

**LOW COST UV DISINFECTION SYSTEM FOR DEVELOPING COUNTRIES:**  
**FIELD TESTS IN SOUTH AFRICA \***

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**ABSTRACT**

A recently invented device uses UV light (254nm) to inexpensively disinfect community drinking water supplies. Its novel features are: low cost (about US \$600), robust design, rapid disinfection (12 seconds), low electricity use (40W), low maintenance (every 6 months), high flow rate (15 l/min) and ability to work with unpressurized water sources. The device could service a community of 1000 persons, at an annual total cost of 14 cents US per person.

This device has been tested in a number of independent laboratories worldwide. The laboratory tests have confirmed that the unit is capable of disinfecting waters to drinking water standards for bacteria and viruses.

An extended field trial of the device began in South Africa in February 1997, with lab testing at the municipal water utility. A unit installed at the first field site, an AIDS hospice near Durban, has been in continuous operation since August, 1997. Additional test sites are being identified. We describe the results of the initial lab tests, report the most recent findings from the ongoing field test-monitoring program, and discuss plans for future tests.

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## INTRODUCTION

As of 1994, more than 1 billion people in the world still lacked adequate access to safe drinking water [WHO/ WSSCC/UNICEF, 1996]. Each year, people largely from this population experience 900 million episodes of the diarrhea or diseases closely associated with waterborne pathogens present in dirty drinking water [Economist, 1998]. The problem of unsafe drinking water is recognized to be not an isolated technical problem, but interrelated to the problems of adequate water supply, community education in public hygiene, access to sanitation, and effective and safe disposal of human and animal wastes [USAID, 1990]. Nevertheless, a device or technology that offers affordable, simple, robust and low-maintenance disinfection of drinking water can be an important part of the solution.

Some current technical approaches to providing drinking water to this population segment, and their drawbacks, are listed next. (1) Deep tubewells fitted with handpumps, while perhaps the simplest system to operate, require expensive drilling rigs, are immobile sources, and often produce hard water that some communities find distasteful; (2) Chlorine disinfection also treats larger organisms and offers residual disinfection, but can be expensive with its need for special operator training and a supply chain of a potentially hazardous material; (3) Boiling water over a biomass cookstove, the most well known and reliable treatment method, demands labor, and imposes high economic, environmental, and human health costs.

## UV DISINFECTION OF DRINKING WATER

The use of ultraviolet (UV) light to disinfect water of water-borne pathogens capitalizes on the germicidal properties of a narrow range of the UV spectrum. Given proper dosage, UV wavelengths ranging from 240 to 280 nanometers (nm) deactivate, or effectively kill, microorganisms by damaging their DNA so as to prevent the DNA, and the organism, from replicating [Harm, 1980]. The UV dose, measured in microwatt-seconds per square centimeter, is the product of UV intensity and exposure time: dosages for a 90% kill of most bacteria and viruses range from 2,000 to 8,000  $\mu\text{W}\cdot\text{s}/\text{cm}^2$ , while dosages for *Giardia*, *Cryptosporidium*, and other large cysts and parasites are an order of magnitude greater (approximately 60,000-80,000  $\mu\text{W}\cdot\text{s}/\text{cm}^2$ ) at a minimum [Wolfe, 1990].

Most current UV systems use a low-pressure or medium-pressure mercury vapor lamp and expose water to UV by pumping the water around a sleeve within which the UV lamp is supported. Typical system dosages of 25,000 to 38,000  $\mu\text{W}\cdot\text{s}/\text{cm}^2$  reduce only bacterial and viral concentrations by 3 to 4 logs [Wolfe, 1990]. (Systems which seek certification in the U.S. under the applicable NSF standard must deliver a dose of 38,000  $\mu\text{W}\cdot\text{s}/\text{cm}^2$ .) UV systems can be coupled with a prefilter to remove those larger organisms (worms and cysts) and particulates

with attached bacteria that would otherwise remain viable after passage through the UV system. The prefilter also clarifies the water to improve light transmittance and therefore UV dose throughout the entire water column.

In theory, UV systems compare favorably with other water disinfection systems in terms of cost, labor, and the need for technically trained personnel for operation and maintenance. UV treatment with the unit described in this paper is rapid and, in terms of primary energy use, approximately 6,000 times more efficient than boiling over a biomass cookstove. UV-treated water, like boiled water, must be handled and stored hygienically. UV treatment does not offer residual disinfection, and some bacteria can repair their DNA and reactivate after a few days of exposure to visible light [Harm, 1980]. Reactivation of bacteria, when it occurs, is on the order of a 1-log increase in post-treatment concentration; reactivation is related to UV dosage, and one study found that water dosed with  $130,000 \mu\text{W} \cdot \text{s}/\text{cm}^2$  showed no reactivation after 24 hours [Lindenauer and Darby, 1994]. Our laboratory experiments for testing reactivation of E. Coli have yielded similar results.

### **UV WATERWORKS (UVWw)**

In the summer of 1993, prompted by the outbreak in India of a mutant strain of cholera ("Bengal" Cholera) against which there was no vaccine, we initiated a design effort for a low-cost, robust, and low maintenance device for drinking water disinfection. We found that the cost of disinfecting water with a UV dose of  $40,000 \mu\text{W} \cdot \text{s}/\text{cm}^2$  was attractively low at 2 US cents per metric ton of water. However, the available UV water disinfection systems had two drawbacks: they all (1) required a pressurized source of water, due to various filters integral to the devices, and (2) used a UV-transparent sleeve to separate the UV lamp from the surrounding water stream. This sleeve rapidly fouled with biofilm and chemical deposits, reducing its UV-transparency, and thus required frequent mechanical and chemical cleaning. This was beyond the technical and time resources of the communities we hoped to help.

Our goal was to disinfect communities' drinking water collected by hand from surface sources, or with handpumps. The water entering the device might have a pressure of only a few cm of water column. Thus, we decided to do away with any integrated filter (and the need for pressurized water to push it through the filter). If filtering was necessary, it would have to be done outside the device, using a slow sand filter, or an in-line filter cartridge if one had a pressurized line. We circumvented the sleeve fouling problem with a design having a bare UV lamp supported below a reflector, above the free surface of flowing water. There are no solid surfaces prone to fouling between the water and the UV lamp. We set the design maintenance interval conservatively at 6 months. Our initial design was wholly of welded stainless steel sheet, consumed 40 Watts, disinfected 30 liters per minute (lpm), and cost us about US\$900 to fabricate.

Limited field tests of this design were conducted in India. The Indian communities informed us that the flow capacity of the device was far higher than necessary, and that the devices were too bulky and costly. In response, we developed the present design (shown schematically in Figure 1) that still uses 40 Watts, but now disinfects 15 lpm, is much more compact, and has a substantially lower manufacturing cost. The unit is designed to treat water with a UV extinction coefficient of  $0.3 \text{ cm}^{-1}$ , equal to that of the average effluent from US municipal wastewater treatment plants.

## LABORATORY TESTS OF UVWw UNITS

We present descriptions and a table (Table 1) summarizing 10 lab-based tests of the UVWw units conducted both within LBNL and at independent laboratories within the U.S. and abroad. As discussed above, the UVWw device has evolved through two generations of prototypes; only one test of the first generation (UVWw 1.x) unit is included in this summary.

1. In 1996, the UVWw 1.x prototype 8 gpm (30 lpm) device was tested at the Haffkine Institute, a national laboratory of pathology and infectious diseases in Bombay, India. Although the current UVWw design uses half the flow rate, the tests of the 1.x prototype are still a valuable demonstration of the UVWw technology's effectiveness against a range of pathogens. In the tests at the Haffkine Institute, each of 10 different waterborne pathogenic organisms (including *E. coli*, *Salmonella typhi*, *Vibrio cholerae*, *Shigella Dysenteriae*, and *Pseudomonas aeruginosa*) were separately suspended in chlorine-free tap water. The initial concentrations of the pathogens were approximately 1,000,000 colony-forming units (CFU) per deciliter of water. In each case, the UVWw treatment reduced pathogen concentrations to below detectable levels (per ml water, for a reduction of at least 4 logs) in the outflow water, and the Institute reported that this water met applicable bacteriological drinking water standards.

2. Later in 1996, scientists at Lawrence Berkeley National Lab (LBNL) tested a UVWw 2.x prototype 4 gpm (15 lpm) unit. They collected two water samples from a local creek (Strawberry Creek on the UC-Berkeley campus) with well-documented problems of unhealthful fecal coliform bacteria contamination. The samples varied in turbidity (10 and 80 NTU) and initial coliform bacteria content (10,000 CFU and 1,000 CFU per 100 ml, respectively). In both samples, the UV treatment reduced coliform bacterial levels by at least 4 and 3 logs, to below detection limits.

3. A subsequent test performed at LBNL in November 1996 compared two methods - one appropriate for field use (Colilert<sup>1</sup> MPN tubes as presence-absence tests) and the other the

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<sup>1</sup> Colilert (a product of IDEXX Laboratories, Inc.) turns sample from clear to yellow if any coliform bacteria are present.. The Standard Methods for the Examination of Water and Wastewater refers to this test as Chromogenic Substrate.

standard lab-based test (membrane filtration<sup>2</sup>) - for detecting *E. coli*. We seeded de-ionized water (estimated UV extinction coefficient =  $0.01 \text{ cm}^{-1}$ ) with non-pathogenic *E. coli* and pumped this water through the UVWw 2.x unit at 4 gallons per minute. Membrane filtration tests indicated a concentration between 500,000 and 600,000 CFU per 100 ml in the inlet water, while the less-precise Colilert test indicated a concentration no less than 100,000 CFU per 100 ml. Both test methods indicated the treated outflow water had no detectable *E. coli*, suggesting a 5-6 log reduction resulting from the UVWw unit.

4. At LBNL in the spring of 1997, we modified a UVWw 2.x unit to test field water samples that were of insufficient volume to be tested in the laboratory under actual flow conditions (4 gallons/minute) through the unit. Instead of the sample water flowing through the unit at 15 lpm, we used a tray of water to hold the sample volume in the unit and expose it for 12 seconds with an aluminum shutter (12 seconds is the length of exposure in the unit for flowing water). Using this method we evaluated samples from Berkeley's Strawberry Creek and South Africa's Inanda Dam reservoir (near Durban). Membrane filtration found the Strawberry creek samples to have total colony counts reduced by 4 logs by the UVWw. Two tests of the Inanda Dam water found that filtering the water before treatment improved performance by 1 log, from 3 to 4 log reduction.

5. In July 1997, A test of the UVWw 2.x unit's performance on field site water was performed at the Durban Metro Water laboratory in Durban, South Africa. LBNL and Durban Metro staff collected an untreated sample of water from the field site and exposed it to UV in the unit using the same 'tray' method developed at LBNL in its spring 1997 tests. This test found that the unit reduced the coliform concentrations by 6 logs. The inlet water, which had a UV extinction coefficient close to that of distilled water, had initial concentrations of 20 million coliform CFU/100 ml (this was in part due to an old in-line carbon filter unrelated to the UVWw project; the filter was subsequently removed, improving water quality to 6000 CFU/100 ml just by this action!).

6. A test performed in September 1997 in the Philippines Department of Health (in conjunction with the University of the Philippines) found an early prototype of the UV 2.x unit to reduce an estimated 100,000 CFU/ml concentration of *E. coli* to less than detectable levels (less than 1 CFU/100 ml). (The inlet concentration remains only an estimate because their test equipment got contaminated during the inlet concentration measurements. The outlet concentration was measured reliably and was reported.) The test method used in this experiment reports only the

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<sup>2</sup> Membrane filter method according to Standard Methods for the Examination of Water and Wastewater, 18th ed. (1992), Method 9222 B. Petri dishes prepared with HACH brand m-ENDO prepared broth, a total coliform broth.

presence or absence of coliform bacteria and is not intended to provide a measure of concentration of these organisms.

7. A test was conducted by Societe Generale de Surveillance (SGS Philippines) in October 1997 on deep well water. The well water did not have detectable coliforms, but there were other bacteria present, as indicated by a heterotrophic plate count of 12,200 CFU/ml in the water. In the UV-treated water this concentration was reduced by at least 4-5 logs to <1 CFU/ml.

8. An experiment in December 1997-January 1998 at SGS Philippines investigated unit performance limits and the potential for bacterial reactivation after UV treatment. Bacterial concentration in water seeded with approximately 500,000 CFU/ 100 ml *E. coli* was reduced by at least 5 logs to below detectable limits. The treated water had no detectable coliforms for the two weeks it was kept in storage and samples at the lab.

9. The National Water Commission (Comision Nacional del Agua, "CNA") of Mexico, which is under the Department of Health (Secretariat de Salud) of the Mexican federal government, carried out their first laboratory tests of UVWw over December 1997- January 1998. For these tests, the CNA purchased a UVW2.3NC unit from WaterHealth International. They tested the performance of UVWw for treating 'wild' water seeded with various microbes in two independent tests. The results of these tests were good. The CNA reported telephonically to WHI that in their tests UVWw removes all the biological organisms from water that are claimed in WHI literature to be treatable with the unit. They also faxed a one page summary of the results of the first of the two tests to WHI on March 12, 1998. WHI is awaiting a copy of the written report of these tests. These tests will be repeated once more during April, 1998, on a UVWw unit randomly selected by Mexican government inspectors from the WHI factory.

10. BioVir Laboratory in Benicia, CA began comprehensive tests of the UVW2.3NC unit in February, 1998 which are ongoing. Initial results show that, for water with a UV extinction coefficient of approximately  $0.1 \text{ cm}^{-1}$  (typical of tap water), the unit delivers a UV dose of approximately  $160 \text{ mW-s/cm}^2$  (four times the current NSF regulatory standard of  $38 \text{ mW-s/cm}^2$ ), a 5-6 log reduction of *E. coli*, and a 7-log reduction of *Klebsiella terrigena*. The dose measurement was performed using a dose-response calibrated strain of *Bacillus subtilis* spores as recommended by NSF Standard 55. A final report will be generated this summer after further tests, including those required for full compliance with Standard 55, have been completed.

## **GOALS AND WORK PLAN OF FIELD TESTS IN SOUTH AFRICA**

The primary objectives of the field-test in South Africa are to: (1) identify and correct any design problems and unanticipated technical flaws in the device, and ensure its compatibility with the user preferences and requirements in South African communities; (2) evaluate and document the field performance of the device and its effectiveness in limiting the occurrence of waterborne

biological contaminants in drinking water; (3) determine appropriate media and delivery systems for (a) community placement and acceptance of the device, (b) the necessary user education to assure sanitary and exclusive use of disinfected water for drinking and food preparation, and (c) relevant community education in public hygiene and sanitary practices; and (4) determine the content and delivery systems for technical training of maintenance personnel, local management systems for community ownership and operation of the device to ensure its ongoing functioning.

We plan to start up the field sites for UVWw in a phased manner, thus enabling us to improve our approach in the later stages of the work from the lessons learned in the early stages. The first site, operational since August 1997, has been monitored biweekly with pre- and post-treatment samples. The next two sites will be intensively monitored (about 50 samples a week for 50 weeks) for the bacterial contamination along the drinking water chain, from the outlet of the device, to the household storage cisterns, to the water in the drinking cups.

The community placement of the device, and community education and management of the technology will be organized by working with local NGOs who have the trust of the community and who understand the local customs, politics, and issues. We will document the outcome of various approaches to address these important dimensions of the problem.

#### **UVWw PERFORMANCE AT THE FIRST SOUTH AFRICAN FIELD SITE**

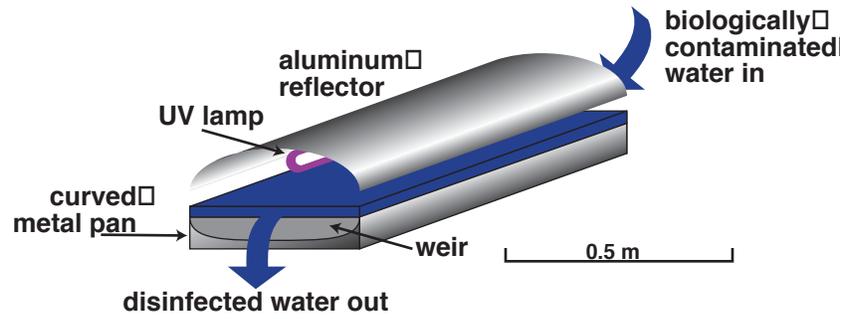
We measured the borehole water from the field test site to have a UV extinction coefficient almost identical to that of distilled water. It also was visually clear. In lab tests in Durban (Test #5, above), exposing three 170ml samples in a 4 cm deep layer for ten seconds in the UV unit reduced initial coliform concentrations of 6 million CFU/100ml to an average of 6 CFU/100ml, a  $10^6$  reduction. With these results in hand, we installed the unit to disinfect the water supplied to the kitchen at the Lily of the Valley HIV hospice for orphans, outside Durban. The UV lamp in the unit is continually on, and water is passed through the unit on demand. Flow to the unit is pressurized and controlled by a manually-operated ball valve. The maximum flow rate was set at 8 liters/minute, which is adequate for the hospice needs (primarily preparation of baby formula and providing drinking water in feeding bottles). The treated water is delivered immediately by gravity flow from the unit to the kitchen sink by a four-foot length of copper pipe. In our initial test of the installation, we measured 4,000 coliform (including 200 E. coli) CFU/100ml in the untreated water entering the unit, and no detectable coliforms in the treated water leaving the UV unit.

The biweekly sampling of the unit began in November (Table 2). Two samples are collected for analysis. Untreated (“Before UV”) samples are collected at a separate tap slightly upstream of the unit; treated (“After UV”) samples are collected at the kitchen sink pipe outlet.

Samples collected from December 22 onwards began to indicate worsening water quality at the kitchen tap, but data were inconsistent. Attempts to resolve the inconsistencies and identify the cause of bacterial contamination in the water at the kitchen tap (by suggesting various additional tests) were unsuccessful between January and March 1998. One of the authors (DG) visited the site in April 98 and with various tests determined that the unit was functioning fine and according to specifications, however, the outlet chamber and the outlet pipe had never been cleaned since the initial installation. (Our installation crew had left written instructions to clean them every two months). After cleaning these parts by pouring boiling water through the outlet chamber, we obtained the satisfactory performance in the last column of Table 2.

### **CONCLUDING REMARKS**

Several independent laboratory tests of the UVWw unit indicate a delivered dose potential of 160 mW-s/cm<sup>2</sup> and bacterial load reductions of 3 to 6 logs in both seeded and “wild” water. The Lily of the Valley field test is the first long-term test of the unit. Deep borehole water from the Lily of the Valley AIDS hospice was found to be contaminated with fecal and total coliforms. The UVWw unit successfully treated this water for the first 4.5 months (early August - late December) and again after cleaning the outlet port and pipe. During these periods, the delivered drinking water met and meets WHO and USEPA bacterial standards. The results so far suggest that the unit continued to deliver good disinfection performance without any maintenance, however, attention must be paid to periodic (recommended every 2 months) cleaning of the outlet chamber and pipes to control biofilm growth. We are beginning to explore other measures to slow the growth of such biofilm for the future sites.



**Figure 1.** Simplified schematic of the interior of UV Waterworks. The housing (not shown) is made of rugged molded plastic or metal.

**Table 1.** SUMMARY OF LAB-BASED TESTS OF UVWW UNITS

<b>Test location</b>	<b>Factors tested</b>	<b>Findings</b>
Haffkine (using 30 lpm unit)	Various pathogens	Unit reduced a range of pathogens by at least 4 logs to below detectable limits
LBNL	Strawberry creek, turbidity	Unit reduced <i>E. coli</i> in 10 and 80 NTU creek water by at least 4 and 3 logs to below detectable limits
LBNL	Colilert vs. Membrane filtration	Unit reduced <i>E. coli</i> in DI water by 5 to 6 logs to below detectable limits
LBNL	“Tray” method	Modified unit reduced creek and reservoir water coliforms by 3 to 4 logs
Durban Metro	Performance on field site water	Modified unit reduced groundwater coliforms by at least 6 logs to below detectable limits
Philippines Dept. of Health	<i>E. coli</i> performance	Unit reduced coliforms to below detectable limits
SGS Philippines	Heterotrophs	Unit reduced heterotrophic organisms by at least 4 logs to below detectable limits
SGS Philippines	Performance and stored samples	Unit reduced <i>E. coli</i> by at least 5 logs to below detectable limits; treated water stored for two weeks had no detectable <i>E. coli</i> .
Mexican Water Commission	Performance	Unit performed effectively (details forthcoming)
BioVir Lab	Unit dosage, <i>E.coli</i>	Unit delivers 160 mW-s/cm <sup>2</sup> dose to tap water, reduced seeded <i>E. coli</i> by over 5 logs

**TABLE 2. LILY OF THE VALLEY SAMPLE ANALYSES THROUGH 6 JAN. 1998 (CFUS/ 100 ML)**

	4 Aug. 1997	10 Nov. 1997	24 Nov. 1997*	8 Dec 1997	22 Dec 1997	6 Jan. 1998	6 April 1998
Before UV:							
Total coliforms	~4,000	>3,000	>800	344	>1,000	>1,000 0	236
E. coli	2	0	0	0	>1,000	n/a	2
Salmonellae	n/a	0?	0	0	>1,000	n/a	1
Other Enterobacteriaceae	~5,000	0	0	12	>1,000	n/a	163
AFTER UV:							
Total coliforms	0	0	1	0	25	87	0
E. coli	0	0	0	0	4	1	0
Salmonellae	n/a	n/a	0	0	16	3	0
Other Enterobacteriaceae	~5	0	0	8	>1,000	159	0

\* The 24 Nov. samples were approximately 38C when delivered to the lab.

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