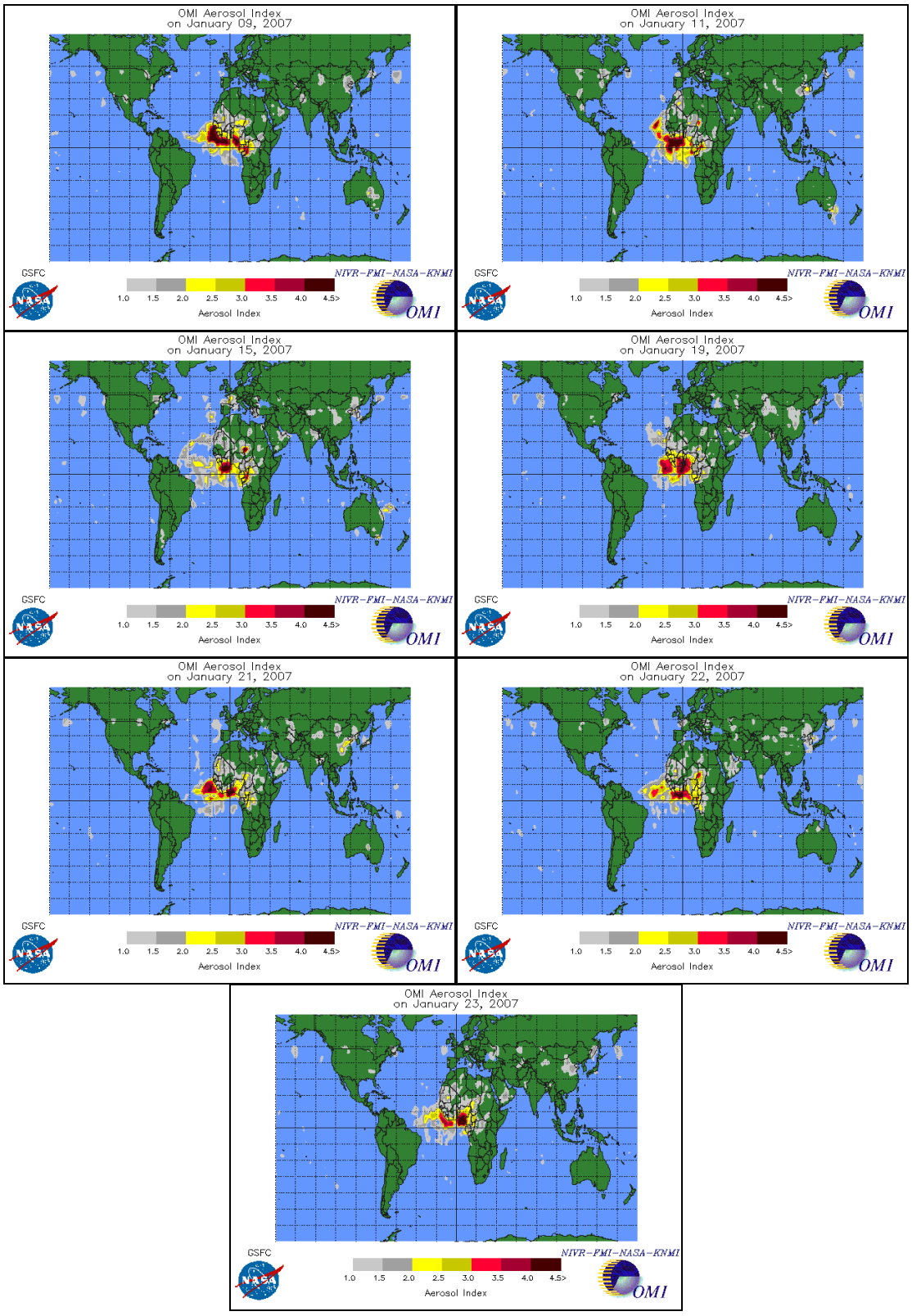
4. Each of the five-liter samples (25 liters total) should be filtered using a standard nylon filter (100 micron mesh).

5. After filtering the 25-litre sample, the material filtered should be carefully back-washed (using clean water from a borehole well or bottled water) into transparent glass (0.5 liter capacity is suggested).

6. Examine the glass by raising it to a light source (e.g. sunlight) and estimate the density of organisms swimming around. Grade the density of swimming organisms on a scale of 0-10. A grade of 10 would indicate a density such that there is hardly any room for organisms to move around, a grade of 5 would indicate that about half of the column of water is free of organisms, and a grade of 0 indicates zero organisms swimming around.

It is very important to use the same size transparent glass each time to view the swimming organisms and to estimate their density. Use a hand-held magnifying lens to check for cyclopoid copepods to get a sense of their relative numbers. Cyclopoid copepods move in zigzag pattern (e.g., these dart around), are pear shaped, usually have a single red eye, are white in color, and are about 1 to 3 mm in size. One may see adult females with egg pouches on its side (see above figure)" (CDC 2004).

Appendix B – OMI Aerosol Index Maps



Appendix C – Calculation of Peak Potential Radiation

Find the potential peak radiation (I_o) in mid-January (Julian day, D = 15), at noon (H = 12) in Tamale, Ghana (latitude, $\varphi = 9.5^o$):

$\tau = (H + 12) \times \pi/12 = (12 + 12) \times \pi/12 = \underline{2\pi}$ [rad]

$\delta = 23.45\pi/180 \times \cos[2\pi(172 - D)/365] = 23.45\pi/180 \times \cos[2\pi(172 - 15)/365] = \underline{-0.370}$ [rad]

where δ is the declination of the sun

$\sin\alpha = \sin\delta\sin\varphi + \cos\delta\cos\varphi\cos\tau$
$= \sin(-21.2^o)\sin(9.5^o) + \cos(-21.2^o)\cos(9.5^o)\cos(360^o)$
$= -0.060 + 0.920$
$= \underline{0.860}$

where α is the angle of the incoming solar radiation with a tangent plane at some point on the earth-atmosphere surface

$I_o = W_o\sin\alpha$
$= 1353(0.860)$
$= \mathbf{\underline{1164 W/m^2}}$

where W_o is the solar constant = 1353W/m^2

Calculations done assuming cloudless skies, no radiation scattering or particulates in the atmosphere and the measurement being taken just above the earth's surface, thereby negating any reflective effect (ie. albedo = 0).

(Bras 1990)

Appendix D – Calculation of % UV Loss due to Harmattan Haze

Assumptions:

1) Negligible synergetic effect of UV-radiation and temperature (ie. negligible pasteurization).
2) Linear log reduction of TC w.r.t radiation.
3) Proportion of total radiation that is UV (350 – 450nm wavelength) remains constant.
4) UV fluence can be averaged, over the exposure time.

Requirements for 3 log reduction of TC using SODIS

Total solar radiation, for 5 hours = 500W/m^2 ≡ 2500W.hr/m^2 (EAWAG 2002) for plastic PET SODIS bottle on a clear, cloudless day.

This is equivalent to a UV radiation fluence of 555 W.hr/m^2 (EAWAG 2002) ≡ 555/5hrs = 111W/m^2 for 5 hours exposure (*assumption 4*).

Observations for 1 log reduction in TC (from SODIS experiment results)

An average of 800W/m^2 total radiation produced a ~1 log reduction in TC.

Thus, we expect a UV radiation value of 800 x 111/500 = 180W/m^2 (*assumption 3*), under clear sky conditions.

Since only a 1 log TC reduction occurred, under *assumption 2* the water could only have been exposed to 1/3 x 111 = 37W/m^2 UV radiation.

Therefore, 37/180 x 100 = 21% of the expected UV radiation on a clear day reaches the ground.

This represents a loss of 100 – 21 = **79%** UV radiation in the dust haze.

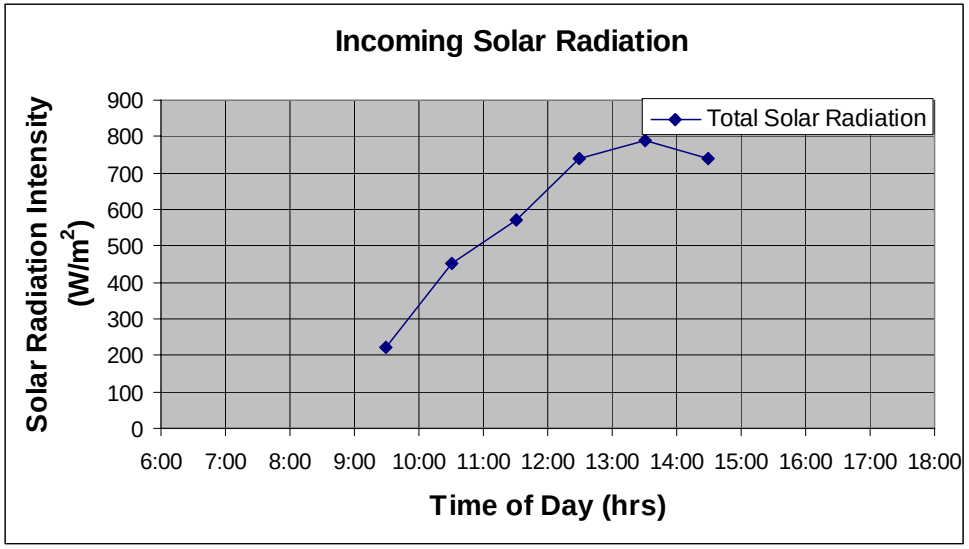
Appendix E – Results & Calculations

E.1 – 01/09/2007

Date: 01/09/2007
Weather: Very hazy. Harmattan dust in air.
Visibility: Poor
Test site: GILLBT Guesthouse, Tamale, Ghana
Water from: Ghanasco Dam (POST ALUM)

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)		
	Actual (W/m^2)	≈ Total Elapsed* (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*	
9:30					5.5		817		**PRE ALUM**
9:30	220	0	23.0		3.75		13		**POST ALUM**
10:30	454	337	29.0						
11:30	573	851	32.5						
12:30	740	1507	36.0						
13:30	788	2271	39.0						
14:30	738	**3034**	39.5				176.0		
	Avg.	**607**	**33.2**						

*Sum of averages of *actual* radiation values.

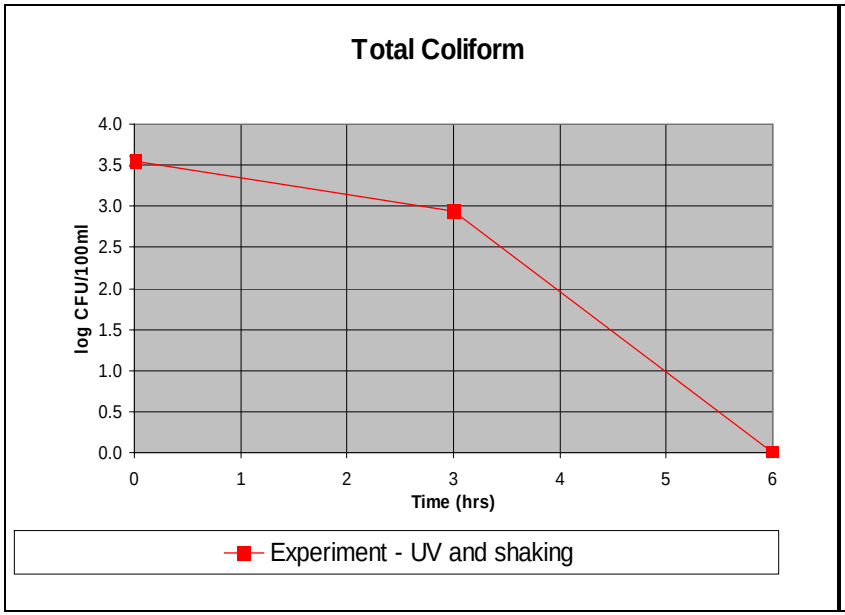


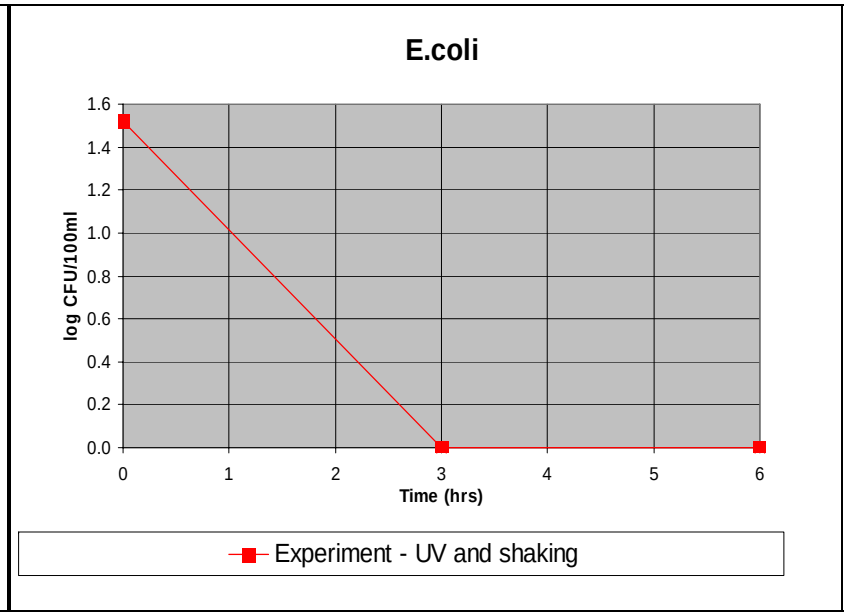
Date: 01/09/2007
Water from: Ghanasco Dam

		MEMBRANE FILTRATION					3M PETRILFILM					H_2S P/A Test After	
	Dilution	Colonies Counted		Coliform (CFU/100ml)			Colonies Counted		Coliform (CFU/100ml)				
Sample # **	Factor	Blue	Red	E.coli	Total	Remarks	Blue	Red	E.coli	Total	Remarks	24hrs	48hrs
B1		0	5			RAW (PRE ALUM)							
1	100	1	202	100	20300								
B2		0	5										
2	500	0	150	0	75000		1	104	100	10500			
B3		0	3				4	86	400	9000			
3	500	0	162	0	81000								
B4		0	2										
4	1000	0	55	0	55000								
B5		0	4			POST ALUM							
5	10	0	TNTC	0									
B6		0	3										
6	50	0	93	0	4650								
B7		0	2										
7	100	1	23	100	2400								
B8		0	3			3 hrs sun							
8	10	0	85	0	850		0	16	0	1600			
B9		0	3										
9	20	0	44	0	880								
B10		0	2			6 hrs sun							
10	5	0	0	0	0		0	0	0	0			
B11		0	1										
11	10	0	0	0	0								

NB : This set of results may have been hampered by the leaching of the container due to the shaking, as is seen by the sharp increase in turbidity from the start, to the finish of the experiment. Furthermore, as it was the first use of the container, other chemicals (cooking oil remnants-container was used to store oil previously-, detergent used to clean container), may also have affected results.

	MEMBRANE FILTRATION SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
Raw	25	57,825			1.4	4.8		
0	33	3,525			1.5	3.5		
3	1	865			0.0	2.9		
6	1	1			0.0	0.0		

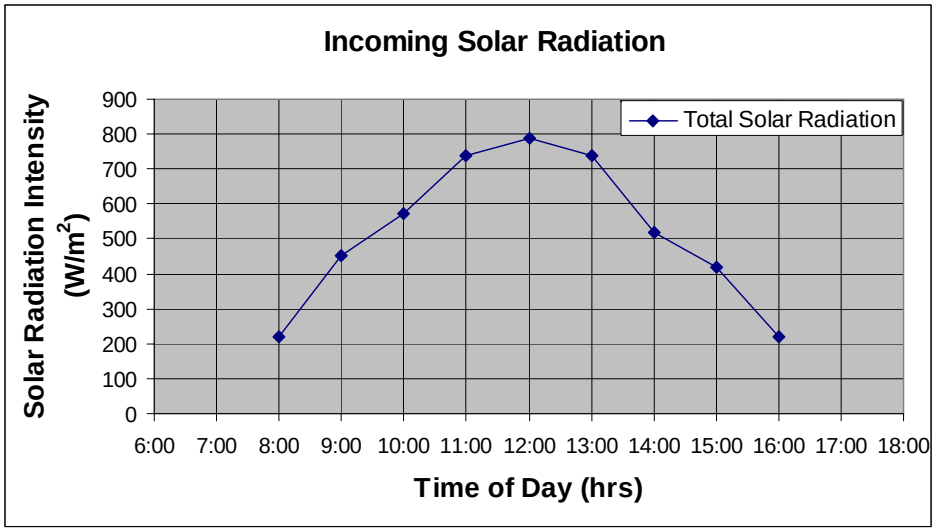




E.2 – 01/11/2007

Date: 01/11/2007
Weather: Very hazy. Harmattan dust in air.
Visibility: Average
Test site: GILLBT Guesthouse, Tamale, Ghana
Water from: Datoyili Dam

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
8:00	220	0	25.5	25.5	5.75	5.75	136	108
9:00	454	337	28.0	27.5				
10:00	573	851	31.0	31.0				
11:00	740	1507	35.0	35.0				
12:00	788	2271	37.5	37.0				
13:00	738	3034	41.0	41.5				
14:00	520	3663	42.0	42.0				
15:00	420	4133	42.0	42.0				
16:00	219	**4453**	41.0	41.0				
	Avg.	**557**	**35.9**	**35.8**				

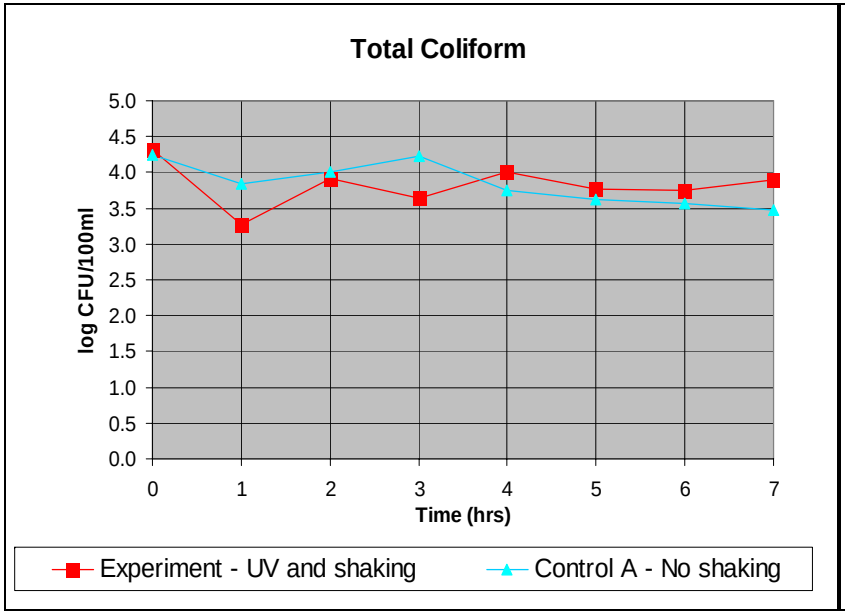


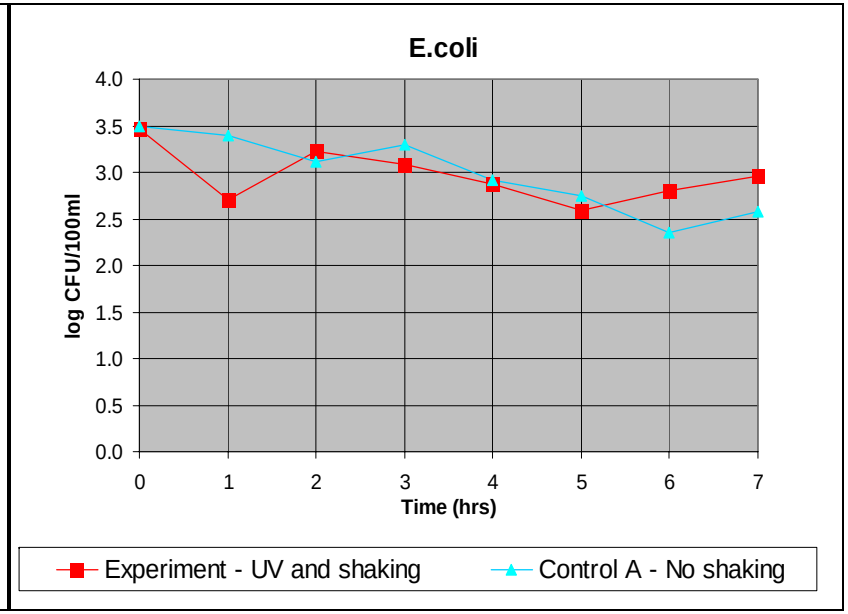
Date: 01/11/2007
Water from: Datoyili Dam

		MEMBRANE FILTRATION					3M PETRILFILM					H_2S P/A Test After	
	Dilution	Colonies Counted		Coliform (CFU/100ml)			Colonies Counted		Coliform (CFU/100ml)				
Sample #	Factor	Blue	Red	E.coli	Total	Remarks	Blue	Red	E.coli	Total	Remarks	24hrs	48hrs
B0a		0	0			SOLAIR							
0a	100	13	198	1300	21100								
B0b,c		0	0				26	88	2600	11400		P	P
0b	500	5	30	2500	17500								
0c	1000	5	18	5000	23000								
B0d		0	0			Control A							
0d	100	17	86	1700	10300								
B0e,f		0	0				29	76	2900	10500		P	P
0e	500	7	30	3500	18500								
0f	1000	4	19	4000	23000								
B1a		0	0			SOLAIR							
1a	100	5	18	500	2300	error	40	110	4000	15000		P	P
B1b		0	0										
1b	500	1	2	500	1500	error							
B1c		0	0			Control A							
1c	100	20	76	2000	9600	error	27	96	2700	12300		P	P
B1d		0	0										
1d	500	6	3	3000	4500	error							
B2a		0	1			SOLAIR							
2a	100	12	86	1200	9800		28	77	2800	10500		P	P
B2b		0	0										
2b	200	11	24	2200	7000								
B2c		0	1			Control A							
2c	100	10	100	1000	11000		44	70	4400	11400		P	P
B2d		0	0										
2d	200	8	38	1600	9200								
B3a		0	0			SOLAIR							
3a	100	8	42	800	5000		26	92	2600	11800		P	P
B3b		0	0										
3b	200	8	11	1600	3800								
B3c		0	0			Control A							
3c	100	14	150	1400	16400		23	65	2300	8800	leakage	P	P
B3d		0	0										
3d	200	13	72	2600	17000								

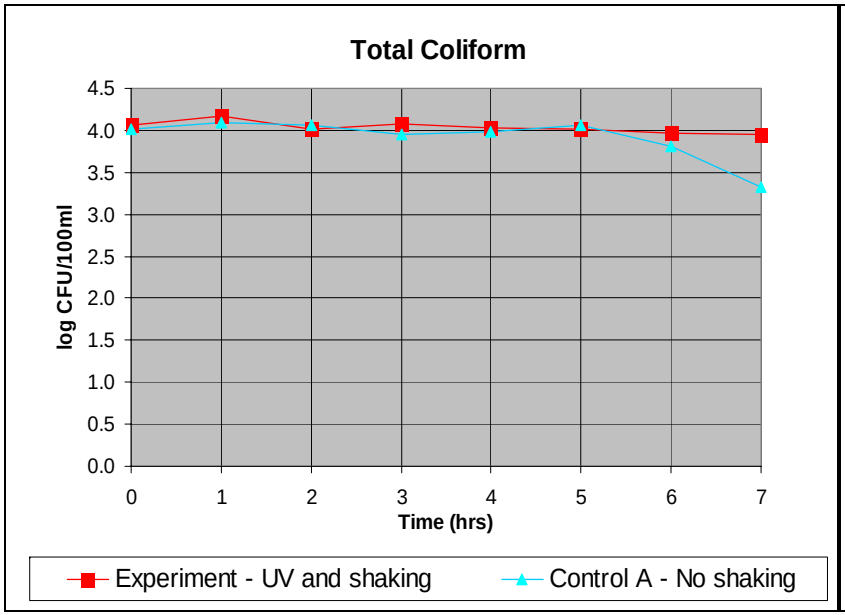
B4a		0	0										
4a	50	24	249	1200	13650		29	80	2900	10900		P	P
B4b		0	0										
4b	100	3	62	300	6500								
B4c		0	0										
4c	50	11	169	550	9000		21	76	2100	9700		P	P
B4d		0	0										
4d	100	11	11	1100	2200								
B5a		1	0										
5a	20	19	293	380	6240	clear colonies	21	84	2100	10500	leakage	P	P
B5b		0	0										
5b	50	8	98	400	5300	clear colonies							
B5c		0	0										
5c	20	25	291	500	6320	clear colonies	23	91	2300	11400		P	P
B5d		0	0										
5d	50	12	30	600	2100	clear colonies							
B6a		0	0										
6a	10	93	TNTC	930			9	85	900	9400		P	P
B6b		0	0										
6b	20	17	268	340	5700								
B6c		0	0										
6c	50	3	60	150	3150		10	55	1000	6500		P	P
B6d		0	0										
6d	100	3	38	300	4100								
B7a,b		0	0										
7a	10	TNTC	TNTC				20	69	2000	8900		P	P
7b	20	45	350	900	7900								
B7c,d		0	0										
7c	50	7	44	350	2550		2	19	200	2100		P	P
7d	100	4	30	400	3400								
B8a,b		0	0										
8a	5	TNTC	TNTC				13	60	1300	7300		P	P
8b	10	TNTC	TNTC										
B8c,d		0	0										
8c	50	2	28	100	1500		4	25	400	2900		P	P
8d	100	6	25	600	3100								

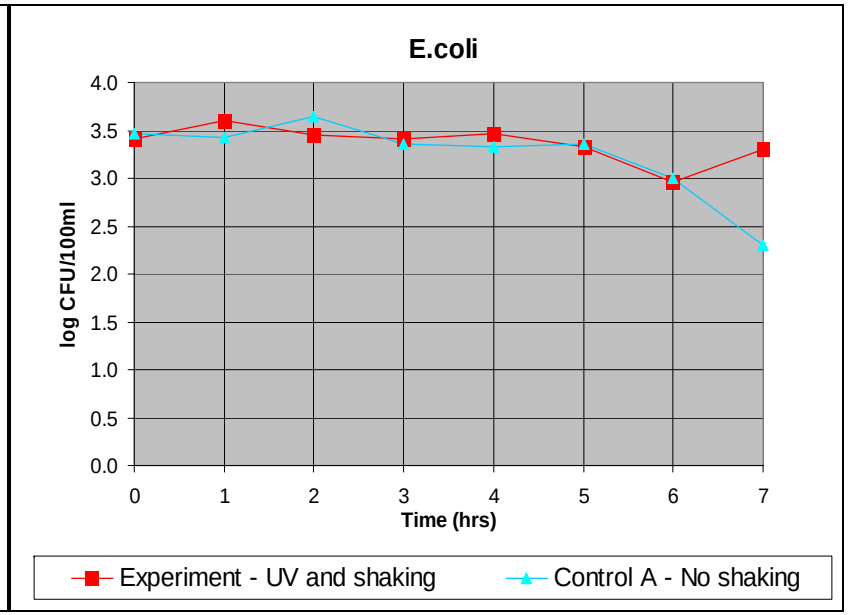
	MEMBRANE FILTRATION SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	2,933	20,533	3,067	17,267	3.5	4.3	3.5	4.2
1	500	1,900	2,500	7,050	2.7	3.3	3.4	3.8
2	1,700	8,400	1,300	10,100	3.2	3.9	3.1	4.0
3	1,200	4,400	2,000	16,700	3.1	3.6	3.3	4.2
4	750	10,075	825	5,600	2.9	4.0	2.9	3.7
5	390	5,770	550	4,210	2.6	3.8	2.7	3.6
6	635	5,700	225	3,625	2.8	3.8	2.4	3.6
7	900	7,900	375	2,975	3.0	3.9	2.6	3.5





	3M PETRIFILM SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	2,600	11,400	2,900	10,500	3.4	4.1	3.5	4.0
1	4,000	15,000	2,700	12,300	3.6	4.2	3.4	4.1
2	2,800	10,500	4,400	11,400	3.4	4.0	3.6	4.1
3	2,600	11,800	2,300	8,800	3.4	4.1	3.4	3.9
4	2,900	10,900	2,100	9,700	3.5	4.0	3.3	4.0
5	2,100	10,500	2,300	11,400	3.3	4.0	3.4	4.1
6	900	9,400	1,000	6,500	3.0	4.0	3.0	3.8
7	2,000	8,900	200	2,100	3.3	3.9	2.3	3.3

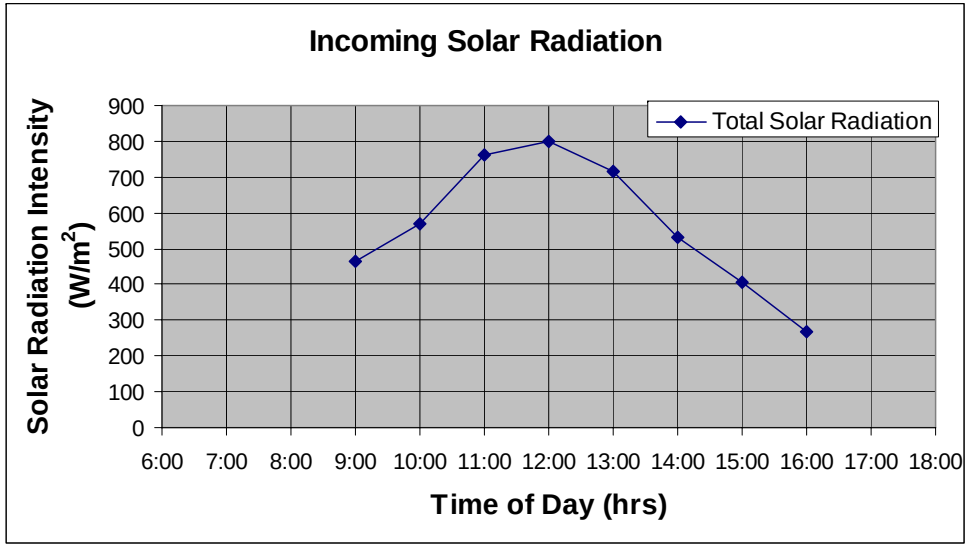




E.3 – 01/15/2007

Date: 01/15/2007
Weather: Very hazy. Harmattan dust in air.
Visibility: Average
Test site: GILLBT Guesthouse, Tamale, Ghana
Water from: Libga Dam

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
9:00	463	0	23.0	23.0	6.75	6.75	19.2	24.0
10:00	571	517	28.0	28.0				
11:00	761	1183	31.5	32.0				
12:00	799	1963	35.5	36.0				
13:00	717	2721	38.0	38.5				
14:00	530	3345	39.5	39.5				
15:00	408	3814	41.0	41.0				
16:00	267	**4151**	40.0	40.0	5.5	5.5	44.9	19.3
	Avg.	**593**	**34.6**	**34.8**				



Date: 01/15/2007
Water from: Libga Dam

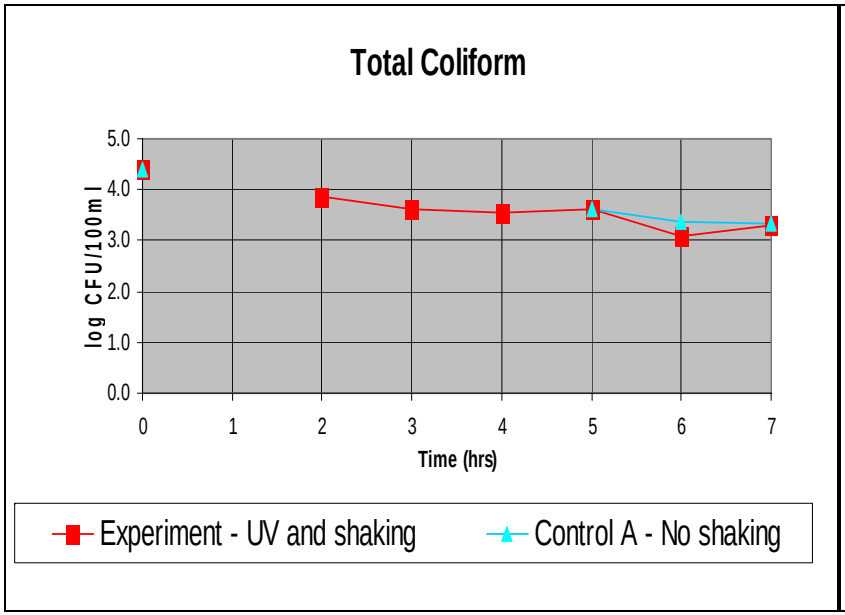
		MEMBRANE FILTRATION					3M PETRILFILM					H_2S P/A Test After	
	Dilution	Colonies Counted		Coliform (CFU/100ml)			Colonies Counted		Coliform (CFU/100ml)				
Sample # **	Factor	Blue	Red	E.coli	Total	Remarks	Blue	Red	E.coli	Total	Remarks	24hrs	48hrs
B0a		spoiled	spoiled			bad dist. water							
0a	100	1	124	100	12500	OK	1	152	100	15300		P	P
B0b		spoiled	spoiled			bad d. water							
0b	500	0	74	0	37000	OK							
B0c,d		spoiled	spoiled			bad d. water							
0c	100	spoiled	spoiled	assume same as above		bad d. water	1	180	100	18100		P	P
0d	500	spoiled	spoiled	assume same as above		bad d. water							
B1a		spoiled	spoiled			bad d. water							
1a	50	spoiled	spoiled			bad d. water	1	170	100	17100		P	P
B1b		spoiled	spoiled			bad d. water							
1b	100	spoiled	spoiled			bad d. water							
B1c,d		spoiled	spoiled			bad d. water							
1c	50	spoiled	spoiled			bad d. water	2	177	200	17900		P	P
1d	100	spoiled	spoiled			bad d. water							
B2a						light red col.							
2a	50	2	150	100	7600	OK	1	160	100	16100		P	P
2b	100	spoiled	spoiled			bad d. water							
B2c,d		spoiled	spoiled			bad d. water							
2c	50	spoiled	spoiled			bad d. water	1	157	100	15800		P	P
2d	100	spoiled	spoiled			bad d. water							
B3a						light red col.							
3a	20	2	300	40	6040	OK	0	144	1	14400	0 e.coli unlikely	P	P
B3b						light red col.							
3b	50	1	44	50	2250	OK							
B3c,d		spoiled	spoiled			bad d. water							
3c	50	spoiled	spoiled			bad d. water	1	159	100	16000		P	P
3d	100	spoiled	spoiled			bad d. water							
B4a						light red col.							
4a	20	1	250	20	5020	OK	1	104	100	10500		P	P
B4b						light red col.							
4b	50	1	35	50	1800	OK							
B4c,d		spoiled	spoiled			bad d. water							
4c	50	spoiled	spoiled			bad d. water	1	113	100	11400		P	P
4d	100	spoiled	spoiled			bad d. water							

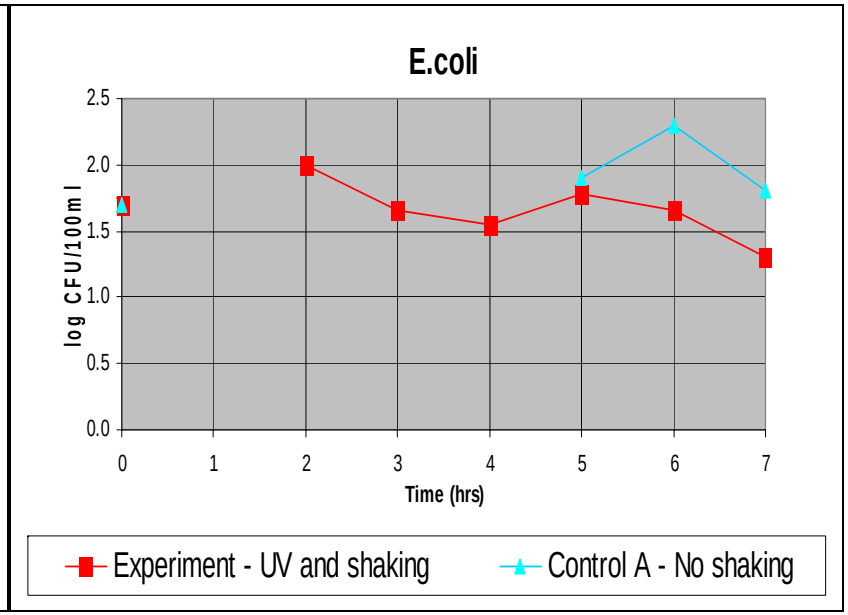
B5a						light red col.							
5a	10	TNTC	TNTC			OK	2	105	200	10700		P	P
B5b		0	0			Blank							
5b	20	3	200	60	4060	Good							
B5c,d						light red col.							
5c	20	4	200	80	4080	OK	0	100	1	10000		P	P
5d	50	spoiled	spoiled			bad d. water							
B6a						light red col.							
6a	10	5	130	50	1350	OK	0	73	1	7300		A	P
B6b						light red col.							
6b	20	2	55	40	1140	OK							
B6c,d						light red col.							
6c	20	7	166	140	3460	OK	1	64	100	6500		A	A
6d	50	5	22	250	1350	OK							
B7a						light red col.							
7a	5	2	TNTC	10		OK	0	69	1	6900		A	P
B7b						light red col.							
7b	10	3	200	30	2030	OK							
B7c,d						light red col.							
7c	10	9	208	90	2170	OK	0	60	1	6000		P	P
7d	20	2	100	40	2040	OK							

****where subcripts a,b are values for the SOLAIR experiment and c,d are values for Control A - Applicable to all subsequent results**

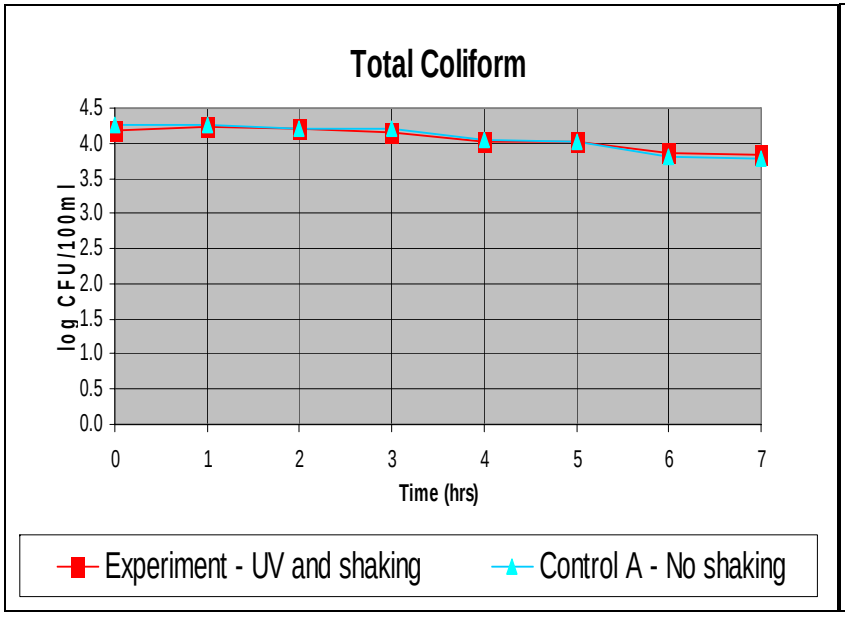
NB: Incomplete set of results due to contaminated distilled water.

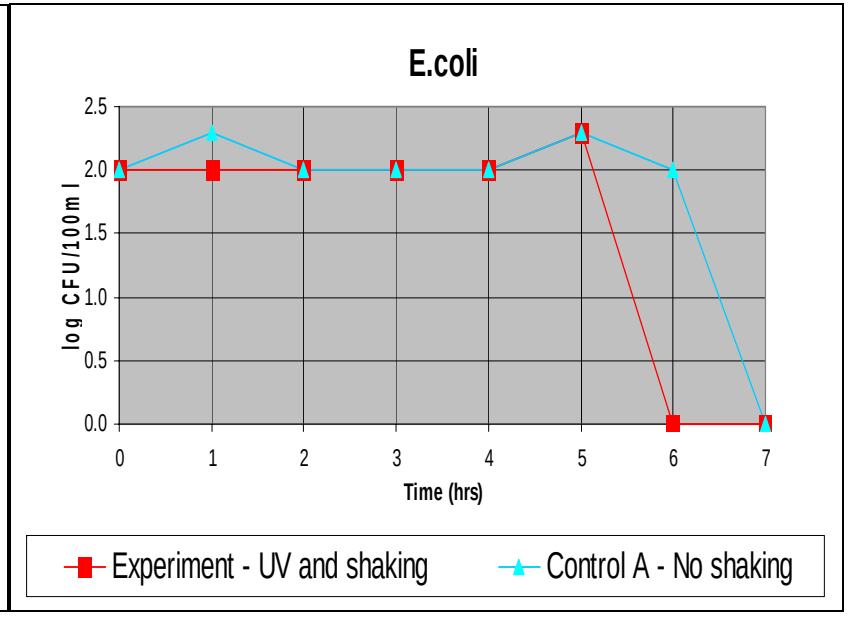
	MEMBRANE FILTRATION SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	50	24,750	50	24,750	1.7	4.4	1.7	4.4
1								
2	100	7,600			2.0	3.9		
3	45	4,145			1.7	3.6		
4	35	3,410			1.5	3.5		
5	60	4,060	80	4,080	1.8	3.6	1.9	3.6
6	45	1245	195	2405	1.7	3.1	2.3	3.4
7	20	2030	65	2105	1.3	3.3	1.8	3.3





	3M PETRIFILM SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	100	15,300	100	18,100	2.0	4.2	2.0	4.3
1	100	17,100	200	17,900	2.0	4.2	2.3	4.3
2	100	16,100	100	15,800	2.0	4.2	2.0	4.2
3	100	14,400	100	16,000	2.0	4.2	2.0	4.2
4	100	10,500	100	11,400	2.0	4.0	2.0	4.1
5	200	10,700	200	10,700	2.3	4.0	2.3	4.0
6	1	7,300	100	6,500	0.0	3.9	2.0	3.8
7	1	6,900	1	6,000	0.0	3.8	0.0	3.8

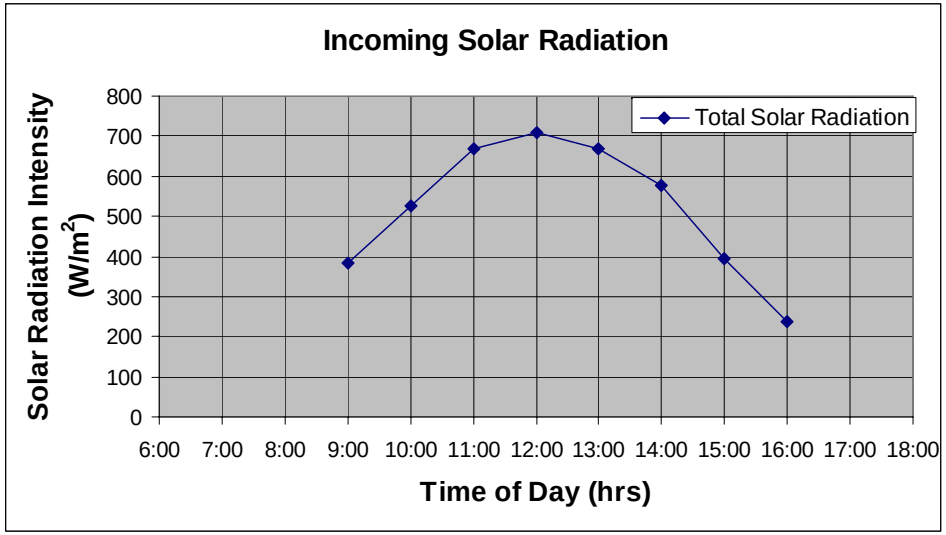




E.4 – 01/19/2007

Date: 01/19/2007
Weather: Very hazy. Harmattan dust in air. Windy
Visibility: Poor
Test site: GILLBT Guesthouse, Tamale, Ghana
Water from: Unprotected well at Shishegu

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
9:00	384	0	23.5	23.5	5.25	5.25	12.5	12.5
10:00	527	456	27.0	27.0				
11:00	670	1054	30.5	31.0				
12:00	707	1743	34.0	34.0				
13:00	668	2430	36.0	36.0				
14:00	577	3053	37.0	37.5				
15:00	395	3539	38.0	38.0				
16:00	238	**3855**	37.5	38.0	5.25	5.25	11.5	12.7
	Avg.	**551**	**32.9**	**33.1**				



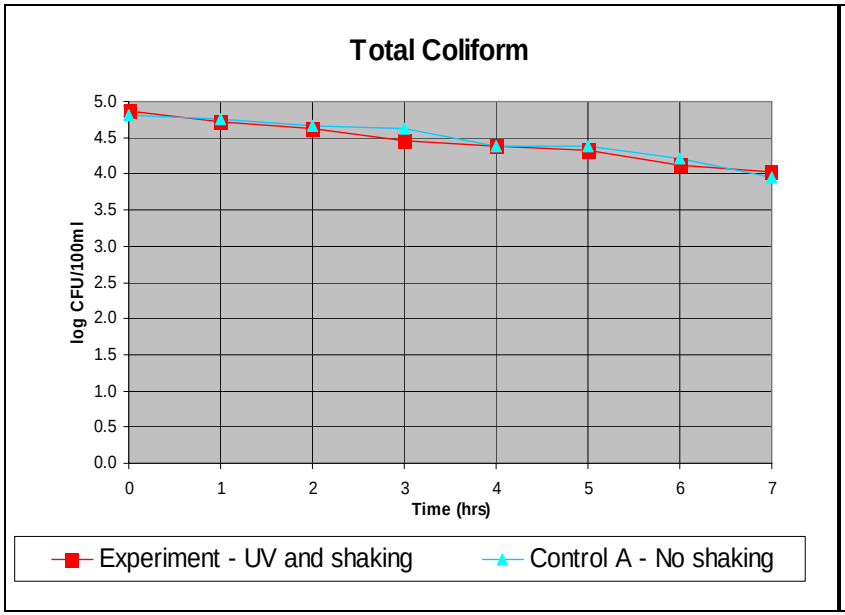
Date: 01/19/2007

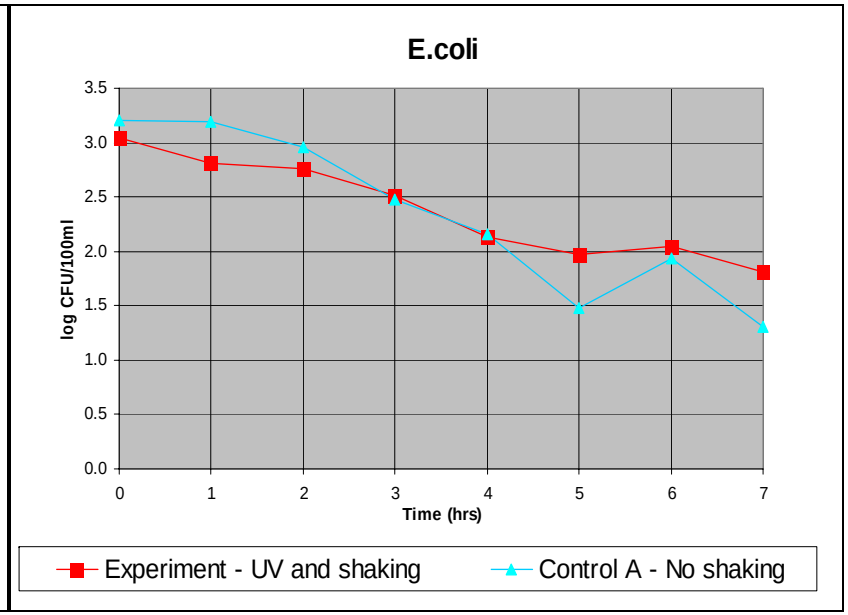
Water from: Unprotected Well at Shishegu

		MEMBRANE FILTRATION					3M PETRILFILM					H_2S P/A Test After	
	Dilution	Colonies Counted		Coliform (CFU/100ml)			Colonies Counted		Coliform (CFU/100ml)				
Sample # **	Factor	Blue	Red	E.coli	Total	Remarks	Blue	Red	E.coli	Total	Remarks	24hrs	48hrs
B0a		0	0										
0a	100	12	600	1200	61200		1	83	100	8400		P	P
B0b		0	0										
0b	500	2	166	1000	84000								
B0c,d		0	3										
0c	100	7	520	700	52700		1	73	100	7400		P	P
0d	500	5	152	2500	78500								
B1a		0	0										
1a	100	8	517	800	52500		0	65	1	6500		P	P
B1b		0	2										
1b	100	5	535	500	54000								
B1c,d		0	0										
1c	100	18	545	1800	56300		1	78	100	7900		P	P
1d	100	13	560	1300	57300								
B2a		0	0										
2a	50	7	650	350	32850		0	87	1	8700		P	P
B2b		0	1										
2b	100	8	504	800	51200								
B2c,d		0	30										
2c	100	14	430	1400	44400		3	108	300	11100		P	P
2d	100	4	460	400	46400								
B3a		0	0										
3a	20	13	1200	260	24260		0	86	1	8600		P	P
B3b		0	0										
3b	50	8	660	400	33400								
B3c,d		0	15										
3c	50	6	TNTC	300			1	89	100	9000		P	P
3d	100	3	423	300	42600								

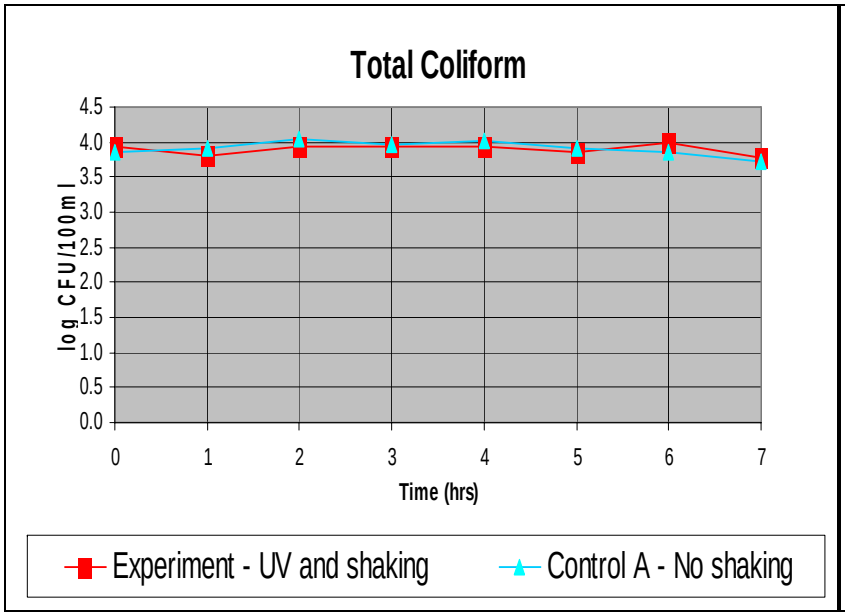
B4a		0	2										
4a	10	11	TNTC	110			0	88	1	8800		P	P
B4b		0	1										
4b	20	8	1200	160	24160								
B4c,d		0	0										
4c	20	7	TNTC	140			0	105	1	10500		P	P
4d	50	3	476	150	23950								
B5a		0	0										
5a	10	11	2000	110	20110		1	73	100	7400		P	P
B5b		0	0										
5b	20	4	1088	80	21840								
B5c,d		0	0										
5c	20	3	899	60	18040		0	80	1	8000		P	P
5d	50	0	600	0	30000								
B6a		0	0										
6a	5	16	2320	80	11680		0	100	1	10000		P	P
B6b		0	0										
6b	10	14	1450	140	14640								
B6c,d		0	0										
6c	10	11	1305	110	13160		0	73	1	7300		P	P
6d	20	3	957	60	19200								
B7a		0	0										
7a	5	10	1740	50	8750		2	56	200	5800		A	P
B7b		0	0										
7b	10	8	1276	80	12840								
B7c,d		0	0										
7c	5	2	1885	10	9435		0	53	1	5300		A	P
7d	10	3	812	30	8150								

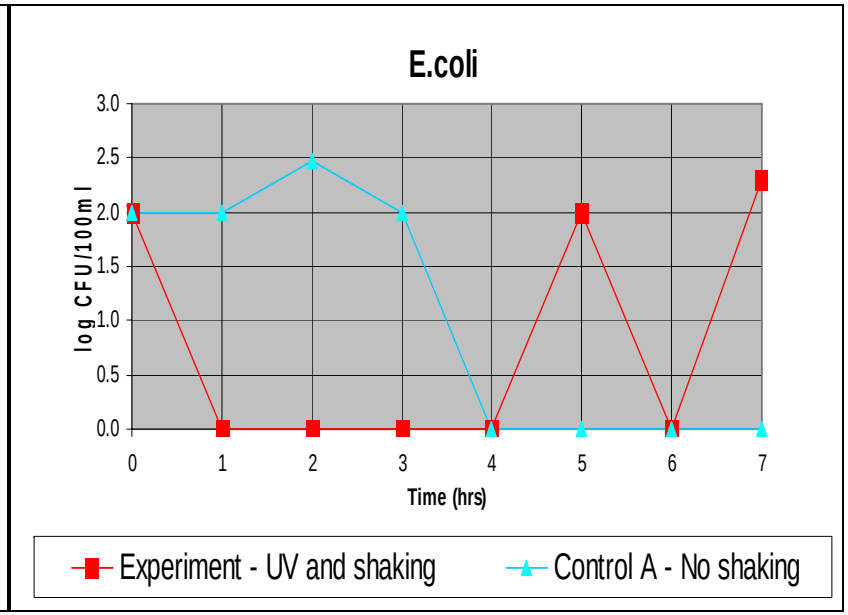
	MEMBRANE FILTRATION SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	1,100	72,600	1,600	65,600	3.0	4.9	3.2	4.8
1	650	53,250	1,550	56,800	2.8	4.7	3.2	4.8
2	575	42,025	900	45,400	2.8	4.6	3.0	4.7
3	330	28,830	300	42,600	2.5	4.5	2.5	4.6
4	135	24,160	145	23,950	2.1	4.4	2.2	4.4
5	95	20,975	30	24,020	2.0	4.3	1.5	4.4
6	110	13160	85	16180	2.0	4.1	1.9	4.2
7	65	10795	20	8793	1.8	4.0	1.3	3.9





	3M PETRIFILM SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	100	8,400	100	7,400	2.0	3.9	2.0	3.9
1	1	6,500	100	7,900	0.0	3.8	2.0	3.9
2	1	8,700	300	11,100	0.0	3.9	2.5	4.0
3	1	8,600	100	9,000	0.0	3.9	2.0	4.0
4	1	8,800	1	10,500	0.0	3.9	0.0	4.0
5	100	7,400	1	8,000	2.0	3.9	0.0	3.9
6	1	10,000	1	7,300	0.0	4.0	0.0	3.9
7	200	5,800	1	5,300	2.3	3.8	0.0	3.7

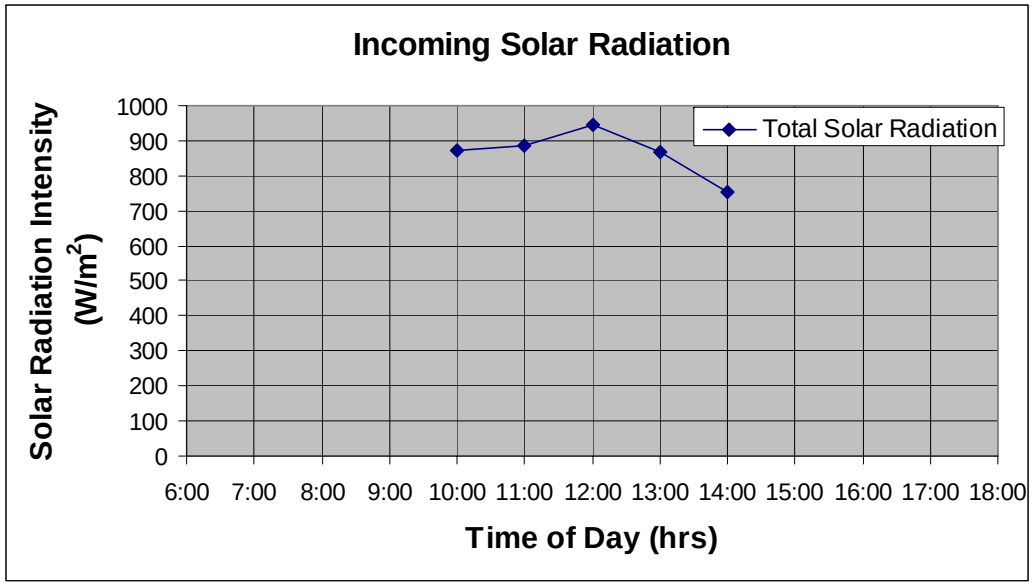




E.5 – 01/21/2007

Date: 01/21/2007
Weather: Slightly hazy. Blue skies. **Visibility:** Good
Test site: GILLBT Guesthouse, Tamale, Ghana **Water from:** N/A

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
10:00	870	0						
11:00	884	877						
12:00	945	1792						
13:00	869	2699						
14:00	755	**3511**						
	Avg.	**878**						

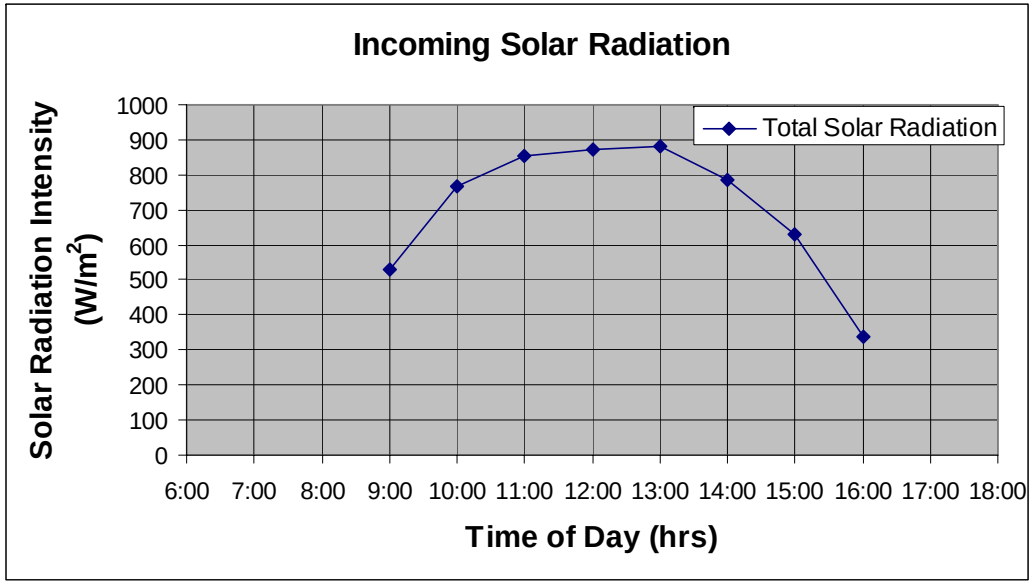


E.6 – 01/22/2007

Date: 01/22/2007
Weather: Slightly hazy. Blue skies.
Test site: GILLBT Guesthouse, Tamale, Ghana

Visibility: Good
Water from: Well at Savelugu + GILBBT tap water + previous exp. water

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
9:00	531	0	25.5	25.5	5.25	5.25	16.1	16.0
10:00	768	650	31.0	31.0				
11:00	852	1460	34.5	35.0				
12:00	873	2322	37.5	37.5				
13:00	881	3199	42.0	42.0				
14:00	784	4032	42.0	42.0				
15:00	630	4739	43.0	43.0				
16:00	340	**5224**	43.0	43.0	5.25	5.25	19.5	17.6
	Avg.	**746**	**37.3**	**37.4**				



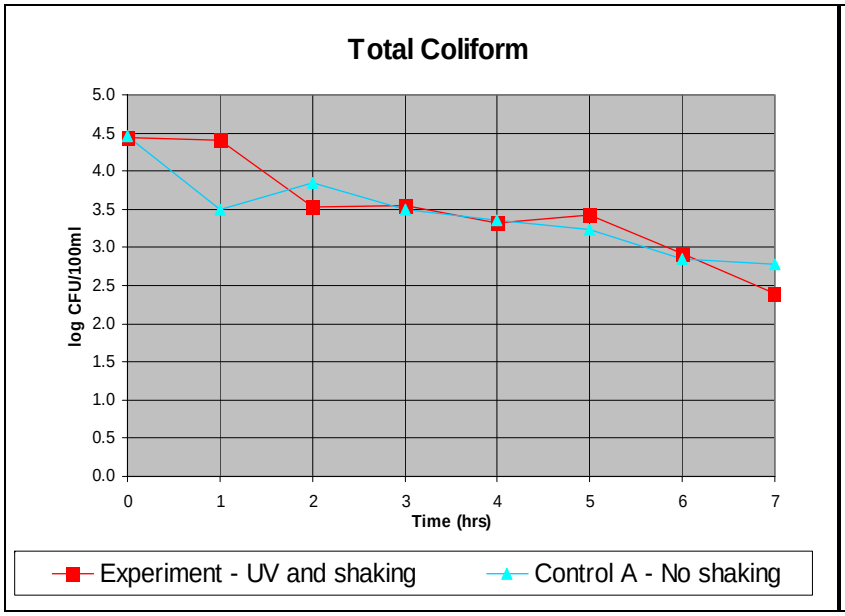
Date: 01/22/2007

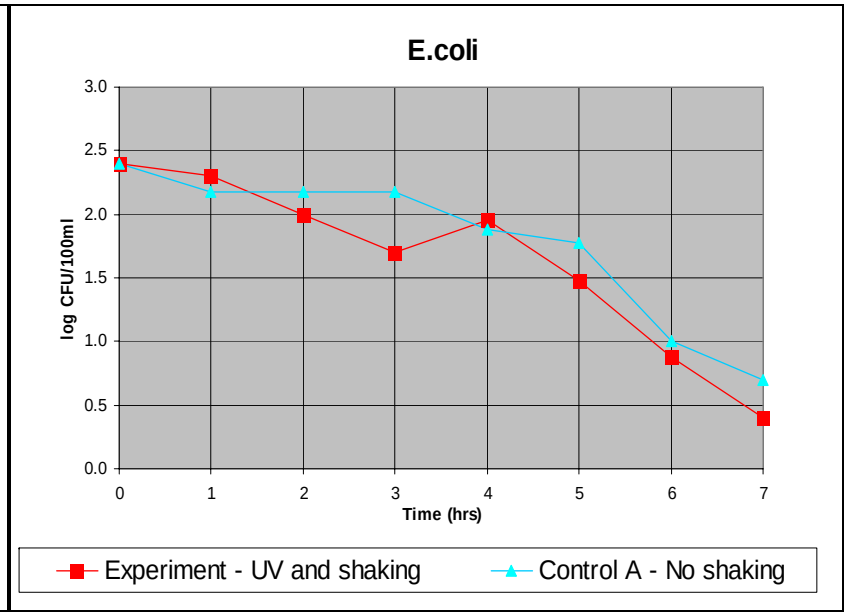
Water from: Well at Savelugu + GILBBT tap water + previous experiment water

		MEMBRANE FILTRATION					3M PETRILFILM					H_2S P/A Test After	
	Dilution	Colonies Counted		Coliform (CFU/100ml)			Colonies Counted		Coliform (CFU/100ml)				
Sample # **	Factor	Blue	Red	E.coli	Total	Remarks	Blue	Red	E.coli	Total	Remarks	24hrs	48hrs
B0a,b		0	0										
0a	100	0	196	0	19600							P	P
0b	500	1	70	500	35500								
B0c,d		0	0										
0c	100	0	82	0	8200							P	P
0d	500	1	97	500	49000								
B1a,b		0	0										
1a	100	spoiled	spoiled			smudged						P	P
1b	200	1	127	200	25600								
B1c,d		0	0										
1c	100	1	20	100	2100							P	P
1d	200	1	20	200	4200								
B2a,b		0	0										
2a	100	1	30	100	3100							P	P
2b	100	1	36	100	3700								
B2c,d		0	0										
2c	100	1	65	100	6600							P	P
2d	200	1	36	200	7400								
B3a,b		0	0										
3a	50	2	100	100	5100							P	P
3b	100	0	20	0	2000								
B3c,d		0	0										
3c	100	2	35	200	3700							P	P
3d	100	1	26	100	2700								

B4a,b		0	0										
4a	20	4	175	80	3580							P	P
4b	50	2	10	100	600								
B4c,d		0	0										
4c	50	1	70	50	3550							P	P
4d	100	1	9	100	1000								
B5a,b		0	0										
5a	10	4	246	40	2500							P	P
5b	20	1	141	20	2840								
B5c,d		0	0										
5c	20	1	79	20	1600							P	P
5d	50	2	34	100	1800								
B6a,b		0	0										
6a	5	1	188	5	945							A	P
6b	10	1	72	10	730								
B6c,d		0	1										
6c	10	0	47	0	470							A	P
6d	20	1	46	20	940								
B7a,b		0	0										
7a	5	1	58	5	295							A	P
7b	10	0	21	0	210								
B7c,d		0	0										
7c	5	0	163	0	815							A	A
7d	10	1	38	10	390								

	MEMBRANE FILTRATION SUMMARY							
	Experiment		Control A		Experiment		Control A	
Time (hrs)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (CFU/100ml)	Total Coliform (CFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)	E.coli (logCFU/100ml)	Total Coliform (logCFU/100ml)
0	250	27,550	250	28,600	2.4	4.4	2.4	4.5
1	200	25,600	150	3,150	2.3	4.4	2.2	3.5
2	100	3,400	150	7,000	2.0	3.5	2.2	3.8
3	50	3,550	150	3,200	1.7	3.6	2.2	3.5
4	90	2,090	75	2,275	2.0	3.3	1.9	3.4
5	30	2,670	60	1,700	1.5	3.4	1.8	3.2
6	7.5	837.5	10	705	0.9	2.9	1.0	2.8
7	2.5	252.5	5	602.5	0.4	2.4	0.7	2.8

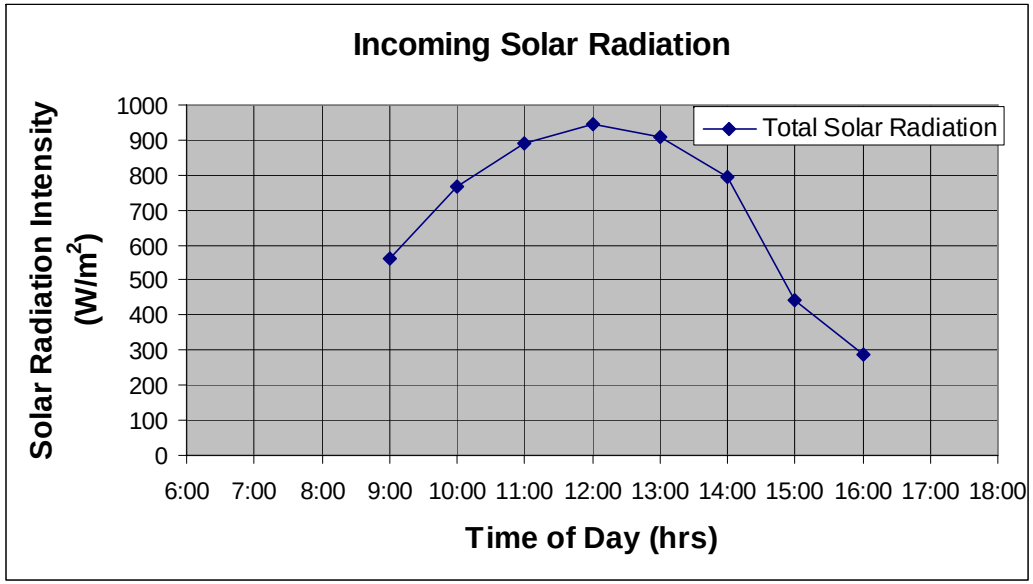


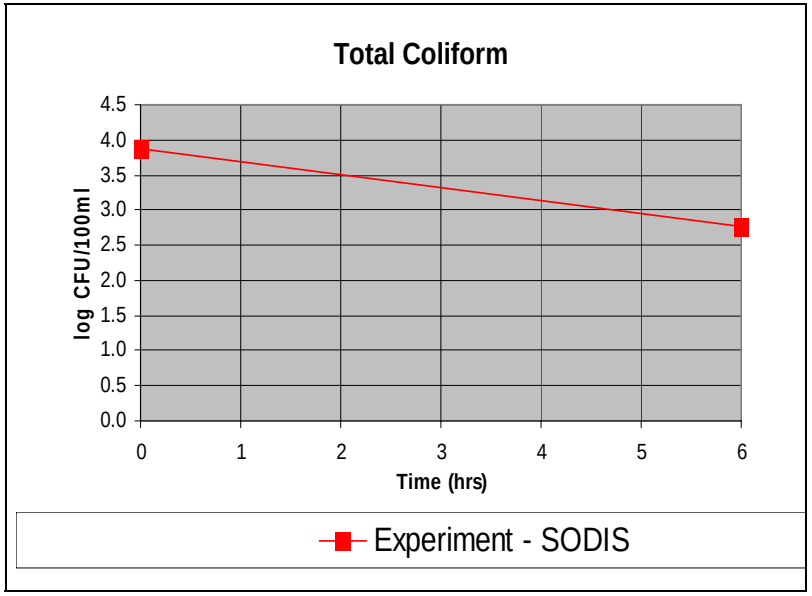


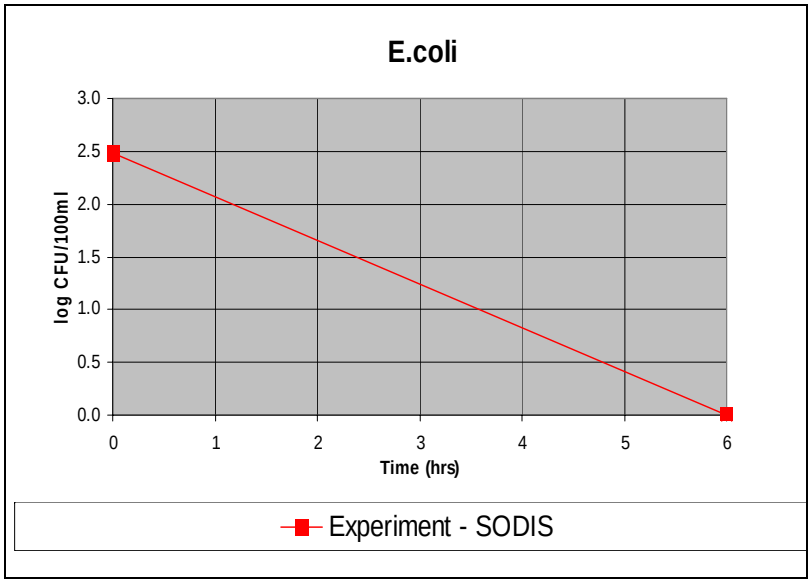
E.7 – 01/23/2007

Date: 01/23/2007
Weather: Slightly hazy. Blue skies.
Visibility: Good
Test site: GILLBT Guesthouse, Tamale, Ghana
Water from: Unprotected well at Shishegu (SODIS TEST)

Time	Total Radiation		Temperature (°C)	pH	Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*SODIS*	*SODIS*	*SODIS*	
9:00	560	0	27.0	5.25	13.4	Start SODIS
10:00	766	663	34.0			
11:00	890	1491	42.0			
12:00	944	2408	48.5			
13:00	909	3335	51.0			
14:00	793	4186	53.0			
15:00	445	**4805**	50.0	5.25	12.6	End SODIS
16:00	287	5171				
	Avg.	**739**	**43.6**			




Total Coliform
log CFU/100ml
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Time (hrs)
Experiment - SODIS


E.coli
log CFU/100ml
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Time (hrs)
Experiment - SODIS

Date: 01/23/2007
Weather: Slightly hazy. Blue skies.
Test site: GILLBT Guesthouse, Tamale, Ghana

Visibility: Good
Test: 1.RADIATION INSIDE TRANSLUCENT 10L HDPE CONTAINER
2.RADIATION INSIDE PLASTIC 1.5L PET BOTTLE (blue tint)

Time	Total Actual Radiation (W/m^2)	Total Radiation inside 10L HDPE container* (W/m^2)	% Penetration
9:00	560	340	61%
10:00	766	402	52%
11:00	890	420	47%
12:00	944	417	44%
13:00	909	403	44%
14:00	793	365	46%
15:00	445	254	57%
16:00	287	199	69%
			53% *Average*

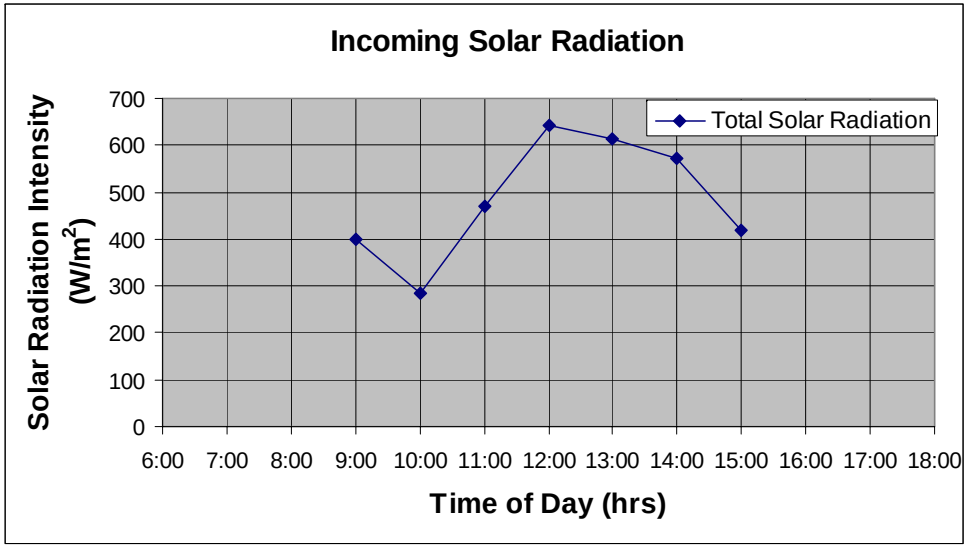
Time	Total Actual Radiation (W/m^2)	Total Radiation inside 1.5L PET bottle** (W/m^2)	% Penetration
9:00	481	424	88%

**HDPE container standing upright, with pyranomenter placed at the bottom of the container (worst case).*
***PET bottle with long side resting on ground.*

E.8 – 02/01/2007 (Accra)

Date: 02/01/2007
Weather: Slightly Hazy. Partly cloudy to cloudy. **Visibility:** Good
Test site: Accra, Ghana **Water from:** N/A

Time	Total Radiation		Temperature (°C)		pH		Turbidity (NTU)	
	Actual (W/m^2)	≈ Total Elapsed (Whr/m^2)	*Experiment*	*Control A*	*Experiment*	*Control A*	*Experiment*	*Control A*
9:00	400	0						
10:00	285	343						
11:00	470	720						
12:00	643	1277						
13:00	615	1906						
14:00	573	2500						
15:00	420	**2996**						
	Avg.	**499**						



Appendix F – Effect of shaking on Dissolved Oxygen concentration in water

Date: 04/25/2007
Location: Parsons Lab at MIT
Water from: Charles River
Turbidity: 2.3NTU
Container: 10L HDPE filled to the 3/4 mark, left open to equilibrate with atmosphere for 1 day
DO Meter: YSI Model 57

Time (minutes)	Temperature (^{O}C)	Dissolved Oxygen (DO) Concentration (mg/l)		Comments
		SOLAIR (shaking)	Control A (no shaking)	
0	21.0	9.0	8.9	
5	21.0	8.9	8.9	After SOLAIR shaken for 5 minutes
60	21.0	8.8	8.9	
61	21.0	8.9	8.9	After SOLAIR shaken for 1 minute
120	21.0	8.7	8.6	
121	21.0	8.6	8.6	After SOLAIR shaken for 1 minute
180	21.0	8.8	8.6	
181	21.0	8.9	8.7	After SOLAIR shaken for 1 minute

Container: 0.6L PETE filled to the 3/4 mark, shaken for 1 minute, then filled to the top

Time (minutes)	Temperature (^{O}C)	Dissolved Oxygen (DO) Concentration (mg/l)		Comments
		SODIS Trial 1	SODIS Trial 2	
0	21.0	8.8	8.6	
1	21.0	8.9	8.7	After bottle shaken for 1 minute

NB: DO saturation at 21^{O}C is 8.92mg/l