THE UV-TUBE AS AN APPROPRIATE WATER DISINFECTION TECHNOLOGY: An Assessment of Technical Performance and Potential for Dissemination

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I. Introduction

Globally, millions of people die each year from waterborne disease that could be prevented through a combined effort of improved water supply and sanitation. In this project I address the issue of improved water supply through the design and dissemination of a household-level, or point-of-use, water disinfection technology. The problem of microbiologically contaminated water is very much a physical one with a technical solution. However, the technical problem does not so much concern mechanisms of disinfection – these have been well understood for the last century – rather the design of an *appropriate* solution, i.e. one that is affordable, available, inexpensive, easy to use and reliable. Users must have a sense of ownership and understanding of the technology in order to use it consistently. The real problem becomes designing a technology that balances technical effectiveness with locally available and inexpensive materials into a design that will be appealing to the targeted user.

By balancing the aforementioned goals, the UV-Tube presents one possible tool to improve water quality at the household level.

Over two million people, mostly children under five, die every year due to water related diseases such as diarrhea, shigellosis, dysentery and cholera (WHO 2000). While the problem is due to both lack of high quality water supply and poor or nonexistent sanitation, it has been estimated that diarrhea morbidity could be reduced by 17% through improvement of supply alone (Esrey, Potash et al. 1991). The lack of clean water is an widespread problem, currently one quarter of the world's population does not have access to any source of improved water supply (WHO 2001).

In the United States, municipal chlorination of drinking water, which began in the early 1900s, lead to a drastic decline in the rates of many waterborne diseases, such as dysentery, cholera and typhoid fever, which had ravaged the population during the previous century (Christman 1998). However, for chlorination to be effective it must be combined with a robust distribution system – and this is what is lacking in so many developing countries. In many places water pressure is low or inconsistent and pipes are not well maintained - contaminated water is able to migrate into drinking water pipes at levels too high for the chlorine residual to counteract (Mintz, Reiff et al. 1995, p.948). Until distribution systems can be upgraded, properly maintained, and provided a consistent and appropriate disinfectant residual, municipal chlorination will not be the solution. Instead, safe drinking water can be better ensured through point-of-use treatment, which provides immediate treatment at the tap.

The simplest point-of-use method is the addition of a disinfectant chemical such as sodium hypochlorite. The cost is very low, however, the procedure requires a long contact time and there is some complexity to providing the correct dose: if the amount added is too low, adequate disinfection may not be achieved, but if it is too high, unpleasant taste may discourage consumption (Burch and Thomas 1998).

A comparison of household level disinfection options is shown in Table 1.

Table 1. Disinfection Options

Technology	Affordable	High capacity	Germicidal action	Passive operation
current UV options		✓	✓	✓
Membrane filtration		✓	✓	✓
Slow sand filtration	✓		✓	
Solar box cooker pasteurization	✓		✓	
Solar Puddle pasteurization	✓	✓	✓	
Boiling	✓		✓	
Manual chemical addition	✓	✓	✓	
Automated chemical addition		✓	✓	✓
Reverse osmosis		✓	✓	✓
Ozonation		✓	✓	✓
UV-Tube	✓	✓	✓	✓

Table adapted from (Connelly and Kammen 2000)

As can be seen in Table 1, no option other than the UV-Tube provides high capacity, germicidal action, passive operation and is affordable. What separates the UV-Tube from current UV options, is the affordability. UV disinfection does not need to be expensive to be effective. The UV-Tube can built for under $40, and requires only 30W of electricity. In Mexico, where electricity cost is approximately $0.05/kWh, this amounts to approximately $1.00/month. If the UV-Tube were running for 24 hours straight, at 5 L/min and the entire initial cost and the electricity cost were spread evenly over the first 24 hours, then the cost per volume of water disinfected would be $0.0056/L. If the UV-Tube were run continuously and the cost were spread out over the first year, then the cost per volume would be $0.00002/L

All methods, with the exception of chlorine, do not provide a residual concentration of disinfectant to protect against recontamination. If the water is not to be consumed immediately it must be safely stored. Containers with narrow necks have been recommended to decrease the potential of recontamination following treatment with a point-of-use system (Mintz, Reiff et al. 1995). However, recontamination can most easily be avoided if water can be disinfected at a high capacity in a flow-through system, so that there is no need for storage.

The importance of convenience should not be underestimated. A study of women in Ghana found that they considered energy and time more important than water quality in choosing a water source. This was true despite the fact that these women were educated on waterborne disease and one quarter of all child deaths in the region were due to diarrheal disease (Kendie 1992). To account for this reality, an effective water disinfection system will be completely passive, requiring minimal time and effort and no daily maintenance.

Perhaps most importantly, for a point-of-use system to be effective – it has to be installed. Unlike a municipal treatment system in which a small group decides on and maintains the treatment for a large group, with a point-of-use system, the responsibility falls on each household individually. Households have to have access to the technology, knowledge of how to use it, desire to use it and the means to purchase it. Therefore the technology itself should be widely available, built from locally available parts, be easy to understand, affordable and desirable.

Through close interactions with potential UV-Tube users in Mexico, we were able to incorporate their desires and preferences into each stage of the UV-Tube design. The final product can be built from locally available materials, is easy to use and affordable. The UV-Tube also shows a high level of germicidal effectiveness.

II. Research Objectives

This paper introduces the idea of the UV-Tube, a water disinfection device that employs ultraviolet light for disinfection in a highly effective, affordable, passive system that can be built from locally available parts in developing countries. It then describes the research that I conducted under the direction of Lloyd Connelly, from January 2001 through May 2002. This research took place in the Renewable and Appropriate Energy Laboratory at UC Berkeley and in a field site, near Pátzcuaro, Mexico. Although I present the technical components separately from the socioeconomic and cultural ones, they were actually part of an integrated exploration. Preliminary field results drove many of the technical questions and vice versa.

A. Laboratory Experiments

The laboratory component was focused on the quantification of the UV-Tube performance and optimization of the design.

The effectiveness of an ultraviolet water disinfection device is determined by the dose. Because dose is a function of the geometry, the surface properties, the absorbance of the water and hydrodynamics of the reactor, it can not be determined directly. Three methods are commonly used to infer dose. (1) A biological assay uses a measured dose-response relationship of an indicator organism to back-calculate dose based on inactivation data. (2) A mathematical model approximates the bulb as a line of point sources distributing light equally in all directions. Following the point source summation (PSS) formula, the irradiance at each point is then calculated as the sum of the irradiance from all point sources (Blatchley 1997). (3) Chemical actinometry uses a substance that undergoes a predictable and quantifiable photochemical reaction. The concentrations of the reactants in the influent and the products in the effluent are used to calculate dose.

1. Biological Assay: *E.coli*

The principal goal in this phase was to characterize *E.coli* inactivation within the UV-Tube in order to calculate the UV dose provided. *E.coli* inactivation was characterized for a variety of flow rates and transmittance values.

To reach this goal required:

- Construction of a testing apparatus
- Development of an *E.coli* growth procedure to provide a high and stable concentration of bacteria within the feed tank

To characterize the effect of decreased transmittance required:

- Identification of a substance that would decrease transmittance of the water
- Development of an empirical relationship between concentration of substance and transmittance (the molar extinction coefficient)
- Determination of effect of substance on *E.coli* viability

2. Irradiance Distribution

The objective of this phase was to predict the irradiance distribution within the UV-Tube. This goal was reached by creating a mathematical model, which employed the point source summation method, and taking empirical measurements of irradiance within the UV-Tube. The irradiance distribution could then be combined with a fluids model to predict dose distribution of the UV-Tube. The result would both corroborate biological assay results and the predict performance of potential design modifications.

The model required:

- Analysis of basic geometry of the UV-Tube
- Assumptions concerning bulb output and UV absorption of water
- Translation of numerical model to computer code to facilitate rapid calculations

The empirical measurements required:

- Construction of a UV-Tube with fused quartz filled holes
- Varied absorption of water
- Measurement of irradiance through quartz windows

3. Materials Testing

The goal of the materials testing phase was to compile information on the effect of UVC on potential UV-Tube construction materials.

Materials testing required:

- Batch testing of PVC and ABS
- Batch testing of galvanized steel and aluminum
- Batch testing of PVC lined with galvanized steel
- Qualitative assessment of degradation
- Literature review of UV effect on materials

4. Bulb Testing

The goal of bulb testing was to provide information on bulb lifetime, warm-up time, output variability and aging.

B. Field Work: Pátzcuaro, Mexico

The goals of the field investigation were to test a community workshop approach for dissemination, gain experience in installations, test the effectiveness when used within a local household and collect user feedback to apply to further design optimization.

Workshop approach required:

- Finding potential UV-Tube study participants
- Discussing water and health, their current water treatment methods
- Providing written building instructions and materials for each participant
- Observing and assisting UV-Tube construction
- Installing systems in participants’ homes for trial period

1. Technical Field Testing

The goal of the technical field testing was to compare the performance of the UV-Tube in a controlled laboratory setting with that in a real household.

The assessment required:

- Testing of water quality of household supply (turbidity, coliform, chlorine)
- Testing performance of UV-Tube (coliform at outlet)
- Prolonged testing of inlet and outlet (twice per week for several months)
- Assessment of material endurance

2. Socioeconomic Testing

Parallel to the assessment of technical feasibility, we aimed to assess the social, economic, and cultural appropriateness.

Specifically, this required examination of:

- Availability of necessary materials
- Costs of materials compared to household income and other indicators of affordability
- Willingness of users to purchase the UV-Tube
- Apparent appropriateness of design within household
- User reported desirability and importance of aesthetics

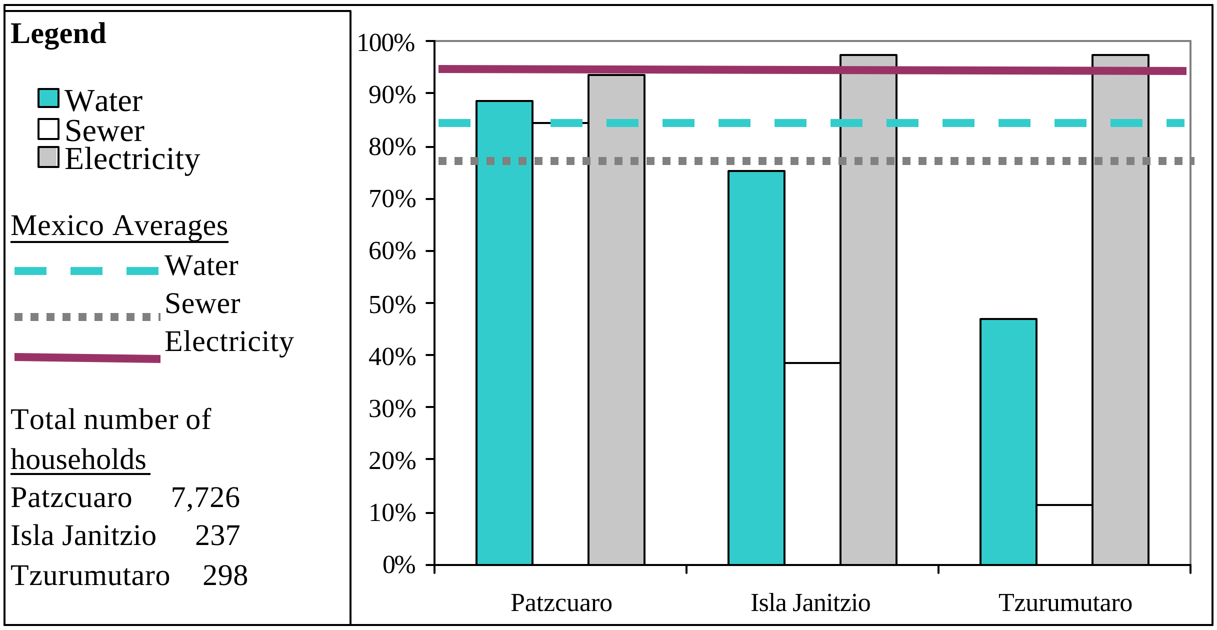
III. Project Background

The UV-Tube was developed and field tested in Pátzcuaro, Mexico (Figure 1). This section provides some background on the project and specifically on water quality and economics in the Pátzcuaro region.

Figure 1 Location of Pátzcuaro and the Villages Surrounding Lake Pátzcuaro

Pátzcuaro, located in the Purépecha Highlands of Michoacan, was selected for this analysis and field study for a variety of reasons. The region is fairly representative of rural Mexico in terms of water quality, water supply, electrification and socioeconomic status of inhabitants. Percentages of households with a piped-in water supply, sewage and electricity in the city of Pátzcuaro, Tzurumútaro and Janitzio (two small towns in the region, see Figure 1), along with the nationwide average are shown in Figure 2.

Figure 2. Percentage of Households with Water, Sewer and Electricity



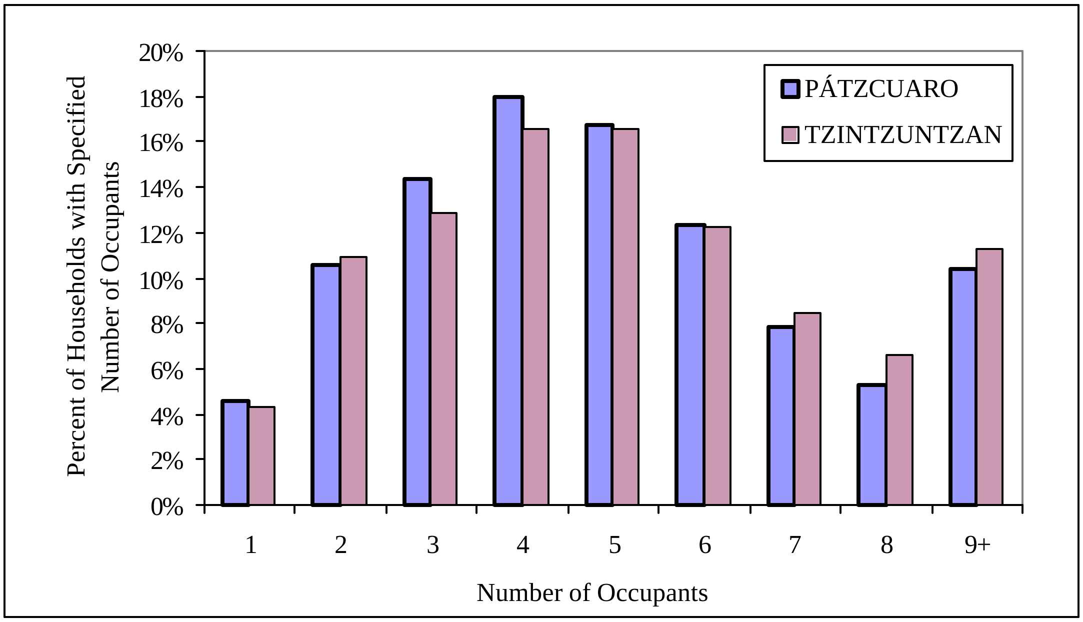
Source: (INEGI 2001)

As is typical for Mexico, about 95% of households are electrified. The percentage of households with access to piped water in Pátzcuaro is approximately the same as the national average (84%), whereas for the smaller villages, it is significantly lower, 75% on the island of Janitzio and just under 50% in Tzurumútaro. Similarly, access to sewer lines in Patzuaro is slightly higher than the national average (78%), but much lower for the smaller villages – 38% on Janitzio and only 11% in Tzurumútaro.

Approximately one quarter of a million people live in the city of Pátzcuaro and in the surrounding villages (Adler Dwek 2001, p.27). The population has increased dramatically, tripling in the last 80 years.

Although the average household size in Pátzcuaro and the surrounding villages is just under 5, a significant percentage of households have 9 or more occupants. Figure 3 shows household size distribution (represented as percentage of total households) for both the city of Pátzcuaro and Tzintzúntzan, a small neighboring village (Figure 1).

Figure 3. Household Size Distribution for Pátzcuaro and Tzintzúntzan



source: (INEGI 2001)

The total population of the city of Pátzcuaro is about an order of magnitude greater than the village of Tzintzúntzan, yet the household size distributions are almost identical. The ten percent of households with nine or more persons would be especially good candidates for the UV-Tube, as the cost per liter of water produced decreases as water use increases.

The water quality is regulated locally, but federal oversight is provided by the National Commission of Water (Comisión Nacional del Agua – CNA). The local Minister of Health administers regular sampling of piped water, testing for coliform and chlorine residual.

Our testing indicated that bacteriological contamination is variable both within the city of Pátzcuaro and in surrounding villages[1]. Testing for total chlorine came back negative in all cases. Sources of water range from deep to shallow wells, to mountain springs, to surface water.

The range of household water purification techniques in the region varies widely, and includes: chemical disinfection, boiling, filtration and purchasing of Coca-Cola brand bottled water (*Risco*).

Each of these methods have certain drawbacks and certain advantages. As can be seen in Table 2, there is no clear "best option". Those who can afford to purchase bottled water tend to do so. This group typically uses bottled water for drinking and cooking, but regular tap water for washing. While purchasing bottled water should provide a high quality water, it requires the daily, or semi-weekly activity of bringing back old bottles, purchasing new bottles and hauling them home. A 20 liter bottle – the most common size used – weighs over 40 pounds.

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[1] Between July and December of 2001 Laura McLaughlin performed both presence/absence tests for total coliform and quantitative tests for *E. coli* in numerous locations around the city.

A one micron fiber filter can be purchased and inserted into plumbing. This type of filter is easy to use, once installed, but fairly expensive. A one micron filter will not protect against some bacteria, nor will it protect against any viruses.

Chemical addition requires a hold time, so it is fairly labor intensive although it can be quite inexpensive. Because it is difficult to know the right dose, water may be overdosed resulting in an undesirable taste. Boiling provides the best germicidal action, but is time consuming, energy intensive and may impart an unappealing look and taste to the water.

Table 2. Common Water Treatment Techniques in Mexico

Characteristics	**Purchase Bottled**	**Boiling**	**Chemical**	**Gravity Filtration**	**Pressurized Filter**	**None – Straight Tap**
Passive/High Capacity	NO	NO	NO	NO	YES	YES
Regular Maintenance*	YES	NO	YES	YES	NO	NO
Germicidal Action	HIGH	HIGH	HIGH	MED	MED	LOW
Taste/Odor/ Organic/ Metal Removal	YES	NO	NO, may add taste/odor	YES	YES	NO
Cost (family of 5)	HIGH	MED/LO	LOW	MED/LOW	MED/HIGH	LOW

* Regular, refers to daily or almost daily

The UV-Tube was created to provide an alternative that is passive, high capacity, requires no regular maintenance and has high germicidal action, at an affordable cost. The costs of the UV-Tube are shown in Table 3. Household income in the Pátzcuaro region is around $300-$400 per month[2], so the costs of the UV-Tube are equivalent to about 1% of household monthly income for the first year and a little over ½% for subsequent years .

Table 3. UV-Tube Costs for Mexico (in $US)

	Initial Cost	Monthly Cost Year 1 (initial cost averaged over first year)	Monthly Cost Year 2… (bulb replacement averaged over year)
Initial Cost	$40.00	$3.33	--
Electricity		$1.08	$1.08
Bulb Replacement	$17.00		$1.42
Total Monthly Cost		$4.41	$2.50

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[2] The range in monthly household incomes reflects the two methods used to make the calculation. In both cases the data were obtained from the Mexican Census INEGI (2001). XII Censo General de Población y Vivienda, 2000. Tabulados Básicos y por Entidad Federativa. Bases de Datos y Tabulados de la Muestra Censal. México, Instituto Nacional de Estadistica, Geografia e Informatica, Mexico.. The first method was to multiply the average number of employed persons per household by the average wage. The second method was to multiply the average wage by the number of employed population and then divide that by the average household size.

For comparison, bottled water for a family of five could cost $10 to $20 per month[3].

In the early 1990s Dr. Ashok Gadgil, a Senior Staff Scientist at Lawrence Berkeley National Laboratory, was stirred by the thousands of Bengal cholera deaths in India and neighboring countries to create an affordable, highly effective water treatment system. He found that using UV light it would be possible to disinfect water at a cost of a few cents per metric ton. He eventually designed a high capacity low-cost water disinfection system suitable for health clinics, hospitals and communities. The product, called UV Waterworks, is currently sold through Water Health International (Napa, CA), a for-profit company. Due to the product's high initial cost, however, it is not a realistic solution for rural disinfection at the household level.

After completing his PhD in Mechanical Engineering at UC Berkeley, Lloyd Connelly helped install some of the UV Waterworks devices in Mexico. While in the field, Dr. Connelly found that there was an additional need for a less expensive and simpler household system. In the Pátzcuaro region where Dr. Connelly was working, many households had water piped into their homes already, making a community disinfection system less desirable. In response, Dr. Connelly downscaled and simplified the technology, creating the "UV-Tube". Dr. Connelly won the World Bank Development Marketplace competition and received funding for further testing and field trials of the technology.

The dissemination model is an integral part of the UV-Tube vision. It has been widely acknowledged that successful technology transfer projects rely on user involvement and investment (Agarwal 1983; Purdey, Adhikari et al. 1994). To that end, a community organized construction workshop could be an appropriate dissemination strategy. The UV-Tube can be built from locally available parts, and the construction is fairly straightforward. Participants would gain an understanding of how the UV-Tube works, be able to perform repairs, and come away with a sense of ownership of the device. A study by the Nepal Health Development Project cites pride and ownership as well as householder knowledge of repairs as two key factors in successful and sustained use of improved cook-stoves (Purdey, Adhikari et al. 1994). The workshops would be organized by a local NGO, government agency, or community leaders. Organizers would incorporate water-health education and then supply UV-Tube building instructions, construction tools and possibly the materials as well. The UV-Tube Project in Berkeley would provide information and advice to the organizing group, but would not play any direct role in the process.

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[3] This calculation is based on consumption of 1-2 L/day-person and cost of $1.60 per 20-L bottle.

IV. Background: Science and Technology of UV Disinfection

In ultraviolet (UV) disinfection, microorganisms are inactivated by UV light. The light is typically produced by a germicidal or UV bulb, which is essentially the same as a fluorescent bulb, except that it lacks the phosphor coating and the glass exterior is replaced by fused quartz.

UV light is generally defined to be any wavelength of electromagnetic radiation shorter 400 nm and is further broken up into UVA (315-400nm), UVB (280-315nm) and UVC (200-280 nm). UVA and UVB are responsible for sun tanning and sun burning. UVC, which is almost entirely filtered out by the ozone layer, can penetrate cells and damage the DNA. Through the same mechanism UVC inactivates microorganisms.

1. History of UV Disinfection

The bactericidal effects of sunlight were first noted in 1878 (Groocock 1984). In Marseilles, France in 1910 the city began to use ultraviolet light to treat their drinking water. The practice was abandoned when chlorine became available free of charge as a by-product of soda production (Kolch 1999). Ultraviolet light became important again the 1970s in Europe with the discovery of disinfection byproducts associated with chlorine use (Cardenas, Ravina et al. 1986, p. 27; Bryant, Fulton et al. 1992; EPA 1999).

Currently, UV is used in large-scale drinking water treatment plants in Europe and small-scale drinking water systems around the world. In the United States UV is more widely used in wastewater treatment than drinking water treatment, however, with increasing health concerns regarding disinfection byproducts this may change (Wolfe 1990).

2. Biological Effects

UVC light inactivates microorganisms by damaging their DNA and rendering them unable to reproduce.

Nucleic acids show maximum absorption of light between 260-265 nm (UVC). The absorption leads to the formation of photoproducts that interfere with replication. For example, pyrimidine dimers are formed when two adjacent pyrimidine bases are joined together. These could be two thymines, two cytosines, or a thymine and a cytosine. Dimers are formed by pyrimidine bases (thymine, cytosine and uracil) at a much higher rate than by purine bases (adenine, guanine). The most common photoproducts are cyclobutyl dimers, which are formed when two adjacent pyrimidine bases join to form a four carbon ring. Other photoproducts include pyrimidine adducts, spore photoproducts, pyrimidine hydrates and DNA-protein crosslinks (Harm 1980). These photoproducts inhibit replication thereby inactivating the organism. UVC is capable of inactivating bacteria, virus, fungi, spore forming organisms, and cyst forming protozoa.

It should be noted that although maximum germicidal action occurs at wavelengths between 260 and 265 nm, in many cases the irradiance (or intensity) is quoted given at 253.7 nm, corresponding to the maximum output of low pressure mercury arc lamps commonly used for water disinfection.

3. Reactivation

There is potential for cells to repair themselves either in the dark or by exposure to visible and near UV light (photoreactivation). Cells repair themselves in three ways. (1) Photoenzymatic repair in which exposure to wavelengths between 310-480 nm (near UV – visible) provides the energy for an enzyme to split the pyrimidine dimer; (2) excision-resynthesis, in which the UV photoproduct is excised and replaced; and (3) postreplication repair, in which uninjured portions of either multiple replicate DNA strands or the two complement DNA strands are recombined to form the original sequence (Harm 1980, p.76-121).

4. Disinfection Byproducts

UV treatment, unlike chlorination[4], produces no known disinfection byproducts (Wolfe 1990; Bryant, Fulton et al. 1992; de Veer, Moriske et al. 1994; EPA 1999; Chang, Hsieh et al. 2000; National Drinking Water Clearinghouse 2000).

5. Inactivation and Dose

Dose is the product of irradiance and exposure time. Irradiance is a function of the bulb power and decreases with distance from the bulb due to attenuation and dissipation. The geometry of the reactor and the composition of the water determine how quickly the irradiance decreases with distance from the bulb. Exposure time is governed by the geometry and hydrodynamics of the reactor, which is designed such that the lowest dose received by any of the water is sufficient to achieve the desired reduction in microorganisms. Dose is most commonly measured in μW-sec/cm^2 (equivalent to μJ/cm^2) or mW-sec/cm^2.

The EPA is currently considering 50 mW-sec/cm^2 as an acceptable minimum dose for a UV treatment system. As of September 2000 the National Sanitation Foundation had set a minimum dose of 38 mWs/cm^2 for "visually clear water". The dose needed for various levels of inactivation for different organisms are shown in Figure 4.

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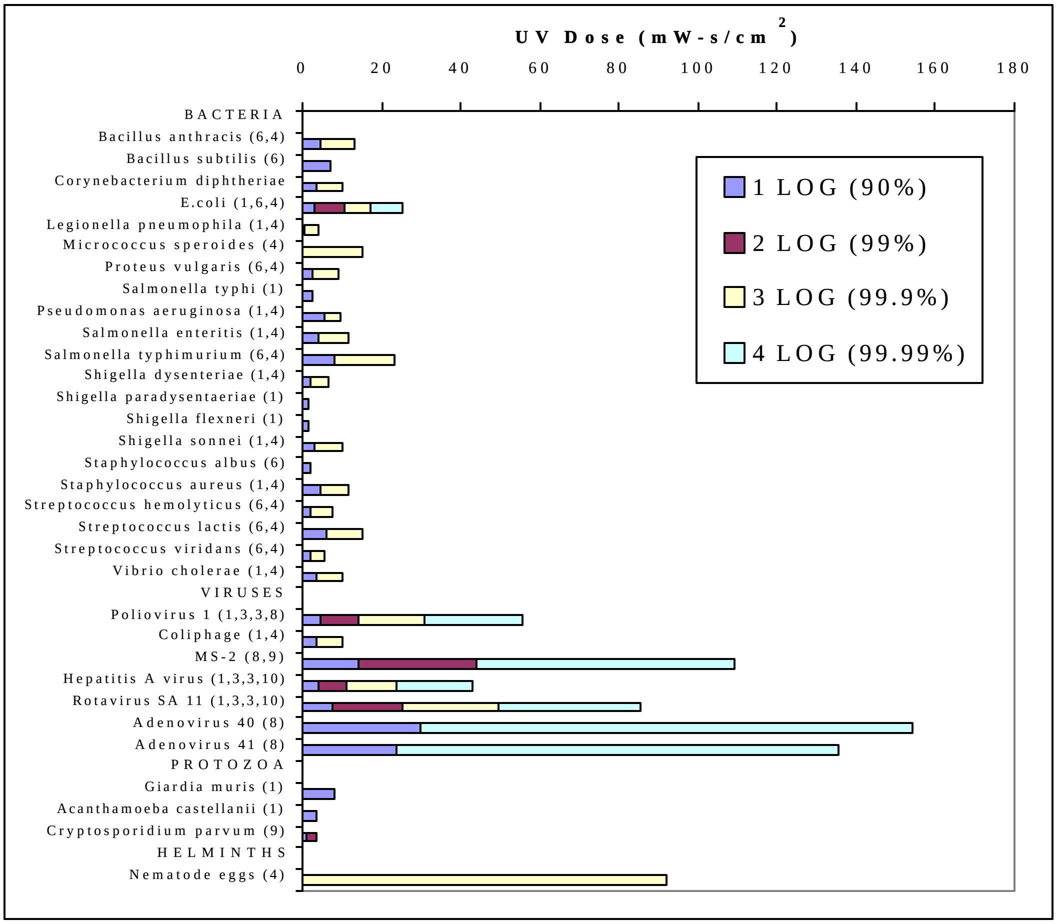
[4] For discussion of disinfection byproducts created by chlorine, see EPA "Alternative Disinfectants and Oxidants Guidance Manual", sections 2.3.1- 2.3.3, pages 56-62 EPA (1999). Alternative Disinfectants and Oxidants Guidance Manual, United States Environmental Protection Agency, Office of Water**:** 346.

Figure 4. UV Dose Response Data from Various Sources



Sources: (1) (Wolfe 1990); (3) (Malley 2000); (4) (Triangular Wave Technologies Inc 1997); (6) (Koller 1952); (8) (Qin and Gerba 1996); (9) (Shin, Linden et al. 2001); (10) (Battigelli, Sobsey et al. 1993)

6. Absorption Coefficient

UV light is absorbed by certain constituents of the water including natural organic matter (NOM), nitrate, iron and manganese (Kolch 1999). As the absorbance – or the amount absorbed – increases, the transmittance – or the amount that goes through – decreases exponentially. Knowing the range of expected absorbance of the influent is very important in predicting the performance of a UV system.

a. Measurement

The ultraviolet absorption in water is measured by passing a collimated beam of UV light at 254nm through a 1 cm thick sample. Distilled water is used as a reference to calculate I_o, the initial irradiance. The irradiance through the sample I_T is used to calculate the percent transmittance (T):

Equation 1

$$T = (I_T/I_o) \times 100$$

The Absorbance (A) is calculated by the Beer-Lambert Law as:

Equation 2

$A = \log_{10}(100/T)$

Absorbance is linearly related to the concentration of the substance that is absorbing the light:

Equation 3

A = å x ι x [C]   where å is the molar extinction coefficient [M^{-1}cm^{-1}]
é is the path length [cm]
[C] is the concentration of substance [M]

The absorption coefficient (á) is then defined as:

Equation 4

á = å[C] or A/é   [cm^{-1}]

The absorbance from all UV-absorbing substances in the water is just the sum of the molar extinction coefficients of each substance multiplied by the concentration of each, or the Absorbance (as measured in spectrophotometer), divided by the path length:

á = Σ(å$_i$[C$_i$]) = A/é

By examining Equation 2, we see that the absorption coefficient is base ten. To convert for use with the natural log, the absorption coefficient must be converted to base e:

á(base e) = 2.303á(base 10)

If not specified, it can be assumed that the absorption coefficient is base 10.

b. Expected Values

Absorption coefficients in drinking water are expected to be in the range of 0.01 to 0.2 cm^{-1}. The Absorbance of seven drinking water samples taken around the Pátzcuaro region were in the range of 0.002 to 0.009, which correspond to absorption coefficients of 0.002 to 0.009cm^{-1} (base 10) or 0.005 and 0.021 cm^{-1} (base *e*). A sample taken from a muddy puddle, had an Absorbance of 0.048, or an absorption coefficient of 0.111 cm^{-1} (base e). According to Snicer et al., water with an absorption coefficient of 0.125 would be considered of fair water quality (1997, p.22).

Just as the recommended dose has not been standardized, neither have allowable levels of UV absorbing compounds. However, maximum concentrations of iron and manganese have been recommended at 0.03 mg/l and 0.02 mg/l, respectively (Kolch 1999) and turbidity less than 5 NTU (Bolton 2001). The issues of turbidity and particulate concentration are discussed in the next section.

c. In Testing Performance of UV-Tube

Both sodium thiosulfate pentahydrate ($Na_2S_2O_3$*H_2O) and instant coffee can be used to artificially increase the absorption of the water. Sodium thiosulfate, which is used to dechlorinated tap water, is also a strong absorber of UV (Cardenas, Ravina et al. 1986, p.36). Instant coffee can be used to simulate natural organic matter (Blatchley, Do-Quang et al. 1998).

7. Particle Association and Turbidity

Turbidity is often thought to be a limiting feature in ultraviolet disinfection. However, investigations have shown that particles, as long as they are not UV-absorbers, do not significantly reduce the overall irradiance by either shading or scattering, but only when organisms are embedded within them (Linden and Darby 1998, p.215). Emerick et al. found that the coliform removal efficiency was not well correlated with the total concentration of particles, but rather with the concentration of particle associated coliform. The authors note that their results pertain only to coliform and the data are lacking on other pathogen behavior with regard to particle association (Emerick, Loge et al. 1999).

Particle suspension can increase the apparent absorption coefficient – as measured by a spectrophotometer – by scattering rather than absorbing light (Linden and Darby 1998, p.214). This effect can lead to under-prediction of design capabilities. In the US this effect would only be a concern in wastewater treatment, however in developing country applications, high particle concentration may be relevant in drinking water as well.

8. Bulb Types

The maximum UV absorbance of DNA, 260-265 nm, coincides well with peak output of low pressure mercury arc lamps at 253.7 nm. Two different types of lamps are typically used in water disinfection, medium pressure and low pressure mercury vapor arc lamp. Table 4 displays these differences.

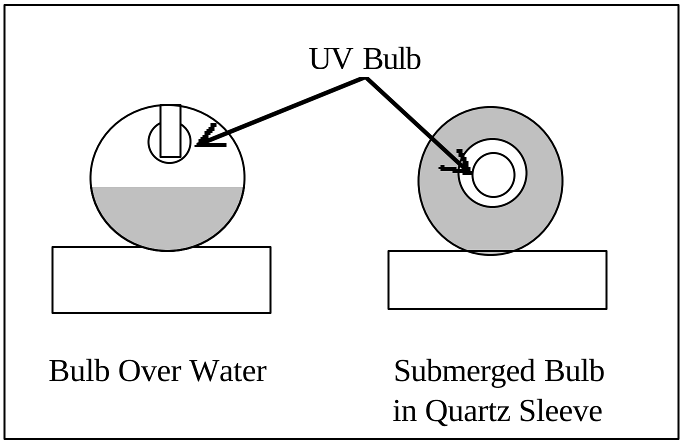
Table 4. UV Lamp Types

Characteristic	Low Pressure, Low Intensity	Medium Pressure, High Intensity
Typical Energy Use:	60 W	5,000 W
Percentage Output at 253.7 nm:	88%	44%
Ozone Production:	NONE	Possible, quartz can be doped to prevent formation
Susceptibility to Cooling:	YES	NO
Suited for Water Quality Type:	Good	Poor
Benefits:	More efficient	Smaller, Less maintenance

9. Designs

In the early part of the century the bulb over water design, as shown in Figure 5, was considered the only feasible design due to concerns of lamp fouling.

Figure 5. Comparison of Bulb Over Water and Submerged Bulb Designs



Currently, pressurized systems with submerged lamps are much more common, as a submerged bulb can lead to essentially a doubling in efficiency. When the bulb is placed in the middle of the flow, the water depth (i.e. path length of light) is reduced. In these designs the bulb and wiring are surrounded by a quartz sleeve to isolate the electronics from the water and to protect the bulb against temperature fluctuations. Cold water may decrease the output of the bulb or break the casing. Fused quartz is the most common sleeve material, as it is nearly transparent to UVC. The lamp(s) may be aligned parallel (reducing head loss, increasing contact time and minimizing short circuiting) or perpendicular (facilitating lamp cleaning and replacement), to flow. A reversed design, in which water flows through a quartz or teflon tube surrounded by UV lamps, is also used in some small scale systems. In both cases the quartz sleeves are susceptible to fouling by organics, hardness, algae and biofilms[5].

More recently, some systems have returned to the simpler, suspended lamp design, in which water flows under the bulb at atmospheric pressure. In these designs bulb fouling is significantly reduced and electronics are separated from water by use of a weir. These two elements create a less expensive and more easily constructed design.

10. Limitations of UV Disinfection

In terms of large scale UV disinfection of municipal drinking water, the lack of a residual concentration of disinfectant is probably the greatest limitation. However, for household level water treatment, without storage, a residual is not necessary. Currently, UV technology is more expensive than chlorination, at least partially due to the lack of economies of scale. In addition, information is somewhat limited on factors affecting UV disinfection and means of quantifying dose (Wolfe 1990).

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[5] In large scale systems bulb fouling is address by either removing bulbs periodically for cleaning, installing automatic wipers or using on-line mild acid chemical cleaners.

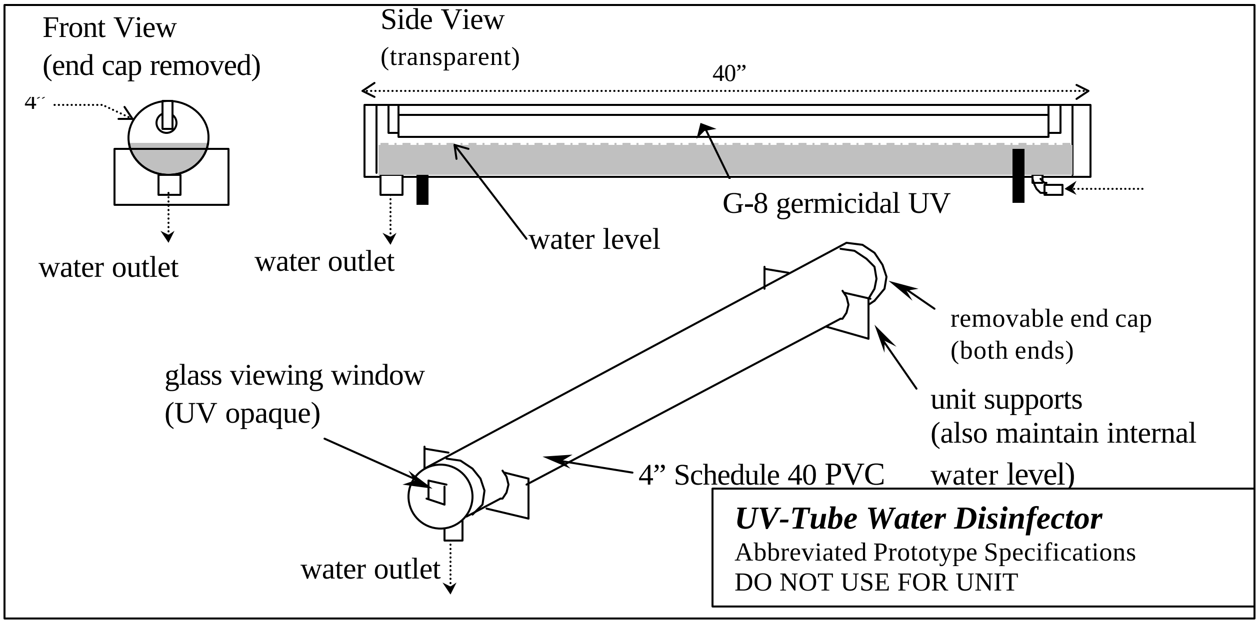
V. Evolution of the UV-Tube Designs

The design criteria of the UV-Tube represent a balance between cost, technical feasibility, local availability of materials, ease of construction, and aesthetics. Recognizing that all of these factors are context-specific, the UV-Tube was always envisioned to have many possible constructions. Initially, Dr. Lloyd Connelly thought of suspending a UV lamp within the rooftop water tanks that are common in rural Mexico. Tanks are necessary because the piped water distribution system, does not provide sufficient or consistent water pressure. Households collect water in rooftop tanks when there is pressure, store it and gravity feed it to their home plumbing. Due to technical complications with designing a system in the storage tank, and the cost of the storage tank itself, Dr. Connelly decided to design a system for the inside of the home. In addition, the risk of post-disinfection contamination is reduced the closer the user is to the disinfection system.

A. Generation I

Polyvinyl Chloride, or PVC, is a ubiquitous piping material sold throughout the developing world. It is commonly available in 4-in and 6-in diameters with fitted end caps. The original design, named Generation I and shown in detail in Figure 6, used plastic inserts to create weirs, thereby setting the water height and residence time.

Figure 6. Generation I UV-Tube Design

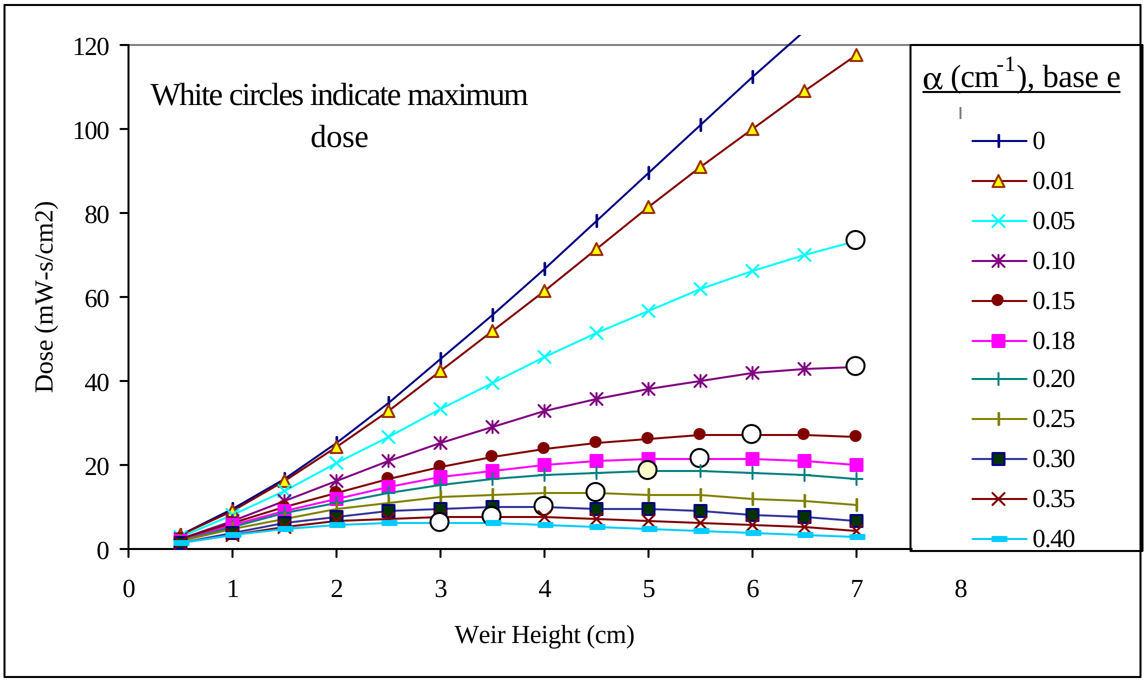


Source: Connelly, Lloyd (2000). Expanded Proposal for the World Bank Development Marketplace (http://home.earthlink.net/~lloydconnelly/UVTUBE.html)

The inlet was placed at the bottom of one end, the tube was intersected with two plastic slabs and the outlet was a thick slot at the bottom of the opposite end. The outlet is intentionally not round, so as to discourage the placement of further piping, to reduce the risk of re-contamination.

There is trade-off in effectiveness between hydraulic residence time and water height. The weir height determines both the hydraulic residence time and the maximum depth through which the water must travel. Therefore, the optimal weir height is a non-linear function of the absorption characteristics (i.e., the absorption coefficient, α) of the water. As shown in Figure 7, the maximum dose received for very clear water (á < 0.10) increases with increasing weir height. For water with a higher absorption (á = 0.30) the dose increases to a maximum at a weir height of 4 cm and then decreases. The more the light is attenuated through the water, i.e. the higher the absorption coefficient, the shorter the optimum weir height.

Figure 7. Dose as a Function of Weir Height



Note: White circles indicate maximum dose for each absorption. Data are from PSS Model output, described in section VII beginning on page 45. Code input for Engineering Equation Solver (EES) used to compile the above predictions can be found in Appendix A.

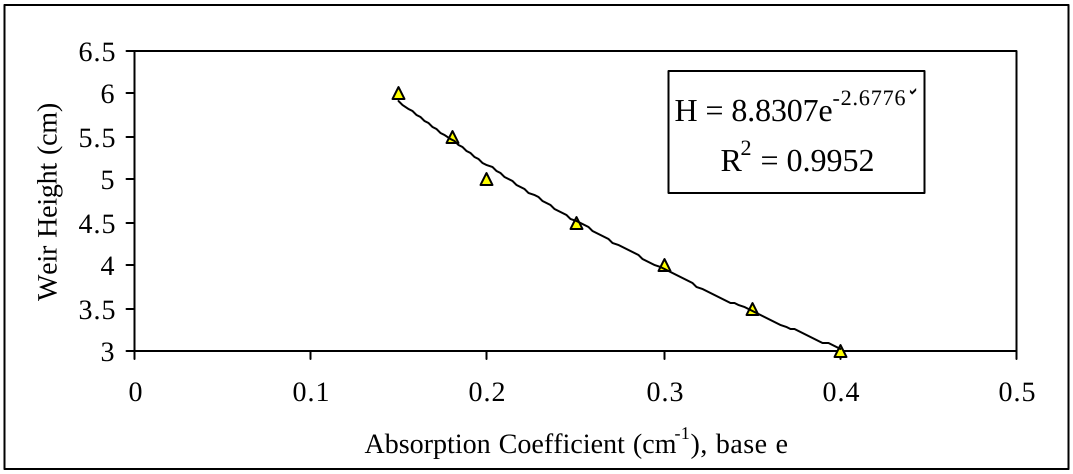
Using the data shown in Figure 7, an exponential curve (Figure 8) was fit to the optimal weir height values for each absorption coefficient value.

The following equation was determined using least squares method:

Equation 5

$$WeirHeight\,(H) = 8.8307e^{-2.6776a} \qquad R^2 = 0.9952$$

Figure 8. Optimal Weir Height as Function of Absorption Coefficient (5 L/min Flow Rate)



Initially a weir height of 4 cm was used. Based on the above predictions, and expected absorption coefficients less than 0.20, an even higher weir height might be recommended. However, the design is limited by the overall diameter of the tube. Due to additional water that accumulates over the weir height during flow (about 0.6 cm for 5 L/min flow, for further discussion see page 48) and the 4-5 cm that the bulb takes up, a 4 centimeter weir is maximum height without risking bulb wetting.

Indications that it would be preferable to line the plastic tubing with some type of metal inspired new designs.

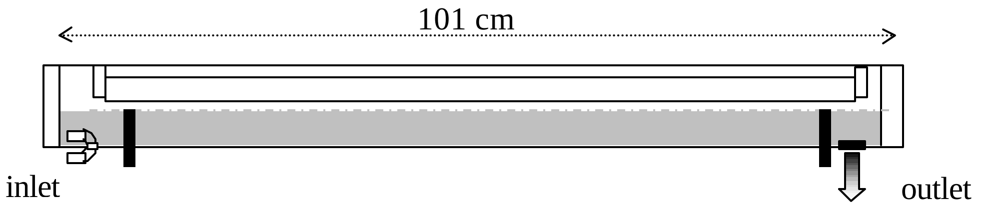
B. Generation II

The Generation I design was altered to facilitate a metal lining, simplify the design, and reduce the risk of leaks (Figure 9). The two plastic weirs posed a problem for a simple and secure liner, were difficult to build and provided extra contacts for potential leakage. The generation II design replaced the double weirs with a one inch PVC pipe inserted into one end of the tube to act as both the outlet and the weir. This smaller pipe protruded into the tube at the desired weir height. The inlet was placed on the top of the opposite end. In this design the smaller tube would still have to be lined on the outside and perhaps the inside and the main liner would have to fit around the tube.

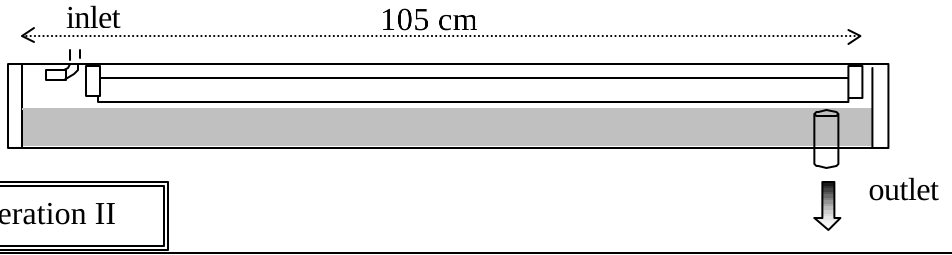
C. Generation III

To further simplify the lining of the plastic tube, a third design was created. Rather than the smaller tube jutting into the UV-Tube from the bottom, a smaller tube would be inserted flush with the end cap, such that it would drain at a water height of 4 cm (Figure 9). As in the Generation II tube, the inlet would be placed on the top of the opposite end. The design allows for a clean insertion of a metal liner. In the case of leakage, the metal tray could easily be replaced and reinserted. A large hole on the bottom, through the plastic only, was added to this design. This feature would alert the user to leakage in the liner and not allow any water to bypass the light by traveling under the metal.

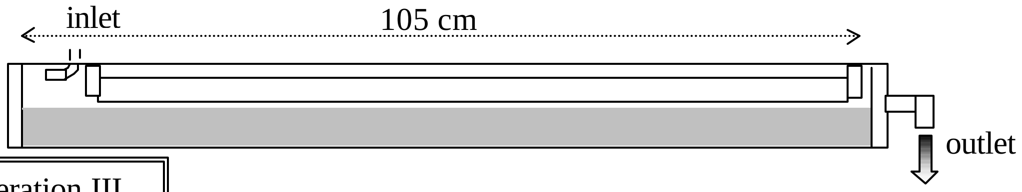
Figure 9. Three UV-Tube Designs: Generation I, II and III



a. Generation I



b. Generation II



c. Generation III

All three generations could be constructed with either the 18” (G15 or G25) bulb or the 36” (G30) bulb. Generations II and III are fully or ¾ lined with either stainless or galvanized steel sheeting. Prior to insertion of liner, a ½ -1-in hole is drilled in the bottom of the plastic. The liner is then placed inside and sealed against the tube with silicon glue. The hole in the plastic is intended to indicate if the seal has been broken and prevent water from bypassing the light and traveling under the liner.

The use of other materials, such as pottery or concrete, has inspired the thoughts of new designs. For example, the tube shape could be replaced with a rectangular shape, depending on the materials.

D. Generation IV: Pottery

After receiving preliminary results on chlorinated organic compounds in the PVC UV-Tube, we began to explore new materials altogether. Many common plastics are more stable than PVC, however, none are commonly found as four inch diameter piping with end caps.

The prevalence of locally crafted pottery in the Pátzcuaro region inspired the idea of a pottery UV-Tube. Lead-based glazes are commonly used in Mexico in general, because they allow the firing temperature to be depressed, while adding a desirable look to the finished piece. Lindia Liu, an Environmental Science undergraduate student, tested the effect of UV on pottery from

Mexico, as her senior thesis. Although her results are somewhat inconclusive, they do indicate that even the pottery that is purported to *not* contain lead, probably does and the lead is released with exposure to UV light.

After discussing the possibilities with some local potters in Berkeley, we decided to build and test an unglazed pottery UV-Tube. The first one, shown in Figure 10, was built by Ross Spangler (Berkeley, CA). We assisted Ross in rolling out the slabs of Terra Cotta, shaping the design using a simple mold and then low firing it. This design is fitted with a stainless steel lid to house the bulb and provide the inlet. A fitting for the outlet is attached to the hole shown in the photograph in Figure 10.

Figure 10 Pottery UV-Trough

After firing the pottery UV-Tube, nicknamed the “UV-Trough”, it was filled with water. Capillary action was observed and the outside had begun to sweat within the first twenty minutes. After a couple of hours the volume of water had been reduced substantially and there was a small puddle underneath the UV-Tube, presumably where evaporation had not been possible. The piece was placed under UV light for five days, after which time no iron was detected in the water.

VI. Laboratory Experiments to Characterize Performance

The dose provided by the UV-Tube was assessed through a biological assay and a mathematical model.

A. Biological Assay

A biological assay using *E.coli* was performed in order to estimate dose for a variety of flow rates and UV absorption values. *E.coli* concentrations were maintained in the feed water, then measured in the inlet, i.e. preceding the UV-Tube, and the outlet.

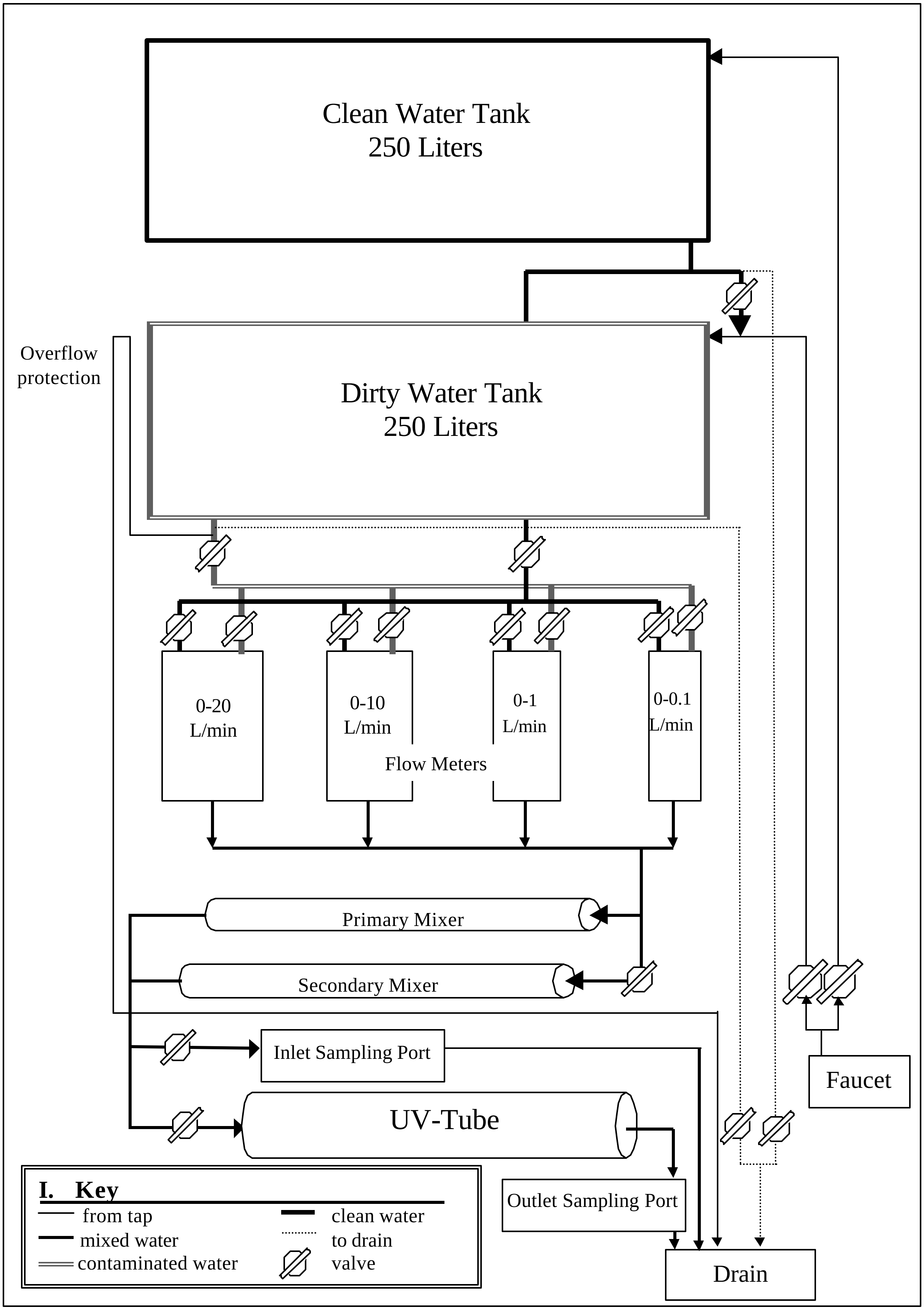
1. Methods

a. Testing Apparatus

A testing apparatus was built to provide varying concentrations of contaminated water at varying flow rates. The apparatus, shown in Figure 11, was comprised of two, 250-L tanks placed vertically on a metal stand. Each tank was connected to the faucet for filling and to the sink for draining. The top tank – containing clean water - also flowed into the bottom tank – containing bacteria contaminated water. Both were connected to a set of four flow meters ranging in flow from 0.1 to 20 L/min. After the flow meters, the two flows met and mixed in either one or two static mixers, depending on the total flow rate. For flow rates above 5 L/min both mixers were used. The combined water then either exited to a sampling port or flowed into the UV-Tube. In addition, there was an overflow drain from the bottom tank that drains automatically if the water level reaches within approximately 1 inch of the lid.

The two large tanks provided a high volume of water for prolonged testing. The range of flow meters allowed precise mixing of clean and dirty water to vary the inlet concentration to the UV-Tube. Valves into the flow meters from each tank controlled the volumes of each input. Valves at the other side of the flow meters controlled to total flow rate. This setup was intended to provided the potential for varying the total flow rate without changing the relative contribution from each tank.

Figure 11. Testing Apparatus



b. *E.coli* Growth

E.coli was used as the indicator organism. Several procedures were created and modified in order to obtain a stable concentration greater than 10^6 CFU/100mL in the testing tank.

In all cases *E.coli* (ATTC #11775) was obtained from Hach Company (Loveland, CO) in a dehydrated form and then rehydrated with enclosed broth, according to manufacturer's instructions. The top tank was filled with tap water and dechlorinated with 25g of sodium thiosulfate pentahydrate ($Na_2S_2O_3$*$5H_2O$). This water was left overnight to equilibrate to room temperature (~20°C). The following day, approximately 10 liters of water was drained from the top tank into the bottom tank, *E.coli* was added, and then the remaining dechlorinated water from the top tank was added to the bottom tank to provide turbulent mixing.

(i) Direct Addition: March 14, 2001

E.coli were rehydrated and added directly to the dechlorinated water in the bottom tank. In this case 30g sodium thiosulfate were added instead of 25g.

(ii) Anaerobic Incubation: April 16, 2001

E.coli were rehydrated and incubated inside of a closed 10-mL tube of Lauryl Tryptose (LT) Broth, at 35°C for 23.5 hours.

(iii) Aerobic Incubation: May 22, 2001

E.coli were rehydrated and placed in an open beaker (50-mL or 100-mL) with the contents of 2, 10-mL tubes of LT Broth and incubated at 35°C for 24 to 36 hours. The solution was stirred slightly to aerate prior to, and once during, incubation. This change represents an increase in nutrient broth as well is incubation time. All tests conducted after May 22nd followed this procedure.

c. *E.coli* Enumeration

Membrane filtration method was used to quantify *E.coli* concentrations (Hach 1997, p.459-463).

During testing samples were collected prior to the UV-Tube (inlet samples) and after the UV-Tube (outlet samples). Usually one inlet sample was collected at the beginning and one at the end of the testing period. The inlet samples were serial diluted to 10^{-5}, 10^{-6} and 10^{-7}. Outlet samples were diluted 10^0, 10^{-1}, 10^{-2} and 10^{-3}, depending on the range of expected concentrations. Samples were filtered through a 0.45 ìm GM-Metrical membrane filter (Gelman Laboratory, Ann Arbor, MI) and placed on a petri dish with 2 mL of m-ColiBlue24® Broth (Hach 1997). Blanks were prepared at the start and between samples, after washing filtration apparatus in the same manner as that used between samples. The full procedure is included as Appendix B.

d. For Variable Absorption Coefficients

Sodium thiosulfate pentahydrate, the dechlorinating agent, and dissolved instant coffee were both used to increase the absorption coefficient of the water. A range of concentration and the absorbance values were measured using a spectrophotometer and the molar extinction coefficients was calculated. For coffee, a *dry mass extinction coefficient* was developed, as it is not clear what the molarity of instant coffee is.

(i) Effect of Instant Coffee on *E.coli* Viability – Small Batch Test

Two, 1-L beakers of water with *E.coli* were removed from the testing apparatus, before the coffee was added. To one of the beakers, 200mg of coffee was added. After a couple of hours (the duration of a testing period) samples from each beaker were measured for *E.coli* concentration.

(ii) Effect of Instant Coffee on *E.coli* Viability – 24-h Test

E.coli concentration was measured for a period of 24 hours in the tank both with and without coffee. In both cases, *E.coli* were incubated, at 35°C, in an open 100-mL beaker with 2 tubes of Lauryl Tryptose broth for 28:45 hours. Water had been dechlorinated with 25 +/- 0.5 grams of sodium thiosulfate, and had a temperature of 24-25° C when *E.coli* was added. In the second experiment, 58.5 g (0.234 g/L) of coffee was added along with *E.coli*.

2. Results

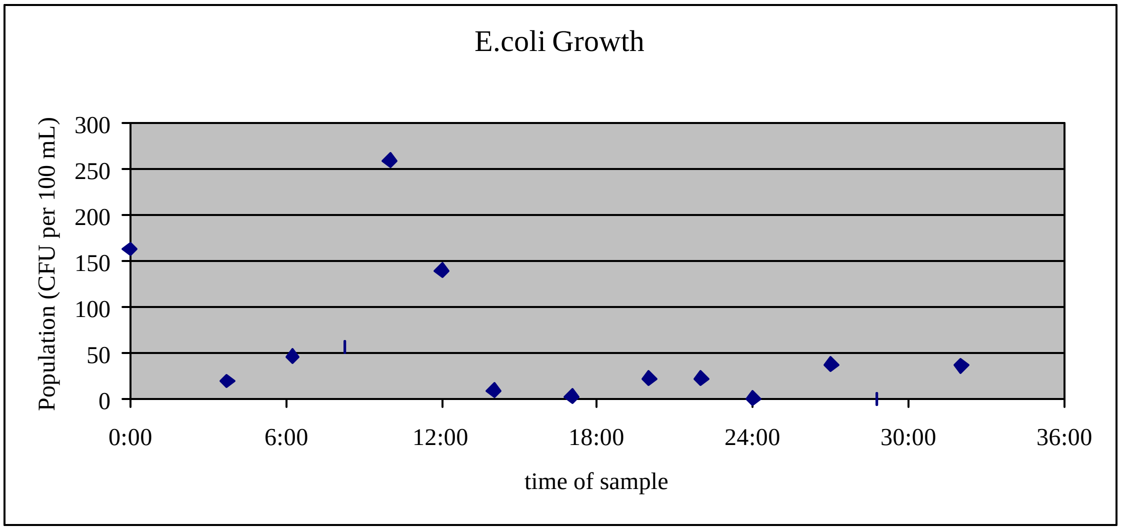
a. *E.coli* Growth

As described previously, several procedures were developed and improved to create a high and constant concentration of *E.coli* inside the testing tank. All results are for samples from the tank itself, not from incubated broth.

(i) Direct Addition

The concentrations of *E.coli* following direct addition of the rehydrated bacteria into the tank are shown in Figure 12.

Figure 12. *E.coli* Growth March 14, 2001

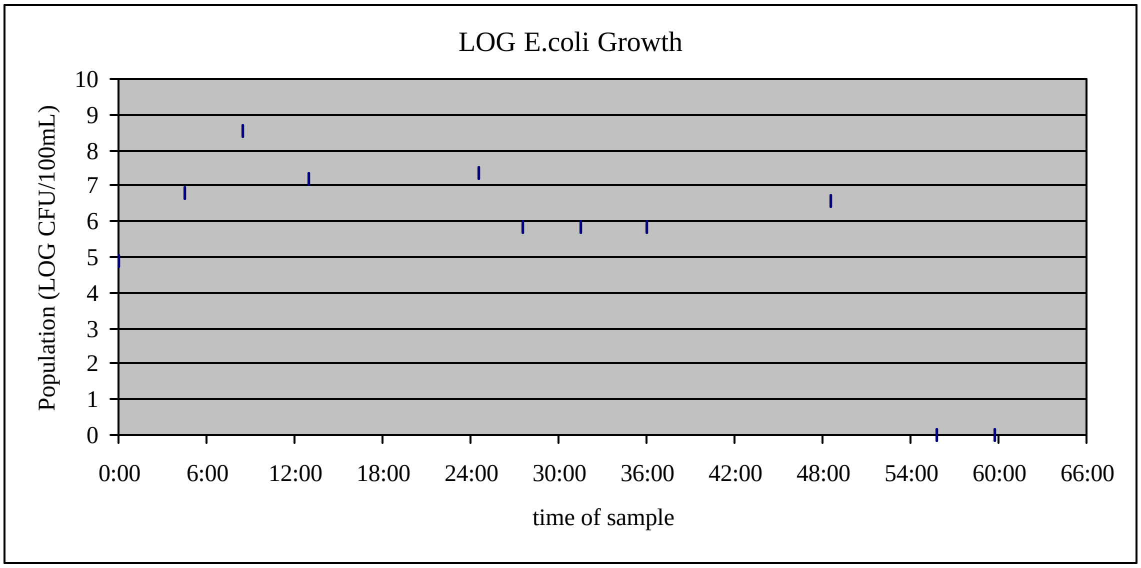


The highest concentration, which was approximately 250 CFU/100mL was measured after 10 hours. In most samples less than 50 CFU/100mL was measured.

(ii) Anaerobic Incubation

As can be seen in Figure 13, the concentrations are 3-7 orders of magnitude greater than without incubation in broth. The concentration of *E.coli* remained between 10^6 and 10^7 CFU/100mL for approximately 48 hours.

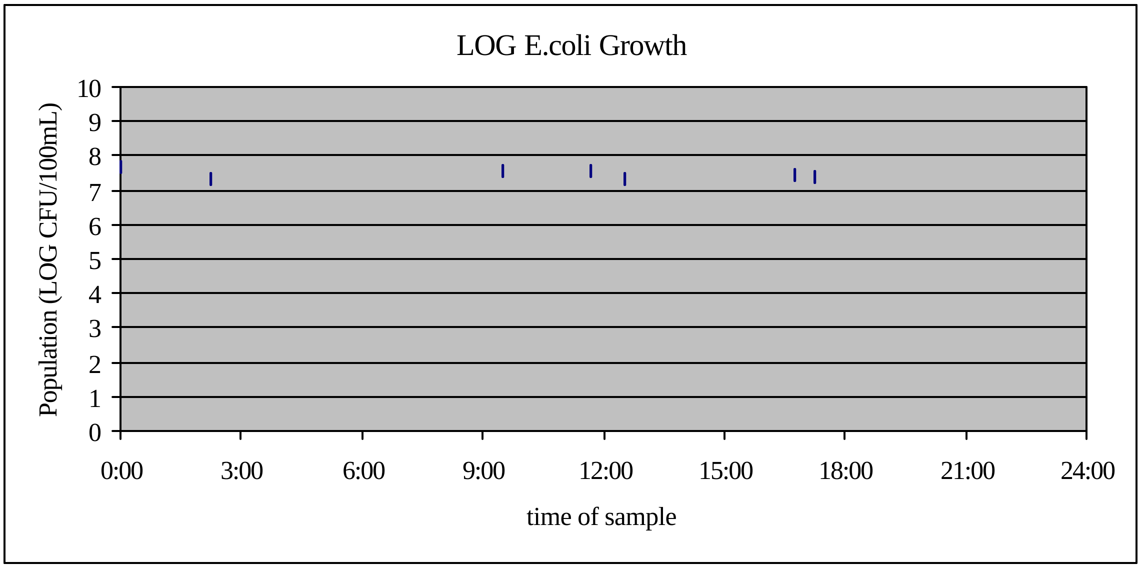
Figure 13. *E.coli* Growth April 16, 2001



(iii) Aerobic Incubation

As can be seen in Figure 14, following aerobic incubation the concentration of *E.coli* remained constant around 10^7 CFU/100mL.

Figure 14. *E.coli* Growth May 26, 2001

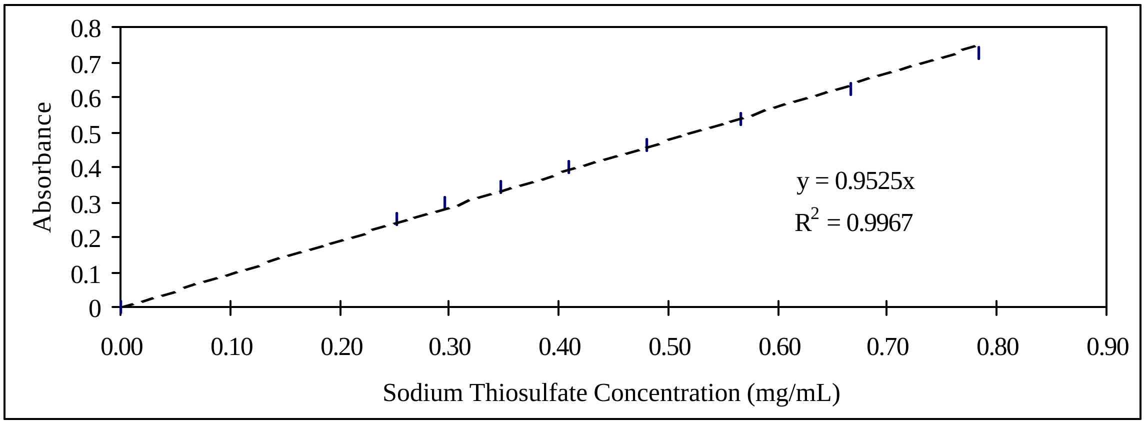


b. Addition of Coffee and Sodium Thiosulfate to Vary Absorbance

(i) Sodium Thiosulfate

As shown in Figure 15, the concentration of sodium thiosulfate in tap water is well correlated with the measured absorbance. The best fit line has an R^2 value of 0.997, with a forced intercept at zero, and a slope 0.9525.

Figure 15. Effect of De-chlorinating Agent on Absorption Coefficient



Note: Measurements were performed by Sarah Brownell in August 2001, using a Pharmacia Ultraspec® III UV/Visible Spectrophotometer.

The following empirical equation relating concentration of sodium thiosulfate and absorbance due to sodium thiosulfate was developed:

Equation 6

$$\text{Absorbance(from } Na_2S_2O_3) = 0.9525[Na_2S_2O_3] \text{ (g/L)}$$

Given a molecular weight of 248 g/mol and a path length of 1 cm, the molar extinction coefficient is:

å = $3.84x10^{-3}M^{-1}cm^{-1}$

(ii) UV Absorption by Instant Coffee

Coffee concentration correlated well with the measured absorption coefficient. Data for coffee concentrations ranging from approximately 0.02 to 0.4 mg/mL are shown in Figure 16. The R^2 value for the best fit line is 1.00 with a forced intercept at zero. The relationship between absorbance and coffee concentration was found to be :

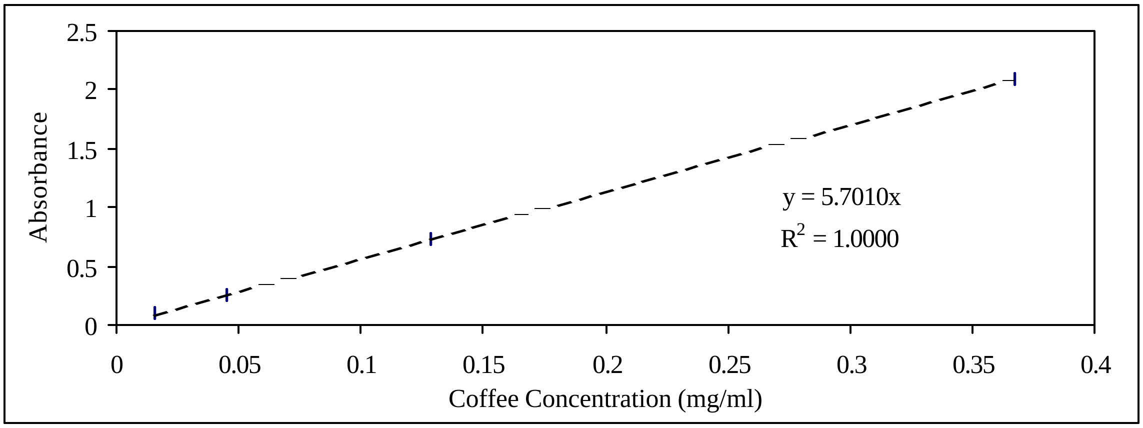
Equation 7

$$Absorbance(\,fromCoffee) = 5.7010[\text{Coffee(mg/ml)}\ ]$$

Because coffee does not have a molecular weight, the *dry-mass* extinction coefficient is simply equal to the slope:

å$_{dry\text{-}mass}$ = 5.7010 mL/mg-cm

Figure 16. Coffee Concentration and Absorption Coefficient



Note: Measurements were performed by Sarah Brownell in August 2001, using Folgers® Classic Roast Coffee Crystals and a Pharmacia Ultraspec® III UV/Visible Spectrophotometer.

Coffee concentration and absorbance also correlate well with turbidity, as seen in Figure 17. The R^2 value is 0.994 with a forced intercept of zero. The correlation is shown in Equation 8.

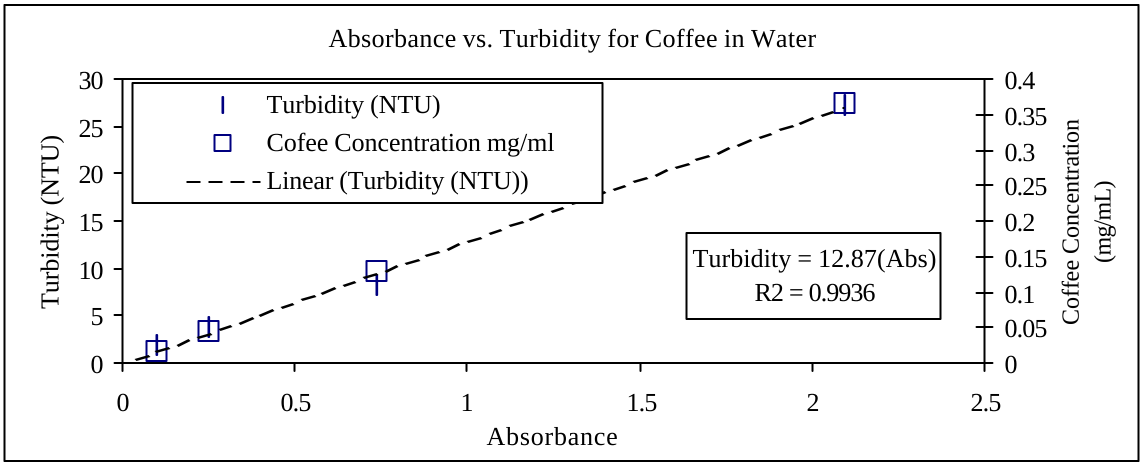
Equation 8

$$Turbidity(fromCoffee) = 12.87(Absorbance) \qquad \text{or}$$

$$Absorbance(fromCoffee) = \frac{Turbidity(NTU)}{12.87}$$

However, because coffee is a strong absorber of UV light, the trend observed here between turbidity and absorbance cannot be translated to any other turbid water, unless all turbidity can be accounted for by instant coffee.

Figure 17. Turbidity Measurement, Coffee Concentration and Absorption Coefficient



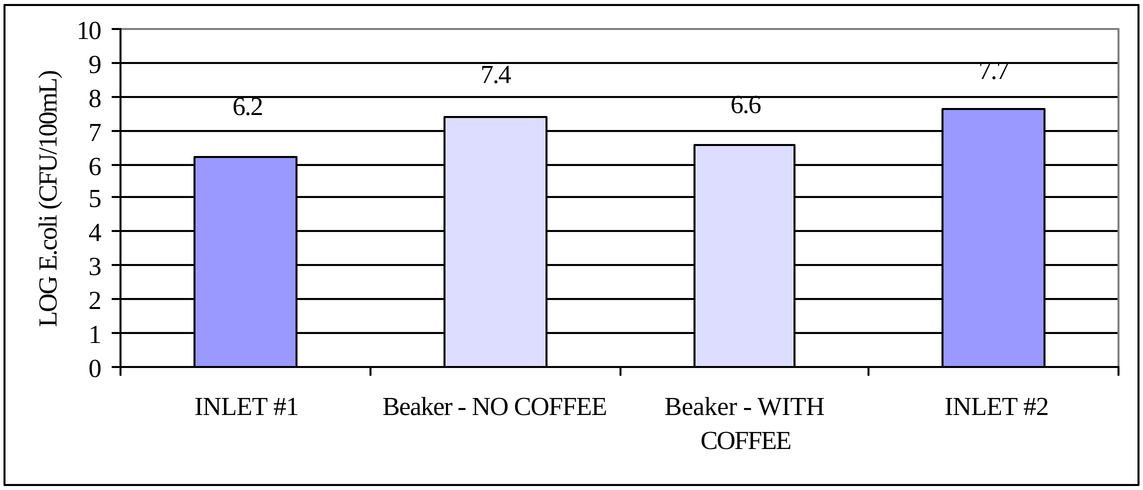
Note: Measurements were performed by Sarah Brownell in August 2001, using Folgers® Classic Roast Coffee Crystals and a Pharmacia Ultraspec® III UV/Visible Spectrophotometer and a Hach Pocket Turbimeter™.

(iii) Effect of Instant Coffee on *E.coli* Viability

At the concentrations used, pH was not lowered enough to affect *E.coli* viability. At a concentration of 0.4 mg/mL the pH was measured to be 6.0.

The results for the beaker test, which can be seen in Figure 18, show a slight, but not statistically significant, effect on *E.coli* viability. The difference between the concentration of *E.coli* with and without coffee (0.8 log units) is less than that between the first inlet sample and the last.

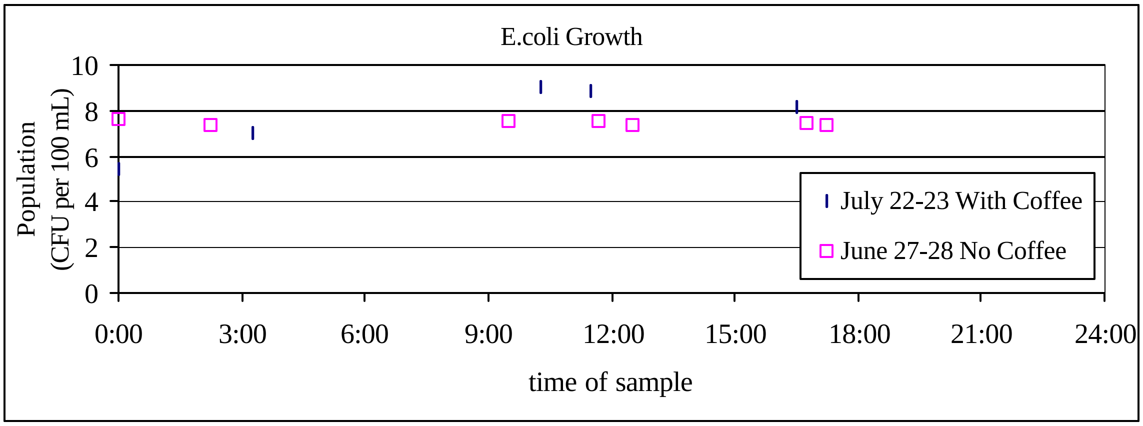
Figure 18. Effect of Coffee on *E.coli* – Beaker Test



Note: Testing was performed on June 21st, 2001 with the assistance of Tina Prevatte.

In the 24 hour experiment, the pH of the water with coffee was 6.89. The concentrations over time for *E.coli* with and without coffee are displayed in Figure 19. The effect of coffee on *E.coli* appears to be negligible.

Figure 19. *E.coli* Concentration with and without Coffee



Note: Testing on June 27-28 was performed with the help of Tina Prevatte. Testing on July 22-23 was performed by Sarah Brownell and Tina Prevatte.

c. UV-Tube Performance

Between April and July of 2001, nine experiments were run to measure performance of UV-Tube at different flow rates and three to measure performance of the UV-Tube at different flow rates with an increased absorption coefficient. A summary of all results is shown in Table 5. Only four samples – as highlighted in Table 5 – did not show total removal. With the exception of the April 23rd sample, the absorption coefficients (base e) are fairly high: 0.55 and 0.88 for 4 L/min flow rate and 0.38 for 8 L/min flow rate.

Table 5 Data Summary for *E.coli* Testing

Date	Na-thio g/L	Coffee g/L	Abs calc	á base e	Log Inlet	Flow Rate (L/min)	Log Outlet	**Log Reduction**	Total Removal	Plates with 0
23-Apr-01	0.1	0.00	0.10	0.22	6.13	2	2.10	**4.03**	NO	
03-May-01	0.1	0.00	0.10	0.22	6.32	2	0	**6.32**	YES	3
04-May-01	0.1	0.00	0.10	0.22	7.08	2	0	**7.08**	YES	2
06-May-01	0.1	0.00	0.10	0.22	6.37	2	0	**6.37**	YES	1
04-May-01	0.1	0.00	0.10	0.22	7.08	3	0	**7.08**	YES	2
03-May-01	0.1	0.00	0.10	0.22	6.32	4	0	**6.32**	YES	3
06-May-01	0.1	0.00	0.10	0.22	6.37	4	0	**6.37**	YES	1
21-Jun-01	0.1	0.20	1.24	2.85	6.94	4	0.78	**6.17**	NO	
28-Jun-01	0.1	0.05	0.38	0.88	6.47	4	4.01	**2.47**	NO	
03-May-01	0.1	0.00	0.10	0.22	6.32	5	0	**6.32**	YES	3
04-May-01	0.1	0.00	0.10	0.22	7.08	5	0	**7.08**	YES	1
06-May-01	0.1	0.00	0.10	0.22	6.37	5	0	**6.37**	YES	1
22-May-01	0.1	0.00	0.10	0.22	6.99	5	0	**6.99**	YES	2
04-May-01	0.1	0.00	0.10	0.22	7.08	6	0	**7.08**	YES	3
06-May-01	0.1	0.00	0.10	0.22	6.37	6	0	**6.37**	YES	1
29-Jun-01	0.1	0.01	0.16	0.38	7.80	6	0	**7.80**	YES	3
04-May-01	0.1	0.00	0.10	0.22	7.08	7	0	**7.08**	YES	3
22-May-01	0.1	0.00	0.10	0.22	6.99	7	0	**6.99**	YES	2
06-May-01	0.1	0.00	0.10	0.22	6.37	8	0	**6.37**	YES	2
10-May-01	0.1	0.00	0.10	0.22	6.20	8	0	**6.20**	YES	1
29-Jun-01	0.1	0.01	0.16	0.38	7.80	8	3.19	**4.61**	NO	
04-May-01	0.1	0.00	0.10	0.22	7.08	9	0	**7.08**	YES	3
06-May-01	0.1	0.00	0.10	0.22	6.37	10	0	**6.37**	YES	1
10-May-01	0.1	0.00	0.10	0.22	6.20	10	0	**6.20**	YES	1
22-May-01	0.1	0.00	0.10	0.22	6.99	10	0	**6.99**	YES	2

On May 10, 2001, a 30-ìm filter was attached to inlet of the tanks to block particulate iron from entering the system. It remained in place for all experiments after May 10th. Prior to addition of the filter some iron may have been entering the system. Since the absorbance was calculated based only on sodium thiosulfate and coffee concentrations, it may represent an underestimate for these early tests.

According to the method used, only plates with colonies between 50 and 200 are considered statistically significant (Hach 1997, p.461). The remaining data are displayed in Table 6.

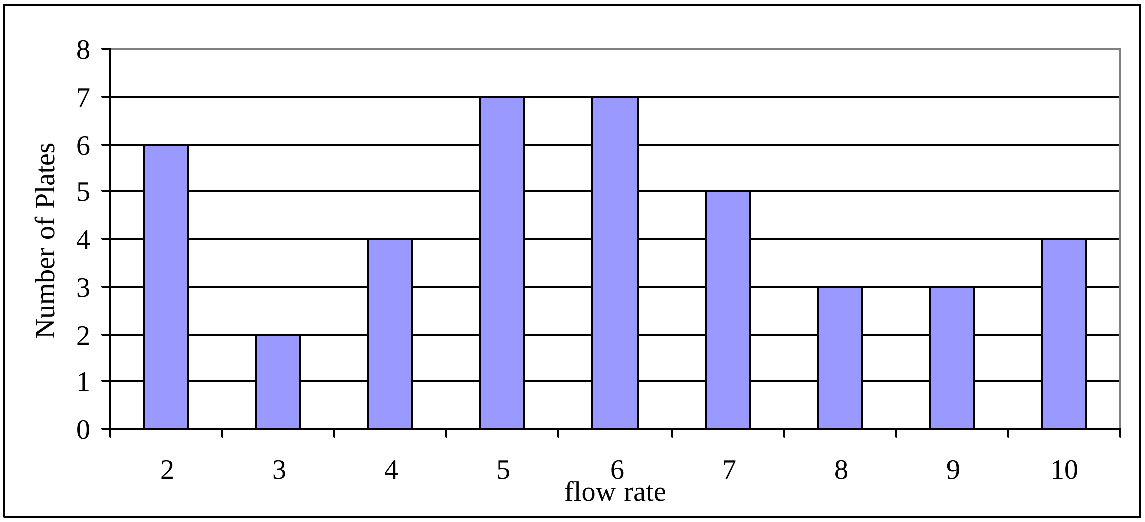
Table 6. Compilation of Data in which Plate Count was between 50 and 200

Date	Na-thio g/L	Coffee g/L	á Calc	á base e	Log Inlet	Flow Rate (L/min)	Log Outlet	**Log Red**	30-ìm filter
23-Apr-01	0.1	0	0.10	0.22	6.13	2	2.10	**4.03**	NO
28-Jun-01	0.1	0.05	0.38	0.88	6.27	4	4.01	**2.26**	YES
29-Jun-01	0.1	0.012	0.16	0.38	7.80	8	2.93	**4.87**	YES

The first experiment on April 23, 2001 produced somewhat anomalous results. The removal of *E.coli* increased with increasing flow rate. The bulb may have been initially coated with debris that was eventually burned off, or the bulb may have warmed up from the time between low and high flow rate tests. It is also possible that there had been a very high iron concentration that would not have bee accounted for in the calculation of the absorption coefficient.

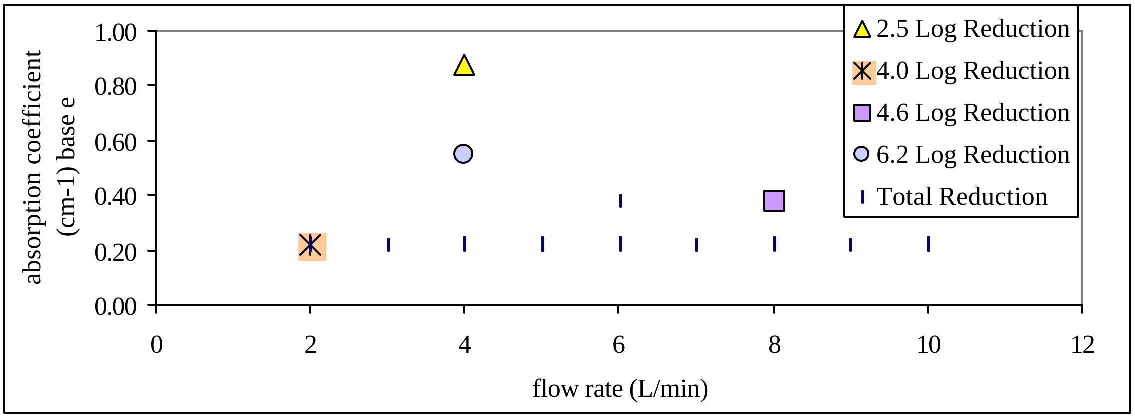
Although not technically countable, the majority of results from all testing show total removal of *E.coli* at flow rates up to 10 L/min, absorption coefficients greater than 0.22 cm^{-1} (base e) and inlet concentrations of at least $10^{6.3}$ CFU/100 mL. Figure 20 shows the number of plates, from effluent, with total removal (or 0 CFU/100mL) for each flow rate. The number of plates represents the sum of all dilutions for each experiment. In all cases, except for one, the absorption coefficient was 0.22; Three samples for the 6 L/min flow rate had an absorption coefficient of 0.38, due to the addition of coffee.

Figure 20. Number of Samples Representing Total Removal for á 0.22 cm^{-1}



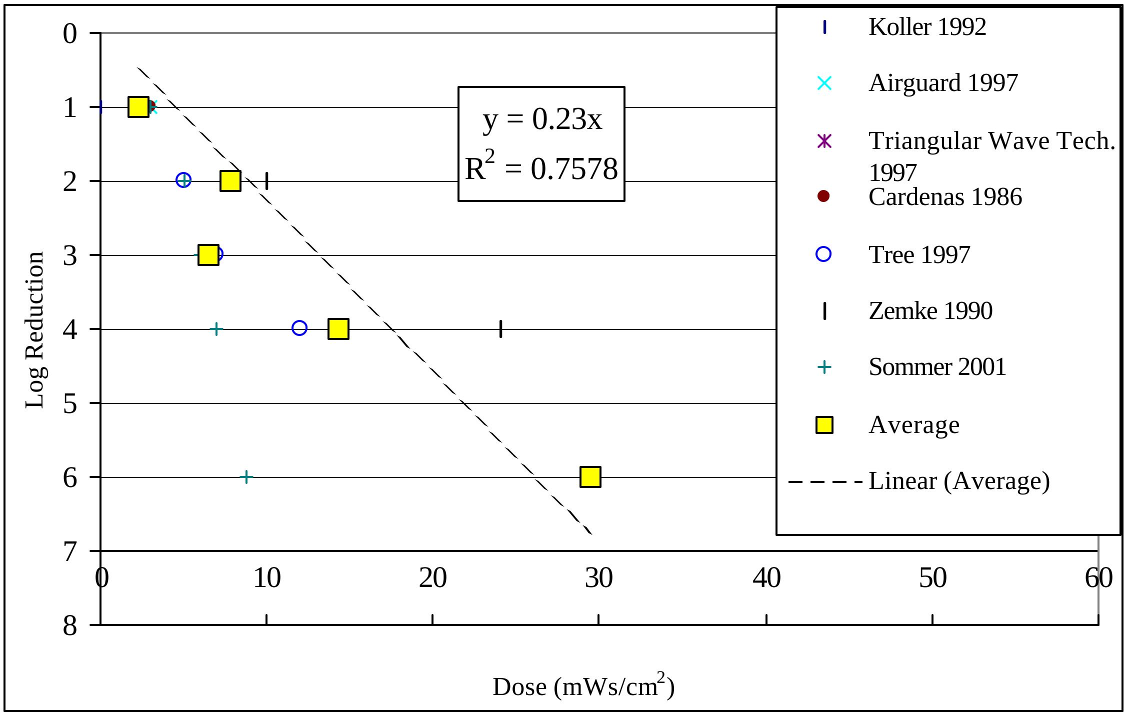
All results displaying reasonably consistent dilutions, although not necessarily with plate counts between 50 and 200, are displayed in Figure 21. All data except four points showed a total reduction. The higher absorption coefficients are due to added coffee.

Figure 21. Compilation of Biological Assay Data for *E.coli*



The reduction in *E.coli* is compared to dose-response data to back calculate dose. Dose-response data for the strain of *E.coli* used in this study was not found in the literature. A compilation of data from a variety of sources, using various nonpathogenic strains is shown in Figure 22.

Figure 22. Dose Response Data for *E.coli*



Sources: (Koller 1952; Cardenas, Ravina et al. 1986; Zemke, Podgorsek et al. 1990; Airguard 1997; Tree, Adams et al. 1997; Triangular Wave Technologies Inc 1997; Sommer, Lhotsky et al. 2000)

None of the papers discuss the absorbance characteristics of the water used to develop these dose response relationships. The average, as shown in Figure 22. indicates that a 6 log reduction is equivalent to a dose of 30 mWs/cm^2. Because almost all samples, with absorption coefficients less than 0.38 cm^{-1}, base e, showed a total removal, the dose of 30 mWs/cm^2 would be a minimum.

d. Contamination with Total Coliform

Throughout testing some plates became contaminated with total coliform. The origin of the contamination was found to be the dilution water in at least one case. The colonies were never numerous enough to block out *E.coli*, so in most cases they were noted, but assumed not to influence the results.

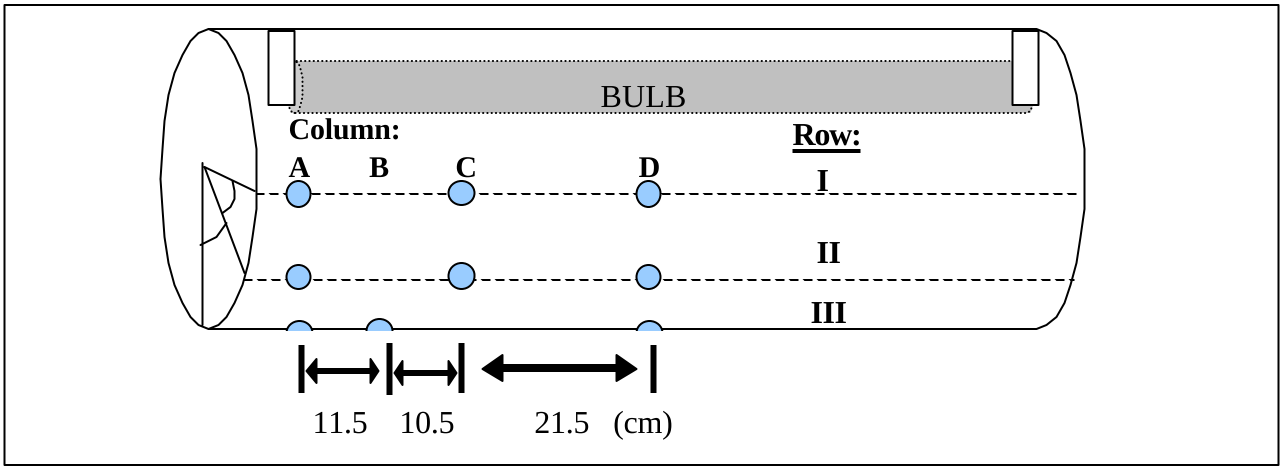
B. Irradiance Distribution within the UV-Tube

1. Measured Values

Irradiance measurements were taken through quartz windows inserted in the UV-Tube to compare with modeled values.

As a testing device, a UV-Tube was constructed as usual, lined with a galvanized steel gutter, and nine, 1-in diameter holes were drilled and fitted with 0.5-cm thick fused quartz (type 021, optically polished), which is transparent to ultraviolet light. The UV-Tube was filled with water and irradiance was measured through the quartz windows using a Spectroline® Digital Radiometer.[6] Placement of windows is shown in Figure 23.

Figure 23. UV Irradiance Measurement Set-Up



Note: Irradiance Test-Tube was constructed by Sarah Brownell and Laura McLaughlin

As shown above, the windows were placed in three rows, starting from one end of the bulb and moving towards the center. Row I was perpendicular to the top of the UV-Tube, row II was 45° from perpendicular and row III was at the bottom, or 90° from perpendicular. Column A aligned with the end of the bulb, column B was 11.5 cm from A – and only had a hole in row III – column C was 22 cm from A – and only had holes in rows I and II – and column D was 43.5 cm

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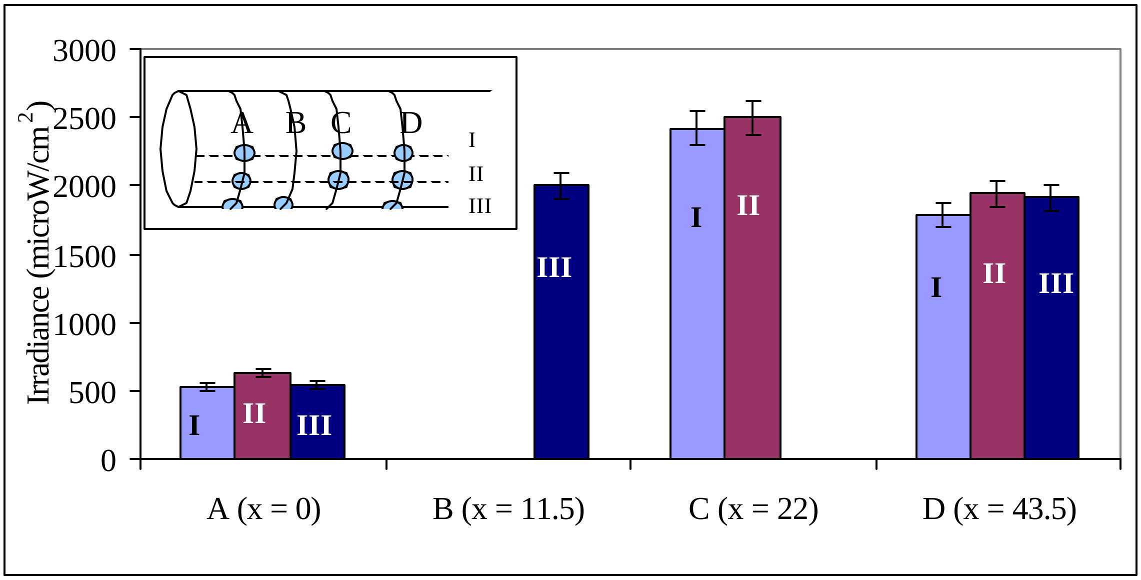
[6] Radiometer was electro-optically calibrated by manufacturer in on June 1, 2001. The above testing was completed in July 2001.

from A. The water height was set at 4 centimeters. While rows II and III were completely submerged, Row I was only about 25% under water.

Tap water was added and the bulb was turned on and allowed to warm up for 10 min. Irradiance was measured at the nine windows and the results are displayed in Figure 24.

Figure 24. Irradiance Results for Tap Water, through Quartz Windows



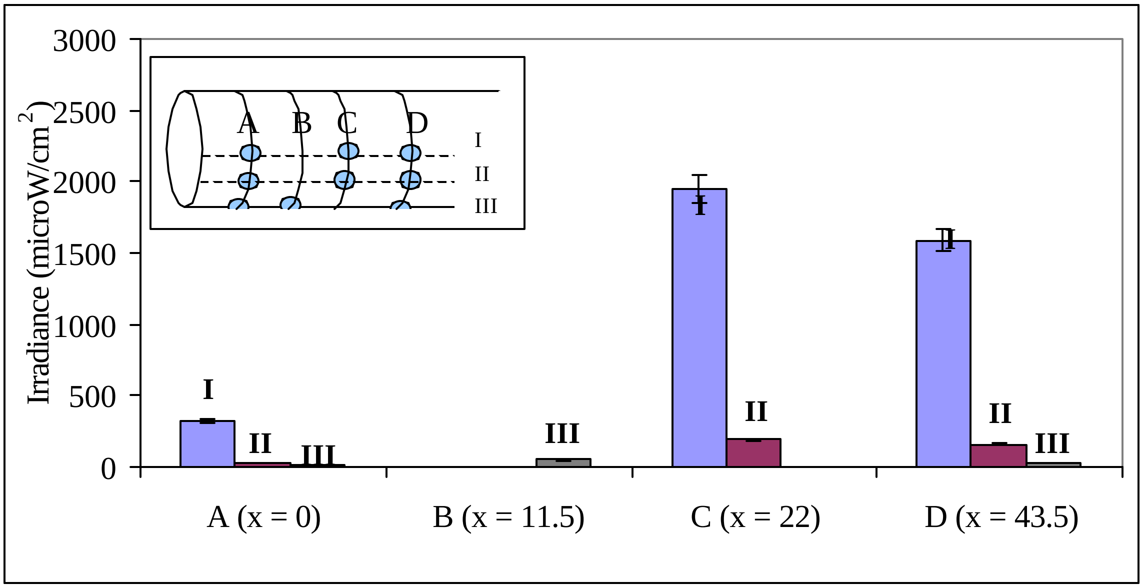
Note: Measurements were taken by Sarah Brownell on July 20, 2001.

Not surprisingly, the lowest values are for the three points at the end of the bulb, column A. Surprisingly, the three points near the center of the bulb (column D) had lower values than those one quarter of the way, and one eighth the way into the bulb (columns B and C). This result may be due to inconsistent placement of the quartz window.

The irradiance hitting the meter would be expected to decrease from row I to row III due to attenuation through water and air. This trend is not observed in the data shown in Figure 24; the variability within each column is smaller than 5% error of the instrument.

Next, transmittance was varied with the addition of instant coffee. Irradiance measurements were taken for each point. For example, results for water with a turbidity of 2.2 NTU are shown in Figure 25.

Figure 25. Irradiance Results for Coffee, Turbidity 2.2 NTU



Note: Measurements were taken by Sarah Brownell on July 20, 2001.

In Figure 25, with the increased absorbance of the water, measured irradiance dropped only slightly in row I and much more in rows II and III. The difference between the rows, in this case, was due to the fact that row I was only partially underwater, whereas rows II and III were totally submerged. As can be seen in columns A and D, the irradiance measured decreased as the path length through the water increased.

2. Bulb Warm-Up Data

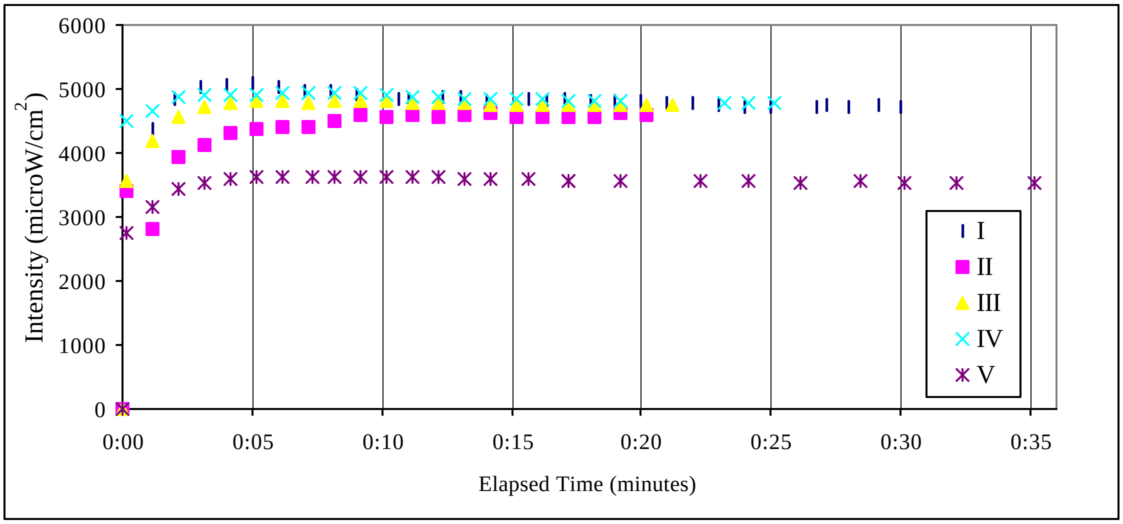
Bulb warm-up experiments were conducted using a UV-Tube wired with various bulbs and ballasts (Table 7). Irradiance was measured about 10 cm into the tube at the bottom with a Spectroline® Digital Radiometer. The results are compiled in Figure 26.

Table 7 Set Up for Bulb Warm-Up Testing Experiments

Label	Date	Bulb	Ballast
I	07/08/01	New GE T8, 30W bulb	Intended for T12, 40W bulb (from Mexico) Sola Basic Balastro bajo factor de potencia, encendido normal
II	07/10/01	New GE T8, 30W bulb	Intended for T12, 40W bulb (from Mexico) Sola Basic Balastro bajo factor de potencia, encendido normal
III	07/10/01	New GE T8, 30W bulb	Intended for T8, 32W bulb NAIS Electronic Instant Start Ballast
IV	07/10/01	New Ushio T8, 30W	Intended for T8, 32W bulb NAIS Electronic Instant Start Ballast
V	07/11/01	Aged GE T8, 30W bulb	Intended for T8, 32W bulb NAIS Electronic Instant Start Ballast

GE = General Electric

Figure 26. Germicidal T8, 30 Watt Bulb Warm-up Experiment



The steepest warm-up period occurred in the first two to three minutes. In all except for one case, the peak output occurred within the first five minutes. There is a notable difference between the first two trials, both involving the GE bulb and the Mexican ballast. The two trials were performed on different days, and the sensor may have been placed closer to the end of the bulb on the second day, accounting for the consistently lower irradiance. The aged GE bulb had the lowest irradiance, about a 30% lower than the new GE bulb. The difference between instant start and ballasts with separate starters was not significant, nor was the difference between the 32 Watt and the 40 Watt ballast.

3. Bulb Aging

The lower irradiance measure in the aged GE bulb (Figure 26) raised concerns about bulb aging. Germicidal T8 bulbs are generally recommended for replacement after one year. One source states that bulbs should be replaced after 8,000 to 12,000 operating hours (Kolch 1999). The General Electric (GE) bulbs used in Mexico and laboratory testing at Berkeley are rated for 7,500 hours, given a 3 hour average operating time (General Electric 2002). Because each start slightly decreases the bulb lifetime, longer operation periods, as would be the case with the UV-Tube, would increase the bulb lifetime. The 7,500 hours (approximately 10 months) is a minimum lifetime. GE will not release any more detailed information on output deterioration.

C. Materials Degradation

Ultraviolet light, especially in the UVC range will degrade a variety of materials. The first half of this section reviews what is known about certain materials and their interaction with ultraviolet light. The second half presents results from degradation tests conducted for the UV-Tube.

1. Material Interactions with Ultraviolet Light

Experimental data in the literature are generally concerned with degradation from sunlight and are therefore limited to UVA and UVB (280-400nm). Although the type and degree of degradation is likely a function of the particular exposure wavelength, we assume here that degradation in the UVA and UVB range is at least an indicator of potential degradation in the

UVC range. As it turns out, the degree of degradation is generally found to be inversely proportional to wavelength. Andrady et al. report a linear relationship between the logarithm of the damage and wavelength of exposure(1998, p. 101) However, others point out that the distribution of UVA, UVB and UVC could have “unexpected consequences”(Camilleri 2000, p.77). Finally, although considerable effort has gone towards understanding both how to both stabilize against and improve their breakdown of materials in the presence of sunlight, little analysis of expected final breakdown products exists, at least for plastics.

a. Organic Polymers (Plastics)

The rate of degradation of polymers increases with temperature. Beyond a threshold temperature the rate generally increases exponentially:

$$RATE \propto e^{\frac{T}{14.4}} \qquad \text{(Camilleri 2000, p.77)}$$

For polyvinyl chloride (PVC), the threshold value, above which temperature increases the reaction rate, is 50 deg C(Camilleri 2000, p.77).

(i) PVC (polyvinyl chloride)

The literature is abundant with evidence of PVC breakdown from exposure to sunlight. PVC is considered a very soft plastic. Tensile strength has been shown to decrease by 43% and 26% in Saudi Arabia and Florida, respectively, after a 24 month exposure (Andrady, Hamid et al. 1998, p.97). Other researchers, interested in accelerating the breakdown of PVC as a waste management technique, found that initial exposure to UVC light, increased the rate of degradation under visible light (Torikai and Hasegawa 1999).

Some concerns have been raised by environmental groups, such as GreenPeace, regarding the chemicals given off when PVC burns, one of which is hydrochloric acid (GreenBuilding Inc. 1994, p.10). This may be relevant if the UV-Tube is getting burnt on the inside.

(ii) ABS (Acrylonitrile-butadiene-styrene)

ABS, named after its three principal polymers, offer high impact resistance, good dimensional stability at high temperature and electrical resistance. The addition of carbon black as a UV stabilizer is reported to infer UV resistance to the material. No information was found on ABS and UVC. However two references were found on building UV disinfection systems with ABS for a fish tank (www.wetwebmedia.com/bizuvs.htm; www.fishgallery.com/pos/prod/775.html) and for home waste water treatment (www.pwmag.com/articles/online_articles/uv.htm).

(iii) Polyethylene

Similar to PVC, temperature is also a key component in the breakdown of polyethylenes (Andrady, Hamid et al. 1998, p.97).

(iv) Epoxy (glue)

Epoxy polymer based glues provide excellent adhesion to a variety of surfaces and good resistance to water, corrosion, chemicals and impact. They are, however, sensitive to degradation under ultraviolet light. Epoxy is sometimes combined with polyester resins to increase the resistance to UV degradation.

b. Stainless Steel

Stainless steel is generally accepted to be a safe material to use with UVC. Most commercial UV treatment systems use stainless steel containers. Although data are not available, we have confirmed that stainless steel has been tested by other users and found to create no by-products when exposed to the applicable levels of UV light.

c. Galvanized Steel

Galvanized steel is less expensive than stainless. It has a zinc coating which will preferentially corrode to protect iron interior. The coating integrity can be easily compromised by bending or cutting of the metal. No information was available on UV degradation, however galvanized steel is used for many outdoor, high sun exposure applications, such as gutters and flashing.

2. Laboratory Tests on Materials and Ultraviolet Light

Batch tests were conducted to measure contaminants after a 1-3 week exposure time under a 30W GE germicidal low pressure mercury bulb (as used in the UV-Tube). In real use an exposure time longer than a few days would be impossible due to evaporation. These prolonged batch tests were considered an absolute worst-case, improbable scenario.

A UV-Tube was constructed out of polyvinyl chloride (PVC) and then filled to weir height (4 cm) with distilled water. All openings were plugged to prevent loss by evaporation. The bulb was turned on for 435 hours (approximately 18 days) and then the water was sampled and sent to Delta Environmental Laboratories, Ltd. for hydrocarbon analysis. The same procedure was repeated for a UV-Tube constructed out of acrylonitrile-butadiene-styrene (ABS) with light for 396 hours (16½ days).

All samples were analyzed for 59 common volatile organic compounds (VOCs). As shown in Table 8, PVC alone produced 350 milligrams per liter chloride and dropped the pH to 1.8. Eight chlorinated organics were found. With the exception of methylene chloride (dichloromethane), the concentrations of all chlorinated organics met the World Health Organization (WHO) standards.

Table 8. Batch Test Results for Degradation of Plastics

	UV Exposure (days)	Chloride (mg/L)	pH	Benzene (ìg/L)	Chloroethane (ìg/L)	Chloroform (ìg/L)	Chloromethane (ìg/L)	1,1 Dichloroethane (ìg/L)	1,2 Dichloroethane (ìg/L)	1,2 Dichloropropane (ìg/L)	1,3 Dichloropropane (ìg/L)	Methylene Chloride (ìg/L)
Detection Limit				0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
WHO Guidelines		250	<8	10	NA	200	NA	NA	30	NA	NA	20
EPA MCL (2002)		250	6.5-8.5	5	NA	NA	NA	NA	5	5	NA	5
Under Ultraviolet Light												
PVC alone	18.1	350	1.82	0	50	1	115	2.5	28	8.4	13	41
ABS alone	16.5	--	--	1.8	ND	ND	ND	ND	ND	ND	ND	ND
PVC lined with Galvanized Steel; unlined end caps	7	--	--	ND	ND	ND	3.2	ND	2.1	ND	1.1	4.1
PVC lined with Galvanized Steel; lined end caps	7	--	5.72	ND	ND	ND	2.4	ND	1.8	ND	ND	4.4
No Ultraviolet Light												
PVC lined with Galvanized Steel; lined end caps	6	--	5.98	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: ND indicates none detected, -- indicates that value was not tested, NA indicates that the compound is not regulated.

Next, UV-Tubes were lined with galvanized steel and retested. In one case the end caps were left unlined, in the other they were lined. Liners acted as trays, wrapping part way up to the top on both ends, but leaving 6-10 centimeters at the top, i.e. behind the bulb, exposed. As shown in Table 8, lined tubes show much less degradation. The lined end caps reduced the concentrations of chloromethane, 1,2-dichloroethane and 1,3-dichloropropane by 25%, 14% and 100%, respectively. However the tube with lined end caps had a 7% higher concentration of methylene chloride. In both cases all measured compounds fell below the WHO and EPA standards.

A number of tests were conducted to calculate metal leaching by UV. Initially a piece of galvanized gutter and heavy duty aluminum foil, both purchased in Mexico, were submerged under water and subjected to ultraviolet light for 265 hours (approximately 11 days). The results are shown in Table 9. Next two tubes were partially lined with galvanized steel gutters purchased in Mexico. The gutter was adhered to the PVC with silicon glue. In one case, the end caps were also lined with flat galvanized steel, on the other the PVC was exposed.

Table 9. Batch Test Results for Degradation of Metals

	UV Exposure (Days)	Aluminum (mg/L)	Copper (mg/L)	Iron (mg/L)	Zinc (mg/L)
Detection Limit		.02	.01	.01	.01
WHO Guidelines		.2 (color)	2	0.3 (color)	3 (taste)
EPA - MCLs		0.05-0.2	1.0	0.3	5
Under Ultraviolet Light					
Aluminum and galvanized steel pieces in PVC	~11	3	--	0.037	60
PVC lined with galvanized steel; unlined end caps	7	ND	--	ND	43
PVC lined with galvanized steel; lined end caps	7	ND	ND	ND	30
No Ultraviolet Light					
PVC lined with galvanized steel; lined end caps	6	ND	ND	ND	18

Note: ND indicates none detected, -- indicates that value was not tested.

The leaching of zinc from the galvanized steel is likely occurring at the edges where the integrity of the galvanized coating has been compromised. Zinc is present in the water even without exposure to ultraviolet light. A better seal applied to the ends of the galvanized steel liner might be able to reduce the concentration of zinc in the water. Aluminum also leached, although much less than zinc.

3. Qualitative Results

Exposed portion of PVC tubes, in particular around the bulb, appeared burnt. All tubes displayed various stages of color change from completely black to yellowing.

4. Analysis of Degradation Results & Implications for Design

The batch test results can be analyzed in terms of flow-through rates of contamination and concentration after leaving water stagnant overnight with the bulb on and without flushing in the morning. To take an extreme case, the data are analyzed for a flow through rate of 2 liters per minute. A higher flow rate, which would be more realistic, would provide less contamination. Results are shown in Table 10 a and b. The residence time is calculated using a volume of 4.216 liters – which corresponds with a 4 inch diameter tube, 104 centimeters long, filled 4 centimeters high.

Table 10a. Plastic Degradation Results for Two Liter per Minute Flow Rate

	Chloride (mg/L)	Benzene (ig/L)	Chloroethane (ig/L)	Chloroform (ig/L)	Chloromethane (ig/L)	1,1 Dichloroethane (ig/L)	1,2 Dichloroethane (ig/L)	1,2 Dichloropropane (ig/L)	1,3 Dichloropropane (ig/L)	Methylene Chloride (ig/L)
Detection Limit		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
EPA MCL (2002)		250	6.5-8.5	5	NA	NA	NA	NA	5	5
EBMUD Average (2001)	*8.8*	*ND*		*46*		*ND*	*ND*	*ND*		*ND*
Under Ultraviolet Light										
PVC alone	0.028	ND	0.004	0.0001	0.009	0.0002	0.002	0.0007	0.001	0.003
ABS alone	--	0.0002	ND	ND	ND	ND	ND	ND	ND	ND
PVC lined with Galvanized Steel, unlined end caps	--	ND	ND	ND	0.0007	ND	0.0004	ND	0.0002	0.0009
PVC lined with Galvanized Steel, lined end caps	--	ND	ND	ND	0.0005	ND	0.0004	ND	ND	0.0009

Note: EBMUD stands for East Bay Municipal Utility District.

Table 10b. Metal Degradation Results for Two Liter per Minute Flow Rate

	Aluminum (mg/L)	Copper (mg/L)	Iron (mg/L)	Zinc (mg/L)
Detection Limit	.02	.01	.01	.01
WHO Guidelines	.2 (color)	2	0.3 (color)	3 (taste)
EPA – MCLs	0.05-0.2	1.0	0.3	5
EBMUD Average	*0.05*	*ND*		*0.05*
Under Ultraviolet Light				
PVC lined with galvanized steel; unlined end caps	ND	--	ND	0.0090
PVC lined with galvanized steel; lined end caps	ND	ND	ND	0.0063
No Ultraviolet Light				
PVC lined with galvanized steel; lined end caps	ND	ND	ND	.0044

The concentrations of all contaminants are well below the EPA MCL. The chloride and chloroform concentrations are orders of magnitude below the East Bay Municipal Utility District average values.

To take another extreme case, the data are converted to give concentrations after the water has sat under the light for UVC 12 hours. Results are shown in Table 11a and b.

Table 11a. Plastic Degradation Results for 12 Hour Exposure (ig/L, unless specified)

	Chloride (mg/L)	Benzene (ig/L)	Chloroethane (ig/L)	Chloroform (ig/L)	Chloromethane (ig/L)	1,1 Dichloroethane (ig/L)	1,2 Dichloroethane (ig/L)	1,2 Dichloropropane (ig/L)	1,3 Dichloropropane (ig/L)	Methylene Chloride (ig/L)
Detection Limit		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
EPA MCL (2002)		250	6.5-8.5	5	NA	NA	NA	NA	5	5
EBMUD Average (2001)	*8.8*	*ND*		*46*		*ND*	*ND*	*ND*		*ND*
Under Ultraviolet Light										
PVC alone	9.7	ND	1.38	0.028	3.17	0.07	0.77	0.23	0.36	1.13
ABS alone	--	0.1	ND	ND	ND	ND	ND	ND	ND	ND
PVC lined with Galvanized Steel, unlined end caps	--	ND	ND	ND	0.23	ND	0.15	ND	0.08	0.29
PVC lined with Galvanized Steel, lined end caps	--	ND	ND	ND	0.17	ND	0.13	ND	ND	0.31

Table 11b. Metal Degradation Results for 12 Hour Exposure

	Aluminum (mg/L)	Copper (mg/L)	Iron (mg/L)	Zinc (mg/L)
Detection Limit	.02	.01	.01	.01
WHO Guidelines	.2 (color)	2	0.3 (color)	3 (taste)
EPA - MCLs	0.05-0.2	1.0	0.3	5
EBMUD Average	*0.05*	*ND*		*0.05*
Under Ultraviolet Light				
PVC lined with galvanized steel; unlined end caps	ND	--	ND	3.07
PVC lined with galvanized steel; lined end caps	ND	ND	ND	2.14
No Ultraviolet Light				
PVC lined with galvanized steel; lined end caps	ND	ND	ND	1.50

For the unlined PVC tube, the concentration of chloride is above the average EBMUD value, but more than an order of magnitude below the EPA MCL (maximum contaminate level). The chloroform concentration, 0.028ìg/L is more than three orders of magnitude below the EBMUD average value. The values for chloroethane, chloromethane and 1,3-dichloropropane, for which no MCL exists, are in the microgram per liter range, 1.4, 3.2 and 0.4, respectively. The concentrations of 1,1-dichloroethane, 1,2-dichloroethane, 1,2-dichloropropane and methylene chloride are all below the MCL of 5.0ìg/L.

For the ABS tube and all of the lined tubes, the contaminants would all be below the detection level.

5. Health Consequences of Compounds in Lined PVC Design

Health concerns associated with the four VOCs present in the two week batch test of the lined PVC tube are shown in Table 12.

Table 12 Health Concerns of VOCs found in line PVC tube

Compound	MCLG* (ìg/L)	MCL** (ìg/L)	Cancer Category	Type of Damage
Chloromethane ($ClCH_3$)		Not Regulated	Suspected carcinogen	Developmental toxicant
Dichloromethane/methylene chloride (Cl_2CH_2)	0	5	Recognized carcinogen	Short term: Nervous system, blood[1] Long term: liver damage, cancer[1]
1,2-dichloroethane ($Cl_2C_2H_4$)		5	Recognized carcinogen	
1,3-dichloropropane ($Cl_2C_3H_6$)		Not Regulated	none	Suspected gastrointestinal or liver toxicant

*MCLG: Maximum Contaminant Level Goal. Environmental Protection Agency (EPA) non-enforceable standard, based on health concerns.

**MCL: Maximum Contaminant Level. EPA enforced standards for drinking water, part of the National Primary Drinking Water Regulations. Units are equivalent to parts per billion. Determined as a balance between health goals and economic and technical feasibility.

[1] (EPA 2001)

VII. Modeling

In this section the development and evolution of an irradiance distribution model are described. Results from the model are compared with biological assay results.

Irradiance and fluid models have been employed to corroborate biological assay results and to create a predictive tool to aid in assessing design modifications of the UV-Tube. The irradiance model is based on the point source summation (PSS) method, which treats the light bulb as an infinite line of point sources that are summed to give the irradiances at each point within the reactor, creating an irradiance distribution. Summing these irradiance values straight across provides a dose for plug flow hydraulics. Sarah Brownell plans to investigate modeling software that can be combined with the irradiance distribution to obtain a more accurate dose distribution. The system can then be optimized to reduce the variance in the dose distribution. The flow rate will be set such that the minimum dose received by any fluid path is greater than that necessary to provide the desired level of disinfection.

A. Irradiance Distribution

The point source summation method used here is adapted from Blatchley (1997).

Equation 9, from Blatchley (1997, p.2210):

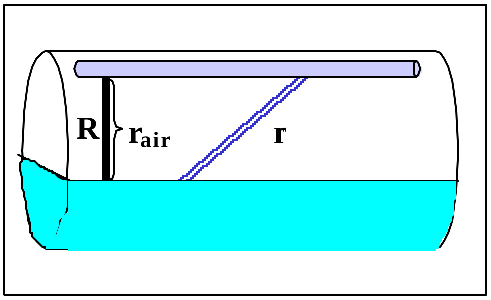
$$Intensity_{\lambda}(R,z)=\sum_{i=1}^{n}\frac{\frac{P_{\lambda}}{n}}{4\pi\rho_i^2}\exp\left[-\left(\sigma_q t_q+\sigma_w\left(R-r_q\right)\frac{\rho_i}{R}\right)\right]$$

P_{λ} – bulb power at 254nm (mW)
n – number of point sources
ρ – distance *i*th point source to receptor site (cm)
σ_q – absorbance coefficient for quartz (cm^{-1})
σ_w – absorbance coefficient for water (cm^{-1})
t_q – thickness of quartz sleeve (cm)
R – radial distance from bulb to receptor site (cm)
r_q – outside radius of quartz sleeve (cm)

Since the Blatchley equation is intended for use with a submerged bulb surrounded by a quartz sleeve, the quartz terms have been eliminated ($ó_q t_q$ and r_q) and a air terms (r_{air} and $ó_{air}$) have been added:

Equation 10

$$Intensity_{(i,j)}=\frac{P}{4n\pi\rho_{i,j}^2}\exp\left[-\left(\sigma_{air}r_{air}+\sigma_w\left(R-r_{air}\right)\frac{\rho_{i,j}}{R}\right)\right]$$



Define:
r_{air} – distance from bulb to surface of water (cm)
$ó_{air}$ – absorbance coefficient of air (cm^{-1})

However, absorption of UVC through air essentially zero, so the ó$_{air}$r$_{air}$ term can be neglected (Blatchley 1997, p.2211):

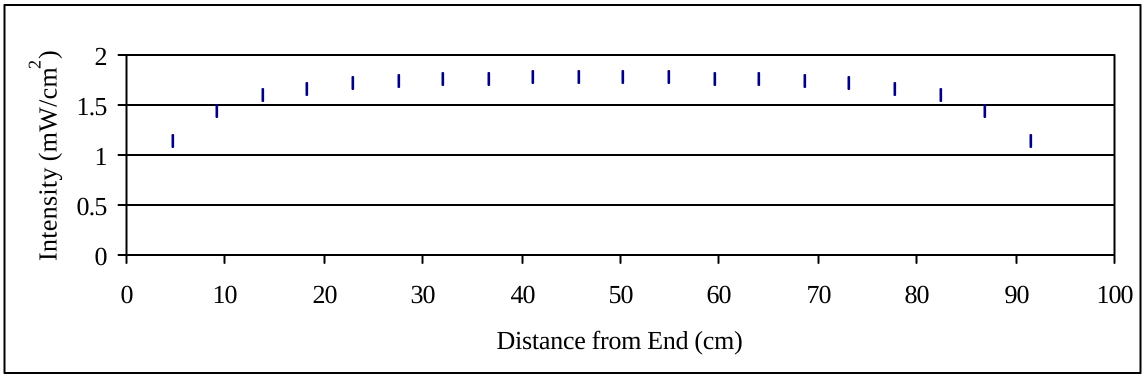
Equation 11

$$Intensity_{(i,j)} = \frac{P}{4np r_{i,j}^{2}} \exp\left[-\left(s_{w}\left(R - r_{air}\right)\frac{r_{i,j}}{R}\right)\right]$$

The irradiance is a function of the distance along the bulb (i) and the distance along a line in the reactor (j). Initial calculations assume water movement is plug flow and that minimal dose will be received by the water at the bottom of the tube. Using Engineering Equation Solver[7] (EES), the calculation is repeated for each point along the bulb and then for each point along the bottom of the tube.

Given the assumptions that the tube is only as long as the bulb (36 inches), the bulb is 6.5 centimeters from the bottom of the tube, the bulb power at 254 nanometers is 6,600 mW, the water is 4 cm deep and the absorption coefficient is 0.01 cm^{-1} (base e), the irradiance distribution along the bottom of the tube is calculated and shown in Figure 27. The EES code used to obtain these values is reported in Appendix C.

Figure 27. Irradiance Distribution Along the Bottom of the UV-Tube (á=0.01 cm^{-1}, base e)



Further complexity was added by accounting for the extra thickness of water as it flows over the weir. The weir, or the outlet is approximated as a sharp-crest, and the equation relating height to flow rate is:

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[7] F-Chart Software, Middleton, WI 53562 / www.fchart.com

Equation 12

$$q = C_{wr}\frac{2}{3}\sqrt{2g}\left(extra\right)^{3/2}$$ (White 1986, p.679)

q – area flow rate (volume flow rate/width)
extra – height of water above weir
C_{wr} – an experimentally determined weir coefficient
g – gravitational constant

The weir coefficient can be approximated as:

$$C_{wr} \sim 0.611 + 0.075\left(\frac{extra}{h}\right)$$ **Equation 13**

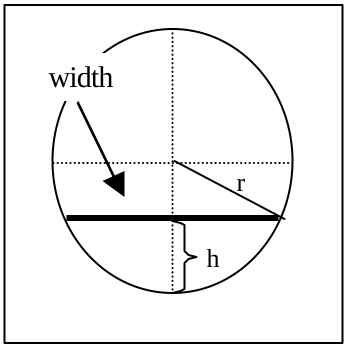
h– weir height (White 1986, p.679)

(Typically the height of water over weir is given as *H;* the weir height as *Y.* Here I have defined these two variables to be consistent with the model.)

The flow rate per unit width (q) is calculated each time using the following equation to calculate width based on the weir height:

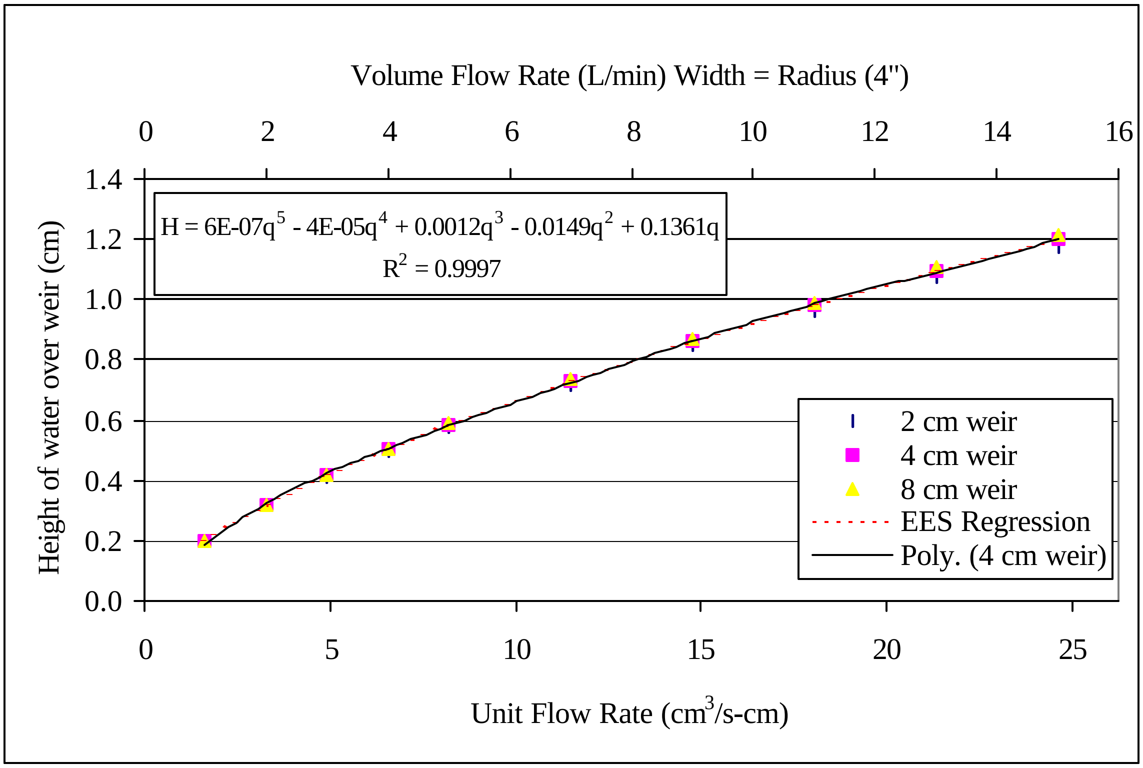
Equation 14

$$width = 2\sqrt{r^2 - (r-h)^2}$$



The weir height and flow rate were varied and predicted values of water height over weir were examined. As can shown in Figure 28, the results are nearly identical for weirs of height 2 cm, 4 cm and 8 cm.

Figure 28. Effect of Flow Rate on Extra Height over Weir and Two Predictive Equations



The height of water over the weir was determined for flow rates ranging from 1 to 15 L/min and channel width equal to the radius of the tube (4 in). A regression was performed and a fifth order polynomial was fit using least fit regression in EES. In Figure 28, this regression was compared to the fifth order polynomial with a forced zero intercept calculated by Excel. The two equations produce essentially the same results within the relevant range of flow rates. The EES regression was chosen to be used in the model.

The second complexity that was added involves the extra portion of the tube before the bulb starts. To take this length into account a *nobulb_inlet* term was added. The difference between the length of the bulb plus the *nobulb_inlet term* and the tube length account for the portion of the tube not directly below the bulb on the opposite end of the tube. The code for this final model appears in Appendix D.

Given the plug flow assumption, dose can be computed as the irradiance at each point times the time at that point. For a given weir height, the cross-sectional area is computed as:

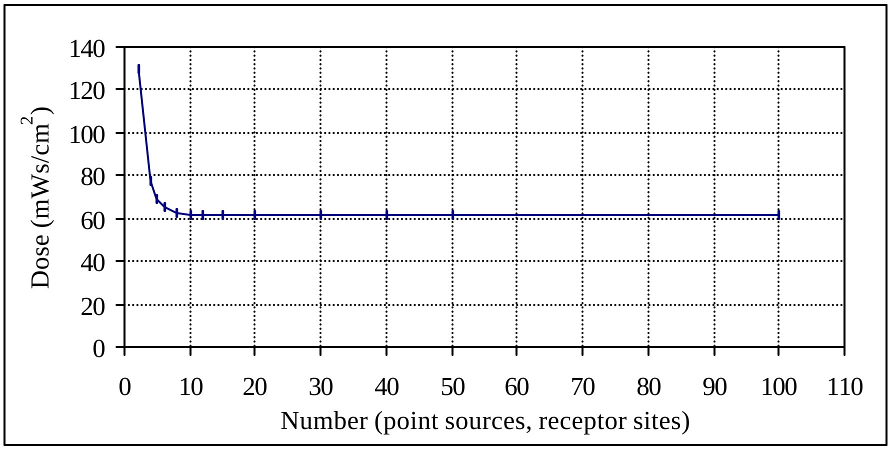
Equation 15

$$Area = \frac{p Radius^2 \arccos\left(\frac{Radius - h}{Radius}\right)}{180} - \left[(Radius - h)\sqrt{2(Radius)h - h^2}\right]$$

The total residence time is computed as the volume (tube length times area) divided by the flow rate. For each point the irradiance is multiplied by the residence divided by the number of points computed. If the tube is divided into 100 points, each irradiance is multiplied by the residence time divided by 100.

As the number of divisions (of the bulb and the tube) increase, the dose calculation decreases rapidly and asymptotes around 8, as shown in Figure 29.

Figure 29 Output Change for Increasing Iterations of Calculations

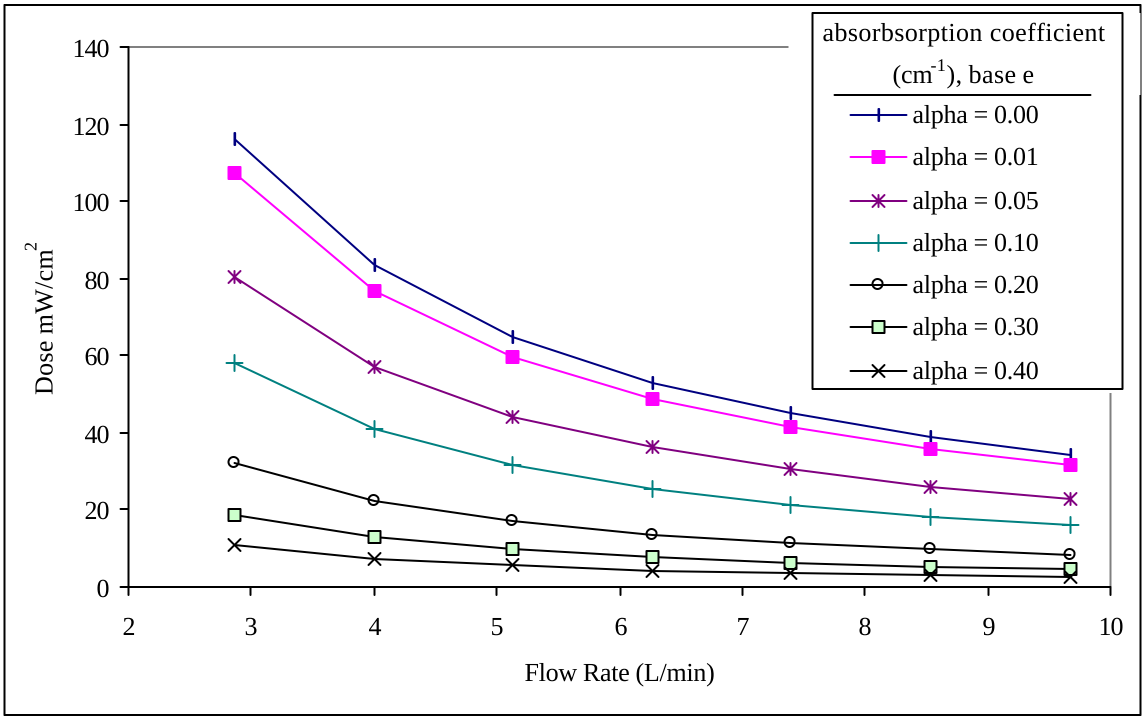


Using the model, and m and n values greater than 20, the dose was calculated as a function of flow rate and absorption coefficient, given the following assumptions:

Radius = 5.08 cm
Tube length = 104.14 cm
Bulb output at 254 nm = 6,600 mW
Weir height = 4 cm
Distance from bulb to bottom of tube = 7.62 cm
Length of tube before bulb starts = 6.35 cm

The absorption coefficient (á) was varied between 0.00 and 0.40 cm^{-1}, base e. Results are displayed in Figure 30.

Figure 30. Dose as a Function of Flow Rate and Absorption Coefficient

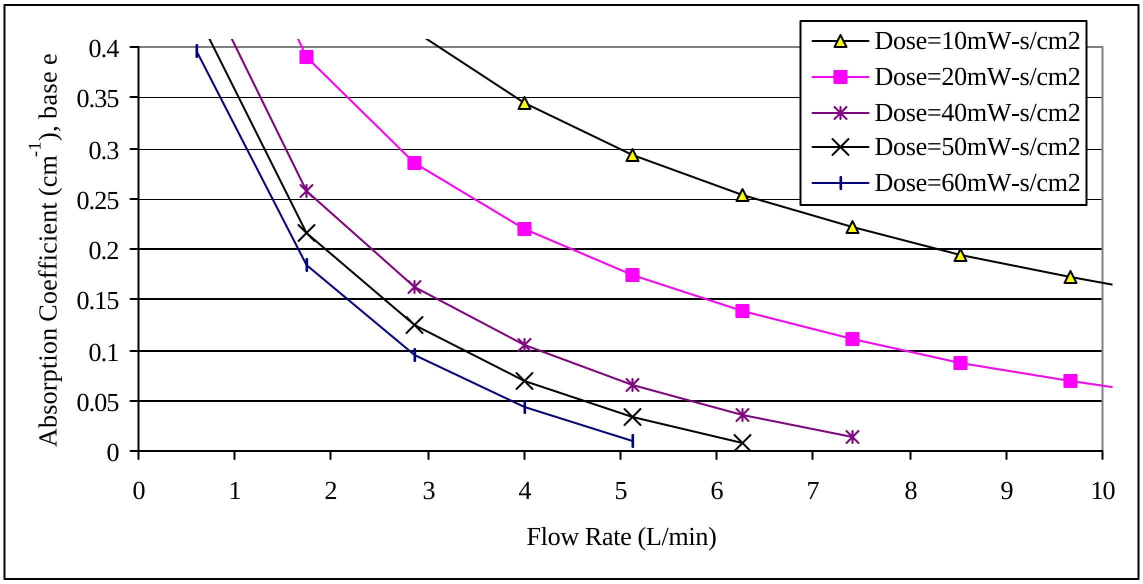


As can be seen in Figure 30, the dose decreases rapidly as flow rate increases for small alpha values. As the absorption coefficient increases the change in dose for increasing flow rate decreases. Therefore, for water with a high absorption coefficient, decreasing the flow rate will not increase the dose by very much. This pattern is one reason why knowing the absorption coefficient is so critical to predicting performance.

Curves such as those in Figure 30 could be used to find the correct flow rate based on the water quality and the necessary dose.

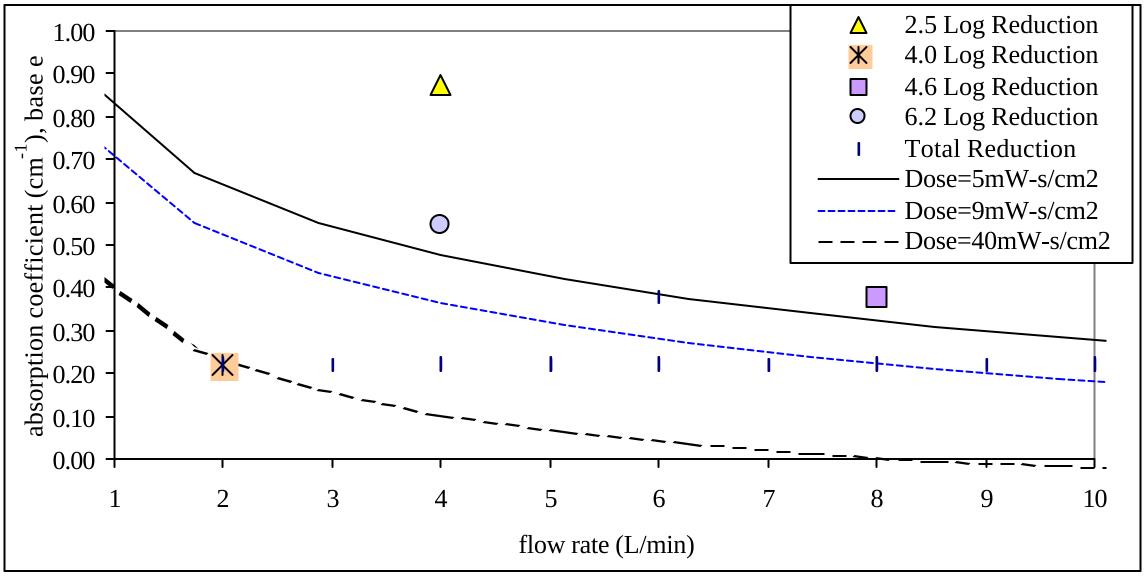
The data can also be displayed in a format analogous to the biological assay data; in Figure 31 dose isolines are shown in terms of flow rate and absorption coefficient, similar to Figure 21.

Figure 31. Dose Isolines in Terms of Flow Rates and Absorbance



For better comparison, model-predicted dose isolines are overlaid on Figure 21, in Figure 32.

Figure 32. Predicted Dose with Experimental Data from Biological Assay



Based on dose-response data for *E.coli* from various sources a 2.5 log removal requires a dose of approximately 11 mW-s/cm^2 and a 4.6 log removal requires a dose of approximately 20 mW-s/cm^2 (Koller 1952; Zemke, Podgorsek et al. 1990; Tree, Adams et al. 1997; Triangular Wave Technologies Inc 1997). Few data were found on 6 log *E.coli* removal. One source gave a value greater than 50mW-s/cm^2 (Zemke, Podgorsek et al. 1990). From Figure 32 total removal points mostly fall between the 9 mWs/cm^2 and 40 mWs/cm^2 dose isolines.

VIII. Field Trial

The UV-Tube design was essentially born in Pátzcuaro, Mexico, and it was there that we returned for further testing. The purpose of the visit was threefold: to validate technical effectiveness (through biological tests) in the field, to assemble opinions and reactions from potential users that would inform into the design process, and to explore dissemination strategies.

In July of 2001, when Laura McLaughlin and I left for Mexico to begin the field trial, there were still many technical questions left unanswered. However, we realized that investigations in the laboratory were only useful up to a certain point, because ultimately the final product would only succeed if it were appealing to the target audience. Precisely because the design was not yet set, it was exactly the right time to incorporate user feedback.

Because we had not answered all of the technical questions and the UV-Tube was not ready to provide water for consumption it was premature to test the dissemination model, as described previously. Instead, our goal was to install systems for prolonged performance testing and interact with potential users to ascertain their preferences. We proceeded with the help of the local NGO that had been involved while Lloyd Connelly was first developing the UV-Tube, *Grupo Interdisciplinario de Tecnología Rural y Apropiada* – Interdisciplinary Rural and Appropriate Technology Group (GIRA). Jaime Navia and Florentino Mota, of GIRA, organized a group of participants who agreed to the conditions of the study. Together we organized and held a workshop for these participants installed the devices in their homes and tested inlet and outlet bacteria concentrations on a biweekly basis. After I returned to Berkeley in August, Laura continued installations and testing through December.

A. The Workshop

Although the study situation was distinct from the independent workshop model, we were able to observe how a workshop would function. Jaime chose people with whom he already had a good relationship and mutual trust. Because of these special circumstances, the interest and enthusiasm of these participants could not be interpreted as an indication of general community interest.

Five families were asked and agreed to participate in the workshop, have the UV-Tube installed and allow follow-up visits to monitor water quality. On the day of the workshop two families were present: one couple, and one man without his wife. Following introductions, Jaime spoke generally about water and health. Participants were well informed about biological contaminants common to water. Both households used bottled water for drinking and cooking needs. One reported only buying the brand *Risco* (made by the Coca-Cola Company) and the other *Santorini* (made by the Pepsi-Cola Company). Jaime informally lead them through a quick calculation of what they each spend on bottled water compared to what would be spent on electricity to power the UV-Tube. Everyone agreed that the electricity cost was minimal compared to what they spend on bottled water.

After some coffee and cookies, we moved to the workshop to begin construction. With all materials laid out and instructions in Spanish (see Appendix E.), participants each built their own UV-Tube. Since researchers and members of GIRA far outnumbered participants, we provided guidance throughout the process. However, it was clear that even in the absence of people with previous UV-Tube building experience, the participants would have been able to follow the instructions and build the UV-Tube without a problem. With our assistance the process took only about two hours. The most difficult part of the construction was cutting the liners for the end caps and the outlet hole and gluing that portion together. It is also interesting to note that the PVC glue purchased in Mexico was much slower drying and less effective than that purchased in California.

B. The Installation

The first installation was scheduled within a few days. On the first visit, we discovered that the outlet tube had come apart from the end cap. We sketched the kitchen area and discussed with the family how, and exactly where, to install the UV-Tube. They suggested attaching shelving brackets to the wall to support the UV-Tube. We examined the chrome faucet in their kitchen sink (see Figure 33) and tried to think of ways to adapt the UV-Tube to flow into the preexisting faucet. Luckily, the couple had a grown son, who lived across the street and happened to be a plumber. He stopped by and provided some much needed suggestions on how to install the UV-Tube. We decided that it would not be possible to preserve the chrome faucet as the outlet.

On the third visit we arrived with an assortment of galvanized steel parts and a garden-hose style valve to replace the lovely faucet. We removed the pink flowering plant and got to work drilling into the concrete wall and removing the existing plumbing. As it turned out there was no way to turn off the water going to the kitchen, so instead all other faucets were opened completely to reduce water pressure and minimize flooding in the kitchen.

On completion we performed some simple water tests and determined that there was no detectable iron, free chlorine or total chlorine. The turbidity was low, around 0.1-0.4. We took an inlet sample by running water through the tube without the light on. This sample later came back positive for coliform bacteria[8]. The following day we repeated all tests. Once again there was no detectable iron, free chlorine or total chlorine. The inlet sample tested positive and the outlet sample (after a 10 minute bulb warm-up and flushing) tested negative. The maximum attainable flow rate at this faucet was 0.75 L/minute.

Figure 33. Kitchen Sink Prior to Installation of UV-Tube

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[8] All field samples were tested with the Presence/Absence Method using Bromocresol Purple Broth. This method meets or exceeds the specifications in Standard Methods for the Examination of Water and Wastewater 19th Ed Hach (1997). <u>Water Analysis Handbook</u>..

C. Effectiveness in the Field

Between July and December of 2001, Laura McLaughlin continued to test the first installed tube twice per week and installed and tested two additional UV-Tubes. The results of outlet samples were consistently negative. The one exception occurred in the first installed tube. Water was observed through the leak detector (bottom of tube) indicating that the liner had somehow become separated from the tube, and water was passing below it. Before Laura could remove the tube and replace the liner she chose to patch the leak detector in order to reduce the leakage of water into the house and reduce the burden on the family. Not surprisingly, after the leak detector was plugged up, some of the outlet samples came back positive for bacteria.

D. Additional Considerations: Importance of Aesthetics

The importance of aesthetics in the design became glaringly evident when we first ripped out the chrome faucet and replaced it with a big white plastic tube (Figure 33). The one meter length of the UV-Tube barely fit between the wall and the sink. In many homes it might not fit at all. In this particular home, given the extremely low flow rate, data suggest that a shorter tube, using an 18 inch 15 Watt bulb would have been effective.

Figure 34 Picture of Installation Site Before and After

E. Results and Conclusions

The workshop was quite successful. To begin with, materials were available. All materials were purchased at a local hardware store in Pátzcauro, with the exception of the bulb and the stainless steel sheeting, which were purchased in Morelia, which is about a 45 minute bus ride away. It is possible that stainless steel may be available right in Pátzcuaro as well. Participants were able to follow the written instructions and build their own UV-Tube.

By October three UV-Tubes were installed and were tested by Laura on a biweekly basis. Most inlet samples were positive for coliform bacteria and all outlet samples were negative.

Laura confirmed the importance of the leak detector under the metal liner. During the time that water was escaping from it, outlet samples were still negative. Once she plugged the detector outlet samples were all positive. This result confirms that not only does the leak detector provide an important indicator of a problem, but it also prohibits contaminated water from bypassing the system.

The installation described above was the first one we had ever done. Because the participants were doing us a favor by participating, we wanted to be the least burden possible, so we attempted to handle the installation ourselves. Laura reported that for the next two installations she stood back and let the users do the work – the result: installations were complete in a matter of hours, rather than days.

The only negative *result* from this field study was the indication that the UV-Tube may not meet the aesthetic concerns of some households. However, the household discussed in the previous section does not necessarily represent the target audience. Not everyone has a chrome faucet, or even an indoor kitchen sink and certainly not everyone can afford to purchase bottled water consistently. The UV-Tube may not be attractive to those who can afford to purchase bottled water. This is an area for further study.

The most obvious solution to the aesthetics problem is to hid the device. But this solution has three problems. First, the UV-Tube is not pressurized, so it must be above the faucet height. Second, there is no residual disinfectant provided, so the longer the path from the UV chamber to the outlet, the more area for contamination. Third, the viewing window provides a safety factor to confirm that the light is on, ideally this window would always be in the line of sight when water is obtained from the UV-Tube.

Indoor and outdoor installations have different concerns and aesthetics may play less of a role if the UV-Tube is to be placed outside.   If the water supply is not consistent and water is stored then the UV-Tube would be attached to a funnel, rather than to piping.

We broadly address aesthetic concerns by considering different materials, smaller sizes and better ways to create an outlet.

F. Future Dissemination: Small Enterprise

Although the workshop conducted with GIRA was successful, the community workshop approach in general necessitates a strong and sustaining organization and does not address any of the aesthetic concerns. On the other hand, if UV-Tubes were disseminated through local entrepreneurial efforts, the local entrepreneurs would have the incentive to create and market an attractive and desirable product. Local entrepreneurs would also provide a sustaining supply of the product and maintenance.

If the UV-Tube Project can assist local entrepreneurs, it will keep the construction, operation and control local, while providing and economic development opportunities.

IX. Conclusions, Recommendations & Future Directions

The UV-Tube provides a balance between technical effectiveness, local availability of parts, ease of use, affordability and appeal.

Although the biological assay results are not able to precisely bracket the dose provided, they show consistent good performance. Dose predicted by the irradiance model is consistent with that indicated by the biological assay.

The Generation III design, a stainless steel lined PVC tube, provides the best balance between technical feasibility, appropriateness and low cost considerations, based on model results, bioassays and the cost of materials in Mexico. Because lining the end caps adds more complexity to the design and does not significantly reduce the degradation products, it can be neglected.

One of the more serious and complex concerns is the materials. The high energy light (UVC) produced by germicidal bulbs is likely to have an effect on many materials, however because UVC is not usually a present in the terrestrial environment – it is almost completely absorbed by the ozone layer – data are lacking on what these effects would be. The results from the batch test with the PVC indicate that, provided they can be scaled linearly, then even at a low flow rate there would be no health concerns. We conclude that if the PVC tube is mostly covered with a metal liner, any contaminants will be at extremely low levels.

Designs involving other materials, such as pottery, or even concrete allow new ways of thinking about the UV-*Tube* and new opportunities for local businesses.

The field results show that, at least in the Pátzcuaro region, materials are available and most likely affordable. There is interest in the design and all participants were able to build a UV-Tube. To work in practice the design must match its intended location. A UV-Tube built for an outdoor water tank would be slightly different from one built for an indoor sink. The UV-Tube should provide some design criteria which leave enough room for customization by the user or producer.

A. Recommendations for Future Work

In the near future we would like the UV-Tube Project to expand from a research project to a support group for dissemination partners around the world. As a support group the Project will continue to investigate many of the same questions, explore new designs, and optimize current designs. In addition, it will support, through resources and information, local partners who are interested in either the community-based model, individual construction and installation or entrepreneurial projects.

Future work should be focused on bringing the UV-Tube Project to the point at which it is able to support international dissemination. Within this context, the most important questions are establishing the dose distribution provided by the UV-Tube and the safety, in terms of material degradation, of the stainless steel lined PVC design and the unglazed pottery design.

It is recommended that the dose for a number of flow rates and absorption values of the water be established using MS-2 coliphage, a nonpathogenic bacteriophage that has a high resistance to UV.

It is also recommended that the stainless steel lined PVC design be subjected to an overnight batch experiment and flow-through experiment, with humic substance in the water and tested for organic contaminants. The pottery design should be subjected to a batch and flow-through experiment and testing for both metals and organics.

If results are satisfactory, the project can proceed with dissemination phase.

The following are specific suggestions for future work:

1. Irradiance Distribution Measurements

Irradiance measurements, as discussed in section VI.B on page 34, should be repeated. Prior to inserting the quartz windows into the holes, irradiance should be measured at these holes. Then, irradiance should be measured with the quartz windows in place, to characterize the loss by the window itself. This loss should be accounted for in the rest of the measurements. Care should be taken to not block the windows with silicon glue and to place the windows parallel to the tube.

2. *E.coli* Dose Response

E.coli dose response curves, for a variety of absorbance values, should be determined empirically using a collimated beam apparatus.

3. Bulb Performance

The bulb output should be measured over one year, using three bulbs and three set-ups: one bulb on at all times, one bulb off overnight and one bulb on for only brief periods during the day, and off at night. Three identical UV-Tubes should be built with a 1 inch hole in the bottom of each, to measure irradiance using a radiometer.

4. Material Degradation

It is recommended that calculations be carried out to estimate the concentrations of VOCs in the air around a PVC UV-Tube.

5. Modeling

Complexity, such as accounting for refraction and reflection, should be incorporated into the irradiance model. Once Sarah Brownell completes a fluids model, it should be combined with the irradiance model.

6. Marketing Research

It is still not clear who exactly the target audience would be. Exploration of different groups' willingness to pay and each of their priorities for a water disinfection technology could help tailor the UV-Tube to meet the needs of users. In particular, we want to better understand what are the different concerns and how do these differ based on current water supply. One question that emerges, is whether bottled water users would be interested in a point-of-use system.

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