J Water SRT — Aqua Vol. 46, No. 3, pp. 127–137, 1997

SODIS—an emerging water treatment process

B. Sommer, A. Mariño, Y. Solarte*, M. L. Salas*, C. Dierolf*, C. Valiente†, D. Mora†, R. Rechsteiner‡, P. Setter§, W. Wirojanagud§, H. Ajarmeh¶, A. Al-Hassan¶ and M. Wegelin, *Swiss Federal Institute for Environmental Science and Technology, Department of Water and Sanitation in Developing Countries (EAWAG/SANDEC), 8600 Duebendorf, Switzerland; *CINARA (Instituto de Investigación y Desarrollo en Agua Potable, Saneamiento Básico y Conservación del Recurso Hídrico), Cali, Colombia; †AyA (Instituto Costarricense de Acueductos y Alcantarillados), San José, Costa Rica; ‡Swisscontact, San José, Costa Rica; §Khon Kaen University in Khon Kaen, Thailand; ¶Royal Scientific Society in Amman, Jordan*

ABSTRACT: This article comprises the work of several research teams which analysed the effectiveness of solar water disinfection (SODIS) in various laboratory and field investigations carried out at different test sites over the last five years. SODIS was applied as batch and continuous flow process (SODIS reactor). The process is most effective with a water temperature of at least 50 °C. Transparent plastic bags allow a 3-log reduction (99.9%) of faecal coliforms and *Vibrio cholerae* through heating and radiation at an UV-A dose of 54 Wh/m^2 over a period of 140 min. The SODIS reactor produces around 100 L of drinking water per square metre of solar collector and day.

SODIS—une technique de traitement de l'eau naissante

RÉSUMÉ: Cet article fait la synthèse des travaux de plusieurs équipes de recherche qui ont analysé l'efficacité de la désinfection de l'eau par le rayonnement solaire (SODIS) grâce à des séries de tests très divers effectuées dans différents sites au cours des cinq dernières années. SODIS a été utilisé avec les méthodes de traitement par lots et en débit continu (réacteur SODIS). Pour que la méthode soit efficace il est crucial que la température atteigne au moins 50°C. Dans des sacs plastiques transparents avec lesquels le chauffage et l'irradiation sont les plus efficaces, la neutralisation la plus rapide de 99,9% de coliformes fécaux et *Vibrio cholerae* a eu lieu dans les 140 min qui suivaient l'irradiation avec une dose d'UV-A de 54 Wh/m^2. Le réacteur SODIS produit environ 100 L d'eau potable par mètre carré d'héliocapteur par jour.

INTRODUCTION

Micro-organisms are vulnerable to heat (pasteurisation) and to UV-A radiation. Since the sun is a free natural source of energy in plentiful supply, specialists initiated research on the development of a reliable and effective low cost water treatment method for the millions of people still lacking safe drinking water in developing countries.

The treatment basically consists of exposing raw water to the sun for several hours. This can be done in bottles or plastic bags (batch process) or in continuous flow systems (SODIS reactors). The latter method is designed to provide disinfected water to institutions (e.g. hospitals or schools). The water disinfection process in bottles or bags is simple enough to be summed-up in clear and foolproof operating instructions for the user at household level. To obtain a safe drinking water quality is therefore feasible by an individual treatment method and at a low price.

The first article on solar disinfection of drinking water was published in 1984 [1]. A workshop on solar water disinfection (SODIS) was held in Montreal in 1988 [2], and the EAWAG (Swiss Federal Institute for Environmental Science and Technology) started assessing the scope of the process in a SODIS project in 1991. The laboratory and field tests in Switzerland were followed in 1993 by collaborative field investigations with CINARA (Instituto de Investigación y Desarrollo en Agua Potable, Saneamiento Básico y Conservación del Recurso Hídrico) in Cali, Colombia. The encouraging results gave rise to further field tests on the inactivation of faecal coliforms (FCO) conducted with local partners in Costa Rica, Jordan and Thailand. In 1995, experiments assessing the inactivation rates and correlation of *Vibrio cholerae* (Vch) and faecal coliforms were conducted with CINARA.

This article is a synopsis of the results and experiences acquired by the research teams of the SODIS project over the last six years. It contains a summary of the test results analysed at the EAWAG, and information on the material and methods used for the batch and continuous flow processes. The results of the field tests are then discussed, summarising the batch test results carried out over the last few years and addressing the

performance of the latest SODIS/SOPAS reactors tested in Costa Rica in 1996. In the solar pasteurisation (SOPAS) reactor the micro-organisms were inactivated only by the thermal effect at a temperature of at least 70 °C without radiation. The last section presents application possibilities and briefs on the ongoing projects.

Determining the scope of the process

In 1991, bacteriologists, photochemists, sanitary engineers and virologists at the EAWAG formed a team to study the effects of solar water disinfection on micro-organisms. They discovered [3] that UV-A radiation of the spectrum of sunlight is mainly responsible for the inactivation of bacteria such as *Escherichia coli, Str. faecalis, Enterococci,* and viruses such as the encephalomyocarditis virus, rotavirus and bacteriophage f2. Another important discovery indicated that water temperatures of at least 50 °C considerably increase the inactivation rate of bacteria, whereas the inactivation rate of viruses steadily increased with temperatures of 20–50 °C. The recorded synergetic effects of solar radiation and thermal water treatment favour a combined use of these two water treatment processes.

FIELD TESTS WITH BATCH PROCESS

Various field tests were conducted at CINARA in Cali, Colombia, at AyA (Instituto Costarricense de Acueductos y Alcantarillados) San José, Costa Rica, at the Environmental Research Centre of the Royal Scientific Society in Amman, Jordan, and at the Khon Kaen University in Khon Kaen, Thailand. The different geographical locations of the test sites allowed to assess the inactivation rates of faecal coliforms under different climatic, physical, chemical, and microbiological conditions. Most field tests comprised physical and microbiological experiments.

Research objectives

Physical tests

The UV-A transmission losses as a function of turbidity and water depth were measured in order to determine the reduction in efficiency of the disinfection process [3,4]. The transmission losses caused by the container material and the solar water heating potential were other objectives which were studied.

Microbiogical tests

The experiments were conducted under various test conditions allowing the assessment of a representative average of the inactivation rates.

MATERIAL AND METHODS

The physical tests

Turbidity and suspended solids were analysed according to the 'Standard Methods' (American Public Health Association, 1989) and with the following equipment:

Turbidity was generally measured with a HACH 100A. In Costa Rica, however, it was measured with a HACH 2100A and, in Thailand, with a Digital Direct-Reading Turbidimeter, Model no. 965-10, (Orbeco-Hellige, USA). The sample quantity of 30 mL was measured by the nephelometric method. Suspended solids (SS) or, in Costa Rica and Thailand, total solids (TS) (dissolved and suspended) were measured gravimetrically.

The UV-A transmission losses as a function of turbidity and water depth were measured with a device consisting of an opaque and a transparent tube of 3 cm external diameter. The transparent tube was filled with water of known turbidity in steps of 10 cm segments and inserted segment-wise into the opaque tube. A sensor at the bottom end of the transparent tube measured the reduction of light intensity after every step. This kind of measurement was carried out with tap, prefiltered and raw water.

Except in Jordan, where a 'Kipp & Zonen CM11' Pyranometer was used, the radiation intensities were measured at all the test sites with a UV-A radiometric sensor, type 'Macam SD 104A-Cos', spectral response 320–400 nm and with a quantum sensor, type LI-COR 'LI-192 SA', spectral response 400–700 nm (visible light).

Soft drink bottles, made of glass or polyethyleneterephtalat (PET), were used as containers. The plastic bags we used were made of 0.15 mm thick, transparent, polyethylene (PE) foil. Filled with about 1–1.5 L of water, the liquid in the bag forms a water layer of about 1 cm depth. Furthermore, larger plastic bags with water depths between 2 and 6 cm or filled with up to 10 L were also tested. Bottles and bags were exposed to the sun on different supports. Some bottles were half blackened, the others were transparent. They were laid on a concrete roof or fixed in a rack at a 45° angle. In Colombia, the bags were spread out on a bare concrete roof or on a black foil covering the concrete. In Thailand, three support material types were tested—wood, microfibre and steel. In Jordan, the bags were laid out either on a reflecting or on a black foil suspended over a wooden table.

The microbiological test

A water bath (turbidity < 1 NTU) with a constant temperature of either 30 or 50 °C was used for the tests with the quartz test tubes. These tubes have very low light transmittance losses. Some test tubes, used as dark controls, were wrapped in aluminium foil to prevent their exposure to the effects of light and placed together with the transparent quartz test tubes in the water bath. A comparison of the difference in the final concen-

tration between micro-organism populations which had been exposed and those which had not been exposed to the light could therefore be drawn. This standardised experimental method makes it possible to compare the effects caused by either light and temperature combined or light and temperature alone in the quartz test tubes experiments conducted in different locations and at different times.

A variation in temperature between 12 and 40 °C does not lead to a significant inactivation of bacteria [3]. Thus, inactivation in the transparent quartz test tubes at 30 °C is predominantly due to irradiation. Inactivation in the dark control at 50 °C is mainly due to the effect of temperature. The quartz test tube tests with transparent tubes at 50 °C show the combined thermal and irradiation effect. Other detrimental factors like competing micro-organisms or chemical composition of the water were not assessed since heat and radiation may predominate in the inactivation process [5].

The containers used for the microbiological tests were of the same type as mentioned earlier. The half-blackened bottles were used, and all the bags were either placed on a black foil or on a steel sheet in order to reach the highest possible water temperatures. The containers were either filled with wastewater or generally with river or pond water. In some tests (Colombia '95), *Vibrio cholerae* were inoculated prior to exposing the water filled containers to the sun. The water temperature was frequently measured and samples were taken at certain temperatures (between 40 and 60 °C) to analyse the remaining concentration of micro-organisms. Solar radiation intensity was also recorded constantly during exposure of the bags to the sun.

Faecal coliform analyses were carried out in compliance with the WHO Guidelines for Drinking Water Quality (WHO 1985), including the use of the Membrane Filter Method.

An 'El Tor' strain of *Vibrio cholerae*, supplied by the Microbiology Department of Universidad del Valle in Cali, Colombia, was used in the tests. The strain was kept in nutrient broth at 35.5 °C for 24 h and the samples were then inoculated at a 1 mL dose before being exposed to solar radiation. Samples of 0.1, 1.0 and 10 mL were inoculated in tubes containing alkaline peptone broth and incubated for 8 h at 35.5 °C. TCBS agar was streaked from positive tubes and incubated for 24 h at 35.5 °C. The yellowish colonies of each culture were identified with five biochemical tests: TSI, LIA, Urea, Motility and Indol (APHA-AWWA-WPCF, 1992; Sandoval, 1991). The most probable number (MPN) was then determined.

FIELD TESTS WITH THE CONTINUOUS FLOW PROCESS

The first SODIS reactor of the EAWAG was tested at CINARA during the summer and autumn of 1994. A year later, other prototypes were tested at the Khon Kaen University (KKU) and at the Environmental Research Centre of the Royal Scientific Society (RSS) in Amman, Jordan. The EAWAG reactor was made in acrylic plastic with a 30 L volume (external dimensions 2010 × 950 × 16 mm). A heat exchanger was always used. Significant faecal coliform inactivation was obtained with exposure times of about 60 min.

KKU developed another reactor which was made of glass with a 30 L working volume (external dimensions 960 × 650 × 75 mm). The sidewalls were insulated with polystyrene and the rear with microfibre (glass wool). A preheater was sometimes also used. A significant faecal coliform inactivation was obtained with a minimum exposure time of 60–75 min and a solar preheater in its flow configuration.

Various material problems caused by insufficient UV-A transmission, light and heat resistance were encountered. The thermoresistance of the micro-organisms [6] in Table 1 hints at the fact that it is not necessary to boil water to disinfect it. As a possible alternative which allowed to circumvent the material problems the SOPAS plant was designed.

The results of former test series are not discussed in detail, as design problems often prevented the regular testing of the plants. However, solutions to these problems contributed to the development of the improved plants, presented in Figs 1 and 2, field tested in Costa Rica in 1996, and whose results are presented in this article.

Table 1 Thermoresistance of micro-organisms [6]

Micro-organisms	Time and temperature for 100% destruction		
	1 min	6 min	60 min
Enteroviruses			62 °C
Rotaviruses	63 °C for 30 min		
Faecal coliforms	at 80 °C complete destruction		
Salmonellae		62 °C	58 °C
Shigella		61 °C	54 °C
Vibrio Cholera			45 °C
Entamoeba Histolytica cysts	57 °C	54 °C	50 °C
Giardia cysts	57 °C	54 °C	50 °C
Hookworm eggs and larvae		62 °C	51 °C
Ascaris eggs	68 °C	62 °C	57 °C
Schistosomas eggs	60 °C	55 °C	50 °C
Taenia eggs	65 °C	57 °C	51 °C

Research objective

Besides testing the improved design of the plants, the experiments aimed at finding the optimal flow rate allowing for complete inactivation of the micro-organisms at the highest possible rate for the SODIS and SOPAS plants.

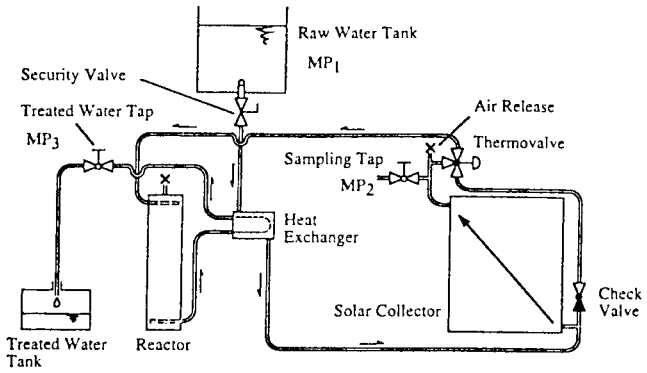

Fig. 1 SODIS plant scheme.

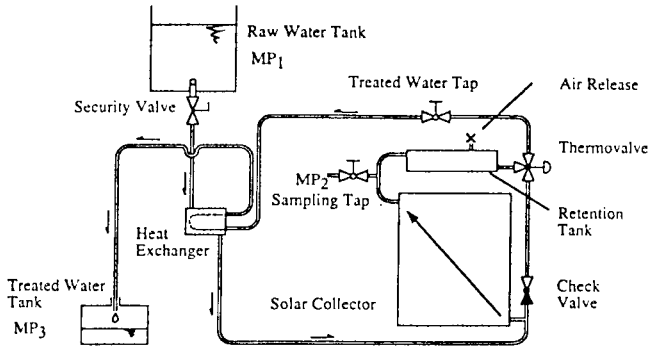

Fig. 2 SOPAS plant scheme.

Every solar driven process is dependent on the solar energy available which depends on the geographical location and cloudiness [5]. The weather dependence of the SODIS and SOPAS processes was determined by tests carried out during almost cloudless to completely overcast days.

The SODIS plant

The SODIS plant uses both the thermal and the radiation effect. Figure 1 illustrates the plant used in Costa Rica equipped with a separate collector and reactor. The water is first heated up in the collector to at least 50 °C, which is the opening temperature of the thermovalve, and then flows through the irradiation reactor. The reactor, of 1.78 m × 0.20 m surface area and 0.10 m water depth, has a volume of 36.5 L. It is made of copper covered by glass. Although it is not equipped with baffles, the observed flow was laminar. After irradiation, the disinfected and hot water flows through the heat exchanger (a cooling system taken from a refrigerator) and preheats the raw water.

The SOPAS plant

The SOPAS plant in Fig. 2 uses only the thermal effect. To make sure that the water is disinfected, it is necessary to heat it to 70 °C and maintain it at this temperature in the retention tank for at least 15 min instead of exposing it to sunlight in a reactor at a water temperature of 50 °C for 60–90 min. The other parts are the same for both plants. The thermovalve of the SOPAS plant opens at 70 °C. The solar collector, produced by Sol Power, San José in Costa Rica, is a conventional flat-plate ECOSOL® collector with an absorber area of 2.14 m^2.

RESULTS

Batch process: physical tests

Experiments revealed that the UV-A intensity decreases rapidly with increasing water depth. This effect is amplified by increasing turbidity. Figure 3 shows the remaining UV-A light as a function of water depth and turbidity, measured in a 3-cm diameter tube, which, compared to the conditions in a translucent bag or an irradiation reactor, leads to a relatively fast light reduction.

The average UV-A transmission losses of the used transparent container material were the following: plastic bottles: ≈ 30%, glass bottles: ≈ 25%, plastic bags: ≈ 10%. The losses for coloured bags are at least six times higher than for transparent bags.

The solar heating potential of the plastic bags is given in Table 2. The heating potential of the bottles is around 50 °C. Large black metal supports were found to be the most effective (Fig. 4) for heating water-filled plastic bags. The smaller the

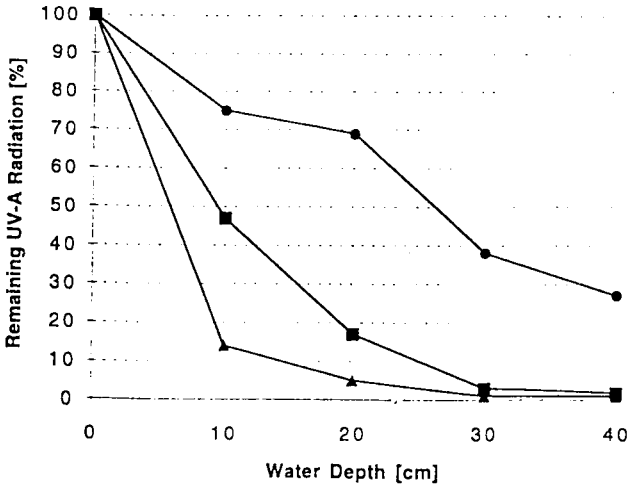

Fig. 3 Reduction of UV-A radiation as a function of water depth and turbidity, assessed in Colombia 95 with measuring tube, (●) tap water (NTU < 1), (■) prefiltered (26 NTU), (▲) raw water (40 NTU).

Table 2 Solar heating potential of plastic bags filled with different volumes of water upon a black metal support

Filled in water volume (L):	1.5	3.5	7	10
Depth of water layer (cm):	1	2	4	6
time (min) to reach 50 °C	75	90	130	160
max. temp. (°C)/required time (min)	60/150	57/150	53/180	53/210

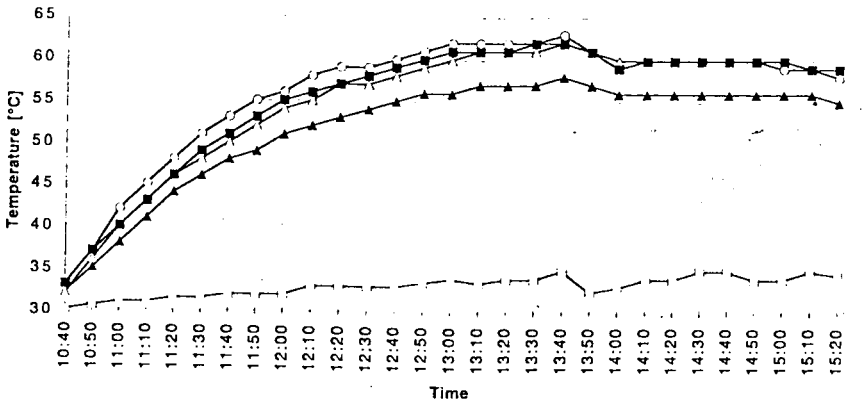

Fig. 4 Curves of the water temperature of bags on (▲) wood, (△) microfibre, (■) small and (○) large metal supports, (□) air temperature.

water depth in the bags laid flat on the support, the faster and higher the heating of the water in the bags.

Batch process: microbiological tests

The reductions of faecal coliforms and *Vibrio cholerae* concentrations given in Tables 3–5 show that the SODIS process is a reliable and effective inactivation method if water temperatures of around 50 °C are combined with UV-A irradiation. In plastic bags, 50°C is reached more easily than in bottles since the ratio of the exposed surface to water depth is higher than in bottles. The correlation between container, water temperature and inactivation of faecal coliforms and *Vibrio cholerae* is illustrated in Figs 5–7.

Faecal coliforms possess a greater temperature resistance than *Vibrio cholerae*, as shown in Fig. 6. The inactivation curve of an experiment with intermittent treatment during low intensity daylight is given in Fig. 8. Intermittent treatment

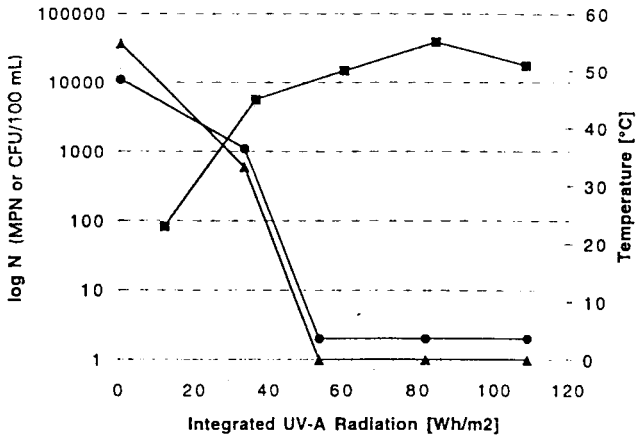

Fig. 5 Inactivation curves of (▲) faecal coliforms and (●) *Vibrio cholerae* in plastic bags, water turbidity 14 NTU, (■) water temperature > 50°C, N = number of cells (faecal coliforms in CFU, *Vibrio cholerae* in MPN).

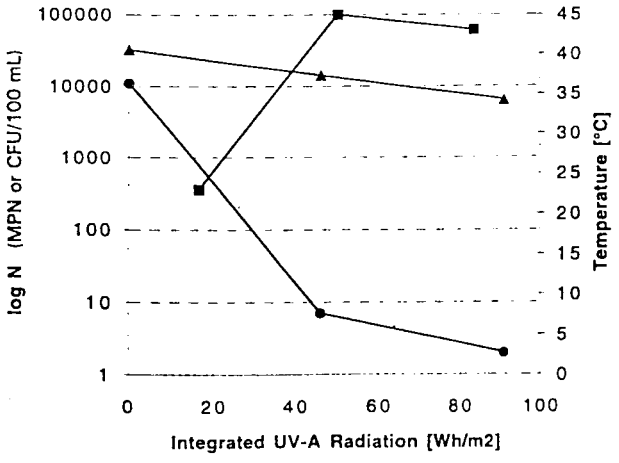

Fig. 6 Inactivation curves of (▲) faecal coliforms and (●) *Vibrio cholerae* in glass bottles, water turbidity 23 NTU, (■) water temperature < 50 °C, N = number of cells (faecal coliforms in CFU, *Vibrio cholerae* in MPN).

Table 3 Inactivation rates of faecal coliforms and *Vibrio cholerae* (where indicated) and test conditions, container: quartz test tube (volume 30 mL)

Test site/year	Test 1 organism	Constant temp. (°C)	Turbidity (NTU)	SS or TS* (mg/L)	Initial conc. (MPN or CFU/100 mL)	Final conc. (MPN or CFU/100 mL)	Exposure time (min)	UV-A (Wh/m^2)	Total reduction (%)	Average reduction in 15 min (%)
Colombia '93	5	30	56	N/A†	2.10×10^4	3.07×10^2	300	86	98.54	4.93
	5b	30	120	N/A	200×10^5	1.53×10^3	360	82	99.24	4.13
	6b	30	24	N/A	3.30×10^4	4.20×10^3	240	31	87.27	5.45
Colombia '95	1A	30	17	17	1.19×10^4	1.90×10^3	300	82	84.03	4.20
	1B	30	17	17	1.19×10^4	7×10^2	300	82	94.12	4.71
	2B	30	15	13	1.06×10^4	1×10^1	300	99	99.91	5.00
	3	50	28	32	2.80×10^3	1	45	12	99.96	33.32
	1/Vch	30	17	17	1.50×10^4	3×10^3	150	57	80.00	8.00
	3/Vch	50	28	32	7.00×10^3	1	23	5	99.99	65.21
Jordan '95	22	50	400	507	1.60×10^4	1.20×10^2	140	58	99.25	10.63
	22	50	0.2	9	1.60×10^3	1×10^1	40	15	99.99	37.50
Thailand '95	21	30	140	270	4.67×10^8	2×10^3	300	85	100.00	5.00
	21	30	21	40	1.28×10^3	0.1	300	85	99.99	5.00
	22	50	108	N/A	1.50×10^9	5.30×10^1	120	28	100.00	12.50
	22A	50	102	140	2×10^6	3.80×10^2	120	25	99.98	12.50
Costa Rica '96	A1	30	20	70	900×10^2	1.30×10^1	300	129	98.56	4.93
	A2	30	20	70	1.10×10^3	1×10^1	300	129	99.09	4.95
	B1	50	30	202	1.30×10^3	3	60	28	99.77	24.94
	B2	50	30	202	1.20×10^3	0	120	55	100.00	12.50

* Experiments in Costa Rica and Thailand.
† N/A: not available.

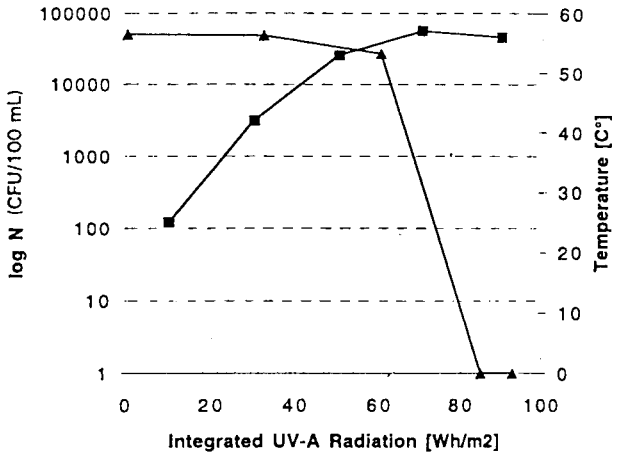

Fig. 7 Inactivation curves of (▲) faecal coliforms in glass bottles, water turbidity 17 NTU, (■) water temperature > 50 °C, N = number of cells (faecal coliforms stated in CFU).

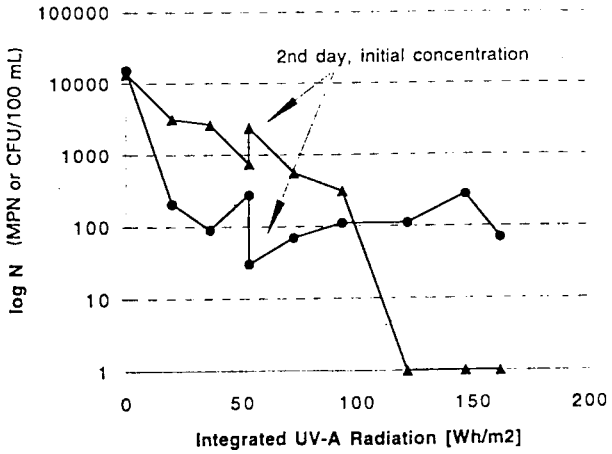

Fig. 8 Inactivation curves of (●) *Vibrio cholerae* and (▲) faecal coliforms assessed over two consecutive days.

Table 4 Inactivation rates of faecal coliforms and *Vibrio cholerae* (where indicated) and test conditions, container: glass (1 L) and plastic bottles (1.5 L)

Test site/year	Test/ container/ organism	Highest temp. (°C)	Turbidity (NTU)	SS or TS* (mg/L)	Initial conc. (MPN or CFU/100 mL)	Final conc. (MPN or CFU/100 mL)	Exposure time (min)	UV-A (Wh/m^2)	Reduction (%)	Average reduction in 15 min (%)
Colombia '93	6/PET	const. 30	14	N/A†	3.50×10^4	9.91×10^3	360	75	71.69	2.99
	6/glass	const. 30	14	N/A	3.50×10^4	9.36×10^3	360	75	73.25	3.05
	7/PET	57	17	N/A	5.10×10^4	1	330	85	100.00	4.55
Colombia '95	11/glass	45	23	24	3.20×10^4	6.40×10^3	310	91	80.00	3.87
	11/PET	45	23	24	3.20×10^4	6.60×10^3	310	91	79.38	3.84
	11/glass/Vch	45	23	24	1.10×10^4	7	110	46	99.94	13.63
	11/PET/Vch	45	23	24	1.10×10^4	2	130	52	99.98	11.54
	12/glass	48	40	75	2.62×10^4	1.15×10^2	270	105	99.56	5.53
	12/PET	48	40	75	2.62×10^4	7.37×10^2	270	105	97.19	5.40
	12/glass/Vch	48	40	75	1.50×10^3	4	270	105	99.73	5.54
	12/PET/Vch	48	40	75	1.50×10^3	2	270	105	99.87	5.55
Thailand '95	31/PET	50	20	32	3.00×10^6	6.80×10^1	200	N/A	100.00	7.50
	33/PET	50	20	33	3.00×10^6	9.40×10^1	200	N/A	100.00	7.50

* Experiments in Costa Rica and Thailand.
† N/A: not available.

Table 5 Inactivation rates of faecal coliforms and *Vibrio cholerae* (where indicated) and test conditions, containers: plastic bags

Test site/year	Test/ depth of water layer/ organism	Highest temp. (°C)	Turbidity (NTU)	SS or TS* (mg/L)	Initial conc. (MPN or CFU/100 mL)	Final conc. (MPN or CFU/100 mL)	Exposure time (min)	UV-A (Wh/m^2)	Reduction (%)	Average reduction in 15 min (%)
Jordan '95	34/3 cm	50	55	134	2.30×10^5	1	135	47	100.00	11.11
	34/3 cm	52	0.5	5	2.30×10^2	1	90	30	99.57	16.59
	35/3 cm	55	N/A†	N/A	5.00×10^5	1	120	43	100.00	12.50
Thailand '95	32/2 cm	52	50	144	8.50×10^5	2	90	19	100.00	16.67
	33/2 cm	53	20	32	3.00×10^6	1	120	44	100.00	12.50
	33/2 cm	50	20	32	3.00×10^6	7	180	64	100.00	8.33
	41/4 cm	55	25	26	5.00×10^6	1	250	81	100.00	6.00
	42/2 cm	56	33	42	6.00×10^6	1	150	58	100.00	10.00
	42/4 cm	52	33	42	6.00×10^6	20	150	58	100.00	10.00
	42/6 cm	52	33	42	6.00×10^6	3	210	78	100.00	7.14
Colombia '95	21/1 cm	55	14	6	3.63×10^4	1	140	54	100.00	10.71
	22/1 cm	50	124	178	3.70×10^4	1	210	78	100.00	6.00
	21.1 cm/Vch	55	14	6	1.10×10^4	2	140	54	99.98	10.71
	22/1 cm/Vch	50	124	178	2.80×10^2	2	250	78	99.29	5.96

* Experiments in Costa Rica and Thailand.
† N/A: not available.

Table 6 Correlations between parallel test series of *Vibrio cholerae* and faecal coliforms

Container	QTT*	QTT	QTT	Bottle glass	Bottle PET	Bottle glass	Bottle PET	Bag PE	Bag PE
Test	2	3	5	11	12	11	12	21	22
Correlation	0.86	0.98	0.96	0.92	0.9	0.82	0.99	0.99	0.99

* QTT: quartz test tube.

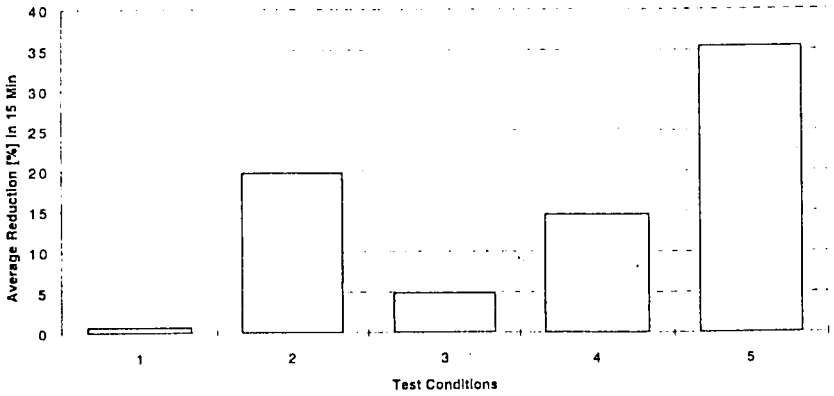

Fig. 9 Average inactivation of faecal coliforms by single and combined effects achieved in quartz test tubes. (1) dark control at constant 30 °C, natural die-off percentage, standard deviation (SD) = 5.3 percentage points (PP). (2) dark control at constant 50 °C, reduction by thermal effect only, SD = 11 PP. (3) translucent quartz test tube at constant 30 °C, reduction by irradiation effect only, SD = 4.7 PP. (4) translucent quartz test tube at constant 50 °C, reduction by combined thermal and irradiation effect, turbidity > 29 NTU, SD = 5.8 PP. (5) translucent quartz test tube at constant 50 °C, reduction by combined thermal and irradiation effect, turbidity < 29 NTU, SD = 3 PP.

does not necessarily lead to a higher UV-A dose to achieve complete inactivation, it only takes longer to attain the dose. At a water temperature of about 30 °C, faecal coliforms were able to recover and grow during the night, whereas *Vibrio cholerae* underwent a further reduction. However, when re-exposed to sunlight the next day, the remaining *Vibrio cholerae* multiplied for a time, whereas the number of faecal coliforms decreased over the same period. The kinetics of micro-organisms during intermittent treatment require further study.

Table 6 correlates the inactivation curves between parallel test series conducted with faecal coliforms and *Vibrio cholerae*. The main reason for the poor correlation in tests 2 and 11 may be due to the lower critical temperature necessary for a *Vibrio cholerae* reduction than for a faecal coliform inactivation. Temperatures of around 45 °C already lead to a significant *Vibrio cholerae* reduction, whereas they only have a small impact on the inactivation rate of faecal coliforms. This is illustrated in Fig. 5 (correlation of the curves = 0.99) and Fig. 6 (correlation of the curves = 0.82).

When comparing the relative average reductions within 15 min (Fig. 9), the combined effect results in the fastest inactivation rates if turbidity is below 29 NTU. Solids in the water lead to incomplete disinfection or to a lower inactivation process efficiency since the solids may shield the micro-organisms from irradiation. Prior to applying the SODIS process, pretreatment (sedimentation, filtration) is therefore recommended with turbid raw water.

Continuous-flow process: physical tests

The SODIS plant in Costa Rica worked very well on sunny days. The necessary water temperature of 50 °C was reached within 50–90 min, succeeded by a steady water flow. According to Fig. 10, the cloudier the day the more difficult it is to reach and maintain the required temperature at 50 °C. As a result, the water flow becomes unsteady, as the thermovalve shuts down as soon as the water temperature drops below 50 °C. As pasteurisation requires a temperature of at least 70 °C for a reliable disinfection, it is not a surprise that the problems encountered with the SOPAS plant are more serious.

Continuous-flow process: microbiological tests

Tables 7–10 contain the test conditions and concentrations of faecal coliforms in the raw water tank (MP_1) at measuring point 1 located after the solar collector (MP_2) and at the treated

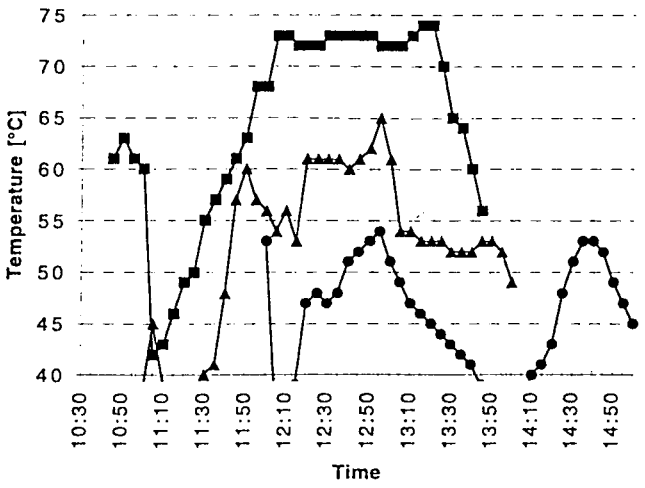

Fig. 10 Temperature fluctuations measured directly after the solar collector (MP_2) at different levels of cloudiness, (■) slightly overcast (so), (▲) 50% clouds (fc), (●) completely overcast (co).

water tap (MP_3) at set times. The tables also contain the gross integrated UV-A and visible light dose to which the plant had been exposed before sampling. Thus, the irradiation available at that time, as well as the heating energy, are better defined than if cloudiness were simply estimated. For test 3.3 'Weather Effects', the flow rate was set at 45.6 L/h for the SODIS plant and at 64.3 L/h for the SOPAS plant.

As in [3,4], no regrowth of faecal coliforms occurred within 24 h at room temperature (≈30 °C), neither after complete inactivation in the batch process nor in the continuous flow process.

Optimisation of the flow rate

Table 7 contains the test conditions and results of the SODIS plant under clear skies. Faecal coliforms were almost completely inactivated in the solar collector throughout the experimental test 3.3E, at a flow rate of up to 54.6 L/h. In other words, in tests A–D, no inactivation occurred in the irradiation reactor; this suggests that the flow rate could be increased to achieve optimum operation.

Table 7 The elimination of faecal coliforms under various test conditions, test 3.2, results of the SODIS plant on sunny days with different flow rates

				Conc. of faecal coliforms at point X and UV-A doses after: Test A, B: 0/60/120/180/240 min, Test C: 0/52/105/157/210 min, Test D, E: 0/45/90/135/180 min			
Test/flow (L/h)	Temp. variation at MP2 (°C)	Turbidity (NTU)	TS (mg/L)	X = MP1 (raw water tank) (MPN/100 mL)	X = MP2 (after solar collector) (MPN/100 mL)	X = MP3 (treated water) (MPN/100 mL)	UV-A (Wh/m^2)
A/24.4	52–74	2.9	64	930/900/1000/900/800	0/0/0/0/0	0/0/0/0/0	0/28/57/82/105
B/31.3	51–73	25	458	2100/1830/1530/1760/1720	34/0/0/0/0	0/0/0/0/0	0/29/59/88/112
C/36.6	52–74	2.5	220	8900/7900/7400/7200/5000	0/0/0/0/0	0/0/0/0/0	0/23/50/76/82
D/45.6	56–70	0.58	144	4600/2730/1050/1020/920	0/0/0/0/0	0/0/0/0/0	0/20/40/58/71
E/54.6	45–74	0.95	144	2700/2800/3000/1930/2150	18/8/0/0/46	0/0/0/0/0	0/20/40/59/77

Table 8 The elimination of faecal coliforms under various test conditions, test 3.2, results of the SOPAS plant on sunny days with different flow rates

				Conc. of faecal coliforms at point X and UV-A doses after: Test A, B, C: 0/45/90/135/180 min, Test D, E: 0/30/60/90/120 min			
Test/flow (L/h)	Temp. variation at MP2 (°C)	Turbidity (NTU)	TS (mg/L)	X = MP1 (raw water tank) (MPN/100 mL)	X = MP2 (after solar collector) (MPN/100 mL)	X = MP3 (treated water) (MPN/100 mL)	Visible light (mol/m^2)
A/45	52–74	2.9	64	930/800/720/740/810	0/0/0/0/0	0/0/0/0/0	0/1696/3424/5121/6728
B/50	51–73	25	458	2100/1160/1970/1270/nm	0/0/0/0/nm	0/0/0/0/na	0/1542/3214/5052/6887
C/56.3	52–74	2.5	220	11000/9000/10800/9800/8500	0/0/1/0/1	0/0/0/0/0	0/1696/3426/5134/6766
D/64.3	56–70	0.58	144	4600/2730/1050/1020/920	0/0/0/0/0	0/0/0/0/0	0/1111/2212/3286/4249
E/75	45–74	0.95	144	2850/1450/2870/1650/3000	230/220/0/0/0	0/25/0/0/0	0/1005/2066/3166/4289

Table 9 The elimination of faecal coliforms under various test conditions, test 3.3, impact of increasing cloudiness on the effectiveness of the SODIS plant, flow rate 45.6 L/h

Test/weather	Temp. variation at MP2 (°C)	Turbidity (NTU)	TS (mg/L)	Conc. of faecal coliforms at point X and UV-A doses after 0/45/90/135/180 min: X = MP1 (raw water tank) (MPN/100 mL)	X = MP2 (after solar collector) (MPN/100 mL)	X = MP3 (treated water) (MPN/100 mL)	UV-A (Wh/m^2)
A, cs	50–73	0.7	109	2020/2000/1970/2100/2000	0/0/0/0/0	0/0/0/0/0	0/19/40/62/78
B, so	see Fig. 10	1.5	104	1940/1900/1870/1940/1860	0/0/0/0/0	0/0/0/0/0	0/19/42/64/85
C, fc	see Fig. 10	0.67	100	1000/3000/1500/1490/1480	53/70/10/11/10	0/0/0/0/0	0/18/35/45/54
D, vc	30–65	0.6	92	>3000/"/"/"/"	>300/1/>300/"/"	0/0/0/0/0	0/10/23/36/45
E, co	see Fig. 10	0.73	88	1640/1580/1560/1560/1300	0/0/30/26/0	0/0/na/"/"	0/10/17/22/31

Table 10 The elimination of faecal coliforms under various test conditions, test 3.3, impact of increasing cloudiness on the effectiveness of the SOPAS plant, flow rate 64.3 L/h

Test/weather	Temp. variation at MP2 (°C)	Turbidity (NTU)	TS (mg/L)	Conc. of faecal coliforms at point X and UV-A doses after 0/30/60/90/120 min: X = MP1 (raw water tank) (MPN/100 mL)	X = MP2 (after solar collector) (MPN/100 mL)	X = MP3 (treated water) (MPN/100 mL)	Visible light (mol/m^2)
A, cs	50–73	0.7	109	2530/2210/1790/2210/1990	0/0/0/0/0	0/0/0/0/0	0/940/1961/3039/4164
B, so	see Fig. 10	1.5	104	1300/1800/1200/1000/1000	0/0/0/0/0	0/0/0/0/0	0/984/2075/3264/4348
C, fc	see Fig. 10	0.67	100	1500/1000/880/1110/1100	0/0/0/0/0	na/na/0/0/na	0/811/1671/2579/3035
D, vc	30–65	0.6	92	>3000/"/"/"/"	300/3/0/0/1	8/124/1/0/0	0/493/1290/2099/2938
E, co	see Fig. 10	0.73	88	1840/1700/1700/1770/1750	50/>400/"/"/"	360/na/"/"/"	0/469/960/1227/1436

The results of the SOPAS plant obtained under clear skies are listed in Table 8. They elucidate the difficulties in reaching and maintaining 70 °C throughout the entire experiment. In test E, incomplete inactivation of faecal coliforms was observed at the maximum flow rate of 75 L/h.

Impact of cloudiness on reliability

As mentioned earlier, the effect of increasing levels of cloudiness was also assessed. Temperature fluctuations during some tests at MP_2 are illustrated in Fig. 10. More clouds means less sunshine and decreasing temperatures. Thus, a lower inactivation rate seems logical since temperatures of around 50 °C for SODIS and 70 °C for SOPAS are crucial for their efficiency. Table 11 contains the relative solar radiation energy monitored in tests A–E. These percentages indicate that there was about three times more energy available for heating and irradiation on a day with a clear sky (test A) than on a completely overcast day (test E).

Table 9 shows that the inactivation efficiency of the SODIS plant is sufficient on days with 50% clouds. The problems encountered on very cloudy days—no steady flow—can probably be overcome by reducing the flow rate. On completely overcast days the available solar energy was insufficient to keep the water hot enough for a steady flow through the system.

The sensitivity of the SOPAS process to weather conditions can result in breakdowns of the flow or incomplete inactivation as shown in Table 10.

Table 11 Comparison of the relative solar energy available on days with different levels of cloudiness

Test	Integr. UV-A after 180 min (%)	Integr. visible light after 120 min (%)
A, clear sky (cs)	100	100
B, slightly overcast (so)	100	100
C, 50% clouds (fc)	64	70
D, very cloudy (vc)	53	68
E, completely overcast (co)	37	33

DISCUSSION

The initial faecal coliform concentration used in the experiments was often much higher (> 10 000/100 mL up to more than 10^6/100 mL) than normally encountered in common rivers or ponds (1000/100 mL or less). During exposure, the reduction in micro-organism concentration was monitored, and water temperature as well as solar radiation were measured. The effectiveness of SODIS is determined by the weather conditions and the climate. Cloudiness, low ambient temperature, especially when combined with strong winds, all reduce the effectiveness of SODIS.

Transparent bottles made of glass or PET, or polyethylene bags were used. In order to obtain the highest possible solar heating yields, the bottles were half-blackened and the bags were laid on black plastic foil or black metal supports. A comparison of Tables 4 and 5 reveals that water is most efficiently treated in plastic bags. This is due to the low transmission losses of the bags and the rapid heating of the water when exposed to the sun in a flat layer of a few cm depth. Therefore, a higher yield of the available solar energy is obtained in the bags than in the bottles.

Two different types of continuous flow reactors were tested. The solar disinfection (SODIS) reactor, using thermal energy and irradiation, with a working temperature of at least 50 °C, and the solar pasteurisation (SOPAS) reactor, using only thermal energy, with a working temperature of over 70 °C.

The performance rates of the SODIS and SOPAS reactors as assessed at different flow rates and weather conditions are given in Tables 7–10. The tests revealed that the SOPAS reactor reaches its working temperature only on clear or slightly overcast days. The SODIS reactor did not work properly during very cloudy weather in which only 50% of the UV-A and 70% of the visible light was available. The data in Fig. 9 reveal that optimum inactivation is obtained by a combined application of thermal energy and irradiation.

Final remarks and planned work

The objective of our investigations is the development of a reliable and inexpensive water treatment method for developing countries, particularly for all those individuals and institutions which cannot afford a communal water supply.

SODIS as a batch process could cover the demand for safe drinking water of single families in rural and urban low income areas. The SODIS continuous flow reactors could provide clean water for hospitals, schools and other institutions with greater water demands. In addition, SODIS could be used in refugee camps or as a temporary water treatment process in emergency situations (e.g. after earthquakes).

The successful and promising field test results of the batch and continuous flow processes now allow a restricted and controlled dissemination of the methods. In a demonstration project programme coordinated by EAWAG/SANDEC, over 700 households will participate in the batch process tests at sites in Africa (Burkina Faso, Togo), Asia (China, Indonesia and Thailand) and South America (Bolivia, Colombia). The design of the SODIS continuous flow plant has been simplified by combining the solar collector and irradiation reactor in one unit. This new SODIS reactor plant will be field-tested at five test sites in Costa Rica and five in Honduras for a period of at least 1 year. As soon as it proves suitable for daily use in developing countries, the SODIS reactor will go into production in Costa Rica with the assistance of Swisscontact (Swiss Foundation for Technical Cooperation).

The objective of the programme is to test the method under various socio-cultural conditions in order to assess its acceptance, suitability of equipment, costs and problems encountered by the users in their daily water treatment routine.

To encourage the exchange of knowledge and experience among institutions active in the field of solar water disinfection, EAWAG/SANDEC intends to set up an information network to disseminate the SODIS technology. This technology can be used by anybody who wishes to do so since EAWAG/SANDEC will not patent it.

BIBLIOGRAPHY

1 Acra A, Raffoul Z, Karahagopian Y. *Solar Disinfection of Drinking Water and Oral Rehydration Solutions*. Paris: UNICEF, 1984.

2 Lawand TA, Alward R, Odeyemi O, Hahn J, Kandpal TC, Ayoub J, eds. Solar water disinfection. *Proceedings of a workshop held at the Brace Research Institute, Montreal, Canada*. International Development Research Centre, IDRC-MR231e, Ottawa, Ontario, Canada, 1988.

3 Wegelin M, Canonica S, Mechsner K, Pesaro F, Metzler A. Solar Water Disinfection: scope of the process and analysis of radiation experiments. *J Water SRT—Aqua* 1994: **43**(3): 154–169.

4 Joyce TM, McGuigan KG, Elmore-Meegan M, Conroy RM. Inactivation of fecal bacteria in drinking water by solar heating. *Appl. Environ. Microbiol* 1996; **62**(2): 399–402.

5 Acra A, Jurdi M, Mu'allem H, Karahagopian Y, Raffoul Z. *Water Disinfection by Solar Radiation: Assessment and Application*. International Development Research Centre IDRC-TS66e. Ottawa, Ontario, Canada, 1990.

6 Feachem R, Bradley D, Garelick M, Mara D. *Sanitation and Disease, Health Aspects of Excreta and Wastewater Management*. John Wiley & Sons, UK, 1983.