CHAPTER 1

EXORDIUM

1.1 INTRODUCTION

Approximately one billion people in developing countries have no access to reliable sources of clean drinking water (Wegelin *et al.*, 1994; Black, 1999). The lack of adequate water supply and the subsequent consumption of faecal contaminated water in these areas, results in a serious exposure of individuals to numerous water-related and water-based diseases. More than 875 million cases of water-borne diarrhoeal diseases are reported annually especially between infants and young children. Of these reported cases, more than 3 million ends in death (Wegelin,1999; Reed *et al.*, 2000). There is an urgent need for simple, effective, and low-cost methods for production of pathogen-free drinking water, especially on household level, which can reduce the incidences of water-borne diseases.

Household level disinfection methods commonly propagated include boiling, addition of chemicals such as chlorine or hypochlorite, and filtration through ceramic filters. The following problems are generally associated with these methods:

- Boiling of water requires energy, usually in the form of firewood or coal in rural or informal settlements. The mentioned sources of energy are becoming more scarce and costly and cannot be afforded or used by many individuals in these areas.

- Disinfection with chemicals is usually rejected due to the undesirable taste and odours acquired by the water. Other objections include costs and the application of incorrect dosages.

- Filtration through ceramic filters is unaffordable by most and these filters are furthermore subjected to frequent clogging and leaking (Wegelin, 1999).

The problems mentioned above calls for the development of alternative small-scale disinfection methods that are effective, practical and simple to use by individuals or households. A low cost and sustainable method which gained support in recent years, makes use of the disinfectant properties of sunlight which is universally available and free of charge, to inactivate and destroy faecal bacteria present in water in a process called solar disinfection (Acra & Ayoub, 1997). Disinfection with solar radiation has been used for centuries, as long ago as 2 000 BC (Bingham, 1985). The advantages of using solar radiation are numerous and include amongst others: it is a natural process with no production of dangerous, toxic, or hazardous by-products; no smell and/or taste are imparted to the water; it exerts a low economical demand; and is easy to apply. The disadvantage however, is that there is no residual disinfection power available to prevent secondary contamination of the disinfected water.

Research into solar disinfection focussed on the development and application of the SOPAS (solar pasteurization) and the SODIS (solar disinfection) processes. The SOPAS disinfection process employs the pasteurization effects of solar radiation at temperatures above 70°C (Joyce *et al.*, 1996), while the SODIS process makes use of the synergistic effect of solar radiation and temperature between 50° and 70°C (Wegelin *et al.*, 1994; Sommer *et al.*, 1997).

Recent research by Reed (1997a) illustrated the critical role dissolved oxygen plays in the inactivation of faecal bacteria during solar radiation, which led to the investigation of a process called solar photo-oxidation. Preliminary laboratory and field results, indicated that solar photo-oxidation even in the absence of thermal effects, may be an alternative useful method of water disinfection on household level in rural communities (Reed, 1997a and1997b, Reed *et al.*, 2000).

The present research reported here assessed the effectiveness of solar photo-oxidative disinfection under controlled laboratory conditions in South Africa, using de-chlorinated tap water contaminated with raw sewage.

1.2 PROBLEM STATEMENT

In South Africa, more than eight million people do not have access to adequate or reliable sources of clean running water. These people obtain water from alternative sources such as streams, rivers, dams, boreholes or wells which are most of the time, heavily contaminated with amongst others, faeces. The consumption of this water leads to high incidences of water-borne diarrhoeal diseases and high mortality rates among infants and the elderly (Genthe & du Preez, 1995, Genthe & Seager, 1996).

Disinfection in these rural poverty-stricken areas with no access to running water is a huge problem (Genthe & Seager, 1996). Various cheap and less sophisticated methods have been in place for some time, including filtration, addition of oxidising chemicals, boiling and aeration, all with limiting application (small volume) and with sometimes unreliable results (Solsona, 1996). Most of these methods require some form of infrastructure and economical investment, and educated or informed use.

Alternative disinfection methods which are efficient, economical, and easy to apply are therefore needed in the South African rural communities. The provision of such a method, together with improvement of sanitation and domestic hygiene, could result in a substantial reduction in the occurrence of water-borne disease and the mortality rate (Genthe and Seager, 1996; Solsona, 1996).

1.3 AIM

The research aims to test through a laboratory evaluation study, that the solar photo-oxidation process is a feasible and applicable disinfection process which could be used in the rural areas of South Africa where clean running water is non-existent.

1.4 OBJECTIVES

The objectives of the present research were:

- To determine through controlled laboratory experimentation, the feasibility and the applicability of the solar photo-oxidation process as an alternative and economical method of disinfection of hand drawn drinking water in the South African rural scenario.

- To observe the effects of selected physical and chemical parameters on the efficiency of the solar photo-oxidation process. The parameters chosen are: heavy and dense cloud cover; high turbidity; colour of plastic containers; volume of water; and seasonal variations of solar radiation intensities and oxygen transfer efficiencies.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

Solar radiation has well known antimicrobial properties and has been used for centuries in food preservation and water treatment. Historians believe that exposure of water to sunlight was practised as long ago as 2 000 BC in India. The rediscovery of this art could prove to save lives in many developing countries (Bingham, 1985).

The application of solar radiation as a disinfectant of water in countries with a consistently sunny climate, has been investigated and illustrated by various authors including Calkins *et al.* 1976; Acra *et al.* 1984 and 1989; Joyce *et al.* 1992 and 1996; McKenzie *et al.*, 1992; Conroy *et al.*, 1993 and 1996; Wegelin & Sommer, 1996 and 1997; and McGuigan *et al.*, 1998 and 1999. A wide range of enteric bacteria and viruses which were variably inactivated by exposure to sunlight radiation, including the physical and chemical factors which influences the practical application of solar disinfection were reported by these authors. The following represents a summary on the results of these investigations. The discussion is divided into three sections, viz., solar radiation, influencing parameters, and solar photo-oxidation.

2.2 SOLAR RADIATION

Introduction

Solar radiation uses solar energy to improve the microbiological quality of water by eliminating the pathogens which can cause water-borne disease (Wegelin, 1999).

Laboratory application

Initially solar radiation investigation was applied under controlled conditions in the laboratory. Acra *et al.* (1984) and Bingham (1985) reported a 99,9% kill of total bacterial populations in 300 minutes and a 99,9% kill of coliform bacteria in 95 minutes of natural contaminated water through solar radiation application. Under normal room conditions, i.e. no direct sunlight, the 99,9% destruction levels were achieved in only 850 minutes and 300 minutes, respectively. When the water samples were placed in complete darkness (no sunlight), the total bacterial population steadily increased, while the coliform bacteria died off naturally at an extremely low rate. Shah *et al.* (1996) sterilized water which was then deliberately contaminated with *Escherichia coli* and exposed to solar radiation for several hours. A decrease from several thousands to less than one coliform unit (CFU) per ml water was observed.

Although most of the researchers focussed mainly on total coliforms (TC) and faecal coliforms (FC) as indicator organisms, the potential application of the solar radiation disinfection process to kill or inactivate other types of pathogenic microorganisms was identified. Both *Acra et al.* (1984) and Bingham (1985) investigated the destruction times for typical microorganisms found in faecally contaminated water. The time required for complete destruction of each microorganisms was found to be: *Pseudomonas aeruginosa* - 15 minutes; *Salmonella flexneri* - 30 minutes; *Salmonella typhi* and *Salmonella enteritidis* - 60 minutes; *Escherichia coli* - 75 minutes; and *Salmonella paratyphi B* - 90 minutes. The results were promising for some of the microbial species, but for *Vibrio cholerae* no really successful data were reported up to date.

The effect of solar radiation on water-borne and water-transmitted pathogenic protozoan and viral species were also investigated. Wegelin *et al.* (1994) reported the inactivation of bacteriophages f2, encephalomyocarditis viruses (EMCV), and rotaviruses by UV-C radiation. EMCV was the most resistant of the viruses, while bacteriophage f2 and the rotavirus showed a 3-log reduction. It was suggested by the

authors that bacteriophage f2 can be used as another indicator organism to monitor efficiency of solar radiation disinfection. Lawand (1988) concluded that the protozoa *Giardia lamblia* can be destroyed to a lesser extent than bacteria and viral cells by solar radiation. Ciochetti and Metcalf (1984) thermally inactivated cysts of *Giardia lamblia*, *Giardia muris* and *Entamoeba histolytica* at 56°C in 10 minutes.

Full-scale field applications

Full-scale field applications were performed on both small and large quantities of water collected for drinking purposes. Calkins *et al.* (1976) were the first to study the effect of solar disinfection in waste stabilisation ponds downstream from a wastewater treatment system. They suggested both UV-A and UV-B radiation to be the important environmental factor highly lethal to most pathogenic microorganisms. In subsequent investigations, the synergistic role of temperature with ultraviolet radiation was emphasized and illustrated. Wegelin *et al.* (1994) concluded that water temperature of between 20° and 40°C did not affect the inactivation of bacteria by UV-A radiation. Synergetic effects were only observed at threshold temperatures of 50°C and higher, when the fluence time required for *Escherichia coli* inactivation was decreased more than three times from 300 to 90 minutes. McGuigan *et al.* (1998) confirmed this conclusion, indicating that strong synergy between optical and thermal inactivation was observed at water temperatures above 45°C, but optimally between 50° and 70°C.

From the full-scale field studies, the SOPAS (solar pasteurization) and SODIS (solar disinfection) processes were developed. The SOPAS disinfection process employs the pasteurization effects of solar radiation at temperatures above 70°C (Joyce *et al.*, 1996), while the SODIS process makes use of the synergistic effect of solar radiation and temperature between 50° and 70°C (Wegelin *et al.*, 1994; Sommer *et al.*, 1997). A problem experienced with the SODIS and SOPAS field applications (both batch and continuous flow), was to maintain a working temperature of between 50° and 70°C, and higher than 70°C, respectively. This could prove to be the limiting factor for application for the process under little supervision and with unqualified technicians.

Full-scale field application of the SODIS process in Kenya gave a three-log reduction (99,9%) of both faecal coliforms and *Vibrio cholerae* over a period of 140 minutes at a UV-A dose of 54 W.h/m^2 (Sommer *et al.*, 1997). The authors stressed the fact that a water temperature of more than 55°C was needed to obtain these results - a process called thermal radiation. Wegelin (1999) confirmed these results while at the same time claiming that the SODIS process can also inactivate the common human parasites *Cryptosporidium* that causes severe diarrhoea.

SOPAS field application was shown by Joyce *et al.* (1996) in a Kenyan rural village, where water samples heavily contaminated with *Escherichia coli* (20 x 10^5 CFU/ml) were totally disinfected within seven hours with no viable cells observed at the end of the experiment or after a lag period of 12-h. This indicates that the bacterial cells did not recover and were irreversible inactivated, damaged and/or killed. What made this results interesting and remarkable was the presence of high and variable turbidity ranging between 5 and 2 000 nephelometric turbidity units (NTU).

Continuous flowing water

The application of solar radiation on continuous flowing water was investigated as the next logical step. Wegelin *et al.* (1994), Wegelin (1995), Acher *et al.* (1994), and Acra and Ayoub (1997) reported three pilot plant applications in Tel-Aviv, Beirut and Costa Rica respectively, operating at a 50 m^3/h continuous flows. The average disinfection time was found to be 35 minutes with a 4- to 5-orders of magnitude faecal microorganism reduction and with no apparent reactivation of the inactivated faecal microbial cells.

In another application, Acra and Ayoub (1997) used mirrors to concentrate sunlight directly onto water containers. A 3-s exposure time was allowed at a flowrate of 0,15 m^3/h, resulting in a 5-order magnitude of microbial killing. No reactivation was evident even after seven days.

Summary

Solar radiation has been investigated and applied in various laboratory and full-scale field studies. The results indicated that almost all the pathogenic microorganisms found in faecally contaminated water, can be destroyed and/or inactivated by the radiation energy from the sun. Solar disinfection may thus offer a way of decreasing the risk of infection in circumstances where (i) the surface waters are faecally contaminated; (ii) where conventional water supplies are unavailable, disrupted or inoperative; or (iii) short term treatment is needed during an outbreak of cholera or bacterial diarrhoea.

2.3 INFLUENCING PARAMETERS

Because normal solar radiation gave variable results, most of the authors looked at a wide variety of parameters which could influence the efficiency of the solar radiation disinfection process, i.e. turbidity; temperature; dissolved oxygen; type, colour and shape containers; presence of sensitizing dyes, organics and other chemicals; volume of water; effective area of penetration and/or depth of water; weather patterns; and type and initial concentration of microorganisms.

Turbidity

Bingham (1985), Wegelin *et al.* (1994) and Joyce *et al.* (1996) investigated the effect of turbidity on the disinfection efficiency of solar radiation. All the authors concluded that high concentration of turbidity (up to 300 NTU) will interfere with the solar transmission and prevent the radiation to reach all of the microbial cells. Particles contributing to the turbidity will shield and protect the microbial cells through attachment or, by scattering the radiation that penetrates the water. In contradiction to this, Joyce *et al.* (1996) reported significant results where water heavily contaminated with *Escherichia coli* (20×10^8 CFU/ml) and with high and variable turbidity ranging between 5 and 2 000 nephelometric turbidity units (NTU), were totally and irreversibly disinfected within seven hours.

Temperature

Temperature was investigated for its individual and synergistic effect on the solar disinfection process (Joyce *et al.,* 1996; Sommer *et al.,* 1997). The conclusion made by the investigators, was that temperatures above 45^{0}C (optimally between 50° and 70°C) will positively influence the disinfection process, whereas temperatures lower than 45°C did not have any significant effect on the disinfection action.

Dissolved oxygen

The influence of dissolved oxygen was observed by Acher *et al.* (1994), Parodi *et al.* (1996) and Reed (1996). The authors agreed that DO acts synergistic with solar radiation during the disinfection process, but only at concentrations of 1,5 mg/l and higher. Through this investigation the solar photo-oxidation process was suggested (Reed, 1996). This disinfection process is described and discussed extensively later in this chapter.

Glass vs plastic containers

The use of glass or plastic water containers, either as bottles or bags, was researched by Shah, *et al.* (1996), Wegelin and Sommer (1996), and Sommer *et al.* (1997). In all the applications, the glass bottles gave slightly better disinfection results than plastic bottles. However, under full-scale field application, plastic bottles were preferred by the community members for convenience and availability. The question whether to use plastic bags or clear bottles is still under investigation, as preliminary results are conflicting. With smaller volumes (2 to 5 litres) the bags are a viable option, but with application on larger scale (up to 25 litres) it becomes impractical. Bottles would thus be preferred with larger volumes. A benefit which the bags have is the higher radiation penetration level which could be achieved together with the rapid increase of temperature to the desired values. The shape of the containers was found to have only a slight increase in the required exposure time. Rounded shape containers proved to be

the best choice, followed by cylindrical, conical and square-shaped containers (Acra *et al.*, 1984).

Colour of containers

The most appropriate colour of the bottles or bags to be used, which would yield optimum results in terms of bacterial destruction, was also investigated. Colourless containers are the best choice as they transmit light in the near ultraviolet region (the most lethal range) as well as visible light, into the contaminated water. Violet and blue containers are next in the priority of use, followed by green, yellow, orange and red. The walls of coloured containers, unlike the walls of colourless or blue containers, obstruct the transmission of the most lethal rays of sunlight (Acra *et al.*. 1984; Bingham, 1985). With the application of SODIS and SOPAS, it was found that black bags and bottles were the best choice, as black absorbs most of the energy from radiation and increases the temperature of the water to the required value (Sommer *et al.*, 1997; Wegelin, 1999).

Effective area or depth of penetration

The effective area of solar UV penetration and/or the depth of the water was investigated by various authors. Calkins *et al.* (1976) suggested that a large surface area for any given volume will make the disinfection process more efficient. Wegelin (1999) indicated that UV-radiation decreases with an increase in water depth, i.e. a water depth of 10 cm will reduce the radiation by 50%. The author concluded that a water depth of six to 10 cm is recommended for containers with large areas available for penetration, while a depth of less than 6 cm must be used if the area of penetration is small. In addition to water depth, the thickness of the container walls will also reduce the radiation which can come in contact with the contaminated water. However, in all cases the reduction in radiation can be overcome by longer radiation periods (Acra *et al.*, 1984).

Presence of interfering chemical substances

The presence of sensitising dyes, organics and other chemicals in the collected water was investigated by various authors (Bingham, 1985; Pelizetti *et al.*, 1990; Acher *et al.* 1994; Spiewak *et al.*, 1996; Acra & Ayoub, 1997). Sensitising dyes (usually methylene blue) in the presence of aeration, acts as an intermediary for the absorption and transfer of sunlight energy to activate DO and/or to destabilize the organic matter and microorganisms as the oxidation target. This results in a higher adsorption rate of energy and faster inactivation and destruction of the microbial cells.

The presence of reasonable concentrations of organic impurities did not hinder the disinfection process, but further research is still needed to investigate the photo-decomposition of photo sensitive organic compounds upon exposure to sunlight. Exposing the water to sunlight can also have a photo-catalytic degradation effect on organic pollutants such as aliphatic and aromatic hydrocarbons, phenols, polychlorodioxins, pesticides, surfactants, amines, and anilines (Pelizzetti *et al.* 1990; Spiewak *et al.*, 1996), can result in formation of CO_2, mineral and inorganic acids and other by-products. Most of these by-products will not have a negative effect on the water quality.

Volume of water

Wegelin (1995) observed the feasible volume of water that can be disinfected with solar radiation. He concluded that one can apply the process to smaller volumes (from 1 to 25 litres) for household use and on large scale continuous flow systems alike. The continuous flow systems were tested at an initial 200-litre capacity per day at an operating temperature of 50°C which was reached within 50 to 90 minutes. A 4-log faecal coliform concentration in the raw water was completely reduced in the reactor. Acher *et al.* (1997) applied solar radiation on a continuous flow plant in Israel with a flow rate of up to 50 m^3/h. Disinfection time was 35 minutes and a decrease in microbial population was between 4 and 5 orders of magnitude with no photo-

reactivation during seven days. Similarly, Fjendbo Jorgensen *et al.* (1998) produced drinking water at 0,050 m^3 per m^2 of solar panels after concentrating heat and solar radiation through a flow through system of copper pipes.

Weather patterns

The influence of weather patterns, specifically cloud cover, and daily and seasonal variations, was discussed and observed by many authors. Clouds tend to reduce the intensity of direct sunlight (both UV and visible light). The thicker the clouds, the more the sunlight is restricted. This as such does not reduce the efficiency, but will necessitate an increase in the time of exposure (anything from one to several hours, depending on the thickness of cloud cover) to ensure germicidal action (Acra *et al.*, 1984). Sommer *et al.* (1997) also assessed the impact of clouds on the process reliability. Their experiments indicated three times more energy to be available for heating and irradiation on a clear day as compared to a completely overcast day. The authors further concluded that a slightly overcast day did not have any effect on solar radiation, while 50% cloud cover reduced the radiation by 36% and a very cloudy day reduces the radiation even further to 47%.

As the intensity of sunlight varies during the day, it is recommended to expose the containers to solar radiation between ten o' clock in the morning and two o' clock in the afternoon, i.e. when the sunlight shows the greatest visible and ultraviolet light radiation intensities. Acher *et al.* (1994) illustrated that the variation experienced in solar radiation levels during the four seasons (spring, summer, autumn and winter), did not influence the disinfection efficiency adversely.

Type and initial concentration of microorganisms

The type and initial concentration of microorganisms will influence the time of exposure and the efficiency of the solar radiation disinfection process. Several species of viruses, algae, fungi and bacteria have shown sensitivity to solar radiation, visible

light and/or temperature (Acher & Juven, 1977; Wei *et al,* 1994). *Streptococcus spp.* showed slightly more resistance to UV radiation than coliforms and specifically, *Escherichia coli*. Enteroviruses and rotaviruses are highly thermoresistant as compared to faecal coliforms and other pathogenic bacteria, such as *Vibrio cholerae* (Wegelin, 1999). When solar radiation and temperature are used synergistically, the resistance are quite significantly reduced.

Higher microbial concentrations have a lower sensitivity to solar radiation. A concentration of not more than 1 000 CFU/100 ml of raw water was suggested for efficient solar disinfection at low exposure time (Wegelin *et al.*, 1994). In reality this concentration is usually much higher in nature. Joyce *et al.* (1996) found for example bacterial concentrations of 10 000 CFU/100 ml of raw water. The authors did not experience any problem in destroying these bacterial cells in a relative short period of exposure (5-h), especially with the synergistic relationship of solar radiation and temperature.

Summary

The disinfection efficiency of solar radiation and the rate of microbial cell inactivation and/or destruction, depends on various influencing factors as illustrated above. Referring to the discussion above, the most important factors are: the intensity of the sunlight and the time of exposure; the type and concentration of bacteria being exposed; the characteristics of the containers; and the clarity of the water and the depth of radiation penetration.

2.4 SOLAR PHOTO-OXIDATION

Reed (1996) evaluated specifically the function of oxygen as a factor which influence the efficiency of the solar disinfection process. The research led to the development of a process called solar photo-oxidative disinfection (SPD). This process is also referred to as the SOL-AIR process (Reed, 1996 and 1997a). The solar photo-oxidation

disinfection process relies on the synergism of two natural available constituents, oxygen from the atmosphere and solar ultraviolet radiation (specifically UV-A and UV-B).

Reed (1996) performed controlled laboratory experiments and showed a $T_{99.9}$ for *Escherichia coli* of 100 minutes under aerobic conditions and 360 minutes under anaerobic conditions. Similarly the $T_{99.9}$ for *Enterococcus faecalis* was 90 minutes aerobically and 1 030 minutes anaerobically. Mixed faecal coliform (FC) populations and faecal streptococci (FS) had $T_{99.9}$ values of 210 minutes (FC aerobic) and 520 minutes (FC anaerobic), 190 minutes (FS aerobic) and 1 600 minutes (FS anaerobic). These results indicated solar radiation will only be fully effective in the presence of dissolved oxygen.

Further studies indicated that the mean inactivation rate of stationary phase *Escherichia coli* and *Enterococcus faecalis* cells have a decreased sensitivity to the physico-chemical stress of UV and oxygen. This would most probably be representative of enteric mixed bacteria populations in natural waters, which are under conditions of restricted growth and nutrient limitation (Reed, 1997b).

Preliminary field studies performed in South Africa and India, showed at 13 to 40% oxygen saturation values, rapid decrease of faecal indicator bacteria within 3 to 6 h, with no evidence of reactivation after 24-h (Reed *et al.*, 2000).

2.5 SUMMARY

From the discussion and literature survey presented above, it can be concluded that extensive research in the field of solar radiation and solar photo-oxidation has been conducted world wide. Solar radiation is a simple process designed to resolve microbiological water quality problems in developing areas which are deprived of safe drinking water. However, the process has its disadvantages and limitations. Solar radiation disinfection will depend on the geographic location and the prevailing

climatic conditions of the said area, and to the daily and seasonal variations which depends on the latitude.

Solar photo-oxidation, on the other hand, needs some more research and full-scale applications to prove its applicability and acceptability within the rural and developing areas of the world. However, preliminary results showed that photo-oxidation may provide a practical, low-cost alternative approach to the microbiological quality of drinking water obtained from sources such as rivers, streams, and boreholes (Reed *et al.*, 2000).

CHAPTER 3

THEORETICAL BACKGROUND

SOLAR PHOTO-OXIDATIVE DISINFECTION

3.1 INTRODUCTION

Solar photo-oxidative disinfection of hand drawn water can be used on household level with very little economical investment or any need of elaborate infrastructures. The process relies on the synergistic effect of solar UV radiation and oxygen from atmospheric air, to lethally affect the bacterial cells in a water source. Solar photo-oxidation consists of four stages which should be exactly followed, in order to ensure optimum faecal coliform destruction (Figure 1). Stage 1 involves the filling of the water containers early in the morning with water direct from the source. The containers must not be filled up to capacity, but some void space should be left at the top of the container for air/oxygen exchange. In stage 2, each container is capped and shaken vigorously for a few minutes to ensure oxygen saturation. Dirt, labels or any visible interferences should be removed from the outside walls of the container. Next, the containers are placed in full and direct sunlight for a minimum period of 3 to 5 hours. Care should be taken that the containers are not shaded by one another or by trees or walls. The time of exposure will depend on the concentration of microorganisms, intensity of UV radiation, turbidity concentration and the presence of other impurities in the raw water. As microorganisms will consume DO during the breakdown of organic matter present in the water, vigorous shaking is applied regularly (at least four times during the total exposure time) to dissolve and saturate oxygen into the water. The final stage involves the storage of the water containers with the disinfected water in a cool place to reduce the temperature of the water to an acceptable value for drinking purposes (Reed, 1997a).

Draw water from a source directly into a transparent or white container

Shake water vigorously and place in direct sunlight for a minimum of four hours. Shake the water again at least four times during the exposure time.

Cool the water, pour and drink.

Figure 1. The photo-oxidative disinfection process (Meyer, 1999).

The following section describes the disinfection actions of each of the components involved in the solar photo-oxidative disinfection process and tries to give an explanation of the synergistic disinfection action ultraviolet radiation and oxygen will have on the bacterial cells.

3.2 DISINFECTION ACTION OF ULTRAVIOLET RADIATION

Sunlight consists of various bands of electromagnetic waves, ranging from invisible ultraviolet rays to the visible and infra red ranges. Ultraviolet radiation falls in the wavelength range of 100 to 400 nm (Figure 2).

a) SOLAR RADIATION WAVELENGTHS (nm)

Invisible range	Visible range						Invisible range
Ultraviolet	Violet	Blue	Green	Yellow	Orange	Red	Infrared
100-400	400-425	425-490	490-575	575-585	585-650	650-700	700-14000

b) ULTRAVIOLET RADIATION WAVELENGTHS (nm)

Vacuum UV Extreme UV	UV-C Far UV	UV-B Mid UV	UV-A Near UV
100 - 200	200 - 280	280 - 320	320 - 400

Figure 2. Spectrum of a) solar radiation and b) ultraviolet radiation (Acra *et al.*, 1984).

Solar radiation is depleted or attenuated through absorption, scattering and reflection in the stratosphere with its thin layer of ozone and the troposphere with its cloud formations and other weather conditions. In the stratosphere the solar UV radiation is absorbed. Shorter wavelengths of UV radiation of up to 350 nm, are more effectively absorbed than longer wavelength radiation. This shields the earth from the biological

harmful radiations below 280 nm, allowing only a fraction of UV-A and UV-B wavelength bands to reach the earth's surface. The ultraviolet component from sunlight is also reflected and scattered in the troposphere by water droplets and ice in the clouds, and by particulate matter such as dust, smoke, haze and smog. The scattering is inversely proportional to the wavelength and is most effective at the short wavelengths. The degree of scattering decreases as follows: UV-B > UV-A > violet > blue > green > yellow > orange > red > infrared (Acra *et al.,* 1984; Lawand *et al.,* 1988).

According to Pelczar *et al* (1993) and McKane & Kandell (1996) the bactericidal action of ultraviolet radiation is focussed on the intracellular material of the bacteria. Ultraviolet light is absorbed by many of the intracellular compounds of the bacterial cell, but the deoxyribonucleic acid (DNA) usually suffers the most damage. If the bacterial DNA is exposed to UV radiation, pyrimidine dimers will form when two adjacent pyrimidines on the same DNA strand, bond together (Figure 3).

Bacterial cells have a repair mechanism in place in the form of special intracellular enzymes which can remove and replace these pyrimidine dimers. If this repair mechanism does not work, the DNA replication is inhibited or altered, causing death or mutation to the microbial cells (Pelczar *et al.*, 1996; McKane & Kandell, 1996).

The highest bactericidal action occurs at a wavelength of 260 nm (in an effective range between 200 and 350 nm), which is where the DNA absorbs the most ultraviolet light. The UV light which actually reaches the earth surface is restricted to a wavelength range from 295 to 400 nm. Of the UV light in this range which actually reaches the earth, the UV-A light with wavelengths between 315 and 400 nm are the most effective in terms of disinfection, accounting for 70% of the bacterial destruction potential. Visible light at wavelengths between 400 and 750 nm

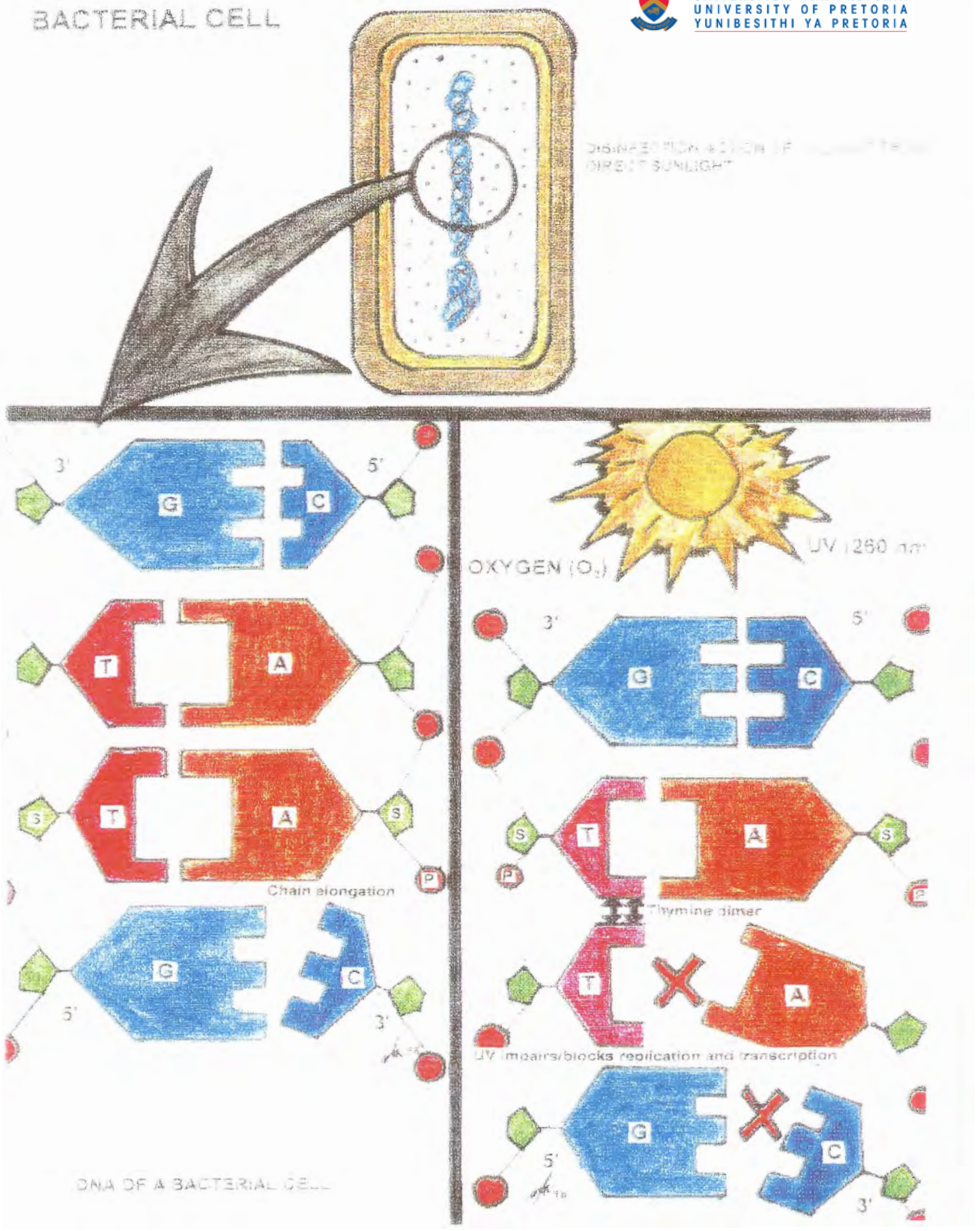

Figure 3. **Disinfection action of UV radiation on the DNA of a bacterial cell (adapted from McKane & Kandell, 1996).**

accounts for the remaining 30% destructive capacity (Acra *et al.,* 1984; Wegelin *et al.,* 1994). The intensity of the sunlight varies with latitude, geographic location, season, cloud coverage, atmospheric pollution, elevation above sea level, and solar altitudes. All these factors contribute towards the limitation of the microbicidal properties of UV light as a sole disinfectant (Solsona, 1996).

3.3 DISINFECTION ACTION OF OXYGEN

Most members of the *Enterobacteriaceae* are facultative microorganisms, growing either in atmospheric air (aerobic) or in the absence of air (anaerobically). Oxygen is usually used for energy-yielding chemical reactions and not for bacterial cell growth. According to Pelczar *et al.* (1993) the toxicity of oxygen for some species of bacteria can be contributed to the molecules produced during oxidation reactions. One of these molecules which are formed is a superoxide radical (O_2^- .):

$$O_2 + e^- \rightarrow O_2^- \quad (1)$$

These superoxide radicals can cause damage to a cell, but are usually converted to hydrogen peroxide (H_2O_2) and hydroxyl radicals ($OH.$) in the presence of ion complexes:

$$2O_2^- + 2H^{2+} \rightarrow O_2 + H_2O_2 \quad (2)$$

Iron complexes

$$O_2^- + H_2O_2 \rightarrow O_2 + OH^- + OH. \quad (3)$$

Hydroxyl radicals are short lived (1/10 000 s) and are one of the most reactive chemical substances known. These substances can damage every kind of molecule found in living cells, including the DNA of microorganisms (McKane & Kandell, 1996).

Various protective mechanisms have been developed by the bacterial cell for protection against hydroxyl radicals, including production of the enzyme superoxide dismutase which will eliminate superoxide radicals by converting them rapidly to hydrogen peroxide (see equation 2). The hydrogen peroxide is then dissipated by catalase to oxygen and water or by peroxidase to water. The elimination of both superoxide radicals and hydrogen peroxide means that equation 3 cannot proceed and hydrogen radicals will not be formed. All the enzymes are produced through information from the DNA, thus if the DNA is to be damaged, this protection mechanism will subsequently be inactive (McKane & Kandell, 1996 and Pelczar *et al.*, 1993).

3.4 SYNERGISTIC DISINFECTION ACTION OF ULTRAVIOLET RADIATION AND OXYGEN

As illustrated in the discussions above, both solar UV radiation and oxygen can inactivate the intracellular material of bacterial cells, specifically the DNA, as disinfectants on their own. When applying both parameters at the same time, solar photo-oxidation, a synergistic effect is observed, with higher inactivation rates for many types and species of faecal coliforms. The synergism could be explained as follows: if the DNA of a bacterial cell is damaged or inactivated (production of pyrimidine dimers) through exposure to solar UV radiation, additional contact and exposure to dissolved molecular oxygen radicals will irreversibly damage the DNA and other cell material by inhibiting the internal repair mechanisms and/or production of essential enzymes needed by the cell. The same should be true if the cell was exposed to oxygen initially and then afterwards to solar UV radiation.

Solar photo-oxidative disinfection is thus an attractive and effective approach to low-income people living in rural and underdeveloped communities. Although the process has shown to be effective under controlled laboratory conditions in the United Kingdom (UK), more laboratory and full-scale field studies need to be initiated and monitored to observe the practical application possibilities and acceptances in South African communities. Practical applications include the provision of treated water to people with no access to clean running water, emergency water supplies, short term treatment after flooding, provision of drinking water to babies and the elderly, provision of oral re-hydration solutions, and short term treatment of sources contaminated with pathogenic bacteria such as during outbreaks of cholera.

3.5 SUMMARY

From the information presented by Reed in 1996 and 1997, a laboratory-scale research project was suggested, proposed, designed and performed by the author to observe and monitor the synergistic effect of photo-oxidative disinfection on coliform microorganisms present in feacally contaminated hand drawn drinking water. The research also observed the effect that some specifically identified physical and chemical parameters would have on the disinfection efficiency of the process.

The following report summarizes and discusses the results obtained from a comprehensive laboratory evaluation study of the solar photo-oxidative disinfection process.

CHAPTER 4

LABORATORY ANALYSES

4.1 INTRODUCTION

The solar photo-oxidative disinfection process was applied under controlled laboratory conditions to de-chlorinated tap water contaminated with raw sewage on the premises of Technikon Northern Gauteng, Soshanguve. All the physical, chemical and microbiological analyses were performed in the microbiology laboratories of the technikon.

4.2 EXPERIMENTAL PROCEDURE

4.2.1 Solar photo-oxidative disinfection

Source of water and sewage

Screened raw sewage was collected from Klipgat Sewage Treatment Works, Soshanguve, Pretoria.

Tap water was de-chlorinated through addition of 0,2 ml of a 3% solution of sodium thiosulphate (Merck, $Na_2S_2O_3.5H_2O$). The de-chlorinated tap water was inoculated (contaminated) with 2% (v/v) raw sewage to give total coliform and faecal coliform counts of between 25 000 and 31 000 CFU/100 ml and 20 000 and 30 000 CFU/100 ml, respectively.

Physical and chemical analyses

Using a calibrated Mettler Toledo (M90) portable meter, the following parameters were measured for each sample taken:

- pH (0 to 14 pH units, resolution of 0,01 pH units)
- temperature (-0,5° to 100°C, resolution 0,1°C)
- total dissolved solids (TDS) (1 to 10 g/l, resolution 0,01 g/l)
- dissolved oxygen (DO) (0 to 20 mg/l, resolution 0,1 mg/l).

All probes had temperature compensation as a standard feature.

A portable Lovibond turbidity meter (DRT 15CE) with a measuring range of between 1 and 1 000 mg/l (+/- 4%) was used to measure the turbidity of the samples. The meter was standardized and calibrated with a 0,02 NTU reference solution.

A Delta Ohm microprocessor controlled quantum photo/radiometer (HD 9021) was used to measure the UV-A and UV-B irradiances over the experimental periods. The UV-A probe measured from 10 nanoWatt/cm^2 to 200 milliWatt/cm^2 (+/- 4%) in the spectral range 315 to 400 nm, peaking at 365 nm. The UV-B probe measured from 10 nW/cm^2 to 200 mW/cm^2 (+/- 4%) in the spectral range 280 to 315 nm, peaking at 312 nm. UV measurements was taken in direct sunlight and for penetration purposes, the probes were placed inside the containers (suspended in the water).

Microbiological analysis

The standard membrane filter (MF) technique was used. Since diluted raw sewage was used, the suggested sample volume of 2 ml was filtered through 47 mm membranes of 0,45 µm (HA-type) and 0,7 µm (HC-type) pore sizes,

respectively. HC-type filters allow improved recovery of stressed faecal coliform, resulting in a more reliable result (Millipore, 1992).

The 0,45 µm pore size filters were transferred aseptically to 65 mm petri dishes containing freshly prepared m-Endo agar (Merck), while the 0,7 µm pore size filters were transferred aseptically to petri dishes containing freshly prepared MFC agar without rosolic acid (Merck). Inverted m-Endo agar petri dishes were incubated at 35°C (+/- 0,5°C) for 24 h and the M-FC agar petri dishes at 44,5°C (+/- 0,2°C) for 24-h.

Enumeration of colonies was performed using the grid system. Colonies with a gold metallic green sheen on the m-Endo agar plates was taken as positive for total coliform growth and light to dark blue colonies on the MFC agar plates as positive faecal coliform growth. Results were reported in number of indicator organisms per 100 ml (CFU/100 ml) using the following formula:

$$CFU/100ml = \frac{cells\_counted}{ml\_sample} x100 \qquad (4)$$

The following microorganisms were positively isolated and identified from the raw sewage: *Escherichia coli* and *Streptococcus sp.* The ratio of *Escherichia coli* to *Streptococcus sp.* in the raw sewage, was 2,3:1. During reactivation studies after the application of the solar photo-oxidative disinfection method, no *Escherichia coli* and *Streptococcus sp.* could be isolated in designs A or B.

Quality control was performed by an independent laboratory which sampled at random and tested as per described method above. A 95% (+/-2%) correlation was maintained throughout experimental period. A coliform confirmation kit from Millipore was used to randomly confirm positive coliform results.

Experimental design

The initial experiment was set up using 5 litre white plastic polyethylene terephthalate (PET) containers. All labels and writing were removed from the container walls prior to the experiment, as these could interfere with the transmission of oxygen and UV radiation through the side walls of the various containers. Four (4) basic experimental designs were set up to observe the influence of sunlight and dissolved oxygen in various combinations:

Design A: 5 litre plastic container (4 800 ml de-chlorinated tap water and 100 ml raw sewage); direct sunlight; shake vigorously to allow oxygen to dissolve in contaminated water; leave open.

Design B: 5 litre plastic container (4 800 ml de-chlorinated tap water and 100 ml raw sewage); direct sunlight; bubble nitrogen gas through for 10 minutes before contamination with sewage in order to remove dissolved oxygen in the water; close tightly with a cap.

Design C: 5 litre plastic container (4 800 ml de-chlorinated tap water and 100 ml raw sewage); indirect sunlight (shade); shake vigorously to allow oxygen to dissolve in contaminated water; leave open.

Design D: 5 litre plastic container (4 800 ml de-chlorinated tap water and 100 ml raw sewage); no sun - direct or indirect (place in dark room); bubble nitrogen gas through for 10 minutes before contamination with raw sewage; close tightly with a cap.

After shaking the bottles every hour, samples were taken, analysed and results recorded for graphical and statistical analyses. Great care was taken to prevent any secondary contamination of disinfected water during sampling, through the use of aseptic techniques.

4.2.2 Cloud cover

The experimental designs and procedures described above were repeated under semi-cloudy and heavily overcast and cool conditions (no direct sunshine with low, thick and dense cloud cover). Physical, chemical and microbiological analyses were performed on samples taken as described previously.

4.2.3 Turbidity

The solar photo-oxidation experimental setup was repeated on water with high turbidity. Turbidity was artificially introduced through the addition of 1,5% calcium carbonate ($CaCO_3$, Saarchem) to give a final average turbidity value of 280 NTU. Physical, chemical and microbiological analyses were performed as previously described on representative samples.

4.2.4 Volume and colour of containers

Volume

Based on the results obtained in the three experiments performed initially, only the solar photo-oxidative experimental procedures were repeated using plastic containers with effective volumes of 2 litres, 5 litres and 25 litres, respectively. The containers were filled up to 95% of their respective capacities. Physical, chemical and microbiological analyses were performed on the samples as described before and results recorded.

Colour

To investigate the influence different coloured plastic will have on the UV radiation penetration into the containers and the water, the solar photo-oxidation experiment was repeated using various coloured 5 litre plastic water containers, i.e. black, yellow, red, blue, white, and transparent. All physical, chemical and microbiological analyses as mentioned before were performed and results recorded.

4.2.5 Seasonal variation

The variations in dissolved oxygen saturation concentrations and UV-A and UV-B irradiation over the 4 annual seasons was monitored. The effect of these variations was investigated by repeating the solar photo-oxidation experiment described earlier over a period of 12 months (May 1998 to April 1999). All physical, chemical and microbiological parameters listed were analysed with described methods, and average monthly results are reported.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 SOLAR PHOTO-OXIDATIVE DISINFECTION

The solar photo-oxidative disinfection process was applied on laboratory-scale to de-chlorinated tap water contaminated with 2% raw sewage. The rate of faecal coliform destruction using both oxygen and solar ultraviolet radiation was compared with the disinfection efficiency when using solar radiation and oxygen as disinfectants on their own, and with the natural die-off of the bacterial cells under stress conditions, i.e. very low oxygen, no light penetration and no food source. The following discussion reports and interpret the results obtained.

5.1.1 Physical and chemical analyses

The measured physical and chemical parameters of the raw water did not change significantly over the experimental period with application of the various designs of the solar photo-oxidation disinfection process. Most of the physical and chemical parameters measured and reported in Table 1 complies with the domestic target water quality guideline ranges for drinking water as described by DWAF (1998).

Although oxygen diffused constantly from the atmospheric air through the walls of the plastic containers and into the water during vigorous shaking (equilibrium restoration), the DO concentration in the containers in both experimental designs A and C, decreased by 0,6 mg/l as some oxygen was consumed during the photo-oxidative reactions of dissolved organic matter (DOM) present in the raw water.

Table 1. Physical and chemical parameter value ranges over the experimental period (solar photo-oxidation).

	EXPERIMENTAL DESIGN			
	A	**B**	**C**	**D**
DO (mg/l)	2,6 - 2,0	0,1 - 0,3	2,5 -1,9	0,1 - 0,51
Temperature (°C)	23,5 - 35,6	23,5 - 35,8	23,7 - 25,8	23,5 - 24,1
TDS (g/l)	1,47	1,54	1,33	1,49
Turbidity (NTU)	1,35	1,36	1,05	1,19
pH	7,04 - 7,59	7,1 - 7,65	7,19 - 7,69	7,14 - 7,57

The slight increase in DO in the experiments where oxygen was removed initially through nitrogen, can be attributed to diffusion from the atmosphere through the walls and into the water. The DO in these two setups never reaches the recommended minimum value of 1,5 mg/l (Reed, 1997a) and therefore did not have a noticeable impact on the FC destruction. The low saturation of oxygen at the specified temperatures, can be explained at the hand of oxygen diffusing through the plastic containers during transport and the duration of the experiment and the activity of the indigenous microflora of the collected water samples

There was an increase in the water temperature from 23,5° to a maximum of 35,8°C with midday temperatures reaching 38°C. The temperature of the water in the shade, ranged from 23,5° and to a maximum of 25,8°C. As a temperature of more than 40°C is needed to play a significant role in thermal disinfection or pasteurization (Metcalf, 1998; Wegelin, 1999), the results indicate that temperature did not have a direct role in the destruction of the coliform organisms in the water samples in the experimental designs.

The TDS levels were high in all the experimental designs. The de-chlorinated tap water had a TDS of 355 mg/l. The concentration was probably increased through the addition of the raw sewage. One would not expect natural water to have such high TDS values, as it could impose an aesthetic problem as it could impart taste to the water. Both the turbidity and pH values of the raw water were acceptable and did not pose any problems for the efficient disinfection of the water.

The ultraviolet radiation levels (both UV-A and UV-B) in the atmosphere and in the water inside the containers are illustrated in Figures 4 and 5. Both the UV-A and UV-B radiation showed an average loss of 30% as the light penetrated through the walls of the white plastic water containers. This loss in radiation did not seem to influence the efficiency of the solar photo-oxidative disinfection processes negatively.

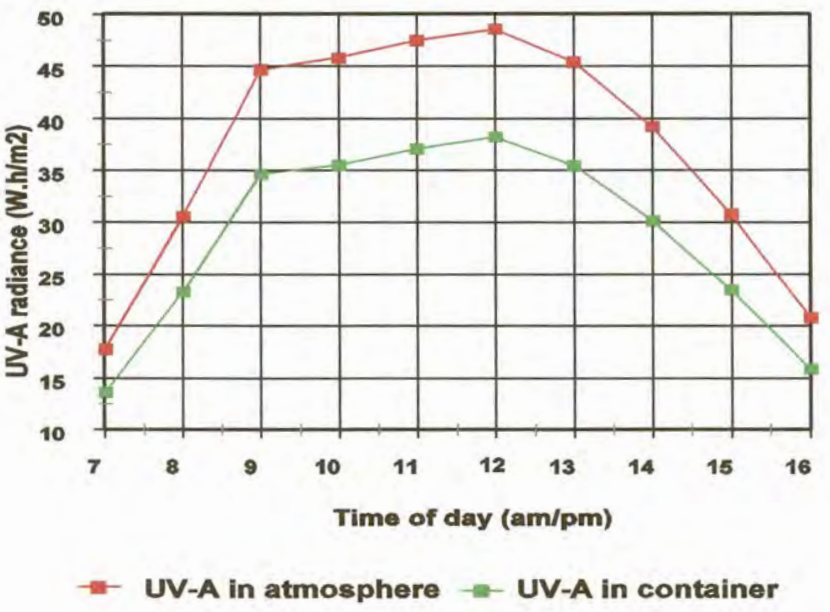

Figure 4. Comparison of UV-A radiation levels in the atmosphere and inside the water in the container.

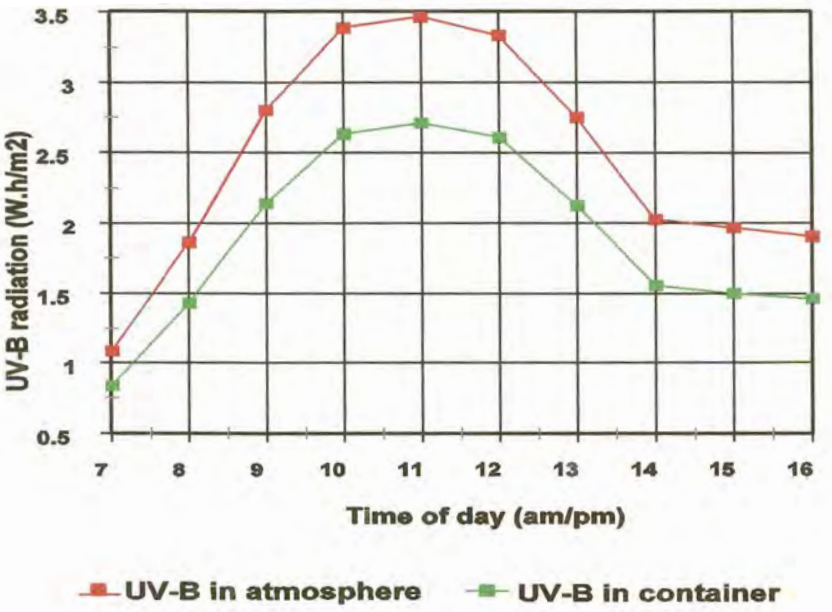

Figure 5. Comparison of UV-B radiation levels in the atmosphere and inside the water in the container.

5.1.2 Microbiological analyses

The mixed FC cultures in the sewage consist of species which are more or less resistant to inactivation by solar radiation and/or oxygen radicals. The analyses of raw sewage for *Escherichia coli* and *Streptococcus sp.* gave a ratio of 2,3:1. As *Escherichia coli* is less resistant, these cells will most probably be the first species to be inactivated and destroyed, followed by the more resistant *Streptococcus sp.* and finally other coliform bacteria. The photo-oxidative inactivation and destruction of the coliforms depends on them to be reasonably metabolically and reproductively active (log growth to stationary phase cells). This will ensure that the target DNA is uncoiled and sensitive to any influence by the two external parameters, *viz.* solar UV radiation and oxygen.

Although both total coliform and faecal coliform analyses were performed on the sampled water, only the FC results are reported in this document due to the following reasoning. Faecal coliforms are essential indicator organisms, which should be absent in drinking water to ensure no adverse health effects on the end users. If the FC concentration in the disinfected water falls in the acceptable target water quality range as prescribed by the DWAF (1998), i.e. 0 CFU/100 ml, then the water is "microbiologically safe", with negligible risk of microbial infections. Thus if the FC concentration was within the acceptable range, an assumption was made that the TC concentration will also be reduced to an acceptable concentration. This assumption was made due to the fact that FC usually makes up more than 90% of the TC in raw domestic sewage.

It can be seen in Figure 6 that the efficiency of solar photo-oxidative disinfection (design A) was indeed better, compared to where solar UV radiation (design B) or dissolved oxygen (design C) was applied as disinfectants on their own. Potable water which complies with the target water quality guidelines and standard as set by DWAF (1998) and the SABS (1984), were obtained within 240 minutes (4-h) when UV radiation and DO was applied in synergism, while UV radiation on its own took 8-h to reach the same level (100%) of FC destruction. Oxygen as disinfectant on its own and the autolysis proned stressed cells (designs C and D), showed a decrease of log 1,59 (97%) and log 0,88 (87%), respectively, from the initial concentration of log 4,3 CFU/100 ml over the total experimental period of nine hours.

As some cells could only be temporary inactivated by the oxygen and/or sunlight, the water was left overnight and sampled after 24-h for FC growth. In designs A and B no reactivation of FC was observed, hence the cells in these designs were irreversibly destroyed and their repair mechanisms inhibited. In designs C and D faecal coliform growth was still observed after 24 hours. The concentration of FC in these experiments increased with 15% from the final concentration obtained on the previous day. The results indicated that there

was a definite reactivation of microbial cells inactivated or stressed with oxygen during the experimental period. This reactivation was probably due to the capability of certain microorganisms to repair the damaged cell material.

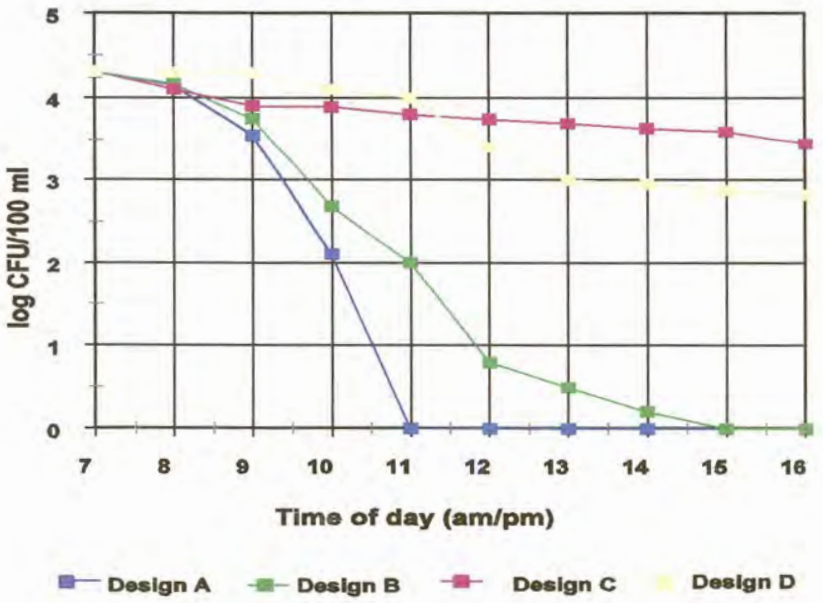

Figure 6. Faecal coliform destruction in all experimental designs (log 0 = not detectable).

Figures 7 and 8 shows that the highest UV-A radiation levels are obtained during 9:00 am and 13:00 pm, while the highest UV-B radiation is obtained between 10:00 am and 12:00 pm. The total FC destruction starts within 1 h after exposure at a low 23 W.h/m^2 UV-A radiation level and increases rapidly with the increase in the radiation intensities of both UV-A and UV-B light over time. It is therefore concluded that the solar photo-oxidative disinfection process should be applied as early in the day as possible, and ideally between 9:00 am and 13:00 pm.

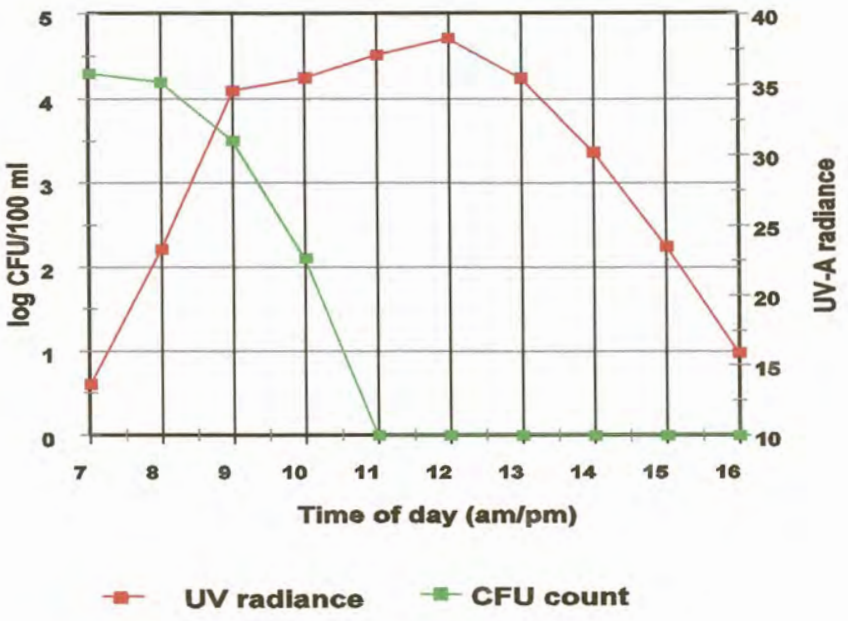

Figure 7. **The relationship between faecal coliform destruction and UV-A radiation during the experimental period (log 0 = not detectable).**

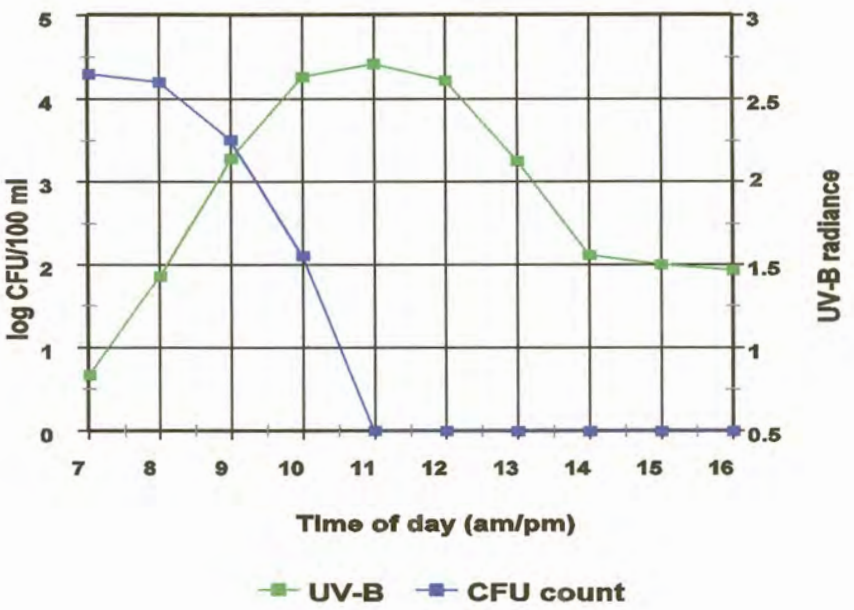

Figure 8. **The relationship between faecal coliform destruction and UV-B radiation during the experimental period (log 0 = not detectable).**

Figure 9 illustrates the relationship between the DO concentration and the log CFU/100 ml destroyed within the water over the total experimental period. The oxygen concentration remained above the critical minimum concentration of 1.5 mg/l at all times, In total 0,6 mg/l of the DO was consumed by the microbial cells and chemical reactions in the water. During the 4 hours it took to destroy the FC completely in the water, the DO was reduced from 2,5 to 2,28 mg/l through production of super oxide and hydroxyl radicals. The rest of the reduction occurring after 4 hours was most probably used by non faecal coliform microorganisms left in the water or because of lower saturation levels due to an increase in the water temperature.

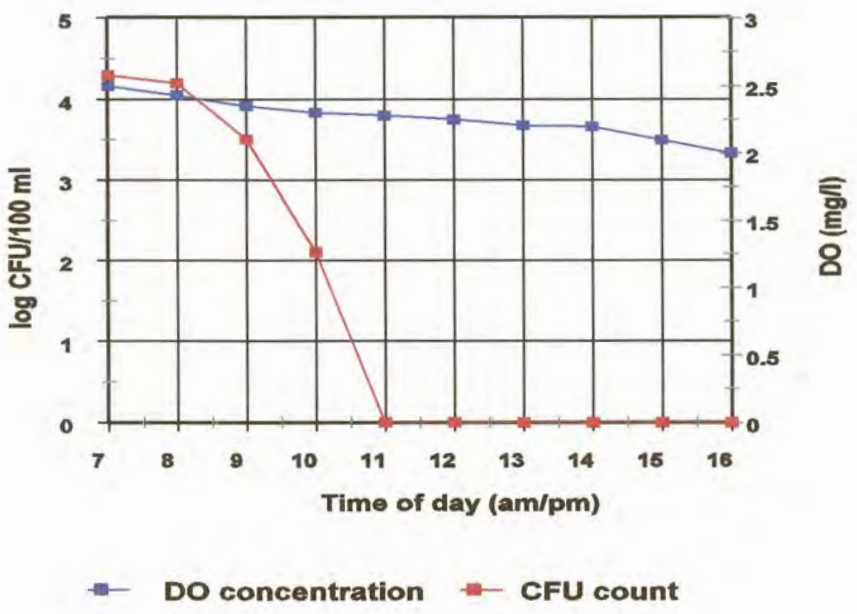

Figure 9. ***The relationship between dissolved oxygen concentration and faecal coliform destruction during the experimental period (log 0 = not detectable).***

5.2 CLOUD COVER

There are many external physical parameters which could influence the efficiency of oxygen and ultraviolet transfer into the water containers and into the main body of water. One of these parameters that needed to be investigated, was cloud cover. The solar photo-oxidation process and all its described variations, was applied to water under semi-cloudy conditions and under conditions with heavy and dense cloud cover. The effect on the ultraviolet radiation intensities, oxygen saturation levels, water temperature and the FC destruction efficiencies are reported here.

5.2.1 Physical and chemical analyses

Referring to Table 2, the DO in designs A and C reached higher concentrations as compared to experiments performed in full sunlight and clear skies. This phenomenon can be explained by the fact that the temperature did not reach similar high values, thus more oxygen will be saturated in the cooler water than in the warmer water. Furthermore, as the bacterial cells were also less metabolically active at these lower temperatures and the organic oxidation was lower, less oxygen was consumed.

Table 2. Physical and chemical parameter value range over the experimental period (heavy and dense cloud cover).

	EXPERIMENTAL DESIGN			
	A	**B**	**C**	**D**
DO (mg/l)	4,8 - 4,4	0,2 - 0,4	4,7 - 4,3	0,2 - 0,6
Temperature (°C)	22,5 - 28,2	22,4 - 24,1	21,9 - 28,3	22,2 - 22,4
TDS (g/l)	1,48	1,51	1,54	1,53
Turbidity (NTU)	1,35	1,29	1,2	1,25
pH	7,54 - 7,8	7,54 - 8,17	7,72 - 8,13	7,75 - 7,93

The TDS, turbidity and pH values were similar to the first experimental values. These three parameters did not have any influence on the efficiency of the various experimental disinfection designs.

As expected, when using the solar photo-oxidation process under semi-cloudy and heavy and dense cloudy conditions, a corresponding reduction of UV-A and UV-B light were observed. The efficiency of disinfection was also reduced under these conditions if compared to the efficiency on sunny days. Figure 10 summarizes the effect low and dense cloud cover will have on the level of UV-A radiation penetrating the water containers. Under semi-cloudy conditions there is a small shift of 1-h in the peak of radiation, but no significant reduction in the intensity of radiation. However, under conditions of heavy and dense cloud cover, a reduction of radiation intensity of between 13 and 66% was observed over the total experimental period. The peak of radiation under these conditions also shifted from 10.00 am to 13:00 pm.

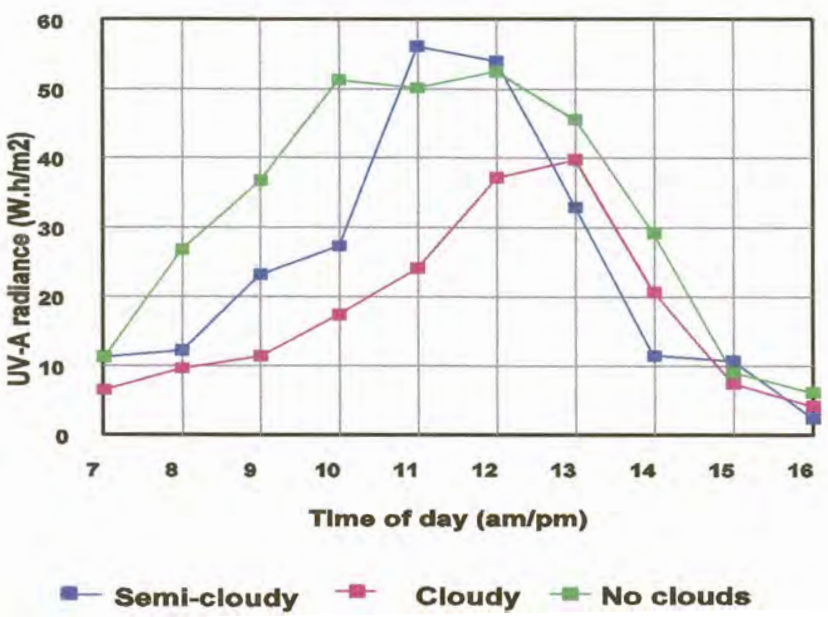

Figure 10. The influence of cloud cover on the level of UV-A radiation that penetrated the water in the containers.

Referring to the UV-B radiation levels, similar influences were observed (Figure 11). The level of radiation was reduced between 11 and 56% under heavy, cloudy conditions, with similar shifts in the times of peak radiation intensity.

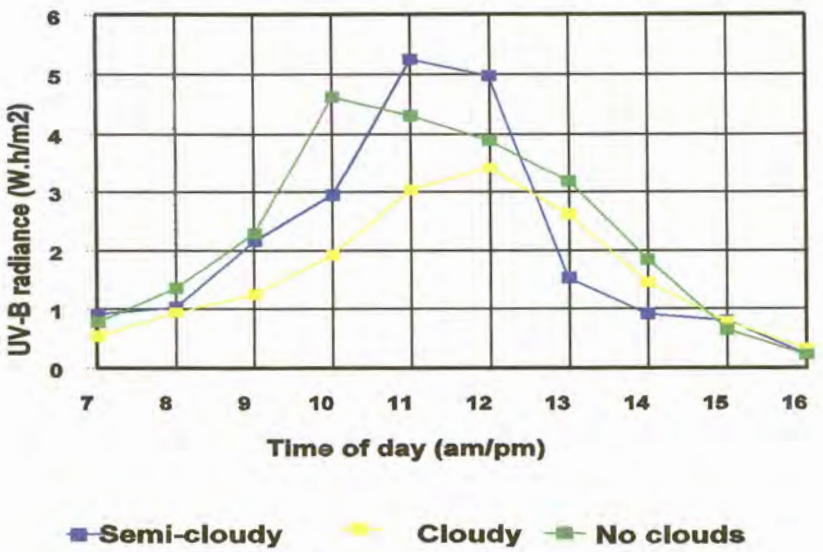

Figure 11. The influence of cloud cover on the level of UV-B radiation which penetrated the water in the containers.

5.2.2 Microbiological analyses

The FC destruction is quite significantly influenced by dense and heavy cloud cover. This influence is depicted in Figure 12. Compared to solar photo-oxidation in full sunlight, the FC is reduced to log 2 CFU/100 ml (99%) following a 9-h exposure time as opposed to 3-h under conditions of full sunlight (Figure 6). Experimental design B reduces the initial FC concentration only up to a final concentration of log 2,51 CFU/100 ml (98%) after the total experimental time as opposed to 3,5-h under sunny conditions. The other two experimental designs showed similar inhibition of the FC destruction rate, with designs C and D reducing the FC concentrations to log 3,01 (94,5%) and log

3,21 (92%) CFUs per 100 ml water sample, respectively. All experimental designs showed growth after a 24 h further incubation, with FC concentrations slightly lower than the last sample taken on the previous day for both designs A and B. There was clear reactivation in the other two designs, with a 12% increase in the concentration of FC after 24-h compared with the results after 9-h on the previous day.

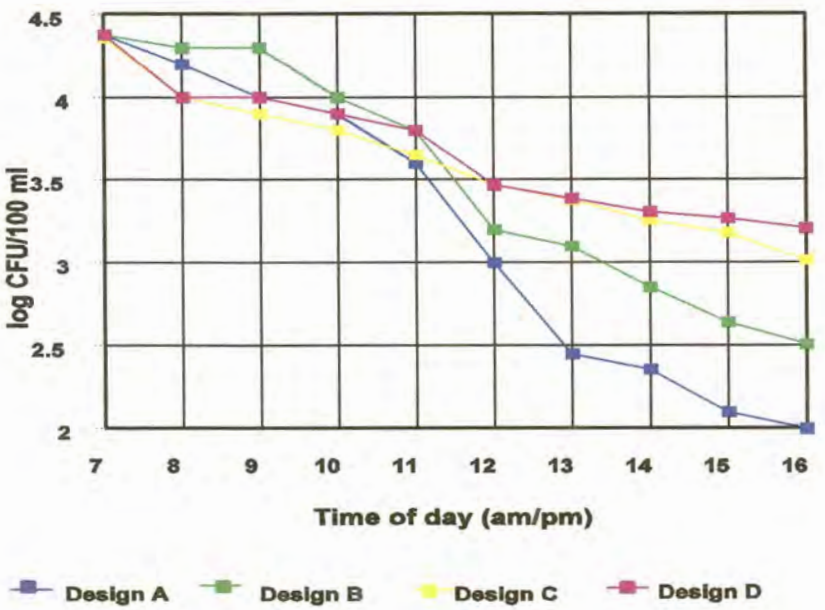

Figure 12. Faecal coliform destruction in all designs under conditions of heavy and dense cloud cover (log 0 = not detectable).

It is worthwhile to note that the FC concentration started to drop exponentially and at a faster rate, after both the UV-A and UV-B radiation reached their respective peaks. This is an indication that solar photo-oxidation does work even under cloudy conditions, but with the solar radiation levels reduced and peak values only achieved 3 hours later, the process exposure time must be adapted for the conditions of the day.

Thus, one can conclude that although the FC destruction was not as good under heavy and dense cloudy conditions and did not result in a water with an acceptable microbiological quality, this could be overcome by longer exposure times or by lowering the initial FC concentrations. Exposure times longer than 9 hours will not always be feasible or possible, but if the disinfection process and water supply is managed and planned well in advance, disinfection can be resumed the following day.

5.3 TURBIDITY

Another physical factor which can have an influence on the efficiency of the disinfection process, is high turbidity (Joyce *et al.*, 1996). The turbidity of the tap water was increased artificially with calcium carbonate from 1,5 NTU to 280 NTU. This made the water milky and visibly turbid. The effect this factor had on the penetration of UV and diffusion of oxygen and finally on the solar oxidative disinfection process is described below.

5.3.1 Physical and chemical analyses

Table 3 summarizes the values of the physical and chemical parameters in the raw water with the high turbidity. The DO values once again was above the critical minimum value of 1,5 mg/l and the temperature below 40°C. A higher rate of oxygen consumption and/or reduction was observed in both experimental designs A and C, 1,4 and 1 mg/l, respectively. This can be attributed to oxidation of DOM and to the high concentration of particles present as turbidity. The turbidity particles collide with the oxygen bubbles, attach to them and carry them with as they settle or float out of the main water body. This was partially overcome, by the vigorous shaking, which broke these attachments and kept most of the oxygen in the water. The TDS and pH values did not have an effect on the various designs of disinfection processes.

Table 3. **Physical and chemical parameter values over the experimental period (raw water with high turbidity).**

	EXPERIMENTAL DESIGN			
	A	B	C	D
DO (mg/l)	2,9 - 1,5	0,1 - 0,7	2,8 - 1,8	0.1 - 0,74
Temperature (°C)	25,1 - 37,5	25,7 - 38,6	23,7 - 26,4	23,8 - 24,4
TDS (g/l)	1,41	1,4	1,54	1,45
Turbidity (NTU)	276	298	285	267
pH	6,86 - 7,93	6,92 - 7,97	7,15 - 8,01	7,13 - 8,01

The turbidity of the raw water was increased more than a 155 fold. According to the results depicted in Figures 13 and 14, the high turbidity did not adversely affect the UV radiation penetration into the water volume.

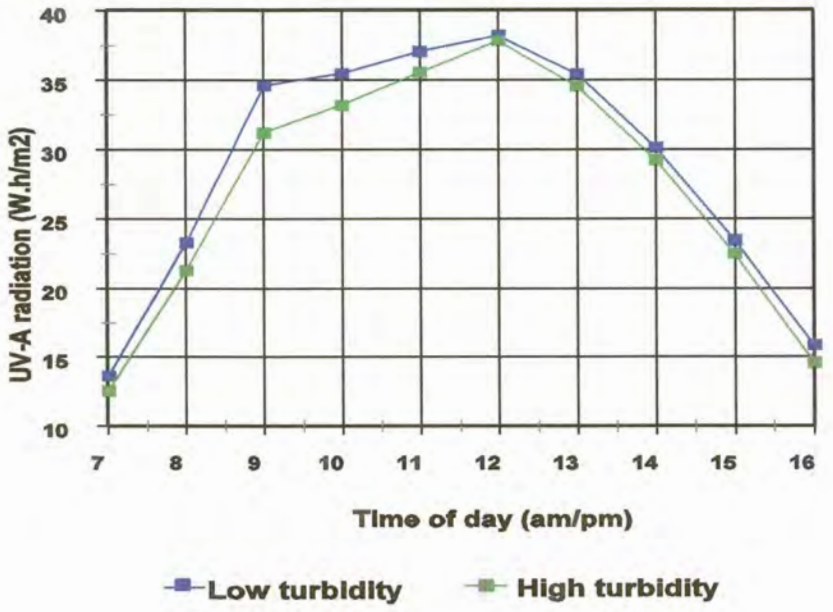

Figure 13. **The effect high turbidity water has on the UV-A penetration levels into the water.**

UV-A radiation was reduced by a maximum of 6% within the first 4 hours of exposure, after which the interference was negligible. Similarly, UV-B radiation was reduced by an average of 5,5% over the full period of exposure. If the turbidity should increase further, the interference will probably be more noticeable.

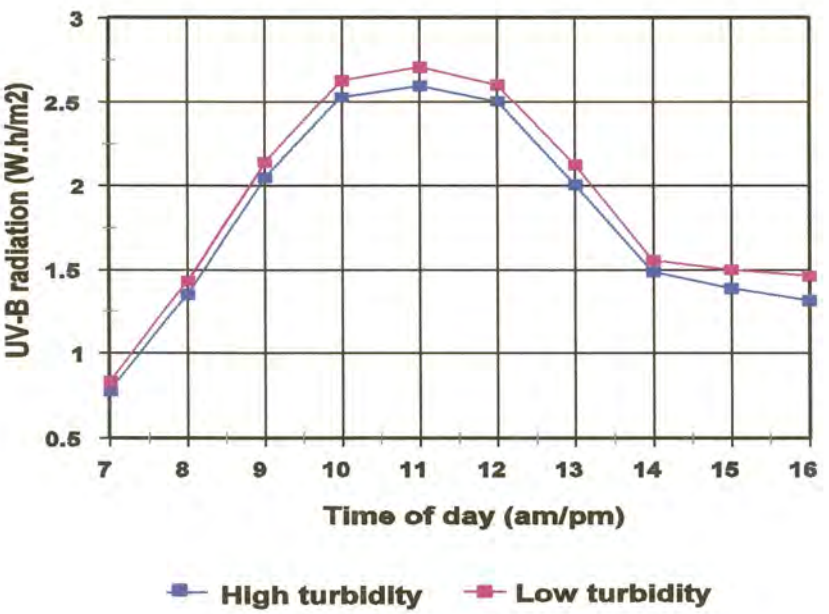

Figure 14. The effect high turbidity water has on the UV-B penetration levels into the water.

5.3.2 Microbiological analyses

The impact higher turbidity has on the experimental designs is summarized in Figure 15. According to Wegelin (1999), visible turbid waters will reduce the disinfection efficiency of the solar disinfection process and should therefore be removed before application of solar or solar photo-oxidative disinfection processes. High turbidity in water decreases the penetration power of the UV radiation and interferes with the direct contact between the microorganisms and the ultraviolet rays.

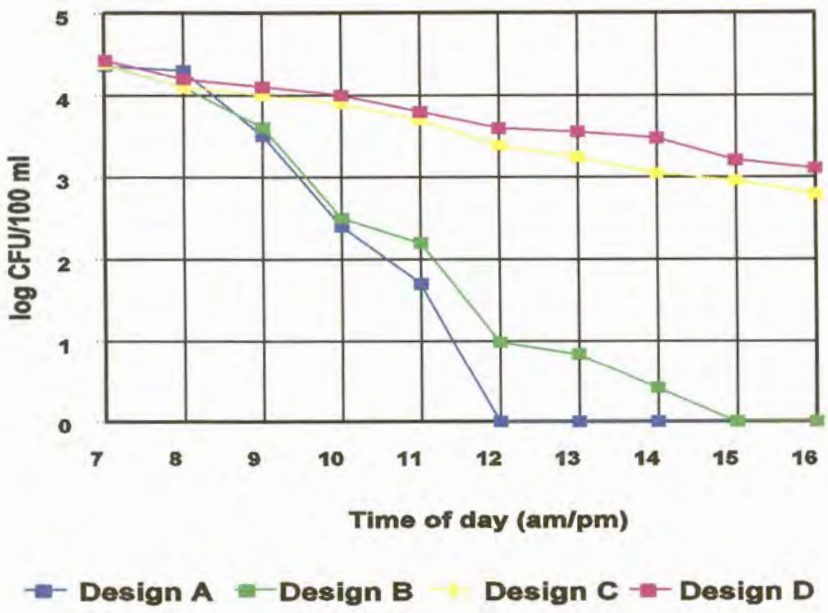

Figure 15. Comparison of faecal coliform destruction in the four experimental designs using highly turbid raw water (log 0 = not detectable).

In this specific application however, the FC present in design A were destroyed after 5-h, which is 1-h slower than the observation in low turbidity waters (Figure 6). UV radiation on its own (design B) took 8-h for complete reduction, which is 3 hours more than the exposure time needed in low turbidity waters. The FC concentration in the two remaining designs, were reduced to log 2,8 (97%) and log 3,1 (94%) CFUs per 100 ml water sample. This is similar to results obtained in low turbidity waters, but with a slightly higher inactivation in design D, the autolysed prone stressed microbial cells.

The results reported here is in contrast to the findings reported by Acra *et al.* (1984) and Wegelin (1999) but similar to the results of Joyce *et al.*, 1996. . One explanation for this is that the negative effect of the high turbidity could have been partially neutralized through the vigorous shaking applied during the

5.4.1 Volume

Physical and chemical analyses

The DO concentration measured in the plastic containers over the 9-h experimental period, were reduced to a larger extent in the 2-litre water container (Table 4). This could be explained by the fact that the water temperature was slightly higher than in the other volumes, and subsequently the oxygen saturation decreases as the water temperature increases (Black, 1999). In the 5 litre and 25 litre containers the DO was reduced gradually, similar to previous observations.

Table 4. Physical and chemical parameter value ranges over the experimental period (various water volumes).

	2l	5l	25l
DO (mg/l)	3,3 - 1,8	3,3 - 2,2	3,8 - 2,16
Temperature (°C)	24,4 - 38,4	27,2 - 36,9	25,3 - 36,5
TDS (g/l)	1,47	1,25	1,28
Turbidity (NTU)	1,2	1,18	1,3
pH	7,45 - 7,53	7,47 - 7,5	7,4 - 7,58

Figure 16 summarizes the penetration of UV-A radiation through the increasing volumes of water in the white PET plastic containers. The smaller the volume, the more radiation can penetrate the water. Radiation penetration decreases of 3% for the 5-litre container and 14,7% for the 25-litre container were observed. This decrease can be attributed to an increase in the depth and the distance the radiation needs to travel with an increase in volume through, i.e. the length of the light pathway. The larger the volume of water, the more the radiation is lost through scattering and reflection. Similar results were observed with the UV-B radiation levels.

experimental period. The shaking would have loosened any microbial cells shielded by the particles contributing towards the turbidity in the water, and exposed them to the DO and solar radiation penetrating through the water container walls.

Even though the high turbidity in the experimental setup did not influence the effectiveness of the solar photo-oxidative disinfection process drastically, it is still advisable to remove any visible turbidity before subjecting the water to disinfection. This will not only serve to prevent any interferences with contact between the microbial cells and the DO molecules and UV radiation penetrating into the water, but also make the water more aesthetically acceptable for drinking purposes.

5.4 VOLUME AND COLOUR OF THE PLASTIC CONTAINERS

From the results of previous research, investigations and applications of solar disinfection methods, it was decided to use PET plastic containers in this laboratory evaluation of the solar photo-oxidative disinfection process. The maximum water volume which can be disinfected easily and efficiently with solar photo-oxidation were investigated. This issue was raised in preliminary studies by Reed (1997c) and also by some community members in the planning stages of this research. As results in the previous experimental designs of this project indicated that the solar photo-oxidative disinfection process worked much more effective than the other designs, it was applied on the various volumes of water. The results obtained are reported here.

The UV-A and UV-B irradiances through the walls of various coloured plastic containers typically used by the rural communities for water transport and storage (blue, black, red, yellow, transparent and white) was compared with the UV-A and UV-B radiation directly from the sun. The radiation levels in the various coloured containers were measured over the full experimental period (9-h) and the effects on solar photo-oxidative disinfection efficiency are reported in the discussion below.

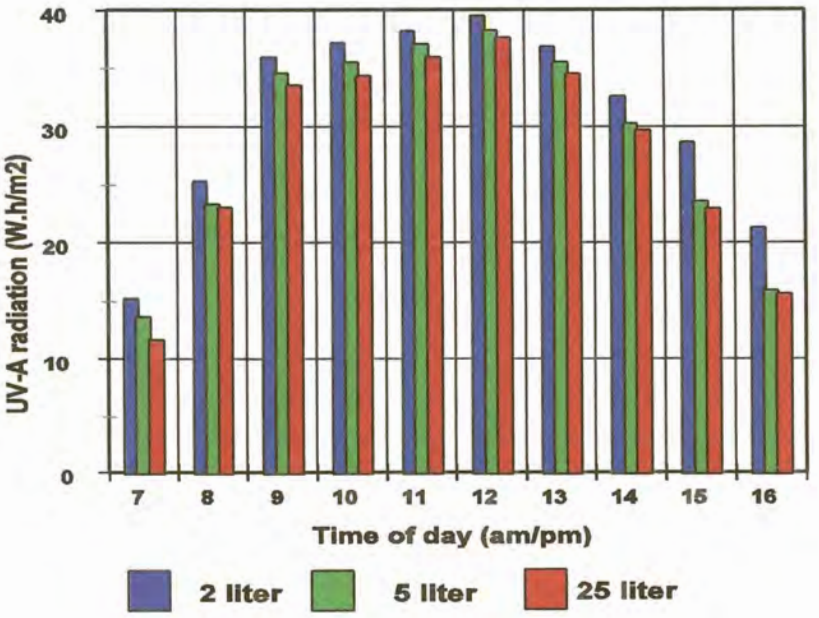

Figure 16. The effect of increased water volume on the penetration of UV-A radiation.

There were major differences in the penetration levels early in the morning (between 7:00 am and 8:00 am) and late in the afternoon (from 15:00 pm and 16:00 pm) (Figure 16). This phenomenon could be explained as follows: as the intensity of the radiation decreases with time, the chance to penetrate deeper into the water decreases. The direct result is lower levels of penetration as observed in the early morning and late afternoon.

Microbiological analyses

Smaller volumes of water (2 litres) showed a total faecal coliform reduction within 3 hours, while the larger volumes of water (5 litres and 25 litres) achieved the same result within a 4-h period with no reactivation after 24-h in any of the containers (Figure 17). This implies that smaller volumes of water could be exposed to sunlight and oxygen over a shorter period of time, while an

increased volume of water needs to be exposed over longer periods of time. It also suggests the possibility that volumes larger than 25 litres could be disinfected with this process. This needs to be investigated, as many households need and use more water as the family grows.

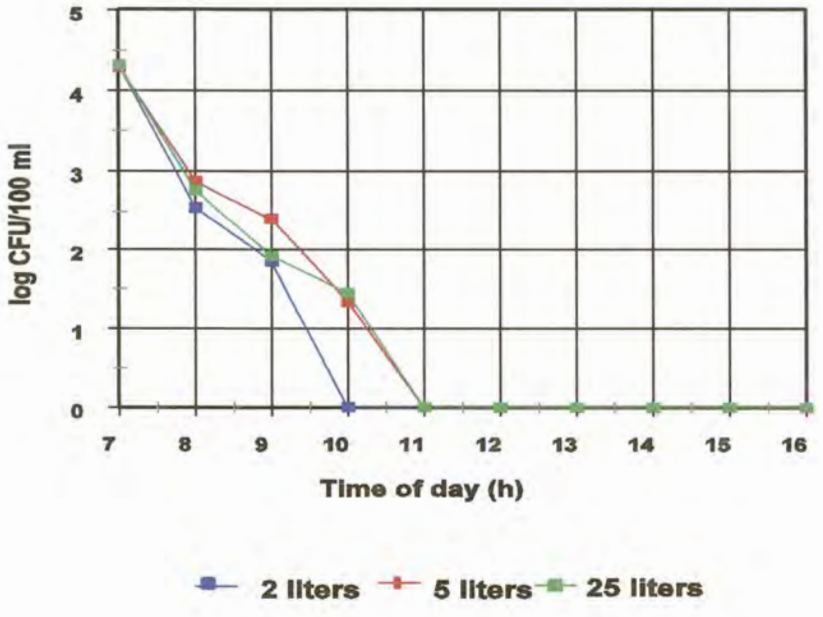

Figure 17. Comparison of faecal coliform destruction in three volumes of raw water over a 9-h experimental period (log 0 = not detectable).

5.4.2 Colour of the containers

Physical and chemical analyses

Table 5 summarizes the physical and chemical analyses in the 5 l coloured plastic containers over the experimental period. The DO concentration present in the water in the various coloured plastic containers, differed from one another. The transparent containers showed the highest concentration of oxygen diffusing into the water, followed by the white, red, blue, black and lastly yellow containers. The poor diffusion can be attributed to the different

types of plastic the various containers were made of. Some types of plastic material are more porous than others, and can therefore allow higher concentration of gases to diffuse into and out of the water inside the containers.

Table 5. Physical and chemical parameter value ranges over the experimental period (5 l coloured containers).

	DO (mg/l)	Temp (°C)	TDS (g/l)	pH	Turbidity (NTU)
White	2,8 - 2,1	23, 5 - 35,5	1,45	7,98	1,25
Transparent	2,85 - 2,0	24,1 - 38,95	1,39	7,85	1,3
Black	1,95 - 1,9	24,1 - 39,21	1,43	7,86	1,6
Red	2,4 - 2,1	23,65 - 36,9	1,34	7,99	1,35
Blue	1,99 - 2,05	24,9 - 37,2	1,39	7,82	1,52
Yellow	2,1 - 1,96	23,87 - 26,78	1,41	7,79	1,23

The temperature of the water inside the black container had the highest temperature because the energy from solar radiation is absorbed more readily by the black coloured plastic. The energy is converted to heat, which in turn will increase the temperature of the water. The transparent container had the second highest temperature, followed by the blue, red, white and yellow containers.

The other physical and chemical parameters, TDS, pH and turbidity had values similar to those observed in the previous experiments. These parameters did not have any noticeable effect on the disinfection action or efficiency.

Transparent and white containers showed the highest penetration of radiation, followed by red, yellow, black and blue (Figures 18 and 19). This is in contrast

with Wegelin *et al.* (1994) and Sommer *et al.* (1997) who indicated that blue and blue-tinted containers allowed high dosages of radiation to penetrate through to the water inside the containers.

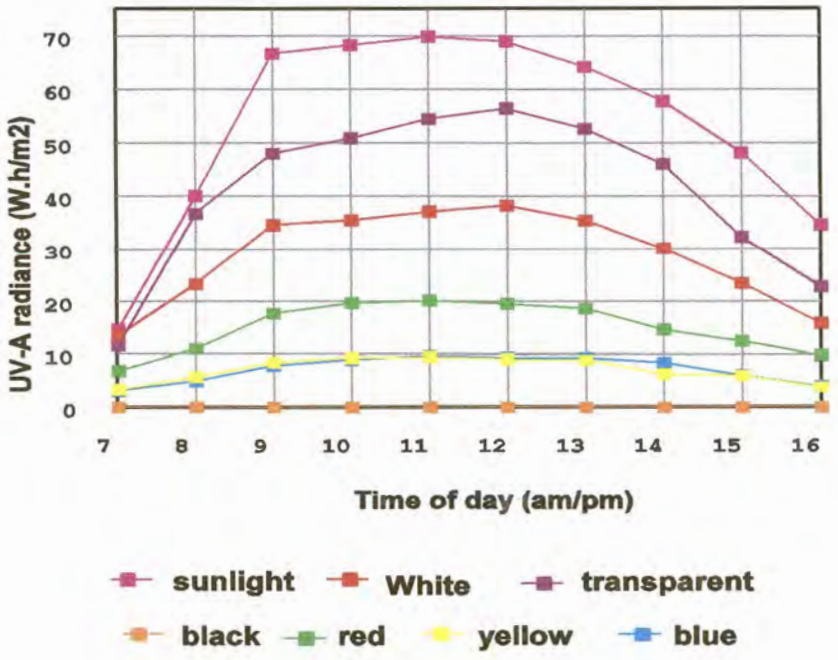

Figure 18. The penetration levels of UV-A radiation through the walls of various coloured plastic containers.

It is interesting to note that on average 52% of the UV-A radiation penetrates the white coloured containers and that 77% penetration is achieved through the transparent containers. The UV-B radiation penetrating the white containers was on average 41% and for the transparent containers, 49,5%.

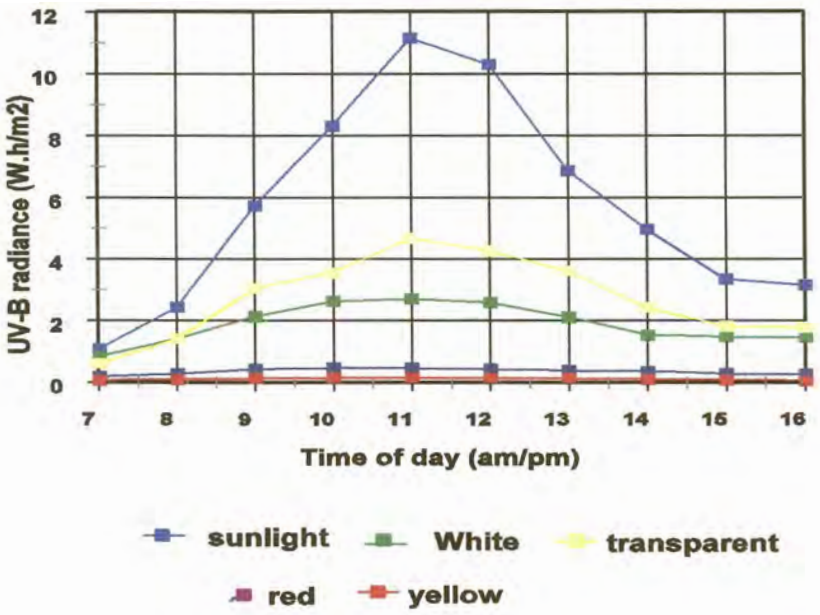

Figure 19. The penetration levels of UV-B radiation through the walls of various coloured plastic containers.

With the information obtained, it is recommended to use transparent or white plastic containers for solar photo-oxidation, and to avoid coloured containers where possible. Red and yellow containers can be used in conditions where no transparent or white containers are available, but one should expect the efficiency of the disinfection process to be lower over and that the inactivation of FC to be lower over the same period of time.

Microbiological analyses

Figure 20 compares the percentage (%) FC inactivation with the maximum UV-A radiation reaching the microbial cells in the various coloured water containers.

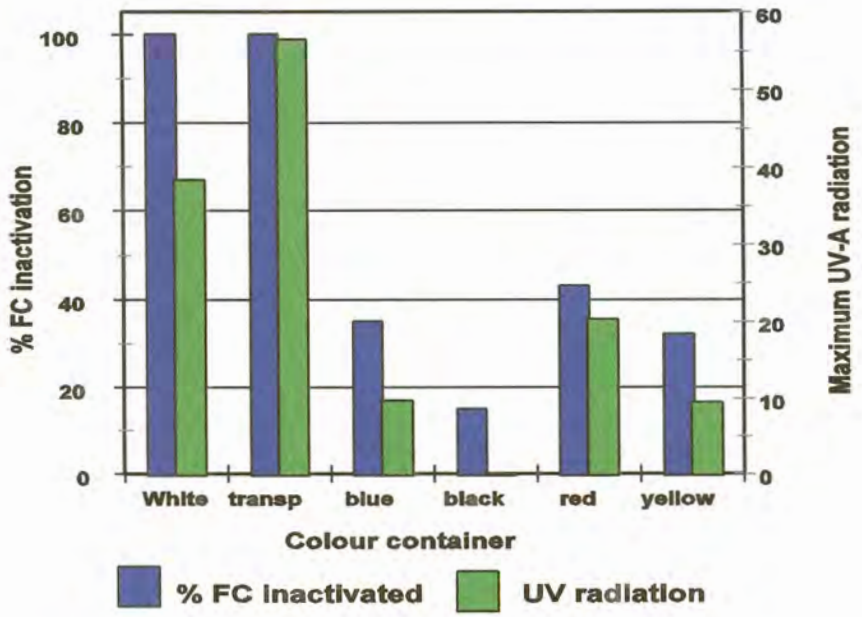

Figure 20. **Percentage faecal coliform destruction in the various coloured plastic containers compared to the maximum UV-A radiation penetrating through the water container over the experimental period.**

As expected with the higher penetration levels achieved, transparent and white containers showed a total destruction of the FC (100%) in the raw water with no subsequent reactivation observed after a 24-h lag period. Low percentage reductions of the initial FC concentration were observed in the other coloured containers: red (38%), yellow (18%), blue (19%) and black (0,5%). The poor reduction achieved in specifically the black containers, can be attributed to no detectable ultraviolet penetration and lower DO concentrations and to the fact that temperature in this container did not reach 40°C, the minimum value needed for thermal disinfection.

5.5 SEASONAL VARIATION OF RADIATION INTENSITIES

The described solar photo-oxidative disinfection laboratory experiments were performed over a 12 month period, from May 1998 through to April 1999, to observe the influence by the seasonal variations in ultraviolet intensities and oxygen saturation on the efficiency of the solar photo-oxidation disinfection process. The monthly average results are reported and discussed in the following section.

5.5.1 Physical and chemical analyses

The DO concentration as illustrated in Table 6, showed an inverse effect with temperature where the concentration obtained in the water was higher in the colder months (March to August) and slightly lower during the warmer months (September to February). This is due to the fact that dissolved oxygen concentrations are higher at cold temperatures which will decrease with an increase in the water temperature (Black, 1999). The other factor which could explain this phenomenon, is that at higher temperatures the microorganisms are more metabolically active and will consume more oxygen during the enhanced rate of oxidation of DOM in the water.

The other three parameters, TDS, pH and turbidity stayed stable over the 12-month period, and did not show any positive or negative influence on the solar photo-oxidative disinfection process (Table 6).

Table 6. Monthly average physical and chemical parameter values obtained over one year (May 1998 - April 1999).

	DO (mg/l)	Temperature (°C)	TDS (g/l)	Turbidity (NTU)	pH
May	2,9	26,3	1,4	1,36	7,65
Jun	3,1	25,45	1,45	1,23	7,98
Jul	3,0	24,8	1,43	1,29	7,34
Aug	2,8	23,1	1,39	1,39	7,55
Sep	2,5	24,95	1,41	1,21	7,98
Oct	2,6	26,87	1,38	1,09	7,61
Nov	2,1	31,0	1,33	1,32	7,68
Dec	2,0	34,61	1,43	1,36	7,56
Jan	2,3	34,06	1,40	1,3	7,66
Feb	2,4	29,43	1,39	1,26	7,80
Mar	2,7	28,0	1,29	1,29	7,82
Apr	2,75	26,99	1,4	1,24	7,83

UV radiation measured in the water container over the experimental period, showed a drastic increase in radiation intensity for both UV-A and UV-B as from September 1998, peaking during December 1998 and steadily decreasing again from January 1999 (Figures 21 and 22). Thus as expected, the radiation levels were lower during the autumn and winter months (March to August) and higher during the spring and summer months (September to February). Radiation levels of UV-A in the cooler months of autumn and winter had an intensity range of between 33,3 and 41,2 W.h/m^2, while in the warmer spring and summer months the range increased to between 54,5 and 67,2 W.h/m^2. The UV-B intensity levels in the autumn and winter months was between 2,78 and 5,67 W.h/m^2 and between 6,3 and 8,23 W.h/m^2 in the spring and summer months.

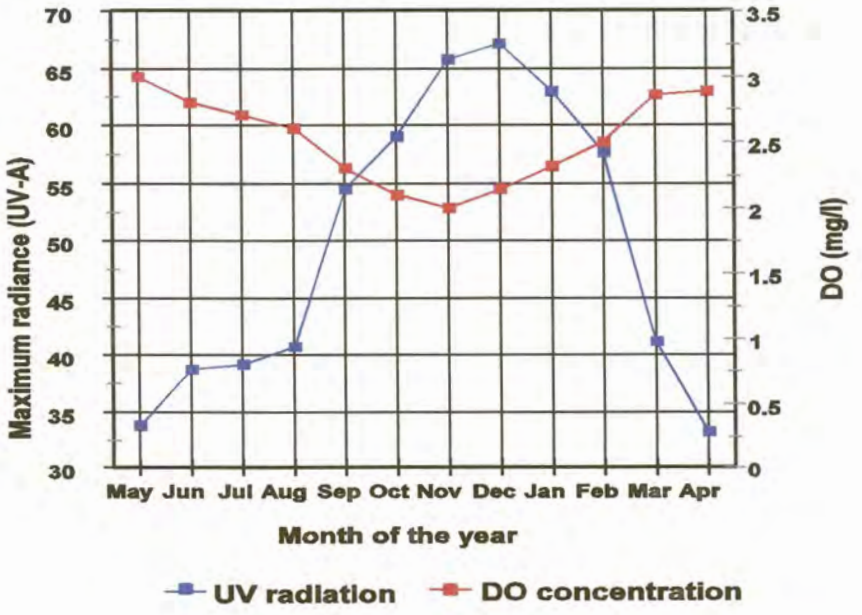

Figure 21. **The correlation between maximum UV-A radiation and average DO over a 12 month period.**

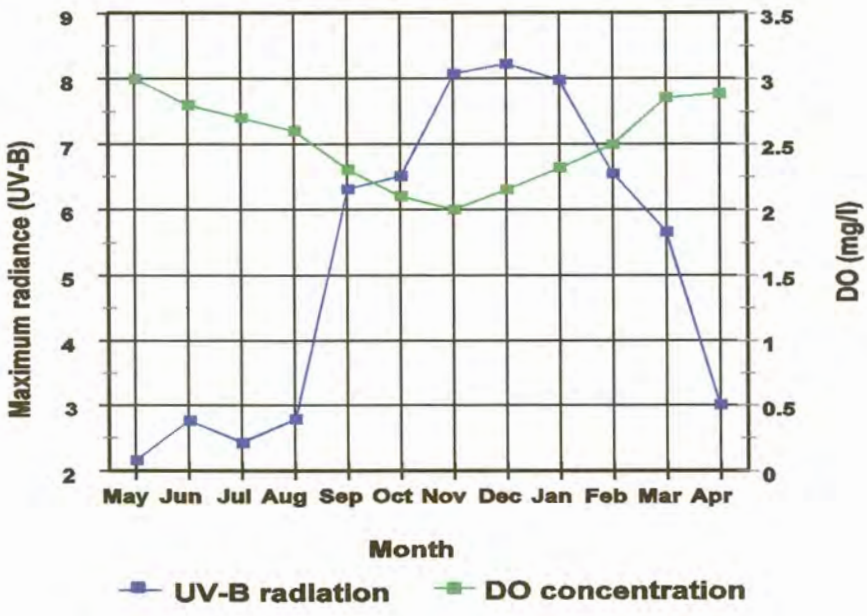

Figure 22. **The correlation between maximum UV-B radiation and average DO over a 12 month period.**

5.5.2 Microbiological analyses

There was no drastic adverse or positive impact on the solar photo-oxidation disinfection process during the various seasons. A similar trend of average faecal coliform destruction from May1998 to April 1999 was observed, with a drastic decrease in efficiency during October 1998 (Figures 23 and 24).

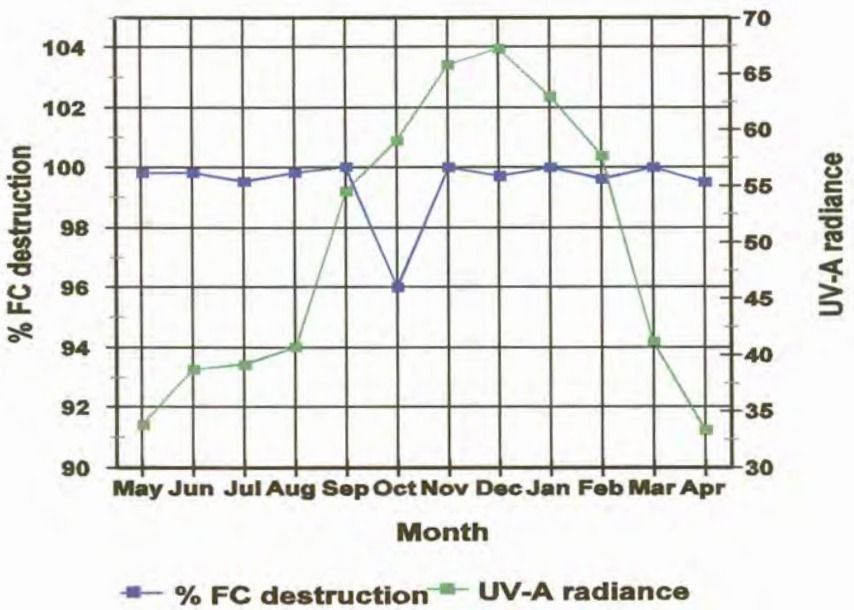

Figure 23. Relationship between the average FC destruction and the maximum UV-A radiation penetration over a period of 12 months.

The decrease in October 1998 could possibly be explained by the fact that the ratio between *Escherichia coli* and *Streptococci spp.* changed from 2,3:1 to 1,4:1. As *Streptococci spp.* have proved to be more resistant to photo-oxidation reactions (Reed, 1997a; Bingham, 1985), the lower FC destruction in the water could be due to the higher concentration of these bacterial species. The other factor worth mentioning, is that October 1998 was an exceptionally dry month. Dry months usually influence the microbial consistency of sewage,

as the more resistant organisms survive and the others are killed under stressful environmental conditions (Reed, 1997a).

The slight reduction in average efficiencies observed during July (99,5%), December (99,7%), February (99,6%) and April (99,5%) could not be explained, as the initial concentration of coliforms did not increase significantly, and the *Escherichia coli/Streptococci spp* ratio and all other physical and chemical parameters remained constant over the full 12 months.

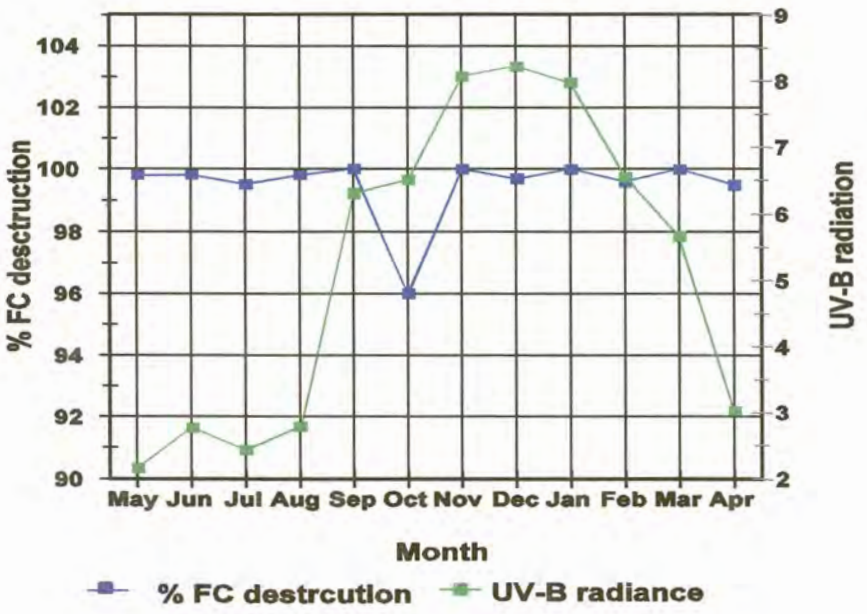

Figure 24. Relationship between the average FC destruction and the maximum UV-B radiation penetration over a period of 12 months.

It can be concluded that the ultraviolet radiation intensities measured inside the water containers was high enough during the 12 month period to penetrate the microbial cells and inactivate the DNA and other cellular material in synergism with the oxygen radicals. This concludes that seasonal variation of radiation intensity levels in South Africa specifically, does not have a major negative impact on the efficiency of the solar photo-oxidative disinfection process.

5.6 SUMMARY

The results presented and discussed above gave significant prove that the solar photo-oxidative disinfection process is indeed a viable option to be applied in a rural setting where water is of poor microbiological quality. It is however implicated that education and training will play an essential role in the applicability and acceptability of this disinfection process within the communities. Members of communities are to be made aware that the water will have to be used as soon as possible after disinfection, as there is no residual disinfection power in the water which could prevent secondary contamination (i.e. secondary contamination due to dust, droppings, and faeces on hands and drinking and cooking utensils).

From the results obtained during the laboratory-scale application of the solar photo-oxidative disinfection process and presented and discussed in this chapter, the main findings of the research are summarized as follows:

- Solar photo-oxidative disinfection efficiency for FC was higher than the disinfection efficiencies of solar radiation and oxygen as disinfectants on their own (section 5.1.2, Figure 6).

- No reactivation of FC cells was observed after 24-h in the water containers which was exposed to both the solar photo-oxidation and solar radiation disinfection methods (section 5.1.2).

- The highest UV-A radiation was obtained between 9:00 am and 13:00 pm, while the highest UV-B radiation was between 10:00 am and 12:00 pm. It is therefore concluded that the solar photo-oxidative disinfection process should be applied as early in the morning as possible (section 5.1.2, Figures 7 and 8).
- The temperature, TDS, turbidity and pH of the hand drawn water did not influence the solar photo-oxidation process adversely (section 5.1.1).

- Under dense and heavy cloudy conditions, significant reduction in the rate of FC destruction was observed, necessitating an increase in the exposure time needed for efficient disinfection (section 5.2.2, Figure 12).

- Under dense and cloudy conditions, reactivation of FC cell growth was observed in all experimental designs after 24-h, but the concentration of CFU was lower than the initial concentration in the hand drawn water (section 5.2.2).

- Both the UV-A and UV-B radiation levels were reduced by the presence of heavy and dense cloud cover. The peak times of radiation were reduced by 1-h (section 5.2.1, Figures 10 and 11).

- Visible turbidity did not influence the effectiveness of the solar photo-oxidative disinfection process drastically. The time for complete FC destruction was reduced by a mere 1-h. However, solar radiation used as disinfectant on its own, showed an increase of 3-h in the disinfection time to achieve the same level of FC destruction as in low turbidity waters (section 5.3.2, Figure15).

- UV-A and UV-B penetration radiation was reduced by 6 and 5,5% respectively by visible turbidity in the water (section 5.3.1, Figures 12 and 13).

- Smaller volumes (2l) of water could be exposed to solar photo-oxidation over a shorter period of time (3-h) than larger volumes(5 and 25l) of water (4-h) (section 5.4.2, Figure 17).

- Radiation penetration levels decreased with an increase of water volume (section 5.4.2, Figure 16). This decrease was more visible early in the morning and late afternoon.

- Transparent and white plastic containers showed the highest total FC destruction in the raw hand drawn drinking water, with no subsequent reactivation after a 24-h lag period. The transparent and white plastic containers were followed in efficiency by red, yellow, blue and black coloured plastic containers (section 5.4.2, Figure 20).

- Transparent and white plastic containers showed the highest penetration of UV-A and UV-B radiation, followed by red, yellow, black and blue (section 5.4.2, Figure 19).

- In South Africa, seasonal variation of UV radiation intensity levels did not have a major impact on the efficiency of the solar photo-oxidative disinfection process (section 5.5.2, Figures 23 and 24).

- UV-A and UV-B radiation levels were lower during the autumn and winter months (March to August) and higher during the spring and summer months (September to February) (section 5.5.2, Figures 21 and 22).

- The DO concentration in the water showed an inverse effect with temperature, with higher concentration measured in the cooler winter months and lower concentration measured in the warmer months (5.5.1).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The results presented and discussed in Chapter 5, illustrated an effective disinfection process, applicable to the rural scenario in South Africa. It is easy to apply, does not need any special equipment or expensive infrastructure and gives repeatable and reliable results. The disinfected water complies with the standards and guidelines for potable drinking water (SABS, 1984; DWAF, 1997).

6.2 PROJECT CONCLUSIONS AND RECOMMENDATIONS

The following major conclusions and recommendations can be drawn from the results described and discussed in the previous chapter:

- The process was effective on smaller volumes of water - 2 to 25 litres. This is enough water for daily use on household level.

- The suitable colour and type of water container to use will be transparent or white and made from of polyethylene terephthalate (PET) plastic. This type of plastic will last longer and will be damaged slower by the radiation from the sun.

- The water containers should be filled as early in the morning as possible and exposed to sunlight from 8:00 to15:00, when the radiation intensity is high.

- The water containers must be in direct sunlight at all times and kept out of the shadows from walls, trees, or other containers.

- Intermittent vigorous shaking is important to dissolve and saturate the oxygen from the atmosphere throughout the total volume of water in the container. This will also serve to keep the microbial cells in suspension in the volume of water and increase the chance of the cells to come in contact with the penetrated and absorbed ultraviolet radiation.

- A minimum of three to five hours is required for effective disinfection, i.e. so that the water complies with the South African Bureau of Standards (SABS) domestic water quality standards and the Department of Water Affairs and Forestry (DWAF) target water guidelines for faecal coliform (FC) concentrations in drinking water. The length of exposure time will depend on the initial concentration of FC present, the minimum DO concentration, the volume of water being disinfected, the colour of water containers used, and the turbidity of the water. It is however recommended that a full day's exposure will be more beneficial (i.e. maximise benefit of solar photo-oxidation and minimising the risk of failure) under field conditions.

- Although high turbidity did not influence the efficiency of the disinfection significantly, it will be advisable to remove any visible turbidity before the disinfection process is applied. This will not only serve to enhance the efficiency of the process by reducing the exposure time, but also make the water more aesthetically acceptable for human consumption.

- In the experimental setup, the containers were left either open or closed with a cap. As the transmission or diffusion of dissolved oxygen (DO) did not occur at significant levels through the container mouth openings, it is recommended that the containers should be kept closed with a cap to prevent any contamination with dust, animal droppings and/or leaves.

- Education of end users will be essential for the successful of the solar photo-oxidative disinfection process. It is especially important to instill in users that

the disinfection process does not leave any residual disinfection capacity after the disinfection is over, and that good hygienic practices will be essential in prevention or minimization of secondary pollution or contamination of the disinfected water.

6.3 RESEARCH RECOMMENDATIONS

The following recommendations are made for future research projects:

- Evaluate and/or develop the use of alternative containers, i.e. plastic bags, which will reduce the path length for effective light transmission through the water, thereby ensuring more effective disinfection.

- Investigate the applicability of the solar photo-oxidative disinfection process to water heavily contaminated with other pathogens such as *Vibrio cholerae*, rotaviruses, *Cryptosporidium spp.*, and *Giardia lamblia*.

- Perform field application in typical rural communities where water is still obtained from alternative sources such as wells, streams, rivers, and dams. This will include amongst others the evaluation of the community members' and individuals' perceptions and acceptance of the process.

- Investigate the possibility of full-scale application in low/intermittent flow water supply works.

CHAPTER 7

REFERENCES

ACHER, A.J. & JUVEN, B.I. 1977. Destruction of faecal coliforms in sewage water by dye sensitized photooxidation. *J.Appl.Envir.Microbiol.* **33**: 1019-1023.

ACHER, A.J., FISCHER, E. & MANOR, Y. 1994. Sunlight disinfection of domestic effluents for agricultural use. *Wat.Res.*; **28** (5): 1153-1160.

ACHER, A., FISCHER, E., TURNHEIM, R. & MANOR, Y. 1997. Ecologically friendly wastewater disinfection techniques. *Wat.Res.*; **31** (6): 1398-1404.

ACRA, A., RAFFOUL, Z. & KARAHAGOPIAN ,Y. 1984. Solar disinfection of drinking water and oral dehydration solutions: Guidelines for household application in developing countries. New York, UNICEF.

ACRA, A., JURDI, M., MU ALLEM, H., KARHAGOPIAN, Y. & RAFFOUL, Z. 1989. Sunlight as disinfectant. *The Lancet*; February, 4: 280.

ACRA, A. & AYOUB, G. 1997. Experimental evaluation of a novel photodynamic water disinfection technique. *J. Water SRT - Aqua*; **46** (4): 218-223.

ACRA, A., JURDI, M., MU'ALLEM, H., KARHAGOPIAN, Y. & RAFFOUL, Z. 1999. Water disinfection by solar radiation: an assessment and application. IDRC Library.

BINGHAM, A.1985. Beirut research finds sun's rays kill bacteria. *World Water*, April: 22-23.

BLACK, M. 1999. Learning what works. A twenty year retrospective view on International and Sanitation cooperation. Washington, DC; UNDP - World Bank.

CALKINS, J., BUCKLES, J.D. & MOELLER, J.R. 1976. The role of solar ultraviolet radiation in 'natural' water purification. *Photochemistry and Photobiology*; **24**: 49-57.

CIOCHETTI, D.A. & METCALF, R. 1984. Pasteurisation of naturally contaminated water with solar energy. *Applied and Environmental Microbiology*, **47**, 223-228.

CONROY, R.M., ELMORE-MEEGAN, M., JOYCE, T, McGUIGAN, K.G. & BARNES, J. 1996. Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. *Lancet*, **348** (9043): 1695-1697.

CONROY, R.M., MEEGAN, M.E., JOYCE, T., McGUIGAN, K. & BARNES, J. 1999. Solar disinfection of water reduces diarrhoeal disease: an update. *Arch. Dis.Child,* **81** (4): 337-338.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY. 1996. South African Water Quality Guidelines. Volume 1: Domestic water use. ISBN 0 7988 5339 5.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY & DEPARTMENT OF HEALTH. 1996. A guide for the health related assessment of the quality of water supplies.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY, DEPARTMENT OF HEALTH & WATER RESEARCH COMMISSION. 1998. Quality of domestic water supplies. Volume 1: Assessment Guide. ISBN 1 86845 416 9.

FJENDBO JORGENSEN, A.J., NOHR, K, SORENSEN, H. & BOISEN, F. 1998. Decontamination of drinking water by direct heating in solar panels. *J.App.Microbiol.* 85 **(3)**: 441-447.

GENTHE, B. & DU PREEZ, M. 1995. Evaluation of rapid methods for the detection of indicator organisms in drinking water. ISBN 1 86845 102 8.

GENTHE, B. & SEAGER, J. 1996. The effects of water supply, handling and usage on water quality in relation to health indices in developing communities. WRC report 562/1/96. ISBN 1 86845 254 9.

JOYCE, T., KENNY ,V., McGUIGAN, K. & BARNES, J. 1992. Disinfection of water by sunlight. *Lancet;* **340** (8824): 921.

JOYCE, T.M., McGUIGAN, K.G., ELMOORE-MEEGAN ,M. & CONROY, R.M. 1996. Inactivation of faecal bacteria in drinking water by solar heating. *Applied and Environmental Microbiology*; **62** (2): 399-402.

LAWAND, T.A., ALWARD, R., ODEYEMI, O., HAHN, J., KANDPAL, T.C. & AYOUB, J. (eds). 1988. Solar water disinfection. Solar water disinfection. Proceedings of a workshop held at the Brace Research Institute, Montreal, Canada. Ottowa: International Development Research Centre, 1988.

MACKENZIE, T.D., ELLISON, R.T. & MOSTOW, S.R. 1992. Sunlight and cholera. *Lancet*; **240**: 367.

McGUIGAN, K.G., JOYCE, T.M., CONROY, R.M., GILLEPSIE, J.B. & ELMORE-MEEGAN, M. 1998. Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. *J.Appl. Microbiol.* **84** (6): 1138-1148.

McGUIGAN, K.G., JOYCE, T.M. & CONROY, R.M. 1999. Solar disinfection: use of sunlight to decontaminate drinking water in developing countries. *J. Med. Microbiol.* **48** (9): 785-787.

McKANE, L. & KANDELL, J. 1996. Microbiology: essentials and applications. McGraw-Hill.

METCALF, R. 1998. Recent advances in solar water pasteurization. Internet access: www.accessorie.com/sbcn/metcalf.htm.

MEYER, V. 1999. Alternative disinfection treatment method of faecal contaminated drinking water: The feasibility and applicability of the Sol-air process in the South African scenario. WRC report K8/299/98.

MILLER, R.L. 1988. Sunlight as disinfectant. *Lancet* **ii**: 912.

MILLIPORE. 1992. Water Microbiology. Laboratory and field procedures. Cat.no. AD323.

PARODI, O., PREISER, K. & VOSSELER, I. 1996. Chlorine or UV? Water purification devices operated by solar photovoltaics. Mediterranean Conference on Renewable Energy Sources for Water Production, 10 - 12 June 1996, Santorini, Greece.

PELIZETTI, E., PRUMAURO, E., MINERO, C. & SERPONE, N. 1990. Sunlight photocatalytic degradation of organic pollutants in aquatic systems. *Waste Management*; **10** (1): 65-71.

PELCZAR, M.J., CHAN, E.C.S. & KRIEG, N.R. 1993. Microbiology. Concepts and applications. ISBN 0 07 049258 1.

REED, R.H. 1996. Sol-air water treatment. 22nd WEDC Conference Proceedings, New Dehli, India.

REED, R.H. 1997a. Solar inactivation of faecal bacteria in water: the critical role of oxygen. *Letters in Applied Microbiology*; **24**: 276-280.

REED, R. 1997b. Sunshine and fresh air: A practical approach to combatting water-borne disease. *Waterlines*; **15** (4): 27-29.

REED, R.H. 1997c. Innovations in solar water treatment. 23rd WEDC Conference, 1997, Durban South Africa.

REED, R.H., MANI, S K. & MEYER, V. 2000. Solar photo-oxidative disinfection of drinking water: preliminary field observations. *Letters in Applied Microbiology*, **30**: 432-436.

SABS. 1984. *South African Standard. Specification for water for domestic supplies*. SABS 241-1984. ISBN 0-626-07010-4.

SHAH, S.K., McBEAN, E.A. & ANDERSON, W.A. 1996. Preliminary studies into the disinfection of potable water using solar radiation. *Canadian Journal of civil Engineering;* **23** (2): 373-380.

SOMMER, B., MARINO, A., SOLARTE, Y., SALAS, M.L., DIEROLF, C., VALIENTE, C., MORA, D., RECHSTEINER, R., SETTER, P., WIROJANAGUD, W., AJARMEH, H., AL-HASSAN, A. & WEGELIN, M. 1997. SODIS - an emerging water treatment process. *J Water SRT - Aqua*; **46** (3): 127-137.

SOLSONA, F. 1996. *Disinfection for small water supplies*. Technical guide. WRC Report C 2878.

SPIEWAK, I., YOGEV, A., MESSALEM , R. & BENMAIR, R. 1996. Solar detoxification of contaminated water using concentrated sunlight and homogeneous photocatalysts. Mediterranean Conference on Renewable Energy Sources for Water Production, 10 - 12 June 1996, Santorini, Greece: 153-158.

WEGELIN, M., CANONICA, S., MECHSNER, K., FLEISCHMANN, T., PESARO, F. & METZLER. 1994. Solar water disinfection: scope of the process and analysis of radiation experiments. *J Water SRT - Aqua*; **43** (3): 154-169.

WEGELIN, M. 1995. News from the solar water disinfection project. *SANDEC News*, (1) May: 19-21.

WEGELIN, M. & SOMMER, B. 1996. Demonstration projects on solar water disinfection. *SANDEC News*; (2) October: 11-13.

WEGELIN, M. 1999. Solar water disinfection - a water treatment option for the year 2000 and beyond. SODIS -mail conference synthesis, March, 1999.

WEI, C., LIN, W.Y., ZAINAL, Z., WILLIAMS, N.E., ZHU, K., KRUZIC, A.P., SMITH, R.I. & RAJESHWAR, K. 1994. Bactericidal activity of TiO_2 photocatalyst in aqueous media: toward a solar-assisted water disinfection system. *Environ. Sci. Technol*, **28**: 934-938.

APPENDIX

1. Meyer, V. and Reed, R.H. 2001. SOL-AIR disinfection of coliform bacteria in hand-drawn drinking water. *Water SA*, **27**(1), 49 - 55, January 2001.

2. Reed, R.H., Mani, S.K. and Meyer, V. 2000. Solar photo-oxidative disinfection of drinking water: preliminary field observations. *Letters in Applied Microbiology*, **30** (6), 432 - 436.

3. Meyer, V. and Reed, R.H. 2000. SOL-AIR disinfection of hand drawn drinking water. *WISA 2000 Biennial Conference*, Sun City, South Africa, 28 May to 1 June 2000.

4. Meyer, V. and Reed, R.H. 1998. SOL-AIR disinfection: a South African perspective. *Interscience '98*, University of the North, October 1998.

SOLAIR disinfection of coliform bacteria in hand-drawn drinking water

V Meyer[1]* and RH Reed[2]

[1]*Technikon Northern Gauteng, Department of Chemistry, Private Bag X07, Pretoria North 0116, South Africa*
[2]*Division of Biomedical Sciences, Department of Chemical & Life Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, NE1 9ST, United Kingdom.*

Abstract

SOLAIR is an alternative disinfection method utilising natural sunlight (specifically UV-A and UV-B radiation) and oxygen (from atmospheric air) to damage, inactivate and/or kill the coliform bacteria found in contaminated water. It is a natural process (virtually self-purification) with no need to add any potentially hazardous chemicals or to use sophisticated and expensive equipment.

The SOLAIR process was applied in a typical South African scenario, i.e., a rural informal village where water for domestic use is drawn from an unlined and heavily contaminated well. Results obtained showed significant reduction (99.99%) in both the faecal and total coliform counts within 4 to 6 h, with no subsequent reactivation of growth after 24 h. The disinfected water complied in terms of bacteriological quality, with both the South African Bureau of Standards (SABS), drinking water standards and the South African Water Quality Guidelines (SAWQG) for domestic use as prescribed by the Department of Water Affairs and Forestry (DWAF). The rate of bacterial reduction depended on various parameters including the type and colour of plastic containers used, the initial concentration of micro-organisms in the drawn water, the irradiation levels of UV-A and UV-B rays, the oxygen concentration and distribution in the water containers, and the presence of visible turbidity.

In South Africa where more than 8 m. people are still using water obtained directly from alternative sources such as rivers, streams, boreholes, wells, community taps and dams, SOLAIR could prove to be an efficient and an economically feasible method to be used for disinfection of hand-drawn water to an acceptable potable standard.

Introduction

Disinfection of water is an essential unit process required to destroy pathogenic micro-organisms resulting in a potable water which is safe for human consumption. Disinfected potable water reduces the occurrence of water-borne diseases and the high incidence of mortality of infants and the elderly (Genthe and Du Preez, 1995; Genthe and Seager, 1996).

However, disinfection in rural, poverty-stricken areas with no running water, remains a huge problem (Genthe and Seager, 1996). Various uncomplicated methods of disinfection have been in place for some time, but most of these methods require some form of infrastructure, economic investment and educated or informed use (Solsona, 1996). These methods include filtration, coagulation, chlorination, and oxidation. Boiling and aeration have also been used with limited application (small volumes) and with sometimes unreliable results (Solsona, 1996).

Disinfection using solar radiation (sunlight), which rendered faecal bacteria inactive by thermal radiation in high turbidity waters, has been applied for centuries (Joyce et al., 1996). A water temperature of more than 55°C was needed to obtain good faecal bacterial cell inactivation. Wegelin et al. (1994), Wegelin and Sommer (1996) and Sommer et al. (1997) developed the SODIS (solar water disinfection) and SOPAS (solar pasteurisation) processes which rely on the synergistic effects of solar radiation and thermal water treatment.

The advantages of using solar radiation are numerous and include: no dangerous, toxic, or hazardous by-products are produced; no smell and/or taste are imparted to the water; it is economical and is easy and simple to apply. The ultraviolet (UV) component of sunlight is, however, filtered out by ozone for example, water droplets, and smoke, so that the UV light which actually reaches the earth's surface is restricted to a wavelength range of between 295 and 400 nm. This limits the microbiocidal properties of solar radiation as a sole disinfectant.

Reed (1996 and 1997a) investigated the role of fresh air (containing oxygen and other gases in variable concentrations) in the efficiency of solar disinfection processes. The toxicity of oxygen as a disinfectant is due to the superoxide and hydroxyl radicals formed during oxidation reactions. These radicals are very reactive but short-lived, limiting their disinfection efficiency. Results recorded indicated that some faecal bacterial species have a resistance to radiation inactivation in the absence of oxygen. The research led to the development of a process called solar photo-oxidative disinfection or SOLAIR.

SOLAIR combines the use of solar (UV) radiation and oxygen from the natural environment in an alternative disinfection method with a higher microbiocidal efficiency than the two disinfectants separately (Reed, 1996 and 1997a,b,c). This method is, in effect, a natural process (self-purification) without the addition of any potentially hazardous chemicals or a need for sophisticated and/or expensive equipment.

The following represents results from a full-scale field application of the SOLAIR disinfection method on hand-drawn drinking water in a typical rural and poverty-stricken scenario.

Materials and methods

Source of hand-drawn water

Water was abstracted from an unprotected well in the Bridgeview Mandela Village near Hammanskraal, Pretoria. The water from the

* To whom all correspondence should be addressed.
☎(012) 799 9098; fax(012) 7999022; e-mail: vermey@mweb.co.za
Received 7 July 2000; accepted in revised form 11 August 2000.

well was hand-drawn using buckets and then transferred to the plastic water storage containers for general domestic use. As the well is not protected or properly lined, it is contaminated by animal, bird and human faeces, polluted soil, polluted groundwater and by the users abstracting water every day.

Experimental set-up

Water was collected from the well into 25 ℓ white/opaque plastic containers which is representative of the containers used by the local community members. The plastic containers were filled with 20 ℓ of the collected water, closed, shaken vigorously for 5 min, and placed in direct sunlight for the duration of the experiment. The containers were shaken every hour after sampling to ensure that the oxygen which diffuses through the plastic, is dispersed evenly throughout the water mass.

Two controls were set up. Control A was deoxygenated by bubbling nitrogen through it and placed in direct sunlight. Control B was placed inside the house of one of the villagers, protecting it from direct solar radiation. Both controls were also shaken every hour directly after sampling the water for microbiological and physical analyses.

Physical analyses

The following physical analyses were performed hourly before shaking of the containers, using a calibrated Mettler Toledo portable meter (M90) with temperature compensation as a standard feature on all probes:

- temperature (- 0.5°C to 100°C, resolution 0.1°C)
- dissolved oxygen (DO) (1 to 10 mg/ℓ, resolution 0.1 mg/ℓ)
- total dissolved solids (TDS) (1 000 to 10 000 mg/ℓ, resolution 100 mg/ℓ)
- pH (0 to 14 pH units, resolution 0.01 pH units)

Turbidity was measured with a portable Lovibond (DRT 15CE) turbidity meter. It was standardised and calibrated with a 0.02 NTU reference solution and measured 0 to 1 000 NTU (+/- 4%).

The UV-A and UV-B irradiances were measured with a Delta Ohm microprocessor controlled quantum photo/radiometer (HD 9021). The UV-A probe measured from 10 nanowatt/cm² to 200 mW/cm² (±4%) in the spectral range 315 to 400 nm, peaking at 365 nm. The UV-B probe measured from 10 nW/cm² to 200 mW/cm² (±4%) in the spectral range of 280 to 315 nm, peaking at 312 nm.

Microbiological analyses

Total coliform (TC) and faecal coliform (FC) analyses were performed hourly during the experimental period and again 24 h after the last sample had been taken. The standard membrane filter (MF) technique was used. As suggested (SABS, 1984 and Millipore, 1992), 100 mℓ water sample volumes were filtered for both TC and FC analyses.

The chosen sample volume was filtered through 47 mm membranes of 0.45 µm (HA-type, Millipore) and 0.7 µm (HC-type, Millipore) pore sizes, respectively. The HC-type 0.7 µm filter membrane was chosen, because this type of membrane allows for the recovery of stressed faecal coliforms, giving a more reliable analytical result.

The 0.45 µm pore membrane filters were transferred aseptically to 65 mm petri dishes containing M-Endo agar (Merck). The inverted petri dishes were incubated for 24 h at 35°C (±5°C). The 0.7 µm membrane filters were transferred to petri dishes containing M-FC agar (Merck) and incubated invertedly at 44.5°C (±0.2°C) for 24 h.

Colonies with a gold metallic-green sheen on the M-Endo agar were considered to be positive for TC growth and, light- to dark-blue colonies on the M-FC agar as positive for FC growth. All results were reported as log CFU (coliform units)/100 ml.

TABLE 1
Average results of physical analyses of water samples (Experiment, Control A and Control B)

Time (h)	pH	Temperature (°C)	DO (mg/ℓ)		TDS (g/ℓ)	Turbidity (NTU)
			Experiment and Control B	Control A		
0	6.5	16	2.1	0	2.1	2.1
1	6.65	16.8	2.3	0.1	2.3	2
2	6.8	17.5	2.5	0.2	2.2	2.05
3	6.6	18.2	2.1	0.1	2.3	2.11
4	6.56	19	2	0.3	2.4	2.1
5	6.8	19.1	1.9	0.1	2.3	2.2
6	6.75	18.4	2.1	0.1	2.2	2.12
7	6.7	18	2	0.1	2.3	2

Results and discussion

Physical analyses

Table 1 summarises the results of the physical analyses performed on the water samples taken every hour from the experimental set-up. It indicates clearly that the SOLAIR process does not have any significant effect on the physical characteristics of the water, because all parameters remained nearly constant over the experimental period. From the data presented in Table 1, it can be seen that temperature does not play a role in the destruction of the TC and FC organisms in the contaminated water as it remains low at around 18°C, even with mid-day atmospheric temperatures in excess of 34°C. This indicates that the UV irradiance and the oxygen diffusing from the atmospheric air, are the only two factors that play a role in the destruction/inactivation of coliform bacteria in the SOLAIR disinfection method.

The DO in the water container ranged between 1.9 and 2.5 mg/ℓ. Oxygen is usually used by bacterial cells for energy-yielding chemical reactions and not for bacterial growth. The toxicity to some species of bacteria (including members of the *Enterobacteriaceae*) is due to superoxide radicals, hydroxyl radical and hydrogen peroxide which are produced during oxidation reactions. All of these molecules can damage the DNA of the bacterial cell. However, some bacteria have developed a protective mechanism in which the enzyme superoxide dismutase is produced. This enzyme converts the superoxide radicals rapidly to hydrogen peroxide, which in turn is dissipated by catalase and peroxidase to water and oxygen. The enzymes are produced through information from the DNA. Thus, if the DNA is damaged/ inactivated by UV irradiation, for example, this protective mechanism will be inactivated (Pelczar et al., 1993).

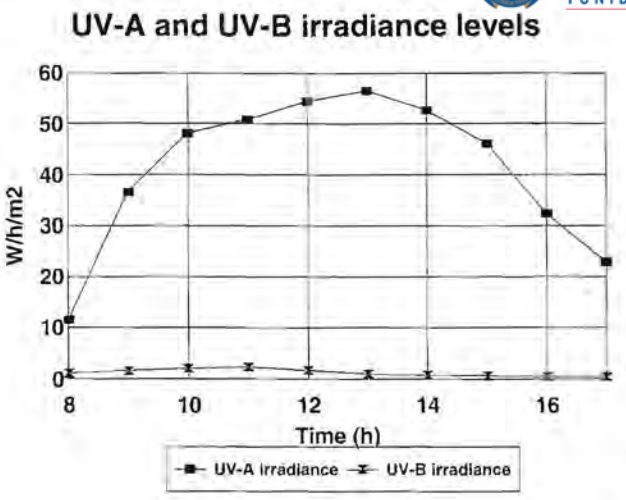

Figure 1
UV-A and UV-B irradiance levels over the experimental period

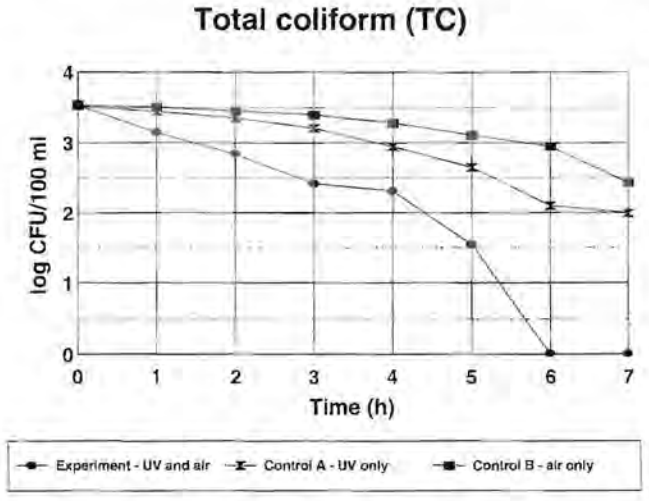

Figure 2
Total coliform concentration over experimental period

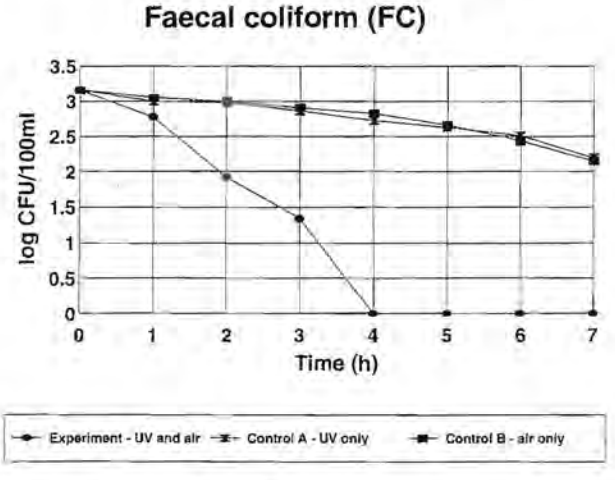

Figure 3
Faecal coliform concentrations over the experimental period

The measured UV irradiance levels are illustrated in Fig 1. As expected, the UV-A irradiance is much higher than the UV-B irradiance, because most of the lower wavelength UV components from the sunlight are filtered by ozone, water droplets, and smoke. The UV light which actually reaches the earth's surface is restricted to a wavelength range of 295 to 400 nm. This, in effect, limits the microbiocidal properties of solar UV light as a disinfectant, as the highest bactericidal action will occur at 260 nm, i.e. the wavelength at which the DNA of a bacterial cell absorbs the most UV light.

SOLAIR disinfection overcame both these limitations by applying solar radiation in the presence of oxygen in concentrations of more than 2 mg/ℓ. This combined effect on bacterial cells can be seen in the results of the microbiological analyses as illustrated in Figs. 2 and 3.

Microbiological analyses

Figure 2 shows that 100% inactivation/destruction of total coliforms (TC) was obtained within a period of 6 h during the application of SOLAIR disinfection to the hand-drawn water. Control A showed a 40% reduction over the same period and only a 43% reduction in cell concentration over the total experimental period of 7 h. Control B had a 17% reduction after 6 h and 31 % after completion of the experiment.

Figure 3 illustrates the faecal coliform (FC) inactivation/ destruction. Within a period of 4 h destruction of FC was 100% effective, while Control A showed a 14% reduction and Control B a 10% reduction in FC concentration after the same period. Controls A and B had final reductions in cell concentrations of 30% and 32% respectively after completion of the experimental period.

After a 24 h lag period, the SOLAIR disinfected water showed no growth on the respective inoculated agar plates. This indicates that the bacterial cells were irreversibly damaged or killed by the said disinfection process. However, increased concentrations of both TC and FC were observed in both controls after the 24 h lag period.

From the data presented above, it can be seen that the disinfection efficiency of the SOLAIR process is higher than the process of using solar UV radiation (Control A) or oxygen (Control B) separately. The disinfected water complied with the potable drinking water standards and guidelines in terms of bacteriological quality as laid down by the SABS (1984) and DWAF (1996a & b), respectively. This will have a major impact on the reduction of incidences of diseases related to poor microbiological water quality.

A major disadvantage of the suggested method, is that no residual disinfection power will be found in the water after treatment with SOLAIR. This makes it very difficult to guarantee that the water is safe from any secondary contamination. Secondary contamination can, however, be limited or prevented, by practising good hygiene in the respective households.

Conclusions

Based on the results of all the field trials, the following conclusions can be drawn:

- SOLAIR is applicable and effective in small volumes of hand-drawn water (2 to 25 ℓ).
- Intermittent vigorous shaking is important during the disinfection period, in order to dissolve and disperse the diffused and DO throughout the volume of water and to ensure contact of all organisms in the water with the absorbed UV light.

- Visible turbidity should be removed before the SOLAIR disinfection process can be applied, because turbidity will interfere with the disinfection efficiency.
- The containers must be kept closed with a lid and must be exposed to full/direct sunlight at all times.
- A minimum of 4 h is required for effective coliform disinfection, i.e., compliance with the SABS (1984) drinking water standards and the DWAF Water Quality Guidelines (1996a & b) for TC and/or FC. This will depend on the initial concentration of micro-organisms, the DO concentration, the UV concentration and the type and colour of plastic container that is used. It was found with further studies that cloud cover did not limit the UV radiation significantly.
- It is emphasised that no residual disinfection power is available after SOLAIR disinfection of the hand-drawn water. Education of the end users is thus imperative for the successful application of the SOLAIR disinfection process, as good hygienic practices will prevent or minimise secondary contamination of the SOLAIR disinfected water.

Acknowledgements

The Water Research Commission (WRC) and the Directorate of Research, Technikon Northern Gauteng funded the project entitled "Alternative disinfection treatment method of faecal contaminated drinking water: The feasibility and applicability of the SOLAIR process in the South African scenario." The fieldwork was performed with the help of senior students enrolled for the National Diploma: Water Care at theTechnikon Northern Gauteng, Soshanguve, Pretoria.

The authors wish to thank Ms AM Nel for editorial support.

References

DWAF (1996a) *South African Water Quality Guidelines. Vol 1: Domestic Water Use*. Department of Water Affairs and Forestry, Pretoria.

DWAF (1996b) *A Guide for the Health Related Assessment of the Quality of Water Supplies*. Department of Water Affairs and Forestry and Department of Health, Pretoria.

GENTHE B and DU PREEZ M (1995) Evaluation of Rapid Methods for the Detection of Indicator Organisms in Drinking Water. WRC Report No 610/1/95.

GENTHE B and SEAGER J (1996) The Effects of Water Supply, Handling and Usage on Water Quality in Relation to Health Indices in Developing Communities. WRC Report 562/1/96.

JOYCE TM, McGUIGAN KG, ELMOORE-MEEGAN M and CONROY RM (1996) Inactivation offaecal bacteria in drinking water by solar heating. *Appl. Environ. Microbiol.* **62** (2) 399-402.

MILLIPORE (1992) *Water Microbiology*. Laboratory and Field procedures.

PELCZAR MJ, CHAN ECS and KRIEG NR (1993) *Microbiology. Concepts and Applications*. McGraw-Hill.

REED RH (1996) Sol-air water treatment. *22nd WEDC Conf. Proc., New Dehli, India.*

REED RH (1997a) Solar inactivation of faecal bacteria in water: The critical role of oxygen. *Lett. Appl. Microbiol.* **24** 276-280.

REED R (1997b) Sunshine and fresh air: A practical approach to combating water-borne disease. *Waterlines* **15** (4) 27-29.

REED RH (1997c) Innovations in solar water treatment. *23rd WEDC Conf.Proc., Durban, South Africa.*

SOMMER B, MARINO A, SOLARTE Y, SALAS ML, DIEROLF C, VALIENTE C, MORA D, RECHSTEINER R, SETTER P, WIRO-JANAGUD W, AJARMEH H, AL-HASSEN A and WEGELIN M (1997) SODIS - An emerging water treatment process. *J.Water SRT - Aqua* **46** (3) 127 - 137.

SABS (1984) *South African Standard: Specification for Water for Domestic Supplies*. SABS 241.

SOLSONA F (1996) Disinfection for Small Water Supplies. CSIR Technical Guide No C 2878.

WEGELIN M, CANONICA S, MESCHNER K, FLEISCHMANN T, PESARO F and METZLER (1994) Solar water disinfection: Scope of the process and analysis of radiation experiments. *J. Water SRT - Aqua* **43** (3) 154 - 169.

WEGELIN M and SOMMER B (1996) Demonstration projects on solar water disinfection. *SANDEC News* (2) 11-13.

Letters in Applied Microbiology 2000, **30**, 432–436

Solar photo-oxidative disinfection of drinking water: preliminary field observations

R.H. Reed[1], S.K. Mani[2] and V. Meyer[3]

[1]Division of Biological and Food Sciences, School of Applied and Molecular Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, UK, [2]Department of Geology, Government College, Kottayam, Kerala, India and [3]Department of Chemistry, Technikon Northern Gauteng, Pretoria, South Africa

0016/00: received 18 January 2000, revised 14 February 2000 and accepted 14 February 2000

R.H. REED, S.K. MANI AND V. MEYER. 2000. The feasibility of using solar photo-oxidation to inactivate faecal bacterial contaminants in drinking water has been evaluated under field conditions in India and South Africa. Freshly drawn samples from all six test water sources were low in dissolved oxygen, at 13–40% of the air saturation value. However, vigorous mixing followed by exposure to full-strength sunlight in transparent plastic containers (1–25 l capacity) caused a rapid decrease in the counts of faecal indicator bacteria, giving complete inactivation within 3–6 h, with no evidence of reactivation. These results demonstrate that solar photo-oxidation may provide a practical, low-cost approach to the improvement of drinking water quality in developing countries with consistently sunny climates.

INTRODUCTION

Water-borne disease is a significant global issue, with approximately one billion people lacking access to a reliable supply of clean drinking water (Black 1999). The consumption of drinking water contaminated with pathogenic microbes of faecal origin is a significant risk to human health in the developing world, especially in remote rural areas and peri-urban 'shanty' communities, with over 3 million deaths per year attributed to water-borne diarrhoeal diseases, especially among infants and young children in poor communities in Africa, Asia and South America (Anon. 1997a). As a result, there is an unmet need for practical systems capable of treating contaminated drinking water in developing countries, thereby reducing the impact of water-borne disease.

In communities with no satisfactory safe drinking water supply, small-scale self-help measures can be used at the household level; these include boiling, filtration and/or chemical treatment (Heber 1985; Anon. 1997b). One small-scale approach that has gained support in recent years makes use of the disinfectant properties of sunlight to treat contaminated water in transparent plastic bottles or plastic bags, in a process termed solar disinfection (Acra *et al.* 1990). Experimental studies have demonstrated that this approach is effective under conditions where (i) the drinking water is subject to contamination with faecal bacteria and (ii) the climate is favourable enough to provide sufficient sunlight (Wegelin and Sommer 1997).

Most of the research into the effectiveness of solar disinfection has focused either on the pasteurizing effects of solar radiation at temperatures above 45–50 °C, in a process termed solar pasteurization (e.g. Ciochetti and Metcalf 1984; Jørgensen *et al.* 1998), or on the synergistic interaction between temperature and solar radiation (e.g. Wegelin *et al.* 1994; McGuigan *et al.* 1998). However, recent laboratory studies have demonstrated that the inactivation of faecal bacteria in sunlight is also strongly dependent upon the oxygen status of the water, due to the formation of free radicals derived from dissolved oxygen via solar photo-oxidation (Reed 1997a). Such observations indicate that solar photo-oxidative disinfection may be a useful approach to water treatment, even in the absence of any thermal effects (Reed 1997b).

The present study was carried out to assess the effectiveness of solar photo-oxidative disinfection under field conditions in India and South Africa, using hand-drawn sources of drinking water. The results show that the contaminant faecal coliform bacteria naturally present in these drinking water sources were inactivated by oxygenation, achieved by vigorous mixing of the water in transparent plastic containers, followed by exposure to full-strength sunlight for up to 6 h.

Correspondence to: R.H. Reed, Division of Biological and Food Sciences, School of Applied and Molecular Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, UK.

MATERIALS AND METHODS

Water sources

All of the water sources tested in the present study were in use by the local communities for drinking and general household purposes. In the Indian field trials (May–June 1997), contaminated water samples were obtained from unprotected dug wells in Jaipur District: sources IN1 and IN2 were wells in the village of Udaipur Gilaria, 10 km north-east of Jaipur, representing heavy contamination and moderate faecal contamination (Feacham 1977), respectively; source IN3 was a moderately contaminated well in Ursewa village, 70 km south-west of Jaipur. The South African field trials (August–October 1998) used sources from Gauteng district: source SA1 was a shallow, unprotected dug well at Mandela village (rural squatter camp), near Mabopane, 38 km north-east of Pretoria; source SA2 was from a site on the Apies river near Hammanskraal, 45 km north of Pretoria; source SA3 was a stream, Soutpan Spruit, Soshanguve, 32 km north-east of Pretoria. All three South African sources were heavily contaminated with faecal bacteria, with over 1000 faecal coliforms per 100 ml (see Table 1).

In all instances, water samples were taken using sterile containers and either tested immediately for physicochemical characteristics (turbidity, temperature and dissolved oxygen) or transported in darkness, within 1 h of sampling, to the Birla Institute of Scientific Research, Jaipur (India) or Technikon Northern Gauteng (South Africa) for analysis of faecal coliforms and solar experimentation.

Physicochemical measurements

Sample turbidity was assayed using either a spectrophotometer (CE1010; Cecil, Cambridge, UK), calibrated in notional turbidity units (NTU) against a formazan standard (sources IN1–IN3), or a turbidity meter (DRT 15CE; Lovibond, Salisbury, UK) (sources SA1–SA3). Dissolved oxygen (mg l^{-1}) and temperature (°C) were measured using either (i) a probe (9010; Jenway, Dunmow, UK) (sources IN1–IN3) or (ii) an M90 system (Mettler Toledo, High Wycombe, UK) (sources SA1–SA3) while solar irradiance was determined using either (i) a pyranometer (SP1100; Syke, Llandrindod Wells, UK) or (ii) a quantum photo/radiometer (Delta Ohm, Hunger, Germany).

Illumination in sunlight

Water samples were incubated in locally obtained, clear plastic containers of either 1- or 22-l capacity (IN1–IN3) or 2- or 25-l capacity (SA1–SA3). Containers were first aerated by vigorous mixing for at least 2 min, to ensure oxygen saturation (Reed 1997b) and then exposed to full-strength sunlight, measured at > 500 W m^{-2} for the duration of the experiment, as required for effective solar inactivation (Acra *et al.* 1990; Wegelin 1999). All containers were shaken (mixed) at hourly intervals, to maintain oxygen equilibration between the water samples and the atmosphere, with sampling every hour from 10 a.m. until 4 p.m. Control samples for all water sources were incubated indoors in darkness.

Enumeration of faecal bacteria

Aliquots of water were processed by standard bacteriological membrane filtration (MF) procedures, using 1·0–100·0 ml water filtered through either GN-6 (Gelman; Michigan, USA) or HC membranes (Millipore, Bedford, MA, USA) and enumerated either on Membrane Lauryl Sulphate medium (Merck, Poole, UK) (Anon. 1994; sources IN1–IN3) or on M-FC agar (Merck) (Anon 1992; sources SA1–SA3). Media were incubated at 44·5 ± 0·5 °C for 24 h prior to counting. The number of presumptive faecal (thermotolerant) coliforms (FC) in each sample is expressed per 100

Table 1 Representative physicochemical and microbiological data for water sources used in field trials of solar photo-oxidation (India and South Africa)

Source	Turbidity (NTU)	Temperature (°C)	O_2 (mg l^{-1})	O_2 saturation (%)	Initial FC (cfu 100 ml^{-1})	FC $T_{99.9}$ (min)
IN1	2·4	27·5	3·1	39	5500	125
IN2	4·0	28·0	2·7	35	900	150
IN3	7·9	23·3	1·1	13	660	220
SA1	2·1	18·8	3·7	40	1450	245
SA2	3·7	19·0	3·2	34	2900	255
SA3	1·5	15·0	4·0	39	6750	280

FC, Faecal (thermotolerant) coliforms; cfu, colony-forming units; FC $T_{99.9}$, 99·9% inactivation time for FC (oxygenated, full sunlight) in plastic bottles of either 1 l (IN1–IN3) or 2 l (SA1–SA3) capacity; NTU, notional turbidity units.

ml, based on the formula: FC per 100 ml = (MF colony count × 100) / (sample volume in ml). For counts of presumptive faecal streptococci (FS), MF samples were enumerated using Slanetz and Bartley medium (Merck) (Anon. 1994) incubated at 44·5 ± 0·5 °C for 48 h prior to counting. All counts were performed in duplicate. Samples were always shielded from direct sunlight during transport to the laboratory and throughout processing to avoid photoinactivation.

RESULTS AND DISCUSSION

Table 1 shows typical data for the physicochemical characteristics of water samples from each source. All were of low turbidity, at under 10 NTU, ensuring the effective penetration of sunlight during solar photo-oxidation experiments, in contrast to other field studies which have investigated the effects of solar treatment on highly turbid water sources where optical inactivation is minimal and thermal inactivation enhanced (Joyce *et al.* 1996; McGuigan *et al.* 1999). The level of dissolved oxygen in freshly drawn water samples was low, at 1·1–4·0 mg l^{-1} O_2, representing 13–40% of the oxygen saturation value at the corresponding water temperature (Green and Carritt 1967). A low dissolved oxygen status is a common feature of many surface and ground waters, due to the limited solubility and low diffusion coefficient of oxygen in water, the consumption of oxygen in redox reactions with inorganic compounds and the respiratory activity of aquatic microorganisms (Malard and Hervant 1999). Previous experiments have shown that failure to increase the oxygen content of water to its air-equilibrated value can substantially reduce the rate of solar inactivation of faecal bacteria (Reed 1997a; Meyer 1999).

Table 1 also shows that all sources were contaminated with FC, ranging from 660 FC 100 ml^{-1} (IN3) to 6750 FC 100 ml^{-1} (SA3). At such levels, the untreated water sources can be regarded as unsatisfactory for human consumption, representing a high risk of transmission of water-borne disease, since they all indicate substantial faecal contamination, of either human or animal origin, failing to meet international guidelines for drinking water quality (e.g. Lewis 1991; Anon. 1997b).

Table 1 also shows the results of preliminary experiments where fully mixed (air-equilibrated) water samples in transparent plastic drinks bottles of either 1 l (IN1–IN3) or 2 l (SA1–SA3) capacity were then exposed to sunlight. The effect of this treatment on the contaminant FC is expressed in terms of the time required to reduce the FC count by 99·9% ($T_{99.9}$, based on a plot of log FC 100 ml^{-1} against time and determined as the time required to give a 3-log reduction in FC 100 ml^{-1}; Reed 1996). All six water samples showed a rapid inactivation of FC on exposure to sunlight under oxygen-equilibrated conditions, while no significant change in FC counts was observed for control samples kept in darkness (data not shown). The $T_{99.9}$ values given in Table 1 are sufficient to give a zero count for FC 100 ml^{-1} within approximately 3–6 h, depending upon the intial FC count, and are comparable to those of earlier experimental studies using water deliberately contaminated either with pure cultures of coliform bacteria or with sewage (e.g. Gameson and Saxon 1967; Evison 1988). To test for the reactivation of sublethally injured bacteria following illumination (Fujioka and Narikawa 1982), samples were kept in darkness for a further 24 h and then tested for FC; there were no detectable counts, confirming that the inactivation was irreversible.

Figures 1 and 2 show time course data for the solar inactivation of faecal indicator bacteria in larger plastic containers holding either 22 l (IN1) or 25 l (SA1) of fully-mixed (oxygen-equilibrated) water from a single representative source from each country. Both sources showed rapid inactivation of FC on exposure to full-strength sunlight, with FC $T_{99.9}$ values only slightly higher than those obtained for the smaller volumes (cf. Table 1), at 150 min for IN1 (Fig. 1) and 290 min for SA1 (Fig. 2), while control samples maintained in darkness showed no measurable change in FC count. Sample IN1 was also assessed for FS, giving a lower initial FS plate count but a similar rate of inactivation compared with FC (Fig. 1). A sample of SA1 made anaerobic by bubbling with nitrogen prior to exposure to sunlight gave a far slower rate of FC inactivation than under air-equilibrated conditions (Fig. 2), confirming an oxygen requirement for the rapid solar inactivation of FC (Reed 1996).

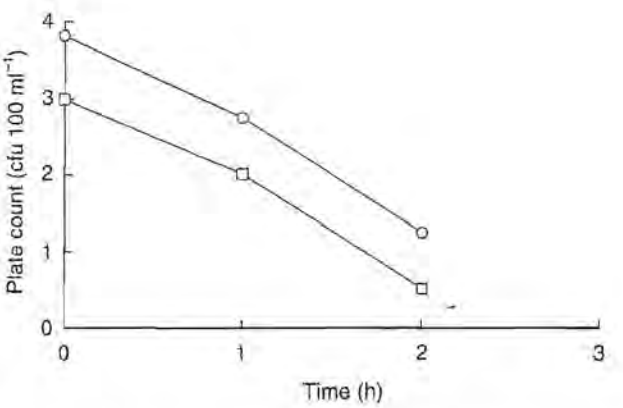

Fig. 1 Inactivation of faecal coliforms (○) and faecal streptococci (□), expressed as colony-forming units (cfu) 100 ml^{-1}, in water samples from source IN1 (22-l plastic container). No counts were detected for either faecal coliforms or faecal streptococci at 3 h

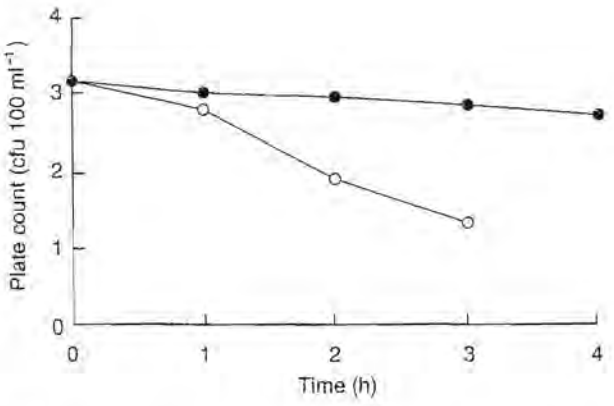

Fig. 2 Inactivation of faecal coliforms (expressed as colony-forming units (cfu) 100 ml^{-1}) in oxygenated (○) and deoxygenated (●) samples from water source SA1 (25-l plastic container). No counts were detected in the oxygenated sample after 3 h

Throughout exposure to sunlight, the temperature of the water samples reached a maximum of 30 °C (SA1–3) and 38 °C (IN1–3). These values are below the lethal temperatures of faecal bacteria (Anon. 1994) and lower than the level required for optimal synergy between optical and thermal inactivation (McGuigan *et al.* 1998; Wegelin *et al.* 1994; Lawand *et al.* 1997). These results clearly demonstrate that solar photo-oxidation is sufficient to inactivate FC bacteria in heavily contaminated water sources under field conditions, supporting the findings of earlier, laboratory-based studies (Reed 1997a). The data obtained using containers of 22 and 25 l capacity are especially promising, since they demonstrate that a volume of water appropriate for the daily drinking requirements of an individual family could be treated using solar photo-oxidation. It is noteworthy that solar photo-oxidation may be particularly relevant in rural India where there are significant problems related to the spread of water-borne disease (e.g. Nigam *et al.* 1997) and where there are records of solar water treatment dating back over 2000 years. As one of the traditional approaches to the provision of 'safe' water in India (Patwardhan 1990) this may assist its implementation, which is influenced strongly by the socio-cultural background of end-users (Wegelin 1999).

REFERENCES

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

Anon. (1992) *Standard Methods for the Examination of Water and Wastewater*, 18th edn. Washington, DC: American Public Health Association.

Anon. (1994) *The Microbiology of Water 1994 Part 1 – Drinking Water. Report on Public Health and Medical Subjects Number 71: Methods for the Examination of Waters and Associated Materials*. London: HMSO.

Anon. (1997a) World Health Report. *World Health Forum* 97, 181–188.

Anon. (1997b) *Guidelines for Drinking Water Quality*, Vol. 3: *Surveillance and Control of Community Water Supplies* 2nd edn. Geneva: World Health Organization.

Black, M. (1999) *Learning What Works. A Twenty Year Retrospective View on International Water and Sanitation Co-Operation*. Washington, DC: UNDP-World Bank.

Ciochetti, D.A. and Metcalf, R. (1984) Pasteurisation of naturally contaminated water with solar energy. *Applied and Environmental Microbiology* 47, 223–228.

Evison, L.M. (1988) Comparative studies on the survival of indicator organisms and pathogens in fresh and sea water. *Water Science and Technology* 20, 309–315.

Feacham, R.G. (1977) Water supplies for low-income communities: resource allocation, planning and design for a crisis situation. In *Water, Wastes and Health in Hot Climates* ed. Feacham, R., McGarry, M. and Mara, D. pp. 75–95. New York: Wiley.

Fujioka, R.S. and Narikawa, O.T. (1982) Effect of sunlight on enumeration of indicator bacteria under field conditions. *Applied and Environmental Microbiology* 44, 395–401.

Gameson, A.H.L. and Saxon, J.R. (1967) Field studies on effect of daylight on mortality of coliform bacteria. *Water Research* 1, 279–295.

Green, E.J. and Carritt, D.E. (1967) New tables for oxygen saturation of sea water. *Journal of Marine Research* 25, 140–147.

Heber, G. (1985) *Simple Methods for the Treatment of Drinking Water*. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit.

Jørgensen, A.J.F., Nøhr, K., Sørensen, H. and Boisen, F. (1998) Decontamination of drinking water by direct heating in solar panels. *Journal of Applied Microbiology* 85, 441–447.

Joyce, T.M., McGuigan, K.G., Elmore-Meegan, M. and Conroy, R.M. (1996) Inactivation of fecal bacteria in drinking water by solar heating. *Applied and Environmental Microbiology* 62, 399–402.

Lawand, T.A., Ayoub, J. and Gichenje, H. (1997) Solar disinfection of water using transparent plastic bags. *RERIC International Energy Journal* 19, 37–44.

Lewis, M.J. (1991) Water fit to drink? Microbial standards for drinking water. *Reviews in Medical Microbiology* 2, 1–6.

Malard, F. and Hervant, F. (1999) Oxygen supply and the adaptation of animals in groundwater. *Freshwater Biology* 41, 1–30.

McGuigan, K.G., Joyce, T.M., Conroy, R.M., Gillespie, J.B. and Elmore-Meegan, M. (1998) Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. *Journal of Applied Microbiology* 84, 1138–1148.

McGuigan, K.G., Joyce, T.M. and Conroy, R.M. (1999) Solar disinfection: use of sunlight to decontaminate drinking water in

developing countries. *Journal of Medical Microbiology* 48, 785–787.

Meyer, V. (1999) *Alternative Disinfection Treatment Method of Faecal Contaminated Drinking Water*. Pretoria: Water Research Commission SA Report KB/299/98.

Nigam, A., Gujja, B., Bandyopadhyay, J. and Talbot, R. (1997) *Fresh Water for India's Children and Nature: Learning from Local-Level Approaches* New Delhi: UNICEF.

Patwardhan (1990) *Our Water, Our Life* New Delhi: CAPART.

Reed, R.H. (1996) Sol-air water treatment. In *Proceedings of the Twenty-Second Water, Engineering and Development Centre Conference*, New Delhi, India. pp. 259–260. Loughborough: University of Loughborough.

Reed, R.H. (1997a) Solar inactivation of faecal bacteria in water: the critical role of oxygen. *Letters in Applied Microbiology* 24, 276–280.

Reed, R.H. (1997b) Sunshine and fresh air: a practical approach to combat water-borne disease. *Waterlines* 15, 27–29.

Wegelin, M. (1999) *Sodis News*, Number 4. Duebendorf: Swiss Federal Institute of Environmental Science and Technology.

Wegelin, M., Canonica, S., Mechsner, K., Fleischmann, T., Pesaro, F. and Metzler, A. (1994) Solar water disinfection: scope of the process and analysis of radiation experiments. *Journal of Water Science Research and Technology* 43, 154–169.

Wegelin, M. and Sommer, B. (1997) Solar water disinfection (SODIS) – destined for worldwide use? *Waterlines* 16, 30–32.

SOLAIR disinfection of hand drawn drinking water

V Meyer* and Dr R H Reed (Poster presentation)

**Technikon Northern Gauteng, Department Chemistry, Private Bag X07, Pretoria North, 0116. Tel: (012) 799 9098 , Fax (012) 799 9022, E-mail: vermey@mweb.co.za.*

Division of Biomedical Sciences, Department of Chemical & Life Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, NE1 9ST, United Kingdom. E-mail: robreed@unn.ac.uk.

Abstract

SOLAIR is an alternative and economical disinfection method utilizing natural sunlight (UV-A and UV-B rays) and oxygen (from atmospheric air) to damage, inactivate and/or kill the faecal bacteria found in contaminated water. It is a natural process (virtually selfpurification) without addition of any potentially hazardous chemicals or need for sophisticated and expensive equipment.

The SOLAIR process was applied in a typical South African scenario, i.e. a rural informal village where water for domestic use is drawn from an unlined and heavily contaminated well. Results obtained showed significant reduction (99.99%) in both the total and faecal coliform counts within 4 to 6 hours, with no subsequent reactivation of growth after 24 hours. The disinfected water complied with both the South African Bureau of Standards (SABS) drinking water standards and the South African Water Quality Guidelines (SAWQG) for domestic use as prescribed by the Department of Water Affairs and Forestry (DWAF). The bacterial reduction depended on various parameters including the type and colour of containers used, the initial concentration of microorganisms in the drawn water, irradiation levels of UV-A and UV-B light, the oxygen concentration and distribution within the containers, and presence of visible turbidity.

In South Africa where more than 12 million of its people are still using water obtained directly from alternative sources such as rivers, streams, boreholes, wells, community taps and dams, SOLAIR could prove to be an efficient and economically feasible method to be used for disinfection of hand drawn water to an acceptable potable standard.

Introduction

Disinfection of water is an essential unit process needed to destroy pathogenic microorganisms resulting in a potable water which is safe for human consumption. Disinfected potable water reduces the occurrence of water-borne diseases and the high incidence of mortality of infants and the elderly (Genthe *et al.* 1994, Genthe and Du Preez, 1995, Genthe and Seager, 1996).

However, disinfection in rural, poverty-stricken areas with no running water, remains a huge problem (Genthe and Seager, 1996). Various cheap and less sophisticated methods have been in place for some time, but most of these methods require some form of infrastructure and economical investment and educated or informed use (Solsona, 1996). These methods include amongst others filtration, coagulation, chlorination, and oxidation. Boiling and aeration has also been used with limiting application (small volumes) and with sometimes unreliable results (Solsona, 1996).

Disinfection with solar radiation (sunlight) is a method which has been used for centuries (Joyce *et al.*, 1996). The advantages of using solar radiation are numerous and include: no production of dangerous, toxic, or hazardous by-products; no smell and/or taste are imparted to the water; it is a natural process with low economical demand and it is easy and simple to employ. The disadvantage is that there is no residual disinfection power to prevent and control secondary microbiological contamination.

SOLAIR is an improved disinfection method which makes use of both the ultra violet (UV) radiation from the sun and oxygen from the natural environment (Reed, 1996 and 1997). The process is a natural process (selfpurification) without the addition of any potentially hazardous chemicals or need for any sophisticated and expensive equipment. The method can be easily applied, with very little supervision and economical investment.

The following represents results from a full-scale field application of the proposed SOLAIR disinfection method in a typical rural and poverty-stricken setting.

Materials and methods

Source of hand drawn water

Water was abstracted from an unprotected well in the Bridgeview Mandela Village near Hammanskraal. The water is being hand drawn with buckets and then transferred to the plastic water containers for drinking purposes and general household use. As the well is not protected, it is contaminated by animal, bird and human faeces, polluted soil, and by the users abstracting water every day. The well is also contaminated by oil and petrochemical products through contaminated groundwater.

Experimental setup

Water was collected from the well in 25 liter clear white or opaque plastic containers representative of the containers used by the local community. The water containers were shaken vigorously for 5 minutes, closed and placed in direct sunlight for the duration of the experiment. The containers were shaken every hour after sampling to distribute the available oxygen throughout the water mass.

Two controls were setup. Control A was deoxygenated by bubbling nitrogen through it and placing it in direct sunlight. Control B was placed inside the house of one of the villagers, protecting it from direct solar radiation. Both controls were also shaken every hour, directly after sampling the water for microbiological and physical analyses.

Physical analyses

The following physical analyses were performed hourly during the field trials using a calibrated Mettler Toledo portable meter (M90):

- temperature (- 0,5°C to 100°C, resolution 0,1°C)
- dissolved oxygen (DO) (1 to 10 mg/l, resolution 0,1 mg/l)
- total dissolved solids (TDS) (1 to 10 g/l, resolution 0,01 g/l)
- pH (0 to 14 pH units, resolution 0,01 pH units)

All probes used had temperature compensation as a standard feature.

Turbidity was measured with a portable Lovibond (DRT 15CE) turbidity meter. It was standardized and calibrated with a 0,02 NTU reference solution and measured 0 to 1000 NTU (+/- 4%).

The UV-A and UV-B irradiance were measured with a Delta Ohm Microprocessor controlled Quantum Photo/Radiometer (HD 9021). The UV-A probe measured from 10 nanowatt/cm^2 to 200 mW/cm^2 (+/- 4%) in the spectral range 315 to 400 nm, peaking at 365 nm. The UV-B probe measured from 10 nW/cm^2 to 200 mW/cm^2 (+/- 4%) in the spectral range 280 to 315 nm, peaking at 312 nm.

Microbiological analyses

Total coliform (TC) and faecal coliform (FC) analyses were performed hourly during the experimental period and again 24 hours after the last sampling period. This was essential to monitor for any reactivation of microbial growth. The standard membrane filter (MF) technique was used. As suggested in Standard Methods (Millipore, 1992), 100 ml water sample volumes were filtered for both TC and FC analyses.

The chosen sample volume was filtered through 47 mm membranes of 0.45 μm (HA-type, Millipore) and 0.7 μm (HC-type, Millipore) pore sizes, respectively. The HC-type 0.7 μm filter membranes were chosen, as it allows the recovery of stressed faecal coliforms, giving a more reliable analytical result.

The 0.45 μm pore membrane filters were transferred aseptically to 65 mm petri dishes containing M-Endo agar (Merck). The inverted petri dishes were incubated for 24 h at 35°C (+/- 5°C). The 0.7 μm membrane filters were transferred to petri dishes containing M-FC agar (Merck) and incubated invertedly at 44.5°C (+/- 0.2°C) for 24 h.

Colonies with a gold metallic green sheen on the M-Endo agar were taken as positive for TC growth and light to dark blue colonies on the M-FC agar as positive for FC growth. All results were reported as log CFU (coliform units)/100 ml.

Results and discussion

Physical analyses

Table 1 summarizes the results of the physical analyses performed on the water samples taken every hour from the experimental set up. It is clear that the SOLAIR process does not affect the physical characteristics of the water, as all parameters stayed nearly constant over the experimental period. From the data in table 1, it can be seen that temperature does not play a role in the destruction of the TC and FC organisms in the contaminated water as it stays low at around 18°C even with midday atmospheric temperatures in excess of 34°C. This indicates that the UV irradiance and the supplied oxygen from the atmospheric air, are the two major factors playing a role in the destruction/inactivation of bacteria in the SOLAIR disinfection method.

Table 1. Results of physical analyses of water samples during field trials (experiment and controls)

Time (h)	pH	Temperature (°C)	DO (mg/l)	TDS (g/l)	Turbidity (NTU)
0	6.5	16	2.1	2.1	2.1
1	6.65	16.8	2.3	2.3	2
2	6.8	17.5	2.5	2.2	2.05
3	6.6	18.2	2.1	2.3	2.11
4	6.56	19	2	2.4	2.1
5	6.8	19.1	1.9	2.3	2.2
6	6.75	18.4	2.1	2.2	2.12
7	6.7	18	2	2.3	2

Oxygen is usually used by bacterial cells for energy yielding chemical reactions and not for bacterial growth. The toxicity to some species of bacteria (including members of the *Enterobacteriaceae*) is due to superoxide radicals, hydroxyl radical and hydrogen peroxide produced during oxidation reactions. All of these molecules can damage the DNA of the bacterial cell. However, some bacteria has developed a protective mechanism in which the enzyme superoxide dismutase is produced. This enzyme convert the superoxide radicals rapidly to hydrogen peroxide, which in return is dissipated by catalase and peroxidase to water and oxygen. The enzymes are produced through information obtained from the DNA. Thus if the DNA is damaged/ inactivated by UV irradiation for example, this protective mechanism will be inactivated.

The measured UV irradiance levels are illustrated in Figure 1. As expected the UV-A irradiance is much higher than UV-B irradiance, as most of the lower wavelength UV components from the sunlight are filtered out by ozone, water droplets, and smoke. The UV light which actually reaches the earth's surface is restricted to a wavelength range of 295 to 400 nm. This in effect limits the microbicidal properties of solar UV light as a sole disinfectant, as highest bactericidal action will occur at 260 nm, i.e. the wavelength at which the DNA of a bacterial cell absorbs the most UV light.

SOLAIR disinfection overcomes both these limitations by applying solar radiation in the presence of oxygen in concentrations of more than 1 mg/l. This combined effect on bacterial cells can be seen in the results of the microbiological analyses as illustrated in Figures 2 and 3.

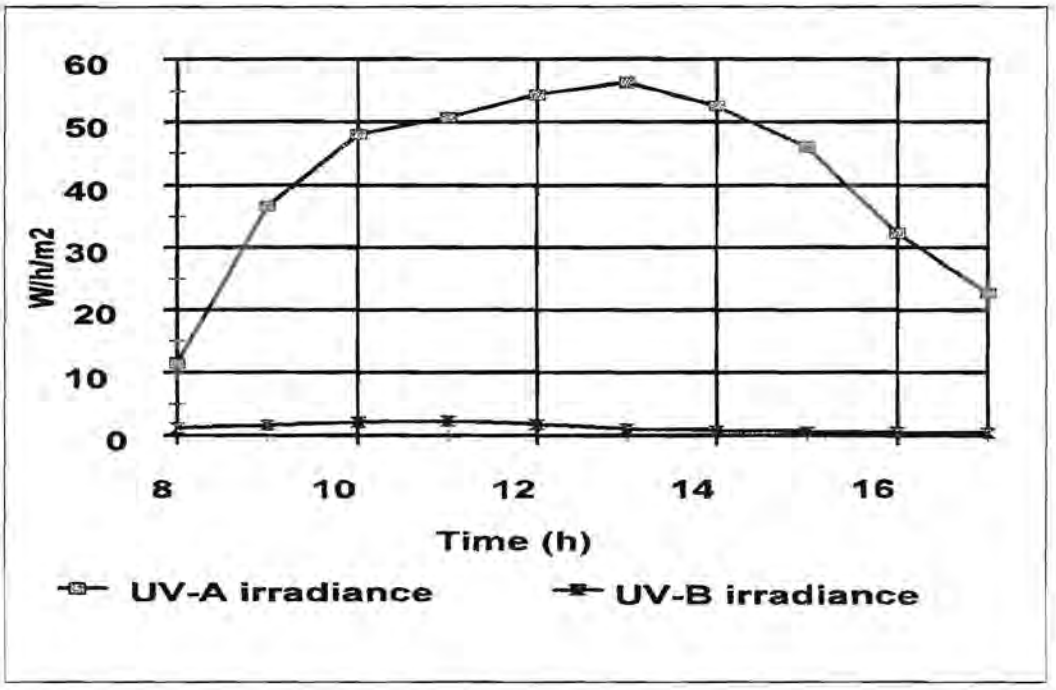

Figure 1. UV-A and UV-B irradiance

Microbiological analyses

Figure 2 shows that 100% inactivation/destruction of total coliforms (TC) was obtained within a period of 6 hours after application of the SOLAIR disinfection process to the hand drawn water. Control A showed a 40% reduction over the same period and a 43% reduction in cell concentration over the total experimental period. Control B had a 17% reduction after 6 hours and 31 % after completion of the experimental period.

Figure 3 illustrates the faecal coliform (FC) inactivation/destruction. Within a period of 4 hours, there was an effective 100% destruction of FC, while control A showed a 14% and control B a 10% reduction in FC concentration after the same time. Controls A and B had final reductions in cell concentrations of 30% and 32% after completion of the experimental period.

After a 24-hour lag period, the SOLAIR disinfected water showed no growth on the respective agar plates. This indicates that the bacterial cells were irreversibly damaged or killed by the said disinfection process. However, increased concentrations of cells were observed in both controls after the same period of time.

From the data presented above, it can be seen that the disinfection efficiency by using the SOLAIR process is indeed higher than using solar UV radiation or oxygen separately. The disinfected water complied with the potable drinking water standards and guidelines as laid down by the SABS and DWAF respectively. This in itself will have a major impact on the reduction of incidences of diseases related to water in a poor microbiological condition.

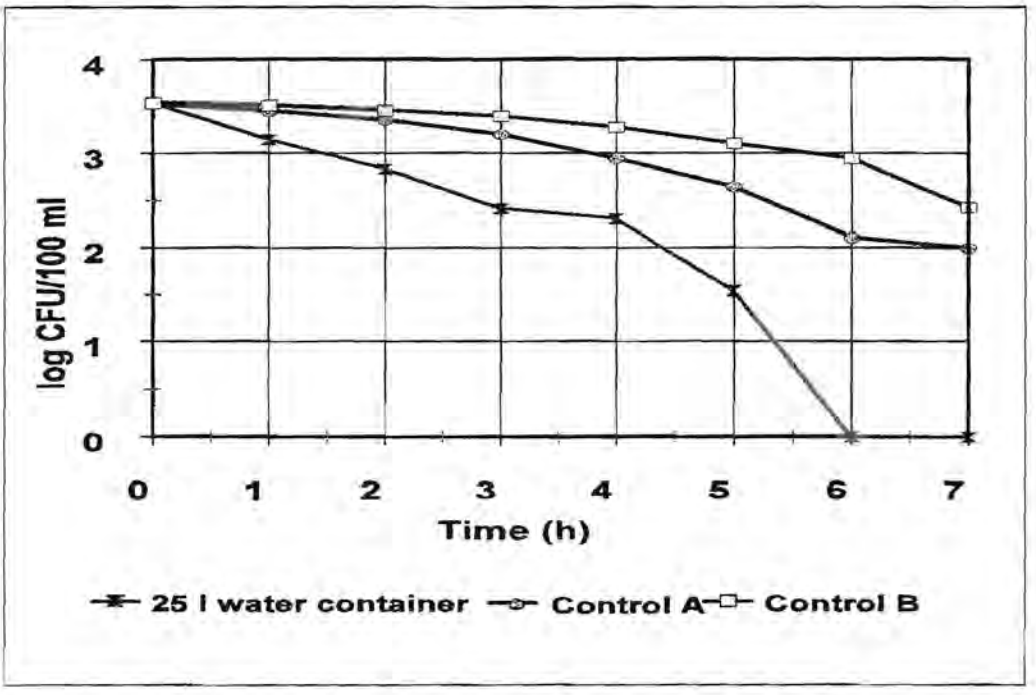

Figure 2. Total coliform (TC) analyses results.

A major disadvantage observed lies in the fact that no residual disinfection power can be found in the water after treatment with SOLAIR. This makes it very difficult to guarantee that the water is safe from any secondary contamination. Secondary contamination can however be overcome or limited, by application of good hygienic practices in the respective households.

When summarizing the results of the field trials, the following recommendations were made:

- SOLAIR is applicable and effective in small volumes of hand drawn water (2 to 25 l)
- Intermittent vigorous shaking is important during the disinfection period, to dissolve and distribute the oxygen throughout the whole volume of water and to ensure contact of all organisms in the water with the absorbed ultra violet light
- Visible turbidity should be removed before disinfection process is applied
- The containers must be kept closed with a lid and exposed to full/direct sunlight at all times
- A minimum of 4 hours is required for effective disinfection, i.e. compliance with the SABS drinking water standards and the DWAF water quality guidelines for TC and/or FC. This will depend on the concentration of microorganisms, the DO concentration, the UV concentration and the type of container used.

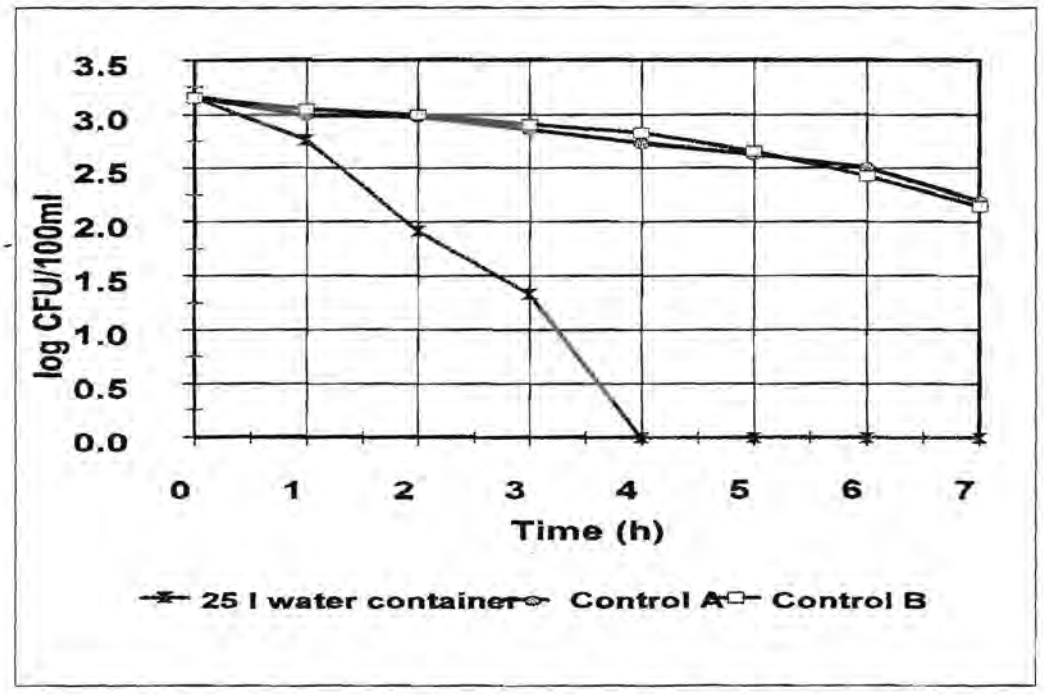

Figure 3. Faecal coliform (FC) analyses.

- Education of the end users is essential for success of the SOLAIR disinfection process. It is especially important to indicate to users of the process, that no residual disinfection power is available and that good hygienic practices will be essential in prevention or minimization of secondary pollution or contamination of the already disinfected water.

Acknowledgements

This study was funded by the Water Research Commission (WRC).

The fieldwork was performed by the following Water Care students of Technikon Northern Gauteng: D Sebaeng, B Mhlangu, M Mosime, M J Baloyi, F Masha and T Malatji.

Ms A M Nel graciously edited the manuscript.

References

CALKINS J, BUCKLES, JD and MOELLER, JR (1976). The role of solar ultraviolet radiation in 'natural' water purification. *Photochemistry and photobiology*, **24**, 49-57.

DWAF (1996). South African water quality guidelines. Volume 1: Domestic water use. Department of Water Affairs and Forestry, Pretoria. ISBN 0 7988 5339 5.

DWAF (1996). A guide for the health related assessment of the quality of water supplies. Department Water Affairs and Forestry and Department of Health, Pretoria.

GENTHE B and SEAGER J (1996). The effects of water supply, handling and usage on water quality in relation to health indices in developing communities. WRC report 562/1/96.

JOYCE TM, McGUIGAN KG, ELMOORE-MEEGAN M and CONROY RM (1996). Inactivation of faecal bacteria in drinking water by solar heating. *Applied and environmental microbiology* **62**(2) 399-402.

MEYER V (1999). Alternative disinfection treatment method of faecal contaminated drinking water: The feasibility and applicability of the SOLAIR process in the South African Scenario. WRC report K8/299/98.

MILLIPORE (1992). Water Microbiology. Laboratory and Field procedures.

REED RH (1996). Sol-air water treatment. *22nd WEDC conference proceedings, New Dehli, India.*

REED RH (1997). Solar inactivation of faecal bacteria in water: the critical role of oxygen. *Letters in Applied Microbiology* **24** 276-280.

REED R (1997). Sunshine and fresh air: A practical approach to combating water-borne disease. *Waterlines* **15**(4) 27-29.

REED RH (1997). Innovations in solar water treatment. *23rd WEDC conference, Durban, South Africa.*

SABS (1984). South African standard: Specification for water for domestic supplies. SABS 241. ISBN 0 626 07010 4.

SOLSONA F (1996). Disinfection for small water supplies. Technical guide. WRC report C2878.

WEGELIN M and SOMMER B (1996). Demonstration projects on solar water disinfection. *SANDEC News* (2) 11-13.

V. Meyer* & Dr R. H. Reed (**Poster** presentation)

*Department Chemistry, Technikon Northern Gauteng, Private Bag X 07, Pretoria North 0116.

Division of Biomedical Sciences, Department of Chemical & Life Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, NE1 9ST, UK

SOLAIR DISINFECTION: A SOUTH AFRICAN PERSPECTIVE.

SOLAIR is an alternative and economical disinfection method utilizing natural sunlight (UV-A and UV-B rays) and oxygen (from atmospheric air) to damage, inactivate, and/or kill the faecal bacteria found in contaminated water. It is a natural process (virtually selfpurification) without the addition of any potentially hazardous chemicals or need for sophisticated and expensive equipment.

In South Africa where more than 12 million of its people are still using water obtained directly from alternative sources such as rivers, streams, boreholes, community taps, and dams, this method could prove to be an efficient, and economically feasible method to be used for disinfection of handrawn drinking water to an acceptable potable standard.

With this in mind, the process was applied in the typical South African scenario. Results obtained showed a significant reduction in both the total and faecal coliform counts within 3 to 4,5 hours, with no subsequent re-activation of growth after 24 hours. The reduction depended on various parameters including the type of containers, the concentration of microorganisms, presence of cloud cover, oxygen concentration and turbidity. The treated water complied in most cases to both the SABS standards and the South African Water Quality Guidelines for domestic use.