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Assessment of a Low-Cost, Point-of-Use, Ultraviolet Water Disinfection Technology

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1 **Abstract**

2 We describe a point-of-use (POU) ultraviolet (UV) disinfection technology, the UV Tube, that
3 can be made with locally available resources around the world for under \$50 US. Laboratory
4 and field studies were conducted to characterize the UV Tube's performance when treating a
5 flowrate of 5 L/min. Based on biological assays with MS2 coliphage, the UV Tube delivered an
6 average fluence of $900 \pm 80 \text{ J/m}^2$ (95% CI) in water with an absorption coefficient of 0.01 cm^{-1} .
7 The residence time distribution in the UV Tube was characterized as plug flow with dispersion
8 (Peclet Number = 19.7) and a mean hydraulic residence time of 36 s. Undesirable compounds
9 were leached or produced from UV Tubes constructed with unlined ABS, PVC, or a galvanized
10 steel liner. Lining the PVC pipe with stainless steel, however, prevented production of regulated
11 halogenated organics. A small field study in two rural communities in Baja California Sur
12 demonstrated that the UV Tube reduced *E. coli* concentrations to less than 1/100 mL in 65 out of
13 70 samples. Based on these results, we conclude that the UV Tube is a promising technology for
14 treating household drinking water at the point of use.

15

16 **Keywords:** drinking water treatment, point-of-use, ultraviolet disinfection, low-cost

17 **Introduction**

18 Waterborne illnesses associated with contaminated water sources, inadequate sanitation, and
19 poor hygiene are a leading cause of morbidity and mortality in the developing world, resulting in
20 more than 1.7 million deaths annually (Ezzati et al. 2002; Pruss et al. 2002; WHO 2002). The
21 burden of disease falls disproportionately on children, contributing significantly to high mortality
22 rates for children under five years old, exacerbating malnutrition (Corteguera 1993), and stunting
23 growth (Checkley et al. 2004).

24

25 Waterborne illnesses are largely preventable through adequate hygiene, sanitation and safe
26 drinking water; thus, one of the Millennium Development Goals (MDG) is to reduce the
27 population without access to safe water and sanitation by 50% by the year 2015. Despite
28 enormous progress over the past five years, 1.1 billion people still lack access to safe drinking
29 water and an accelerated effort is required if the MDG is to be met (WHO and UNICEF 2006).

30 In many regions, providing consistent, centralized water treatment and safe distribution is
31 prohibitively expensive or will take years to implement. One option that may overcome many of
32 these problems is treating drinking water in the household at the point-of-use (POU) (Mintz et al.
33 2001; Sobsey 2002).

34

35 A variety of low-cost household POU water treatment methods have been shown to reduce the
36 incidence of diarrheal illness in field studies in developing countries, including chlorination,
37 flocculation plus chlorination, solar disinfection (SODIS), filtration with commercial ceramic
38 filters, and boiling or heating to 70°C; several authors have reviewed these options (Lantagne et
39 al. 2006; Sobsey 2002). In addition to provision of safe water, safe storage of water in the

40 home, hygiene, and sanitation are also important interventions for reducing diarrheal illness
41 (Fewtrell et al. 2005; Wright et al. 2004).

42

43 Factors that should be considered in choosing an appropriate POU option for water disinfection
44 include effectiveness at eliminating potential pathogens, cost (initial, operation, and
45 maintenance), availability of materials and parts, scale of treatment, mode of treatment
46 (continuous vs. batch), and user preferences regarding time and effort required for operation and
47 water odor and taste. Each of the POU water treatment methods mentioned above has distinct
48 advantages and disadvantages. For example, chlorine is inexpensive but adds an undesirable
49 taste to the water and is not effective against protozoan cysts. Boiling is effective at eliminating
50 almost all microorganisms but is energy intensive and may contribute to deforestation if wood
51 fuel is used. SODIS is very inexpensive but is dependent on adequate sunlight and has a long
52 wait time. The varied nature of drinking water problems, availability of resources, and user
53 preferences necessitate diverse and complementary treatment techniques (Mintz et al. 2001).
54 Therefore, there is a need to continue to develop technologies to add to the POU water treatment
55 toolbox.

56

57 Ultraviolet (UV) light is increasingly being applied instead of chlorination for the disinfection of
58 both drinking water and wastewater in centralized treatment plants, because it is effective at
59 inactivating protozoan cysts and does not produce disinfection byproducts (Masschelein 2002).
60 Commercial UV disinfection units are currently available for household POU water treatment,
61 but their cost is typically high (several hundred \$US), and specialized replacement parts are
62 expensive and may not be readily available in many parts of the world. If UV disinfection was

63 affordable and available, however, it may have advantages for some households, including rapid
64 and continuous treatment of water as it flows from the water source (e.g household tap), little
65 user effort required to produce relatively large volumes of treated water, no change in the taste of
66 the water, and much lower energy requirements than boiling. A clear disadvantage for some
67 households is the requirement for electricity; in addition, the lack of a residual disinfectant will
68 not protect against recontamination after treatment.

69

70 In this paper we describe a point-of-use UV disinfection technology, the UV Tube, that can be
71 made with locally available resources around the world for under \$50 US. The UV Tube was
72 developed and tested using an iterative design process that continuously incorporated feedback
73 from potential users in rural Mexico. The objectives of the research reported herein were to (1)
74 measure the delivered fluence of the UV Tube at 5 L/min; (2) determine the residence time
75 distribution in the UV Tube at 5 L/min; (3) develop a conservative model for estimating the
76 fluence as a function of flow rates and absorption coefficient; (4) assess the safety of the
77 materials used to build the UV Tube; and (5) evaluate the performance of the UV Tube under
78 field conditions.

79 **Methods**

80 The general design of the UV Tube and a protocol for its use are described below. Three types
81 of tests (germicidal effectiveness, hydrodynamics, and materials degradation) were conducted in
82 the laboratory to assess its performance. A simple irradiance model was also developed to
83 provide rough estimates of the impact of flow rate and water absorbance on the germicidal
84 effectiveness of the UV Tube. Following validation in the laboratory, a preliminary, short-term

85 evaluation of field performance was conducted on UV Tubes installed in households in Baja
86 California, Mexico.

87

88 ***Description of UV Tube.*** UV Tubes were constructed from a 65-cm long, 4-in diameter tube
89 sealed with 4-in diameter Polyvinyl Chloride (PVC) end caps (Figure 1). A range of materials
90 was evaluated, as described in Materials Degradation Testing section below. Based on these
91 results, two different designs were used for the remaining research. In one design, the tube
92 consisted of a PVC pipe lined three quarters of the way around with rolled, 26-28 gage, food-
93 grade stainless steel sheet, with the remainder of the tube lined with aluminum foil to protect the
94 PVC from UV exposure. To prevent water from flowing between the stainless steel liner and the
95 PVC pipe, the edges were sealed with a silicone-based sealant; a hole was drilled in the bottom
96 of the PVC pipe to serve as a leak detector. In the other design, the tube was formed by rolling
97 28 gage, food-grade stainless steel sheet into a tube, which was secured at both ends with
98 stainless steel hose clamps; the seam was located at the top of the tube. A General Electric
99 germicidal G15T8 bulb was suspended from the top of the tube with bulb holders on the inside
100 of the pipe. A small window was drilled at the top of the tube and covered with acrylic to enable
101 the user to verify that the bulb is on before treating water. The ballast was mounted in a separate
102 section of 3-in diameter PVC pipe with endcaps to protect it from moisture. Water entered
103 through a 0.5-in copper elbow inlet inserted in the top of the tube, 7 cm from one end and exited
104 through a 1-in PVC elbow outlet inserted in the center of the far end cap, which regulated the
105 water height.

106

107 ***Germicidal Effectiveness Testing.*** Section 6.3 of the NSF/ANSI Standard 55 was used as a
108 model for the biological assay of the UV Tube, but several modifications were made, as
109 described below (NSF Joint Committee on Drinking Water Treatment Units 2002). All bulbs
110 had been used for at least 100 h prior to testing and were allowed to warm up for at least 30 min
111 on the day of the test. Four bioassays were conducted on three separate dates.

112

113 MS2 coliphage (ATTC 15597-B1) was propagated in antibiotic resistant *E. coli* (ATCC 700891)
114 and stored at 4°C (APHA et al. 2005). On the day of each bioassay, about 10 mL of MS2 stock
115 solution (approximately 10^{11} PFU/mL) was mixed with 250 L deionized water, achieving a
116 concentration of about 10^7 PFU/mL. The absorption coefficient (254 nm; 1-cm path length) was
117 measured on a Lambda 14 UV/VIS spectrophotometer (Perkin Elmer, Fremont, CA) and ranged
118 from 0.002 to 0.01 cm^{-1} . Challenge water was pumped from the mixing tank to a 50-L constant
119 head tank from which it flowed by gravity through a flow meter to the inlet of the UV Tube. The
120 UV Tube was operated at full power with a flowrate of 5 ± 0.05 L/min. For each bioassay, the
121 UV Tube was flushed for five unit void volumes (about 3 min). Then, three 50-mL “outlet”
122 samples were collected from the outlet at intervals of 1.5 residence times (about 45 s).

123 Immediately after collecting the third sample, the UV bulb was turned off and the UV Tube was
124 allowed to flush for five unit void volumes. Then, two 50-mL “inlet” samples were collected at
125 intervals of 1.5 residence times from the outlet of the UV Tube (with the UV bulb off). The
126 flowrate and operating volume were recorded. After the UV Tube was drained, another 50-mL
127 “inlet” sample was taken from the tubing entering the inlet of the UV Tube.

128

129 On the same day as each bioassay, the fluence (dose) response for MS2 bacteriophage was
130 measured. Triplicate samples of challenge water were subjected to three to five UV fluences
131 between 0 and 1200 J/m² using a bench-scale quasi-collimating beam (QCB) apparatus
132 (Brownell and Nelson 2006). Using a pipette, 10-mL aliquots of challenge water from the
133 bioassay inlet samples were placed in 60-mm Petri dishes, which were stirred magnetically
134 during illumination. The incident irradiance at the center of the surface of each sample was
135 measured before and after each exposure using a digital UV radiometer (IL1400A, International
136 Light, Newburyport, MS). The average germicidal irradiance was estimated according to Bolton
137 and Linden (Bolton and Linden 2003) using a modified version of the spreadsheet “Germicidal
138 Fluence (UV Dose) Calculations for a Low Pressure UV Lamp” obtained from Bolton
139 Photosciences Inc. (Edmonton, AB, Canada). Exposure time was controlled using a manual
140 shutter and ranged from 0 to 29 min.

141
142 MS2 samples were serially diluted and plated in triplicate according to the double layer agar
143 method (APHA et al. 2005). When cool, plates were inverted and incubated at 35 ± 1 °C for 18
144 ± 2 h and enumerated. Only plates containing 25-250 PFU/mL were used to calculate the titer of
145 the MS2 bacteriophage concentration for each sample.

146
147 ***Analysis of Bioassay Data.*** For each of four tests, fluence was calculated according to Section
148 6.3 of NSF/ANSI 55. In brief, the slope and intercept of the MS2 fluence response curve was
149 used to calculate the average fluence in the UV Tube from the logarithm of the ratio of influent
150 to effluent MS2 concentrations. The influent and effluent values for each test were calculated as
151 the geometric means of the MS2 concentration of three different samples. Each sample

152 concentration was calculated as the geometric mean of at least three replicates. Uncertainty for
153 each fluence calculation was estimated by error propagation. The arithmetic mean of the
154 fluences determined in each of the four tests was calculated to represent the overall average
155 fluence delivered by the UV Tube. The corresponding prediction interval was calculated using
156 the standard error and standard deviation of the four fluence estimates. To assess the sensitivity
157 of the fluence values to different component variables, an individual fluence estimate was
158 calculated for every possible combination of influent and effluent MS2 concentration
159 measurements (1482 in total) and the average slope and intercept values from the fluence
160 response curves.

161

162 ***Flow characterization.*** Three tracer studies were conducted to determine the residence time
163 distribution and mean hydraulic detention time of the PVC-lined UV Tube at a constant flowrate
164 of approximately 5 L/min. The flowrate was set with a flowmeter but measured for accuracy
165 using a stopwatch and graduated cylinder. Approximately 2 mL of Rhodamine WT dye (Fisher
166 Scientific) was injected just above the inlet to the UV Tube using a syringe. The exact amount
167 of dye injected for each test was determined as the difference between the pre- and post-test
168 weight of the syringe. 10-mL samples were collected from the outlet of the UV Tube at 3-s
169 intervals for 3 min. The absorbance of each sample at 555 nm (1-cm path length) was
170 determined and compared with a standard curve to establish the dye concentration of each
171 sample (weight fraction). The operating volume was determined following the test by stopping
172 the flow and immediately placing a beaker under the outlet. After the flowing water was
173 collected, the UV Tube was tipped and the end caps were opened over the beaker to remove any
174 remaining water for measurement by graduated cylinder.

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Materials Degradation Testing. A range of materials was evaluated for constructing UV Tubes to determine if inorganic or organic compounds could be leached or produced in the water due to reactions with UV light under a range of operating conditions. Long-term exposure tests (> 7 d) were conducted with acrylonitrile butadiene styrene (ABS) pipe, PVC pipe, PVC lined with galvanized steel, and PVC lined with stainless steel. During these tests the UV Tube contained stagnant water and the UV lamp was on; after the exposure period, water flow was turned on and the first outlet water was collected. Additional tests were conducted on the stainless-steel lined UV Tube using PVC pipe purchased in the U.S. (same as material used above) as well as PVC purchased in Mexico. A flow-through test was conducted at a minimal flow rate of 0.24 L/min, and additional batch tests (bulb on with no flow) were conducted for exposure times of 1 h and 16 h (simulating overnight).

The inlet water for tests with PVC lined with stainless steel was Berkeley tap water augmented with humic acids (Sigma-Aldrich, Allentown, PA) to a concentration of 40 mg/L (20 mg/L dissolved organic carbon (DOC)). Humic acids have not been shown to produce by-products under UV radiation, but they are known precursors for halogenated disinfection by-products when using chlorine-based disinfectants. They were included in this study to determine if compounds produced from exposing PVC to UV radiation could interact with natural organic matter to produce chlorinated organics. The absorption coefficient of this test water ($\lambda = 254$ nm) was 0.20 cm^{-1} , resulting in about 90% attenuation of the UV light at the deepest part of the reactor. For the other tests distilled water was used.

198 The temperature and pH of all samples were measured in the laboratory and then samples were
 199 sent to Sequoia Analytical (Morgan Hill, CA) for analysis of 59 common volatile organic
 200 compounds (VOCs) according to the US EPA method 524.2. For the UV Tube with the
 201 galvanized steel liner, the sample was also analyzed for aluminum, iron, and zinc.

202

203 **Mathematical modeling.** A conservative irradiance model was developed by modifying the
 204 point source summation (PSS) method for a submerged bulb UV reactor (Blatchley 1997) to
 205 describe our suspended bulb design. Simplifications and assumptions in the model were
 206 designed to be conservative, i.e., to provide an underestimate of the fluence. For example, the
 207 light reflected from the inside surface back into the water was neglected in the model. The key
 208 variables used in the model are illustrated in Figure 2.

209

210 The following equation was used to calculate irradiance (modified from Blatchley, 1997):

$$211 \quad I_{i,j} = \frac{P_{\lambda}}{4n\pi\rho_{i,j}^2} \exp\left[-\left((\alpha \ln(10))(R - r_{air})\frac{\rho_{i,j}}{R}\right)\right] \quad (1)$$

212 Where:

213 $I_{i,j}$ = irradiance at point j due to site i in point source (mW/cm²)

214 P_{λ} = bulb power at 254 nm (mW)

215 n = number of point sources

216 $\rho_{i,j}$ = distance separating site i in point source and site j in receptor (cm)

217 α = absorption coefficient of water at 254 nm (cm⁻¹)

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

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

220
221 Additional calculations accounted for the operational flow-through height of the water
222 (measured), the length of tube on each side of the bulb that was not directly below the light, the
223 residence time, and the cumulative fluence (Cohn 2002). Calculations were performed using
224 Engineering Equation Solver (EES, F-Chart Software, Middleton, WI). The individual
225 irradiance distributions over multiple slices in the direction parallel to flow were summed to
226 compute the average fluence. The hydraulics in the reactor were described assuming ideal plug
227 flow, i.e. the irradiance for each section was multiplied by a fraction of the mean hydraulic
228 detention time equivalent to its fractional volume. As discussed in the results section, the actual
229 flow behavior deviated from plug flow, and the impact on the model is also discussed in the
230 results section. The model was used to evaluate the effects of flow rate and absorption
231 coefficient on the mean delivered fluence, using the following design values: radius = 5.08 cm;
232 tube length = 65 cm; bulb output at 254 nm = 5,000 mW; weir height = 4 cm; distance from bulb
233 to bottom of tube = 7.62 cm; distance between end of UV bulb and PVC endcap = 6.35 cm.

234
235 **Field Performance** During the summer of 2005, a small field trial was conducted in Baja
236 California Sur, Mexico. The purpose of the field trial was to gather information about the user-
237 friendliness of the device, evaluate the performance of the UV Tube under field conditions
238 (including water quality), and explore the feasibility of introducing the device in rural Mexico.
239 Only the water quality component of the study is reported here; a full report of the field trial is
240 reported elsewhere (Reygadas et al. 2007). UV Tubes were installed in the individual homes of
241 24 families in the communities of Los Espiritus (LE) and El Destino (ED); the communities'
242 names have been changed to protect the anonymity of participants. Water sources included

243 springs that were accessed in shallow hand-dug wells (LE) and deeper, concrete-lined wells
244 (ED). Household members obtained water by pumping (gasoline or wind-powered), hand
245 carrying, or transporting it in cars or trucks and stored water in an array of barrels (typically
246 ~200 L) around the house. The mean absorption coefficient for the water sources was 0.012 cm^{-1}
247 ± 0.009 (s.d.). A support to hold the UV Tube was constructed from a plastic 20-L bucket; a
248 second bucket installed above it provided a reservoir, from which water flowed through a small
249 diameter tube to the UV Tube. The flow rate varied from 5 to 3 L/min as the reservoir emptied.

250

251 Each family was visited roughly four times during the field study. During each visit, four types
252 of water samples were collected: water derived directly from springs and wells, source water that
253 had been collected and stored in homes for drinking and other domestic purposes, source water
254 that had been treated by the UV Tube, and source water that had been treated by the UV Tube
255 and then stored in the home. To collect paired samples from before and after treatment,
256 household members were asked to disinfect a batch of water in the presence of the researchers
257 during a brief interview session; they obtained the water from their regular source and passed
258 this water through the UV Tube. Small, sterile plastic bottles (Idexx WV120ST-20) were used to
259 collect samples of the water before it was disinfected and as it exited the UV Tube. Samples
260 were transported in the dark in an uninsulated vinyl bag to the local school building, where a
261 small membrane filtration work area was devised. Samples not immediately analyzed were
262 stored on ice for up to 24 h. Water samples were collected once a week for four consecutive
263 weeks during July of 2005. An additional, fifth round of sampling was completed in September,
264 approximately nine weeks after the fourth round.

265

266 *E. coli* were enumerated in 100 mL samples by membrane filtration with a 0.45 micron
267 nitrocellulose membrane (Millipore). The stainless steel funnel and filter holder (Millipore) was
268 sterilized between samples by spraying with 70% EtOH solution and flaming. The filter was
269 then incubated with nutrient broth (mColiBlue24, Hach) at 35 °C for 24 hours. Doors and
270 windows were closed to prevent air movement, the work surface was sterilized with 70% EtOH,
271 and a small flame was maintained in the center of the work area. The ambient temperature was
272 often greater than 30 °C, and sometimes greater than 35 °C.

273

274 **Results and Discussion**

275 *Germicidal Effectiveness.* The bioassay data are summarized in Table 1. The fluence estimates
276 for the four bioassays were 930 ± 70 , 820 ± 60 , 930 ± 60 , 900 ± 210 (s.e.), resulting in a mean
277 fluence of 900 ± 80 J/m² (95% CI). The prediction interval, or the range within which a new
278 individual measurement of fluence would be expected to fall with 95% confidence, was ± 180
279 J/m², resulting in a range from 720 to 1080 J/m². The collimated beam data were consistent with
280 published results summarized by Batch et al. (Batch et al. 2004), and the regression line from the
281 combined data falls close to the guidelines established by the National Water Research Institute
282 (NWRI 2003).

283

284 The use of only three points in the fluence response curve did not significantly impact the final
285 fluence calculations. When MS2 concentration measurements from collimated beam data
286 collected during different tests were randomly combined with influent and effluent concentration
287 measurements from different tests, variability in slope and intercept explained little of the
288 variability in fluence. Regression analyses of fluences calculated from all possible combinations

289 of individual influent and effluent MS2 concentration measurements showed that effluent
290 number had a large and significant impact on fluence independent of test number but influent
291 number did not. The larger impact of effluent concentration measurements on fluence reflects the
292 fact that the relative variability in effluent MS2 concentration is several orders of magnitude
293 greater than that in influent samples. Together, these data suggest that where resources are
294 limited, the number of collimated beam and influent samples could be reduced without
295 substantially harming data quality.

296

297 According to the Draft USEPA Ultraviolet Disinfection Guidance Manual, UV fluences (doses)
298 of 150 J/m² or more are sufficient to obtain 3-log reduction of the protozoa *Giardia lamblia* and
299 *Cryptosporidium parvum*, and fluences greater than 1860 J/m² achieve 4-log inactivation of
300 virus, thus meeting the criteria established in the Surface Water Treatment Rules (USEPA 2003).
301 For certification of household-scale POU UV disinfection systems by the National Sanitation
302 Foundation (NSF), a minimum delivered fluence of 400 J/m² is required (NSF Joint Committee
303 on Drinking Water Treatment Units 2002). At 5 L/min, the mean fluence provided by the UV
304 Tube was more than twice the NSF requirement. Based on the values given above, this fluence
305 is expected to be sufficient to achieve several log inactivation of protozoan cysts and viruses. It
306 should be kept in mind, however, that the absorbance of the water used for these bioassays was
307 low (0.002 to 0.01 cm⁻¹), and a higher absorbance will significantly decrease the delivered UV
308 dose.

309

310 ***Flow characterization.*** The results of the three tracer studies are summarized in Table 2. The
311 flow rate was maintained at a constant value throughout each test, but varied between 4.96 and

312 5.22 L/min from test to test. The higher flow rates resulted in slightly higher liquid volumes in
313 the UV Tube due to the higher water level over the outlet weir (pipe). The average theoretical
314 HRT (θ), based on the measured volumes and flow rates, was calculated to be 35.8 s. The
315 average experimental HRT (t_{bar}), based on analysis of the tracer curves, was found to be 35.4 s
316 (Levenspiel 1976). The experimentally measured HRT was within 4% of the theoretical HRT in
317 all three tracer tests. In one of the tests, the mean HRT was slightly longer than the theoretical
318 HRT, which may be explained by slight errors in the measurement of the time (starting the
319 stopwatch as tracer was injected), flow rate, and/or operating volume of the UV Tube. The
320 measured dye recovery ranged from 100 to 108%; values above 100% may have resulted from
321 errors in the initial weight of dye, the spectrometer measurements, or in the numerical integration
322 of the discrete data set. Overall, the agreement between the three different tracer tests and the
323 high dye recovery are a validation of the experimental methods.

324

325 The flow pattern in the UV Tube was characterized by the differential residence time distribution
326 curves (Figure 3). Both the tanks-in-series and plug flow with dispersion models were fit to the
327 data. The model parameters were determined by minimizing the squares of the errors using all
328 data points (Haas et al. 1997) by varying either N (tanks-in-series) or the Peclet (Pe) number
329 (plug flow with dispersion); the HRT was fixed as the average value calculated from the tracer
330 tests. The dispersion model, assuming closed boundaries and using the approximation suggested
331 by (Haas et al. 1997) provided the best fit, with $Pe = 19.7$, compared to $N = 11.1$ for the tanks-in-
332 series (shown in Figure 3). Minimizing the errors provided a better fit than the method of
333 moments (Levenspiel 1999). The first tracer exited the UV Tube between 3 and 6 s; visual
334 observations of a clear PVC UV Tube (built for experimental purposes) revealed a somewhat

335 radial velocity distribution, as expected due to shear forces, with faster-moving water at the top
336 and center of the channel. Mixing also occurred as the inlet water plunged into the channel. No
337 internal recirculation was observed visually, nor is evident as multiple peaks in the tracer curves.
338 Finally, no dead spaces were observed, nor revealed by the tracer curves (evident when $t_{\text{bar}} < \theta$).

339
340 **Materials Degradation.** Material degradation due to sunlight and/or UVA and UVB radiation is
341 often studied, but little is known about the effect of 254-nm UVC radiation on the materials we
342 investigated. The results from our tests are summarized in Table 3. For comparison, drinking
343 water guidelines established by the World Health Organization (WHO 2006) and standards set
344 by the US Environmental Protection Agency (US EPA 2003) are shown. In addition, when
345 possible, a maximum acceptable concentration was determined based on the EPA Oral Reference
346 Dose (US EPA 2006), which is an estimate of acceptable daily exposure. The reference dose,
347 given in mg/kg-d, was converted to concentration ($\mu\text{g/L}$) by assuming a 50-kg person consumes
348 5 L of water per day.

349
350 At least one analyte was detected in all of the water samples tested. Benzene was detected in the
351 ABS UV Tube at a concentration slightly lower than the EPA MCL. With the PVC UV Tube,
352 several chlorinated organics were present at concentrations exceeding drinking water standards,
353 and the pH was also unacceptably low. Lining the PVC UV Tube with galvanized steel
354 produced high zinc levels, which cause a foul taste. Based on these results, we advise against the
355 use of unlined ABS, PVC, or the use of galvanized steel as a liner.

356

357 UV Tubes made with PVC purchased in the U.S. and Mexico and lined with stainless steel
358 produced similar results; thus, the data have been combined in Table 3. Lining the PVC UV
359 Tube with stainless steel eliminated production of chlorinated organics and VOCs with the
360 exception of bromomethane and butanone, which are unregulated (bromomethane was proposed
361 and then removed from the US EPA's Contaminant Candidate List in 1998). Furthermore, these
362 compounds were not detectable when the UV exposure time was 1 h or less. Interestingly,
363 chloroform was the only detectable compound (at levels just above the detection limit) during the
364 short-duration tests, and was also present at a similar concentration in the inlet sample that was
365 tested. Thus, the likely source of chloroform was the tap water, which contains average annual
366 concentrations of total trihalomethanes ranging from 27-51 $\mu\text{g/L}$ (EBMUD 2006). Because
367 chloroform is volatile, it may have been removed during the longer duration tests. The only
368 compound that appeared at higher concentrations after longer exposure was acetone. Although
369 we are unsure of its origin, possible sources of acetone include the silicone sealant or residue
370 remaining from the stainless steel sheet manufacturing process; there is no evidence to indicate
371 that these low levels represent a health risk.

372

373 ***Mathematical Model.*** The average fluence delivered by the UV Tube was estimated using the
374 point-source summation model for flow rates between 3 and 10 L/min and with absorption
375 coefficients ranging from 0.01 to 0.16 cm^{-1} (Figure 4). At a flow rate of 5 L/min and absorption
376 coefficient of 0.01, the model estimated a fluence of 812 J/m^2 , compared to the experimentally
377 determined fluence of 900 J/m^2 , which is also shown in Figure 4. Thus, despite the assumption
378 of plug flow hydraulics, the model provided a conservative estimate of the fluence. Although the
379 model should not be used to estimate the exact delivered fluence, the results are useful for design

380 purposes for understanding the quantitative impacts of flow and absorbance. For example, at a
381 flow rate of 5 L/min, an absorbance higher than 0.13 cm^{-1} is likely to lead to fluences lower than
382 the NSF minimum fluence of 400 J/m^2 . These model results are roughly consistent with
383 additional bioassay results that have been conducted in our lab using water with higher
384 absorption coefficients (data not shown). One option for treating water with higher absorbance
385 is to decrease the flow rate. Additional research is needed, however, to validate performance at
386 other flowrates, because tracer experiments have indicated that the mixing regime at the UV
387 Tube inlet changes significantly (data not shown).

388

389 **Field Performance** Ninety-four paired samples were collected of water entering and exiting UV
390 Tubes during household use in Baja California, Sur. In 24 samples, no *E.coli* were detected in
391 either the inlet or outlet samples; in the other 70 samples, the inlet concentration ranged from 1
392 to 243 with a geometric mean value of 15 CFU/100 mL. In 65 outlet samples, no *E.coli* were
393 detected, and the counts in the remaining five samples were 1, 1, 1, 8, and 31 CFU/100 mL. The
394 use of the UV Tube resulted in 20 out of the 24 families having access to water that conformed
395 to the WHO guidelines ($< 1 \text{ E.coli}/100 \text{ mL}$) during all four visits, whereas only one family
396 would have had access to such water without the UV Tube. Thus, the UV Tube effectively
397 lowered the level of bacterial contamination during actual use in the field. However, the
398 presence of *E.coli* in the effluent of five samples suggests that additional research is needed to
399 characterize and improve the performance of the UV Tube under field conditions. In addition,
400 out of 83 samples collected from UV-treated water that had been stored in the home, 17
401 contained *E. coli*. Thus, there was evidence of recontamination or regrowth of *E.coli* during
402 storage, probably due to the use of storage containers without effective seals and the use of a

403 common cup for extracting water. These data illustrate that the lack of residual disinfectant in
404 storage containers is a potential disadvantage of UV treatment compared to chlorination.
405 However, safe storage in containers that do not allow contact with the treated water (e.g., spigot
406 or hand pump) may be able to prevent recontamination.

407

408 **Conclusions**

409 Based on biological assays with MS2 coliphage, the UV Tube delivered an average fluence of
410 900 J/m^2 (95% prediction interval of 720 to 1080 J/m^2) at a flow rate of 5 L/min and an
411 absorption coefficient of 0.01 cm^{-1} . Under the same conditions, the mathematical model
412 predicted a fluence of 812 J/m^2 . Thus, despite its simplicity, the model agreed fairly well with
413 the experimentally determined fluence, and can be used to inform decisions about acceptable
414 operating conditions (e.g., determining the maximum flow rate for water with higher
415 absorbance). The residence time distribution at a flow rate of 5 L/min was characterized as plug
416 flow with dispersion ($Pe = 19.7$) and a mean hydraulic residence time of 36 s. Based on the
417 materials degradation testing, we advise against the use of unlined ABS, PVC, or the use of
418 galvanized steel as a liner for UV Tubes. Lining the PVC pipe with stainless steel, however,
419 prevented production of regulated halogenated organics. A small field study in two rural
420 communities in Baja California Sur demonstrated that the UV Tube reduced *E. coli*
421 concentrations to less than one per 100 mL in 65 out of 70 samples. Additional research is
422 underway to expand the scope of our field studies to comprehensively address the factors that
423 influence the disinfection performance as well as consistent and correct use of the UV Tube over
424 longer time periods.

425

426 The laboratory and field studies reported here suggest that the UV Tube is a promising
427 technology for treating household drinking water at the point of use. Because the UV Tube can
428 be constructed using locally available resources, we believe it is a lower-cost (< \$50 US) and
429 more sustainable option for POU UV treatment compared to commercially available UV
430 disinfection units. Ultimately, by expanding the range of technologies available for POU water
431 disinfection, we hope that the UV Tube will contribute to long-term, sustainable global efforts
432 that empower more households to gain access to safe water.

433

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Table 1. MS2 inactivation data for three bioassay challenge tests of the UV Tube. Calculated values may not correspond directly to raw data due to rounding.

Exp	Inlet (PFU/mL)		Outlet (PFU/mL)		Log Reduction	Fluence (J/m ²)	Standard Error (J/m ²)
	Sample (geomean of 3 replicates)	Geomean	Sample	Geomean			
1	3.5 x 10 ⁸	3.6 x 10 ⁸	9.0 x 10 ³	1.2 x 10 ⁴	4.5	930	70
	3.5 x 10 ⁸		1.1 x 10 ⁴				
	3.7 x 10 ⁸		1.7 x 10 ⁴				
2	3.9 x 10 ⁷	3.7 x 10 ⁸	3.6 x 10 ³	2.6 x 10 ³	4.1	820	60
	2.9 x 10 ⁷		1.7 x 10 ³				
	4.3 x 10 ⁷		3.0 x 10 ³				
3	4.3 x 10 ⁷	3.9 x 10 ⁷	1.6 x 10 ³	8.8 x 10 ²	4.6	930	60
	4.1 x 10 ⁷		8.3 x 10 ²				
	3.4 x 10 ⁷		5.2 x 10 ²				
4	2.3 x 10 ⁷	1.5 x 10 ⁷	4.2 x 10 ²	6.4 x 10 ²	4.4	900	210
	2.0 x 10 ⁷		3.5 x 10 ²				
	1.2 x 10 ⁷		1.9 x 10 ³				
Mean						900	80 (95% CI)

Table 2. Hydrodynamic characteristics of UV Tube based on three tracer studies.

Parameter	Exp 1	Exp 2	Exp 3	Average	St. Dev.
Volume, L	2.91	3.15	3.12	3.06	0.14
Flowrate, L/min	4.96	5.18	5.22	5.12	0.13
Theoretical HRT (θ), s	35.2	36.5	35.8	35.8	0.64
Mean HRT (t_{bar}), s	36.2	35.5	34.5	35.4	0.83
σ^2 , s ²	277	190	179	215	53
θ/t_{bar}	1.03	0.97	0.96	0.99	0.03
Dye recovery, %	100	108	101	103	5

Table 3. Results from analysis of 59 volatile organic compounds and metals in water samples from the UV Tube following exposure to UV light. Compounds not shown in table were not detected in any sample.¹

UV Exposure time	Water type	Number of samples (independent experiments)	pH	Acetone (µg/L)	Benzene (µg/L)	Bromomethane (µg/L)	2-Butanone (µg/L)	Chloroethane (µg/L)	Chloroform (µg/L)	Chloromethane (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)	Zinc (mg/L)	
Detection Limit				5.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.01	
WHO (2006)			△8	NR	10	NR	NR	NR	300	NR	NR	30	40	NR	20	3	
US EPA MCL (2003)			6.5-8.5	NR	5	NR	NR	NR	80 ²	NR	NR	5	5	NR	5	5	
US EPA RfD ³				1,000	40	14	6,000	NR	100	NR	NR	NR	NR	NR	600	NR	
Inlet Water ⁴	0	T+H	1	7.7	12	ND	ND	ND	ND	0.56	ND	ND	ND	ND	ND	--	
PVC w/stainless steel	8.6 min	T+H	2	7.8	15	ND	ND	ND	ND	0.61	ND	ND	ND	ND	ND	--	
"	1 h	T+H	2	7.7	24	ND	ND	ND	ND	0.71	ND	ND	ND	ND	ND	--	
"	16 h	T+H	2	7.7	230	ND	1.2	13	ND	ND	ND	ND	ND	ND	ND	--	
"	> 7 d	T+H	1	6.7	250	ND	1.4	7.7	ND	ND	ND	ND	ND	ND	ND	--	
PVC w/galvanized steel	> 7 d	DI	1	--	ND	ND	ND	ND	ND	3.2	ND	2.1	ND	1.1	4.1	43	
PVC alone	> 7 d	DI	1	1.8	ND	ND	ND	ND	50	1	115	2.5	28	8.4	13	41	--
ABS alone	> 7 d	DI	1	--	ND	1.8	ND	ND	ND	ND	ND	ND	ND	ND	ND	--	

¹ ND = none detected; NR = compound is not regulated; "--" = parameter was not tested; T+H = Berkeley tap water plus humic acids; DI = Distilled water

² Regulated as total trihalomethanes.

³ 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 was converted to µg/L by assuming a 50 kg person consumes 5 L of water per day (US EPA 2006).

⁴ Inlet water (Berkeley tap water plus 40 mg/L humic acids) was measured on only one occasion. The characteristics of the inlet water may have been different on other days.

Figure 1. Schematic of the PVC, stainless steel-lined, UV Tube water disinfection unit.

Figure 2. Variables used in point source summation irradiance model.

Figure 3. Differential residence time distribution curves for three tracer studies and best fit curves for CFSTRs in series and PFR with dispersion models.

Figure 4. UV Tube fluence predicted by the irradiance model as a function of flow rate and absorption coefficient (cm^{-1}) of water. The bioassay results at a flow rate of 5 L/min are also shown.

Figure 1

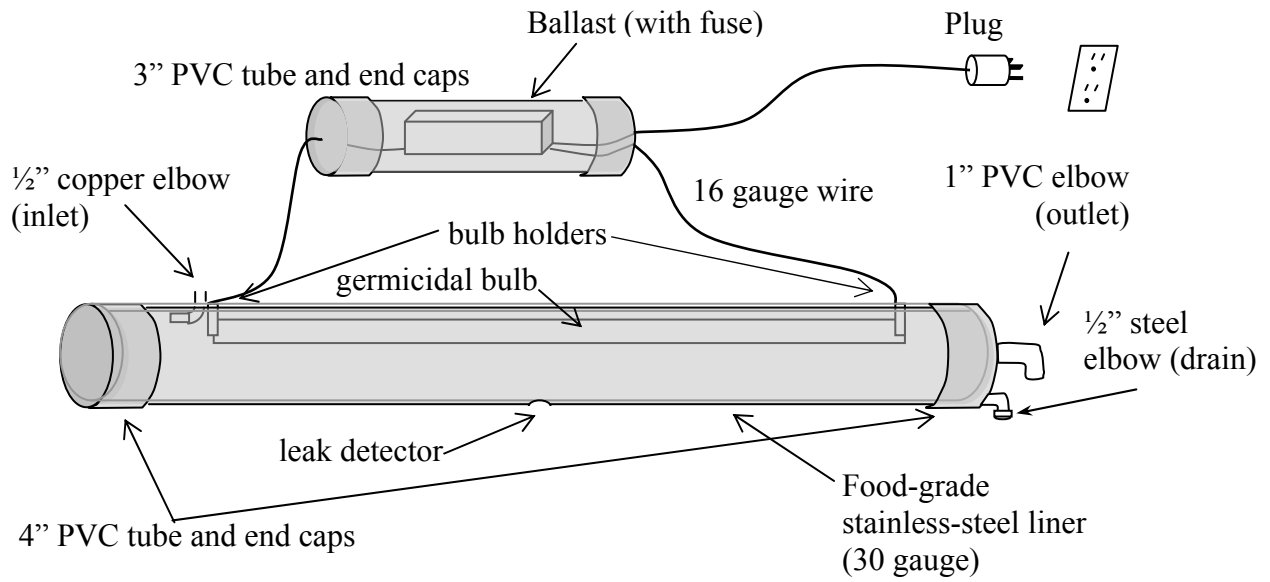


Figure 2

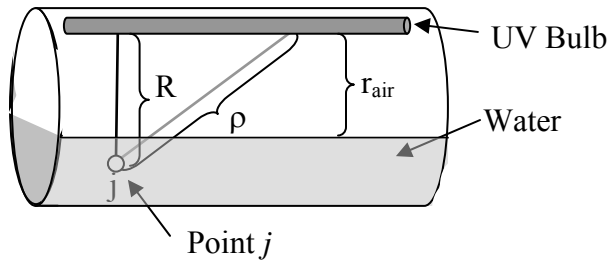


Figure 3

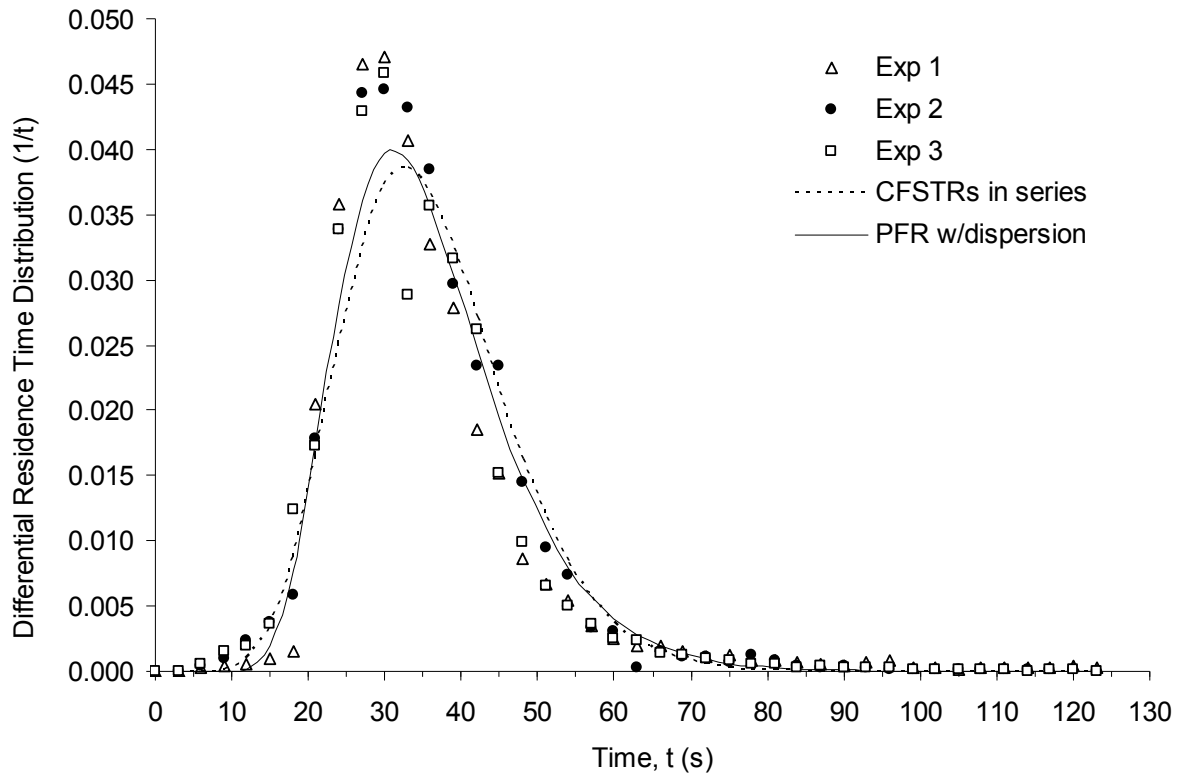


Figure 4

