Design and Evaluation of a Low-Cost Point-of-Use Ultraviolet Water Disinfection Device

*Alicia Cohn,[1] Lloyd Connelly[4], Sarah Brownell[1] Kara Nelson[1], and Daniel M. Kammen[2,3] **

[1]Department of Civil and Environmental Engineering

[2]Energy and Resources Group

[3]Goldman School of Public Policy

University of California, Berkeley, CA

[4]School of Medicine, University of California, Davis, CA

** Address correspondence to: D. M. Kammen, Energy and Resources Group, 310 Barrows Hall, University of California, Berkeley, CA 94720-3050; Email: kammen@socrates.berkeley.edu

ABSTRACT

A wide range of technologies are needed around the world to supply safe drinking water. We have developed a device for disinfecting drinking water with ultraviolet (UV) light at the point-of-use. It is distinct from other UV technologies in that it may be constructed from inexpensive, commonly available materials, thus providing a low-cost option suitable for household use in a

many regions of the developing world. The design criteria and an approach for transferring the technology were developed together with input from potential users in Mexico and prototypes were evaluated in Mexican households. Laboratory experiments to evaluate performance included bioassays, tracer studies and material degradation tests. In addition, an irradiance model was developed as a predictive tool. At a flow rate of 5 L/min, the device provided a fluence of 981 J/m^2 with a 95% confidence interval of ± 98 J/m^2, in water with 98% transmittance. Flow through the device was observed to be plug flow with dispersion; no short circuiting was observed. The irradiance model provided a conservative estimate of the average fluence under the conditions tested and can be used to estimate the average fluence at other flow rates and water transmittances. Materials tests indicated that polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) are not ideal materials for a UV disinfection device due to the formation of small quantities of by-products, such as dichloromethane in the former and benzene in the later, after prolonged exposure. The design tested, a PVC tube almost completely lined with stainless steel, produced no detectable by-products during flow-through use. A follow-on one-year field study in homes in Mexico is planned.

INTRODUCTION

Each day, thousands of people – including significant numbers of children under the age of five – die from waterborne diseases (*1*). These deaths could be reduced by improving water quality along with sufficient provision of water supply and improved hygiene and sanitation (*2*). We developed a useful technology to address this situation with motivation from field studies of water quality based on observations of the village of Tzurumútaro (19°33'N, 101°37'W, 2100 m, population 1709 (*3*)) in the state of Michoacán, Mexico. In this village, members of the *Ejido* (the governing council) take turns adding about half of a gallon of bleach on an approximately

biweekly basis to the cistern that supplies the village's aging water distribution system. The timing and quantity of chlorine addition is highly variable. In addition, the integrity of the distribution system is inconsistent: one house may receive chlorinated water while another receives contaminated water with no residual level of chlorine. In addition, some households at various times adopt a variety of in-house water disinfection technologies of varying reliability. The outcome is a situation where household water quality varies dramatically across socioeconomic, temporal and geographic scales.

Water quality may be improved through more effective central disinfection coupled with a robust distribution system with constant pressure. Alternatively, water quality may be improved at the point-of-use (POU) in the household. While point-of-use treatment may require more effort on the part of individual households, it offers a means for households to affect their water quality independently and immediately. In circumstances such as those encountered in Tzurumútaro, in which a piped water system is available but water is of poor or inconsistent quality, a POU disinfection device offers many advantages.

However, for a POU system to be effective, it must be accessible to those need it most. An accessible system will be affordable, provide excellent pathogen removal, be able to treat a high capacity, operate passively and be constructed from locally available parts. Currently, there is no POU system that fits all of these criteria. In addition, the technology and the approach to technology transfer must be mutually compatible and appropriate. By 'appropriate' we mean well matched to the social, economic and technical realities of the situation, site, or region.

Ultraviolet disinfection offers promise as an accessible POU technology. Recently there has been renewed interest in suspended bulb designs due to the simplicity of construction and associated cost reduction. The research described here was inspired by the work of Ashok

Gadgil of Lawrence Berkeley Laboratory, who found that a flow-through suspended bulb design could provide disinfected water at a cost of a few cents per metric ton (*4*).

In this paper, we introduce an ultraviolet (UV) water disinfection technology that was initially developed in a small rural laboratory on the outskirts of Tzurumútaro, Mexico, followed by extensive laboratory tests, which led to design modifications, at the University of California, Berkeley. This device can operate with pressurized or un-pressurized water. Most parts were purchased locally in a medium sized hardware store in the town of Pátzcuaro, while the bulb and stainless steel were purchased about 50 minutes away in the city of Morelia. Construction requires basic tools available in local hardware stores and takes approximately four hours. The approach and the technology have been through an iterative process of field study and laboratory investigation over the course of several years and together provide a novel alternative for reducing the incidence of waterborne disease. This project is thus an example of what we have previously termed, 'mundane' science (*5*), or appropriate technology

We introduce the design and present results of laboratory experiments to evaluate its performance. The objectives of the laboratory experiments were to (1) determine the average fluence using an MS2 bioassay; (2) characterize the residence time distribution in the ultraviolet disinfection device using a tracer study; (3) model the average fluence provided using the point source summation method; (4) determine the safety of exposing the materials to ultraviolet light by analyzing the effluent water for potential by-products under various batch and flow-through conditions.

MATERIALS AND METHODS

Design of UV disinfection device. The disinfection device consisted of a 65-cm long, 4-in diameter PVC pipe with the lower three quarters lined with stainless steel and the remaining with aluminum foil (Figure 1). Below the aluminum foil a 15-W germicidal bulb (11078, General Electric, Louisville, KY) was suspended from two bulb holders. Each end of the tube was sealed with Vaseline and unlined PVC end caps. On one side a ½-in copper elbow inserted through the top of the tube provided the inlet. On the opposite end cap a 1-in PVC elbow was inserted as the outlet at a height such that the water depth without flow would be 4 cm. A small Plexiglas window, which blocks UV light, was inserted on the top to indicate when the light was on. Prior to inserting and securing the stainless steel liner, a hole was cut into the bottom of the PVC pipe to serve as a leak detector. If during operation the seal between the PVC and stainless steel liner was broken, water would flow below the liner and exit through this hole alerting the user that water may be unsafe to drink.

Biological assay with MS-2. Three independent bioassay experiments were performed over a period of three weeks using a stock solution of MS2, (Escherichia coli bacteriophage ATCC® 15597-B1) prepared eleven months prior, following propagation steps as described in ISO 10705-1 (*6*) using an E.coli host (Escherichia coli ATCC® 15597) and stored at 4°C. Berkeley City tap water was treated with a course filter and dechlorinated by passing through an activated carbon filter (**?**). The absorbance of the treated water was 0.008-0.013 cm^{-1} (transmittance 97-98%). MS2 was added to the feed water, such that the concentration entering the disinfection device was 10^6 PFU/mL. Constant head was maintained in the feed tank and a flow control valve and flow meter were used to produce a constant flow rate to the water disinfection device. Steady-state conditions were established in the device by continuous operation for at least 10

hydraulic residence times. Three 50-mL samples were collected upstream of the device as inlet samples and five 10-mL samples were collected at the outlet. At least one inlet sample preceded and one followed collection of the outlet sample series. MS2 was enumerated in the water samples using the double layer agar method, as first described by Adams (*7*). Once sample was added to host culture, less than one minute passed before the mixture was plated and covered to prevent potential photoreactivation.

A quasi-collimated beam apparatus was used to determine the fluence-response curve for MS2 in the feed water (*8*). Irradiance at the center of the surface of the sample was measured using a Spectroline® Digital radiometer (DM-254XA, Spectronics Corporation, Westbury, NY) and fluence was calculated taking into account various factors, including sample volume, distance from UV source, path length through water and absorbance, as described by Bolton and Linden (*8*). Prior to the first bioassay, a sample of feed water was divided into aliquots that were exposed to a range of fluences: 200, 400, 600, 800 and 1000 J/m^2, each with three replicates, to generate a standard curve. For each study, a portion of the feed water was exposed to three fluences, each with 2 replicates, to confirm that response of the MS2 had not changed.

Determination of hydraulics. Three independent tracer studies were conducted over a two month period. For each study, a 1-mL pulse input of concentrated Intracid Rhodamine WT dye (1/10 dilution of 298-16, Cole Parmer, Vernon Hills, IL) was injected 1 cm upstream of the inlet, using an 5-mL plastic syringe and needle to pierce the tubing, while the disinfection system was flowing at 5 L/min. Effluent samples of approximately 20 mL were collected at 3-s intervals, beginning 9 s after the injection. Samples were analyzed by spectrophotometery at 556 nm.

Mathematical model. An irradiance model was developed by modifying the point source summation (PSS) method for a submerged bulb design, as presented by Blatchley (*9*), to describe our suspended bulb design. Additional detail was incorporated to produce a more accurate depiction of the UV disinfection device. Any simplifications or assumptions were designed to be conservative, i.e., to provide an underestimate of the fluence. For example, the light reflected from the inside surface back into the water is neglected in the model.

The key variables used in the model are illustrated in Figure 2. The following equation is used to calculate irradiance (total power incident per unit area):

$$I_{i,j} = \frac{P_\lambda}{4n\pi\rho_{i,j}^2} \exp\left[-\left(\left(UV_{254}\ln(10)\right)\left(R - r_{air}\right)\frac{\rho_{i,j}}{R}\right)\right]$$

Where:

$I_{i,j}$ = irradiance at point *j* due to site *i* in point source (mW/cm^2)

P_λ = bulb power at 254nm (mW)

n = number of point sources

$\rho_{i,j}$ = distance separating site *i* in point source and site *j* in receptor (cm)

UV_{254} = absorbance of water at 254 nm (cm^{-1})

R = radial distance from bulb to receptor site (cm)

r_{air} = radial distance from bulb to surface of water (cm)

Additional calculations account for the flow-through height of the water, the length of tube on each side of the bulb that is not directly below the light, and the mean hydraulic residence time. Calculations were performed using Engineering Equation Solver (EES, F-Chart Software,

Middleton, WI 53562 / www.fchart.com). The individual irradiance distributions over multiple slices in the direction parallel to flow were summed to compute the average fluence. Plug flow was assumed, i.e. the irradiance for each section was multiplied by a fraction of the mean hydraulic detention time equivalent to its fractional volume. This assumption was used as a first approximation, despite the fact that it is not conservative.

The effect on fluence of varying the flow rate and UV_{254} absorbance was modeled using the following design parameters:

Radius	=	5.08 cm
Tube length	=	65 cm
Bulb output at 254 nm	=	5,000 mW
Weir height	=	4 cm
Distance from bulb to bottom of tube	=	7.62 cm
Length of tube before bulb starts	=	6.35 cm

Material degradation. A range of materials for constructing the UV device were evaluated for their resistance to ultraviolet light during flow-through conditions and during prolonged exposures (Table 2). Initially, two UV units were constructed, one from polyvinyl chloride (PVC) and one from acrylonitrile butadiene styrene (ABS). After material degradation tests indicated that by-product formation with these materials was unacceptable, PVC units lined with either galvanized or stainless steel were evaluated. To determine if there was any difference in by-product formation between PVC manufactured in the United States versus Mexico, units constructed from both materials were evaluated.

For each test, the temperature, UV_{254} absorbance and pH were measured in outlet samples in the laboratory and separate samples were sent to a commercial laboratory (Sequoia Analytical, Morgan Hill, CA) for analysis of 59 volatile organic compounds (VOCs) according to the US EPA method 8260B. Samples from the unit lined with galvanized steel were also analyzed for aluminum, iron and zinc.

A low flow rate, 0.24 L/min, was used for the flow-through tests, corresponding to a theoretical hydraulic residence time (HRT) of 8.6 min. The outlet samples were collected after operation for two HRTs. The longer exposures were achieved by conducting batch tests with exposure times ranging from 1 h to 35 d (Table 2). For the tests with unlined PVC, ABS and PVC lined with galvanized steel, the units were filled with distilled water and the outlet was covered to prevent evaporation. Samples were removed by pipette at the end of the exposure time. For the tests with PVC lined with stainless steel, the procedure was changed slightly to better simulate conditions that might occur during actual use; the outlet was left open to the atmosphere, and after the exposure period, flow was initiated and the first water to exit was collected for analysis. The water used for the tests with PVC lined with stainless steel was also different. Humic acids (Sigma-Aldrich, Allentown, PA) were added to Berkeley City tap water to a concentration of 40 mg/L (equivalent to approximately 20 mg/L dissolved organic carbon (DOC) and a UV_{254} absorbance of 0.200 cm^{-1}). The addition of humic acids was intended to simulate source water with high levels of natural organic matter, which may serve as precursors for disinfection by-products.

RESULTS AND DISCUSSION

Biological assay. Quasi-collimated beam results, shown in Figure 3, provided a relationship between fluence and log inactivation of MS2. Quasi-collimated beam results (not shown) conducted on each of the three testing days were consistent with the standard fluence-response curve (Figure 3). The reciprocal of the correlation given by the data was used to back-calculate fluence based on log reduction of the effluent samples from the disinfection device:

$$Fluence = 246\left(\log\frac{N_0}{N}\right) - 167$$

The logarithm of the MS2 inactivation with 95% confidence intervals for the three testing days, each at 5 L/min, are shown in Figure 4. The mean MS2 concentration in the inlet was used to calculate the log inactivation for each outlet sample. Inactivation results for the UV disinfection system are summarized in Table 1.

It is not clear why a consistently lower inactivation was observed during the first experiment (samples 1-5) compared to the second and third experiments. It is possible that the bulb was dirty due to a longer period of non-use before experiment one. Another possibility is that the bulb output was lower; the bulb used for the experiments had been turned on for less than 100 h, and the output is known to fluctuate during this "burn in" period. Experiments are currently underway to quantify the fluctuation in output during the lifetime of the bulbs. Nonetheless, the mean equivalent fluence of 981 J/m^2 is significantly higher than the 400 J/m^2 minimum fluence required by the National Sanitation Foundation protocol (*10*). For comparison, the fluence provided by the disinfection system was greater than that needed to provide a 4-log inactivation of poliovirus, hepatitis A virus, and rotavirus, as well as a variety of pathogenic bacteria and protozoa (Figure 5). The device would provide a 3-log inactivation of Adenovirus types 40 and 41, which are some of the most UV resistant waterborne pathogens known.

Hydraulics. In Figure 6, residence time distributions for the three tracer studies are plotted. For comparison, the residence time distributions for an ideal plug flow reactor (PFR) with a hydraulic residence time (HRT) of 28 s, in which no mixing occurs in the lateral direction, and an ideal continuous flow-stirred tank reactor (CFSTR), in which mixing is complete and instantaneous, are also shown. The experimental data from the disinfection device at 5 L/min could be modeled reasonably well as 12 CFSTRs in series, or as a PFR with dispersion. Recovery of the tracer was calculated to be 125%, 114% and 100% for experiments 1, 2 and 3, respectively. The apparent recovery of more than 100% of the dye was most likely due to error in the measurement of the volume of dye in the original 1-mL pulse input. The first dye exited between 12 and 15 seconds after it was injected, indicating that there was no significant short circuiting. The mean HRT was calculated to be between 33 and 37 s slightly longer than the theoretical HRT of 28 s, due to tailing. The tailing is likely due to eddies that formed around the inlet or the slower movement of water along the walls of the device. These results support the use of the plug flow assumption as first approximation with the irradiance model.

Mathematical model. The model results show fluence increasing with decreasing flow rate and decreasing absorbance of the water (Figure 7). At lower flow rates the fluence is more sensitive to absorbance than at higher flow rates. The bioassay results, as shown alongside model predictions in Figure 7, indicate a higher fluence than that predicted by the model. Thus, the model can be used to calculate a conservative estimate of fluence. Alternatively, given a specific UV_{254} absorbance and required fluence, the maximum flow rate can be determined. For example, if the UV_{254} absorbance is 0.16 cm^{-1}, a flow rate less than 4.5 L/min would be recommended to achieve the NSF minimum fluence of 400 J/m^2. Similarly, if the flow rate is 9

L/min, the minimum fluence of 400 J/m^2 will be obtained provided that the absorbance is less than 0.04 cm^{-1}. Before operation at flow rates greater than 5 L/min, however, additional experiments would be required to verify that the flow regime does not deviate from plug flow with dispersion. We recommend that the absorbance should be less than 0.10 cm^{-1} for operation at 5 L/min.

Material degradation. As shown in Table 2, the results from the unlined PVC indicated that it should not be used (unlined) to construct the UV device if it is to be used for the production of drinking water. The pH of the water after an 18-day exposure was less than 2; in addition, three other constituents, 1,2-dichloroethane 1,2-dichloropropane and dichloromethane, exceeded the US EPA maximum contaminant level (MCL) for drinking water and dichloromethane and 1,2-dichloroethane exceeded the WHO guidelines (*11,12*). In the unlined ABS unit, after a 16.5-day exposure, 1.8 g/L of benzene was detected. Although this concentration of benzene is below the WHO guidelines and the US EPA MCL, there are health concerns associated with any exposure to benzene. Even though the exposures evaluated were much longer than what would be experienced during normal operation, based on these results we do not recommend the use of unlined PVC or ABS for the construction of UV disinfection units for the production of drinking water.

For the PVC lined with galvanized steel, 4 different VOCs were detected after a 7-day exposure. Although none of the concentrations exceeded the US EPA MCL or the WHO guidelines after this exposure, the limits may be exceeded after a longer exposure. Zinc was detected at a concentration above the EPA secondary MCL, even when the liner was not exposed to UV (data not shown); this limit is based on taste concerns, rather than a health hazard, which

would occur at a much higher level (*13*). Therefore, potential health hazards could be avoided by instructing users to flush the system if a bitter taste were present. Nonetheless, we feel these results indicate that galvanized steel is not an ideal material for the UV disinfection device.

A summary of representative results from tests with US and Mexican PVC lined with stainless steel are presented in Table 2. The tests were conducted on different days, and the quality of the influent water varied slightly. On the first day, no compounds were detected whereas on the second day, 12 μg/L acetone and 0.56 μg/L chloroform were detected. The quality of the inlet water was, not surprisingly, reflected in the outlet water; however, it does not appear that any compounds were generated (at levels above the detection limits) with an exposure of 1 h or less. The chloroform may have originated from the tap water, as average total trihalomethanes in Berkeley City tap water is 67.7 μg/L (*14*). We believe the acetone was released by silicone sealant, which was used in the construction of the feed tank and the UV device.

With exposures of 16 h or longer, an increase in the acetone concentration was observed; however, we do not feel that it represents a health risk because the concentrations were well below the EPA oral Reference Dose. After 16 h, low concentrations of 2-butanone and bromomethane or chloromethane were also detected in the device with Mexican PVC, whereas no byproducts (other than acetone) were detected in the device with US PVC. After 8 d and 35 d, however, these compounds were also detected in the device with US PVC. The device made with Mexican PVC was not tested at exposures longer than 16 h. None of the compounds that were detected is currently regulated in drinking water, although bromomethane is on the US EPA's contaminant candidate list (*15*). However, its concentration was much lower than the existing EPA oral Reference Dose.

Based on these results, we feel that UV unit constructed with PVC and lined with stainless steel is safe for the production of drinking water. Nonetheless, low concentrations of volatile organic compounds that are not regulated in drinking water may be produced if the unit is left on for extended periods of time without flow. Thus, we recommend that the unit be turned off if not in use for more than 1 hour. Additional experiments are underway to evaluate the impact of on/off cycles on UV bulb output and lifetime.

CONCLUSIONS

A wide range of technologies are needed around the world to supply safe drinking water. We have developed a point-of-use UV device that can be constructed, with minimal training, from low-cost, commonly available materials. The final design represents a balance between technical effectiveness, local availability of parts, ease of use, affordability and appeal. The suspended UV bulb eliminates the need for isolating the electrical components from the water and does not require pressurized supply. The use of PVC pipe allows for easy construction and sealing using commercially available end caps, while the stainless steel liner sufficiently protects the plastic from deterioration and the water from by-product formation. Depending on the construction materials used in a region, as well as user preferences, the design can be easily modified; however, any modifications should be tested according to the methods presented in this paper (bioassay, tracer study, and material degradation). We expect that there are many situations worldwide in which this model of household-scale water disinfection could be applied.

We recommend the UV device described in this paper for treating water at 5 L/min if the absorbance is less than 0.1 cm^{-1}; for water with higher absorbance, Figure 7 (or the mathematical model) can be used to determine the appropriate lower flow rate. Source waters with suspended

particles, or turbidity above 5 NTU, should be filtered through a membrane with a maximum pore size of 5 μm before disinfection with UV.

The current design has been certified by the Mexican Institute of Water Technology (IMTA, Cuernavaca, Mexico) as meeting the Mexican national standards for point-of-use water treatment devices. A second phase of household trials are planned to evaluate performance and user acceptance during actual use. Following these trials, the design will be made available in the public domain for distribution. We envision that the UV device can be made accessible to households directly, through community workshops, or manufactured and distributed by local microenterprises.

TABLES

Table 1. Fluence provided by UV disinfection device at 5 L/min as determined by MS2 bioassay

Date	UV_{254} Absorbance (cm^{-1})	Transmittance at 254nm	No. of Samples	Log Inactivation LOG (N_o/N)	Standard Deviation	Mean Equivalent Fluence (J/m^2) (95% Confidence Interval)
02/27/03	0.011	98%	5	3.8	0.53	771 (655-886)
03/07/03	0.013	97%	5	5.1	0.45	1093 (996-1190)
03/12/03	0.010	98%	5	5.2	0.42	1114 (1023-1204)
Mean	0.011	97%	15	4.7	0.79	981 (883-1079)

Table 2. Results from analysis of 59 volatile organic compounds measured in water samples from the UV disinfection device following exposure to UV light. Compounds not shown in table were not detected in any sample.[1]

	UV Exposure	pH	Absorbance (cm^{-1})	Benzene (µg/L)	Chloroethane (µg/L)	Chloroform (µg/L)	Chloromethane (µg/L)	Bromomethane (µg/L)	2-Butanone (µg/L)	1,1-Dichloroethane (µg/L)	1,2-Dichloroethane (µg/L)	1,2-Dichloropropane (µg/L)	1,3-Dichloropropane (µg/L)	Dichloromethane (µg/L)	Acetone (µg/L)	Zinc (mg/L)
Detection Limit				0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	5.0	0.01
WHO Guidelines		<8		10	NR	200	NR	NR	NR	NR	30[3]	40	NR	20	NR	3.0 (taste)
US EPA MCL (2002)[2]		6.5-8.5		5	NR	100[4]	NR	NR	NR	NR	5	5	NR	5	NR	5
EPA oral Reference Dose[5]				40	NR	100	NR	14	6,000	NR	NR	NR	NR	600	1,000	NR
Inlet Water[6]	0	7.8	0.200	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	--
Inlet Water[7]	0	7.7	0.112	ND	ND	0.56	ND	ND	ND	ND	ND	ND	ND	ND	12	--
PVC alone	18 d	1.8	--	ND	50	1	115	ND	ND	2.5	28	8.4	13	41	ND	--
ABS alone	16.5 d	--	--	1.8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	--
PVC w/galvanized steel	7 d	--	--	ND	ND	ND	3.2	ND	ND	ND	2.1	ND	1.1	4.1	ND	43
PVC w/stainless steel[6]	8.6 min	7.8	0.194	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	--
PVC w/stainless steel[7]	8.6 min	7.5	0.099	ND	ND	0.54	ND	ND	ND	ND	ND	ND	ND	ND	13	--
PVC w/stainless steel[7]	1 h	7.7	0.076	ND	ND	0.68	ND	ND	ND	ND	ND	ND	ND	ND	22	--
PVC w/stainless steel[6]	16 h	7.7	0.086	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	160	--
PVC w/stainless steel[7]	16 h	7.5	0.040	ND	ND	ND	ND	1.6	11	ND	ND	ND	ND	ND	240	--
PVC w/stainless steel[6]	8 d	6.7	--	ND	ND	ND	ND	1.4	7.7	ND	ND	ND	ND	ND	250	--
PVC w/stainless steel[6]	35 d	--	--	ND	ND	ND	0.51	ND	9	ND	ND	ND	ND	ND	250	--

[1] ND = none detected; NR = compound is not regulated; "--" = value was not tested.
[2] WHO guidelines compiled from (*11,16,17*); US EPA MCL compiled from (*12,18*).
[3] The draft guidelines for the 3rd edition of the WHO guidelines propose lowering the standard for 1,2-Dichloroethane from 30 µg/L to 4 µg/L (*16*).
[4] Regulated as total trihalomethanes.

[5] Oral Reference Dose (RfD) is an estimate of acceptable daily exposure made by the Integrated Risk Information System. The RfD is given as mg/kg-day, it is converted to µg/L by assuming a 50 kg person consuming 5 liters of water daily (*19*).

[6] This inlet water was used for the tests indicated with the same superscript. The characteristics of the inlet water may have been slightly different on other days. The PVC for these tests was purchased in the United States.

[7] This inlet water was used for the tests indicated with the same superscript. The characteristics of the inlet water may have been slightly different on other days. The PVC for these tests was purchased in Mexico.

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Figure 1. Schematic of UV disinfection device

Figure 2. Variables used in irradiance model

Figure 3. Fluence-inactivation response relationship for MS2 coliphage

Figure 4. Log inactivation of MS2 in UV disinfection device at 5 L/min, showing mean value and 95% confidence interval

Figure 5. Compilation of fluence-inactivation response relationships for a variety of pathogens with mean fluence and 95% confidence intervals provided by the UV disinfection device at 5 L/min

Sources: 1: (*20*); 3: (*21*); 4: (*22*); 6: (*23*); 8: (*24*); 9: (*25*); 10: (*26*)

Figure 6. Residence time distributions: Experimental data for UV disinfection device at 5 L/min, ideal completely mixed, ideal plug flow reactor and 12 CFSTRs in series.

Figure 7. Modeled results for fluence as a function of flow rate for different UV_{254} absorbance values.

Table 1. Bioassay results for medium-length design at 5 L/min

Table 2. Results from analysis of 59 semi-volatile compounds measured in the UV disinfection device following exposure of plastic, metal and water to UV light. Compounds not shown in table were not detected in any sample.

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