Solar Disinfection of Water Using Transparent Plastic Bags

T. A. Lawand, J. Ayoub, and H. Gichenje
Brace Research Institute
Faculty of Engineering
Macdonald Campus of McGill University
Ste-Anne-de-Bellevue, Québec, H9X 3V9,
Tel.: (514)398-7833: Fax: 514-398-7767
E-mail: ael2@musica.mcgill.ca
CANADA.

ABSTRACT

A series of tests exposing contaminated river water in transparent polyethylene bags to solar radiation has indicated that there is a distinct disinfection effect. Generally, for bags of shallow water depths of less than 10 cm, pathogenic bacteria are inactivated after exposures varying from 4 to 6 hours under bright solar radiation conditions. There appears to be a synergetic effect of solar radiation and heat when water temperatures rise above 40 °C. Faecal coliforms are the indicator organisms in this experiment. Tests show total bacterial inactivation when water samples are exposed to direct sunlight for at least 5 hours. Faecal coliforms enumeration was carried out by the Membrane-filtration method using prepared 2 ml ampoules of nutrient agar as the growth medium and at an incubating temperature range of 44.3 °C to 44.7 °C for 24 hours.

1. INTRODUCTION

The need for safe drinking water has always been a basic human concern throughout the world. Water quality depends on its biological and chemical composition. Solar water disinfection (SWD) is a method that can use the available energy of the sun to inactivate harmful organisms found in natural waters. The Brace Research Institute (BRI) has been very active in promoting the SWD process since 1982. Specifically, during the past two years, BRI has conducted experiments in the SWD process, focusing on the suitability of various container materials and shapes for exposing contaminated water to direct solar radiation for the purpose of rendering harmful bacteria inactive. This work has focused mainly on the use of commercially available transparent polyethylene bags as suitable containers in which naturally contaminated water is placed and exposed to the sun for disinfection.

2. BACKGROUND OF THE SWD TECHNIQUE

The use of solar water disinfection techniques has been gaining popularity in the last few years. The process involves exposing a container of small quantities of clear but bacterially contaminated water to the sun. The water container is chosen according to its suitability to allow the maximum penetration of solar rays to the contaminated water. It is generally well known that the ultra-violet

(UV) range of the electromagnetic spectrum, about 300 nm to 400 nm has a bactericidal effect. The advantages of disinfecting drinking water by means of UV radiation energy are generally self-evident. The water itself undergoes no significant change. Materials in solution that give water its pleasing qualities are retained. Nothing is added to the water to impair its taste or odor. Only the bacteria resident in the water become inactivated under exposure to the sunlight, thus rendering them harmless [1, 2].

3. OBJECTIVES

The main objectives of these tests are to verify:

1. the suitability of utilizing transparent plastic bags for the exposure of contaminated water to solar radiation, and
2. that the solar radiation can indeed inactivate faecal coliform bacteria.

As the experiments were undertaken during the summer and autumn of 1995 in Montréal, Canada, it was possible to test the SWD process under a variety of climatic conditions.

4. EXPERIMENTAL SET-UP

4.1 Experimental Design

Natural water samples were taken directly from the nearby St. Lawrence River. Containers tested were clear single and double layered polyethylene bags normally used commercially to transport beverages. These bags are made from a composite of different plastics, the interior layer always being polyethylene. The bags were pre-sterilized, tightly sealed from all sides to prevent contamination from other sources, with a capped spout integrated into the bag wall.

Exposure of the contaminated water samples to the sun was undertaken within plus or minus three hours of solar noon. Instantaneous and cumulative total solar radiation, instantaneous solar ultra-violet radiation, reflected total and ultra-violet solar radiation, all on the horizontal, as well as ambient temperature and water container temperature were recorded. Faecal coliforms bacteria were used as the indicator organisms. Bacteria enumeration was by the membrane filtration technique using prepared 2 ml ampoules of nutrient agar as the growth medium.

4.2 Instrumentation and Equipment

The following items were used in this experiment:

1. a Haenni solarimeter for measuring cumulative total solar radiation and instantaneous incident total solar radiation on the horizontal,
2. a Licor light meter (Model LI-189) for measuring instantaneous incident and reflected total solar radiation on the horizontal,
3. a Spectroline™ Longwave UV (365 nm) meter (model DM-365x) for measuring incident and reflected UV radiation on the horizontal (range from 0 to 19,999 mW/cm^2),
4. thermocouples measuring ambient and water container temperatures,
5. an air fan to maintain container temperatures at or below 40°C,
6. pre-prepared faecal coliforms culture growth medium in 2 ml ampoules (m-FC broth, available

from Millipore (Canada) Ltd.),
7. Petri-dishes with absorbent pads,
8. a vacuum filtration system,
9. an incubator (water-bath). and
10. transparent plastic bags (supplied by Scholle Canada Limited).

4.3 Experimental Procedures and Testing Methods

Clean polyethylene bags were filled with naturally contaminated river water. All samples were placed on white melamine boards and exposed to the sun. In principle, incident solar radiation strikes the outside layer of the bag and is transmitted through to the water inside the bag. Part of the incident radiation is reflected off the bag surface to the atmosphere. This is the rationale for the measurement of reflected total solar radiation as well as reflected ultraviolet radiation. It is essential to measure both parameters to ascertain the amounts of incident solar and ultraviolet radiation actually transmitted by the container.

If a black background board was utilized in place of the white melamine board, then the incident solar radiation would largely be absorbed by the board, thus hastening the increase of the water temperature in the container. Consequently, the synergetic effect of the transmitted solar radiation and elevated water temperatures would be observed. When using the SWD technique in the field, it is preferable to place the water samples on a dark background so as to benefit from the enhanced disinfection from elevated water temperatures. However, this current set of trials focused only on the disinfection properties of solar radiation and not on the combined disinfection effects of solar radiation and elevated water temperatures. This is the rationale for using a white background.

4.3.1Climatic Conditions

Clear and sunny conditions are ideal for the disinfection process, because direct incoming solar radiation can irradiate the plastic water containers more readily. Cloudy and hazy conditions scatter incoming solar radiation, thus less of it reaches the exposed containers. Sky conditions, ambient and container temperatures, total solar radiation reaching the water containers, UV intensity at 365 nm, as well as reflected UV and total solar radiation on the horizontal were measured.

4.3.2 Raw Water Source

Raw untreated water samples were taken from Lac St. Louis, a tributary of the St. Lawrence River water system. The samples were collected some 50 m from the test site near the shoreline located immediately south of the Brace Research Institute office. Water was collected in a bucket fixed to the end of a 2.4 m long pole and transported to the test site in an insulated opaque container (generally, the river water samples are exposed to the sun within 30 minutes after collection). Basically, the water samples used in this experiment were clear and slightly yellowish. As the samples were relatively clean the water was not filtered.

4.3.3 Water Container Materials

To verify the suitability of various transparent materials for water containers, a series of UV transmission tests using a spectrophotometer were undertaken on a number of plastic and glass samples. Consequently, transparent plastic bags were selected according to their high UV transmittance and their availability on the market. As a result, the use of beverage bags manufactured by the Scholle Company was found to be suitable. The bags are made of two layers of polyethylene bonded at the seams and are designed to hold varying quantities of liquid. The size used primarily in this series of tests is 40 cm x 45 cm with a maximum capacity of 7 liters of river water. Any air pockets formed after filling the bags with water can be removed without great difficulty from the special spout integrated into the bag wall. The UV transmittance of these bags was found to be approximately 50% in the 300 nm to 400 nm wavelength range. In later tests, the outer plastic layer was removed and the solar transmittance in the same range increased to 65% .

4.3.4 Depth of Exposed Raw Water Samples

The exposed water sample depth was standardized to about 5 cm. This was accomplished by using same-size containers and the same volume of water sample in each transparent bag. Since this experiment is a batch process, it was necessary to use careful handling techniques to avoid weakening the plastic container.

4.3.5 Duration of Exposure

Generally, the tests were run for a minimum of 4 hours. Most of the bags were exposed for approximately 5 hours. For most trials, the water samples were placed in the sun from 0900 to 1500 hours, weather permitting. Also, as earlier studies have shown the minimum requirements for 99.99% bacterial inactivation are an exposure time of 5 hours and incident solar intensity of 500 W/m^2, this experiment attempted to, as much as possible, adhere to these values [3, 4].

4.3.6 Microbiological Testing

The indicator organisms in this experiment were the faecal coliforms bacteria. These organisms are the thermo-tolerant forms of the total coliforms group. Within this group *E. coli* and Klebsiella species are the organisms of interest to the SWD technique since, when present, they indicate that recent faecal contamination has occurred with the possibility of accompanying enteric pathogens [5]. The Membrane-filter method was used to filter the water samples prior to and at various stages of exposure. After sampling and filtration, the membrane-filter containing the captured micro-organisms is placed on top of m-FC medium consisting of lactose, protein digest, vitamins, bile salts, selective chemicals, and aniline blue dye. The membrane is then placed in a water bath and incubated for 24 hours at 44.5°C+/- 0.2°C, allowing only coliforms of faecal origin to grow into visible blue colonies. Any non-faecal thermophile colonies appearing on the filter exhibit a green, grey, or creamy color.

4.3.7 Other

Thermocouples, placed between the plastic water containers and the white melamine board on which they rested, closely approximated the water temperatures in the containers during the exposure period. This method avoided contamination of the water samples which could have resulted had the containers been opened and closed while taking temperature measurements. Also, precautions were taken to avoid water temperatures reaching 45°C and above, because at these temperatures faecal bacteria will have been inactivated by the synergetic effect of solar radiation and heat - and this would have contravened the second objective of this experiment. During particularly warm periods it was necessary to increase the volume of the exposed water sample to slightly above 6 liters in order to maintain temperatures below 40°C. At times the plastic bags were cooled by a fan, especially during the hotter months of June and July.

5. RESULTS AND DISCUSSION

A total of 42 trials were undertaken from mid-June to mid-September, 1995, with the following parameters held constant:

- *raw water source:* St. Lawrence River near Ste. Anne de Bellevue, Québec;
- *culture media:* nutrient agar in 2 ml ampoules;
- *bacteria count:* Membrane Filtration technique for faecal coliform;
- *water container material:* transparent polyethylene single and double layer bags;
- *exposed water volume:* 6 Liters;
- *exposed water depth:* 6 cm;
- *exposed surface area:* 40 x 45 cm^2.

During the experimental trials, the following were observed, as anticipated:

- high bacteria counts in the sampled river water were noted immediately following heavy or intermittent rains;
- low bacteria counts were noted in calm river water under clear and sunny conditions;
- ambient temperatures were relatively high and stable from June to August. Lower temperatures were recorded in September;
- measured total solar radiation values were low under overcast and hazy conditions - higher under clear and sunny conditions;
- higher reflectivity of total solar radiation from the plastic bags occurred in the morning and late afternoon hours;
- higher solar UV radiation values were measured under clear and sunny conditions.

Results of the 42 trials are shown in Table 1. The major findings include the following:

- total faecal coliform inactivation occurred when water samples were exposed for at least 5 hours under clear, bright, and sunny conditions - regardless of initial densities of faecal colonies;
- total faecal coliforms inactivation occurred when water container temperatures exceeded 40°C under sunny conditions, following exposure of about five hours;
- incomplete faecal coliforms inactivation was observed under overcast conditions and when exposure time was less than 5 hours;
- in 18 of the 42 trials, water container temperatures rose to between 40 °Cand 47°C. In all of these trials, regardless of initial faecal coliform counts, the final faecal coliform count was 0. Exposure times ranged from 3.5 to 5.5 hours;
- in the remaining 24 trials where water container temperatures were below 40°C, the final faecal coliform counts were always 0 - given a minimum exposure time of 5 hours.
- it must be stressed that when testing with natural variable (such as solar radiation, ambient temperatures, and using river water), that it is impossible to carry out strictly controllable tests. However, it is felt that the procedure followed herein is much closer to the reality of the utilization of this system in the field.

Table 1. Summary of results of 42 solar water disinfection trials.

Parameter	Values
Exposure times	2.5 - 7 hours
Initial faecal coliform counts	1 - 260 colonies/100 ml
Midway faecal coliform counts	0 - 149 colonies/100 ml
Final faecal coliform counts	0 - 57 colonies/100 ml
Mean ambient temperatures	14 - 31°C
Maximum ambient temperatures	17 - 22°C
Mean water container temperatures	22 - 41°C
Maximum water container temperatures	28 - 47°C
Mean instantaneous total solar radiation	460 - 910 W/m^2
Cumulative total solar radiation	1.43 - 5.13 kW-h/ m^2.day
Mean reflected total solar radiation	31 - 52%
Mean instantaneous solar ultraviolet (UV) radiation	820 - 1690 mW-h/cm^2
Cumulative solar UV radiation	2540 - 9300 mW-h/c m^2.day
Mean reflected solar UV	7 - 19%

Notes:

- The ranges indicate measured values from mid-June to mid-September, 1995, Ste. Anne de Bellevue, Qc., Canada.
- All total solar and ultraviolet radiation values are measured on the horizontal.
- Reflected radiation is measured by placing the sensors 5 cm above the reflecting surface.

6. SUMMARY OF FINDINGS

One of the aims of this experiment was to simulate, as closely as possible, conditions of actual usage of this SWD technique by persons living in areas with contaminated water.

It is evident from these trials that transparent plastic bags, exposed to at least five hours of solar radiation, can easily be utilized for the disinfection of small quantities of clear but bacterially contaminated water. Moreover, by using a larger volume of water in the plastic bag the effect of rising water temperature was buffered, thus isolating solar UV radiation as the desired parameter to investigate in the inactivation of faecal coliforms.

The mean noted solar exposure time of about five hours was primarily due to the fact that all bags were laid out on smooth, glossy white plastic surfaces. At least one third of the incoming total solar radiation was reflected from the surfaces of the transparent plastic bags, whereas the remaining radiation, particularly in the solar infra-red spectrum, was absorbed by the water in the bags. It would be expected that bags placed on dark surfaces would heat up more quickly and reach a higher temperature, resulting in the complete inactivation of all faecal coliforms in a shorter exposure time.

During the course of these trials no direct attempt was made to investigate the presence of any synergetic effect on the exposed water samples resulting from the combined effects of water temperatures in the range of 40°C - 45°C and direct solar radiation - as it was outside the experimental objectives. However, what appeared to be an effect was noted.

For experimental purposes, the transparent plastic water bags were placed on a smooth, white plastic surface in order to avoid too high an increase in the water temperature. Nonetheless, it was noted that, as the water temperature approached 45°C, the faecal coliforms were inactivated by the apparent synergetic effect of solar radiation and temperature. As a result in these trials, by keeping the water temperature in the bags under 45°C, it was possible to focus on the determination of the effect of solar ultraviolet radiation in contributing to the SWD process. Some of the solar radiation, however, passes a second time through the water container after being reflected by this underlying white board, and this obviously also contributes to the disinfection process. It should be noted that less than 20% of the incoming UV radiation is reflected from the plastic bags - indicating the high degree of absorbtivity of the UV rays in the water.

This series of trials have shown that solar radiation in the UV range can by itself completely inactivate faecal coliforms. Whereas normal water pasteurization temperature can be achieved at 65°C for a residence time of 6 to 8 minutes [6], the complete disinfection of the water at temperatures at least 20°C below this level attest to the fact that the solar UV is also playing a role - and that it would appear, to some extent, that some form of synergetic effect is being manifested at these lower temperature. These findings could form the basis for future investigations in this field.

7. RECOMMENDATIONS

1. The plastic bags certainly proved to be quite satisfactory as an exposure medium. However, because of their lack of rigidity, it is essential that a simple carrying panel be developed so that the utilizers of the technology could go to the source of the contaminated water, fill up the bags and re-transport them back to the location where they will be exposed to direct solar radiation with a minimum of effort and, in particular, with a minimum of handling of the bags. This would permit a much longer useful life for these bags while reducing their handling to a minimum.
2. If the polyethylene bags are to be used continuously, a simple way approximating field conditions must be found to clean and disinfect the bags without re-contaminating them. Bags with attached spouts and caps reduce the opportunities for re-contamination, hence, their use is highly recommended.
3. Notwithstanding the large number of tests, it was not really possible to optimize the SWD test period, i.e. to determine the exact length of time required to disinfect water as a function of the incoming solar radiation and the amount of water in the plastic bag, the degree of turbidity, the level of faecal coliform contamination, the depth of water, etc. It is essential to recognize that there are many variables. Trying to keep some variables constant will permit greater flexibility in interpreting the results with respect to the remaining variables. However this is not easily achieved in actual practice.
4. If higher temperatures are to be obtained during solar exposure, the panel should be equipped with sides not exceeding 5 cm in height which could prevent direct impacting of any transverse winds on the exposed bag. Another manner of operation would be to incline the carrying panel towards the Equator to just below the angle of repose of the plastic bag, thus nominally increasing the incident solar radiation on the bag by 10% to 20%, depending on the location.
5. In practice, transparent polyethylene bags appear to adequately disinfect water even when placed on a white reflective background for 4 to 6 hours. However, the disinfection effect will probably be enhanced if the bag is exposed directly to the sun and placed on a dark surface in order to increase solar radiation absorption, thus raising the temperature of the water in the bag. The synergetic effects of solar radiation and of temperatures above 40°C, which have been observed but not adequately looked into in this experiment, may then be investigated.

7. REFERENCES

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