Disinfection for Onsite Wastewater Treatment Systems

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Evaluation of Disinfection Units for Onsite Wastewater Treatment Systems

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1. INTRODUCTION

The infiltration of partially treated wastewater effluent into the soil, a common practice for many onsite and decentralized wastewater management systems, has the potential to degrade groundwater quality. Of primary concern is the transfer of pathogenic constituents from infected individuals via wastewater to groundwater. While it has been observed that varying degrees of disinfection may occur as wastewater percolates through soil, it is apparent that most soil infiltration systems have not been designed to take advantage of this effect. Instead, soil infiltration systems traditionally have been designed to achieve the function of inexpensive wastewater disposal, which may not be adequately protective of public health. Decentralized treatment systems that include a disinfection process may serve to protect groundwater resources and public health. Further, agencies responsible for the protection of human health require data on the application of technologies for the treatment and disinfection of wastewater, particularly in areas where traditional approaches to wastewater management may not be sufficient.

Problem Statement

Because of the dispersed nature of decentralized wastewater management systems, proper maintenance procedures are sometimes difficult to implement. It is possible that a given process will be required to operate reliably for a long period of time between maintenance activities. Most onsite and small flow applications do not utilize redundant systems to ensure performance; therefore, reliability is of special interest. In some decentralized wastewater applications, disinfection is of particular importance as a barrier against pathogens. Unfortunately, little information is available that can be used to determine the reliability and maintenance intervals required to keep a given small flow disinfection process performing to a high standard. Manufacturer recommendations may be of limited value given the degree of variability that exists in individual and small treatment facilities and other site-specific conditions. In addition, a range of disinfection units are available that may be applied for wastewater disinfection. Thus, research is needed to characterize the performance, reliability, constraints, maintenance needs, and other factors involved in the disinfection of small wastewater flows.

Objectives of Study

The objective of this study was to select commercially available disinfection units and determine the following for each process:

1. Disinfection performance
2. Reliability and constraints of the disinfection methodology
3. Maintenance requirements and frequency
3. Estimated cost of installation and operation

Four commercially available disinfection systems were operated for 9 months at research facilities located at the UC Davis wastewater treatment plant. Disinfection performance was determined by measurement of MS2 coliphage, total coliform, and fecal coliform.

Organization

The report is organized into the following sections (1) an introduction to disinfection systems as they may be applied for the treatment of small wastewater flows, including some of the unique challenges encountered in small systems design; (2) the methodology used for evaluation of each disinfection unit, including the characteristics of the pretreatment system utilized; (3) an assessment of disinfection performance, reliability, maintenance, and cost; and (4) a summary of the primary conclusions.

Acknowledgements

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2. BACKGROUND

Numerous disinfection units are available for wastewater treatment applications, including chlorination, ultraviolet (UV) light, and ozonation systems. However, the use of disinfection for onsite and small wastewater treatment systems has not been practiced commonly because, in part, it was perceived that land disposal of small wastewater flows would not significantly effect groundwater. Unfortunately, it has been determined that conventional onsite treatment systems do have the potential to impact groundwater (Ahmed et al., 2005, Nicosia et al., 2001; Arnade, 1999; Yates, 1985). Therefore, decentralized treatment processes that can be used to ensure safe discharge of wastewater effluents are desirable. As discussed below, the disinfection of wastewater from onsite and small wastewater systems presents special problems related to cost, reliability, and maintenance.

Disinfection Processes for Small Wastewater Flows

The disinfectants used most commonly for small treatment systems are sodium and calcium hypochlorite and UV light (U.S. EPA, 2002). A summary of disinfection processes that may be utilized for small wastewater flows is presented in Table 1. While the processes identified in Table 1 can be used to disinfect wastewater, each process has inherent constraints that may limit general application. For example, ozone is known to be a strong oxidant and has been used for water and wastewater disinfection applications; however, the cost of an effective ozonation system may be prohibitive for small treatment facilities. While effective, chlorine gas (Cl_2) and chlorine dioxide (ClO_2) are not considered for small facilities due to the hazards presented by storage, handling, and application of these chemicals. Other processes that are identified in Table 1 that have been applied for wastewater disinfection include biological filtration and peracetic acid. Membrane filtration and pasteurization, while identified in Table 1, are not discussed further as these processes are not currently feasible for small systems. Additional details on the operation and design of each of these technologies may be found in Crittenden et al. (2005), Tchobanoglous et al. (2003), U.S. EPA (2002), and Crites and Tchobanoglous (1998).

Table 1
Summary of disinfectants used for disinfection of small wastewater flows

Disinfectant	Formula	Form	Constraints or concerns for application to small flows
Sodium hypochlorite	$NaOCl$	Liquid	Corrosive, toxic, formation of carcinogenic by-products, requires chemical feed system, effectiveness may depend on water quality
Calcium hypochlorite	$Ca(OCl)_2$	Solid tablet	Corrosive, toxic, formation of carcinogenic by-products, requires tablet feed system, effectiveness may depend on water quality, non-uniform tablet erosion may affect dose
Ozone	O_3	Gas	Corrosive, toxic, requires a feed gas preparation unit and a pump for injection of ozone, effectiveness may depend on water quality, high output systems will require ozone off-gas destruction
Peracetic acid	CH_3CO_3H	Liquid	Corrosive, toxic, not commercially available, requires a chemical feed system, effectiveness may depend on water quality
Ultraviolet (UV) light	-	UV radiation	Requires periodic lamp maintenance and replacement, fouling can reduce effectiveness, performance sensitive to water quality
Biological filtration	-	Enzymatic activity, predation	Size of filter may be a limitation, expense of obtaining appropriate media, additional research needed to define design, operation, and reliability
Membrane filtration	-	Size exclusion	Dense membranes capable of excluding pathogens, e.g. reverse osmosis, require substantial wastewater pretreatment, energy and maintenance intensive
Pasteurization	-	Heat energy	Energy intensive and process not commercially available

Sodium hypochlorite

Sodium hypochlorite is an oxidizing agent that is able to disinfect water at high rates at relatively low concentrations. Sodium hypochlorite is available in solution concentration ranging from 1.5 to 15 percent, and is the active ingredient in household bleach (3 to 6 percent) and in pool sanitizers (11 to 15 percent). At increased concentrations, the solution decomposes at a higher rate compared to low concentrations. In addition, NaOCl should be stored in a cool, dark area, and in a non-corrosive container.

Because NaOCl is a liquid, it is added to water with a metering pump or suction injector. A suction injector works by feeding liquid chemical through a vacuum created by bulk flow perpendicular to an orifice or through a venturi injector. The amount of chemical injected is proportional to the bulk flowrate as well as characteristics of the injector system. Some systems are available for swimming pools to produce chlorine onsite using electrolysis of a sodium chloride (NaCl) solution, however, this process has not yet been adapted to small flow wastewater disinfection. Regardless of the method of chlorine addition, the use of materials that will not corrode is necessary.

Successful disinfection with hypochlorite depends on the chlorine demand of the water to be disinfected and the wastewater pH. When NaOCl is added to water, it dissociates to form hypochlorous acid (HOCl) and hypochlorite ion (OCl-), collectively known as free chlorine, with a pK value for this reaction of about 7.6 at 20°C. Hypochlorous acid is estimated to be 100 times more effective as a disinfectant; therefore it is desirable to maintain the pH below the pK value. Reduced compounds such as sulfide, ferrous iron, BOD, nitrite, and ammonia react with free chlorine to reduce the effective amount of chemical available for disinfection purposes. The reacted product of free chlorine with other reduced compounds may still exert some disinfecting capacity, and is referred to as combined chlorine. Chloride is also formed by some reactions but has no disinfecting properties. For example, the reacted products of free chlorine and ammonia are known as chloramines, which are not as powerful as free chlorine and are slow reacting, they are used for their long-lasting residual properties in some applications. The oxidation of wastewater in an aeration process can reduce the chlorine demand from these reduced compounds. The chlorine demand of various domestic wastewater flows are presented in Table 2. The chlorine demand listed in Table 2 is the difference between the recommended chlorine dose (amount added to wastewater in mg/L) and the chlorine residual (also known as total chlorine and is the measured sum of free and combined chlorine).

Table 2
Chlorine demand and dose guidelines for domestic wastewaters[a]

Wastewater source	Typical chlorine demand, mg/L	Recommended chlorine dose, mg/L, at given pH		
		6	7	8
Septic tank effluent	30 to 45	35 to 50	40 to 55	50 to 65
Activated sludge type treatment effluent	10 to 25	15 to 30	30 to 35	30 to 45
Packed bed (e.g., sand) filter effluent	1 to 5	2 to 10	10 to 20	20 to 35

[a] From U.S. EPA (1980)

When an oxidizing agent, such as hypochlorite, is added to water, the oxidation-reduction potential (ORP) of the water may be increased. Some disinfection systems that rely on oxidizing agents utilize ORP as an indication of process effectiveness. Handheld meters and online instruments are available for measurement of ORP. Values of ORP may range from 700 to 800 mV when free chlorine is present.

It should also be noted that the presence of TSS, or wastewater particulate matter, may contain embedded pathogenic constituents. Because this organic matter may consume chlorine demand or otherwise limit the diffusion of chlorine to the interior of the particle, the embedded constituents may be shielded effectively from disinfection. Further, the reaction of chlorine with some organic compounds found in wastewater (e.g., fulvic and humic acids) can result in the formation of carcinogenic byproducts. Because the fate of these compounds when discharged to the environment is not known, care should be used in the application of pretreatment systems and controlling chlorine dosage.

Calcium hypochlorite

Chlorine can be stored and applied to water in a concentrated dry chemical form as calcium hypochlorite, which has a chemical formula of $Ca(OCl)_2$. Solid form calcium hypochlorite is available at concentrations of 70 percent available chlorine and may be a powder, granulated, compressed into pellets, or compressed into tablets. As discussed for NaOCl, the potency of the chlorine in $Ca(OCl)_2$ will also decay over time.

The chlorine chemistry is similar to that discussed above for NaOCl, however, the method of addition to water is different because $Ca(OCl)_2$ is applied in a dry form. The methods used to apply $Ca(OCl)_2$ to water include direct application of dry chemical using tablet feeders and chlorination of a side stream and blending with bulk flow in a contact basin. Several systems are available that utilize one of these techniques, with different levels of sophistication and dose control. Dry chemical feeders are ideal for small flow disinfection because they are passive and can be used to apply chlorine for long periods of time with little maintenance requirements. However, the effectiveness of chlorine dose control and the long-term reliability of these processes are not well established. The replenishment of chlorine tablets would be required on a periodic basis as determined by the rate of tablet erosion and characteristics of the tablet feeder system, for example, once every 6 months.

In one field study, tablet chlorinators were found to have effluent concentrations of fecal coliform exceeding 200 MPN/100 mL in 93 percent of samples and no residual chlorine in 68 percent of samples (U.S. EPA, 2002). In another field study of disinfection units used in conjunction with aerated biological treatment systems, Charles et al. (2003) found some tablet chlorination systems with internal blockage and overflow despite quarterly maintenance. Charles et al. (2003) also found chlorination units produced high concentration of disinfection by-products and poor reduction of indicator virus.

Ozone

Ozone (O_3) is a strong oxidant that has been used for many applications requiring odor reduction, disinfection, and color removal through oxidation. Ozone is generated typically by passing oxygen through a corona or dielectric barrier discharge, however some systems utilize UV light to produce ozone. The use of ozone gas for the disinfection of wastewater is well established in both Europe and in the United States. Ozonation systems are relatively expensive due to the common use of dry oxygen as an input gas and a pressurized contactor needed for transferring adequate concentrations of ozone into water for disinfection. Ozone concentrations in solution can be measured using a colorimetric method known as the indigo test (Standard Methods, 1998). In addition, ozonation of water will increase the ORP of the water, as described above for chlorine.

The cost of an ozonation system used to produce ozone with sufficient oxidative power for wastewater disinfection is many times that of comparable chlorination and UV disinfection systems. However, many ozonation units are available for pool and spa applications and manufacturers claim relatively high ozone production rates. While the manufacturer rated ozone output should be sufficient, little or no information is available regarding the effectiveness of pool and spa ozonation systems for disinfection of small wastewater flows. Because ozone output is sensitive to the presence of moisture in air and oxygen content in feed gas, and ozone transfer to water is dependent on temperature, pH, pressure, and design of gas transfer facilities, effective ozonation systems cannot be readily implemented at a low cost.

Peracetic Acid

A review of peracetic acid for wastewater disinfection has been given by Kitis (2004). Peracetic acid (CH_3CO_3H), also known as peroxyacetic acid (PAA) is produced by reacting acetic acid (CH_3CO_2H) and hydrogen peroxide (H_2O_2). The resulting solution contains these three chemicals as well as water and is a strong oxidizing disinfectant. Even though H_2O_2 is known to have disinfecting properties, PAA is considered to be the primary chemical responsible for the disinfection capacity. The PAA concentration typically used in the formulation of commercial products ranges from 5 to 15 percent, as these provide the greatest product stability. More concentrated solutions are also available for industrial applications. When stabilized PAA (commercially available form) is diluted, the solution begins to decompose quickly, with a rate proportional to the ionic strength of the dilution water. Thus, PAA is not easily prediluted before use, which presents special handling problems. In addition, PAA is corrosive to steel, copper, brass, bronze, and galvanized iron, and may affect vinyl and rubber. Glass, stainless steel, pure aluminum, and tin plated iron are compatible with PAA.

A key advantage of PAA is that no harmful by-products are known to form after reaction with wastewater, however, a residual of acetic acid will be present and will exert an oxygen demand. The concentration of PAA used for disinfection of secondary effluent depends on the target organism, the water quality, and the level of inactivation required. For example, a PAA concentration of 5 mg/L and contact time of 20 min was able to reduce fecal and total coliform by 4 to 5 logs in secondary effluent (Morris, 1993). High Ct values (the product of disinfectant concentration in mg/L and time in min) may be necessary to inactive virus or achieve stringent fecal coliform concentrations in treated wastewater. In addition, the cost of PAA is currently (2005) about 3 to 5 times the cost of sodium hypochlorite.

Ultraviolet (UV) light

The production of ultraviolet light with low-pressure mercury vapor lamps at a wavelength of 254 nm has a germicidal effect. The effectiveness of UV disinfection depends on the ability of the UV light to reach the target wastewater constituents for an amount of time necessary to have the desired effect. Therefore, the presence of excessive particulate matter, turbidity, dissolved compounds that adsorb UV, short circuiting of flow through the reactor, and accumulation of substances on the lamp housing, can all reduce the effectiveness of UV systems. Transmittance values for several water qualities are given in Table 3.

The implementation of UV systems will require knowledge of the expected UV dose that will be applied to the water. The UV dose depends on several factors, including UV lamp output intensity, contact time with the UV light, and water quality factors, as presented in Table 4. The UV intensity is a property of the type and power of the lamp and can be measured using a radiometer set for the wavelength of interest, typically 254 nm. The contact time is determined by the configuration of UV reactor and design flowrate. The product of the UV intensity and reactor contact time is analogous to the Ct concept for disinfection with chlorine. The UV lamp output declines over time, typically reaching about 75 percent of the initial output after one year of continuous operation, thus requiring periodic lamp replacement to maintain efficiency. Cycling the lamp on and off is not recommended by manufacturers. Lamp output can be monitored using sensors that detect and measure the UV lamp output. These UV sensors are usually mounted on the UV reactor and can also be used to activate an alarm if the UV output drops below an effective level.

Table 3
Wastewater UV transmittance

Wastewater	Range
Septic tank effluent[a]	45 to 67
Secondary effluent[a]	60 to 74
Sand filter effluent[a]	80 to 87
Drinking water	80 to 95

[a] U.S. EPA (1999, 1980)

Table 4
Typical design values for UV systems[a]

Parameter	Unit	Range
UV dosage	$mW{\cdot}s/cm^2$	100 to 140
Contact time	s	6 to 40
UV intensity	mW/cm^2	10 to 14

[a] Adapted in part from U.S. EPA (1999)

Several manufacturers produce in-line UV disinfection systems that can be used for disinfection of treated effluent. Septic tank effluent or effluent with high TSS would be difficult to disinfect adequately with UV. Fouling of the lamp housing is an especially important consideration. The lamp housing is usually a quartz sleeve that is used to protect the lamp from water and maintain the operating temperature. Sedimentation of particles or precipitation of minerals on the quartz sleeve can reduce the overall amount of UV light reaching the water, which can account for substantial reductions in performance. Some UV systems utilize an automatic or manually operated wiper to clean the quartz sleeve. Other systems use alternative coatings that are more resistant to fouling, such as Teflon.

The amount of fouling that occurs depends on the water quality. For example, carbonate hardness minerals can precipitate on the lamp housing and cause the formation of a white film. The amount of precipitation will depend on the concentration of the minerals in the water and the water temperature. Because the water temperature can increase during periods of no flow, as may happen with small wastewater systems, the rate of precipitation can increase during no flow conditions. Commercially available acid cleaners can be used to remove the precipitate, but eventually the quartz sleeve may need to be replaced. Recirculation of effluent through the UV reactor may reduce fouling and increase performance. For example, a recirculating UV system used for disinfection of treated effluent from a small California community has a median total coliform count less than 2 MPN/100 mL (Crites et al., 1997). In a field study of disinfection units used in conjunction with aerated biological treatment systems and operated on a quarterly maintenance schedule, Charles et al. (2003) found UV systems with a failed lamps and performance of other systems dependent on the presence of particulate matter in the effluent from the pretreatment system. It was found that several of the systems were not able to meet the applicable fecal coliform requirement of 100 CFU/100 mL.

Biological filtration

When wastewater is dosed properly to a biological filter, predation by other microorganisms and contact with bacterial enzymes within the filter are able to inactivate pathogens. Disinfection by biological filtration treatment has a long history of use for the treatment of drinking water (slow sand filtration) and wastewater (intermittent sand filtration). Factors affecting the performance of pathogen removal in intermittently dosed filters include the dose volume, filter medium properties, dosing frequency, and wastewater distribution on the filter.

For effective treatment, dosing frequencies range from 20 to 150 dose/d with hydraulic application rates of 5 to 10 mm/dose. Three logs of coliform and coliphage removal have been achieved using intermittently dosed filters (Vanlandingham and Gross, 1998; Emerick et al., 1997). In other studies, low levels of effluent fecal coliform have been reported, consistently less than 5 CFU/100 mL, and frequently non-detectable (Gross and Jones, 1999).

3. EXPERIMENTAL DESIGN AND METHODOLOGY

The methodology used to conduct the disinfection study is described below. An introduction into the selection process is presented to familiarize the reader with some of the factors that are considered when selecting a disinfection system, including cost and expected performance. A description of the configuration of the disinfection systems, pretreatment system, water quality, and analytical methods used are also presented.

Disinfection Systems Selected for Evaluation

To assess the capability of readily available disinfection units, four systems were selected for evaluation, consisting of a calcium hypochlorite tablet feeder, two UV units (UV-1 and UV-2), and a spa ozonation unit. Systems that were selected for evaluation consisted of commercially available systems. Two disinfection units, the tablet chlorinator and UV-1, were designed for use with onsite wastewater systems. The UV-2 system was recommended for drinking water; however, the water to be treated met the recommended specifications. The ozone unit, while designed for ozonation of pool and spa water, was rated to produce ozone quantities expected to be sufficient for disinfection of small wastewater flows. General information regarding the disinfection unit, cost, energy usage, and recommended maintenance for these systems is presented in Table 5.

Wastewater Pretreatment System

The experimental onsite and decentralized wastewater treatment facility was located at University of California, Davis, wastewater treatment plant. A portion of the raw wastewater from the UC Davis campus was diverted into a septic tank for primary treatment and then distributed to subsequent processes for secondary treatment. For the disinfection study, the septic tank effluent was treated using synthetic media biofiltration, also known as packed bed filtration (Leverenz et al., 2001), as shown on Fig. 1. Packed bed filtration, including intermittently dosed sand and high porosity synthetic media, is a biological process used in onsite and decentralized treatment applications because of its high performance and reliability.

Table 5
Summary of disinfection systems selected for evaluation

Parameter	Disinfection system

	Tablet chlorinator	UV-1	UV-2	Ozonator
Disinfectant	Calcium hypochlorite	Ultraviolet light	Ultraviolet light	Ozone gas
Manufacturer suggested application	Disinfection of water at flowrates to 5000 gal/d and untreated or treated septic tank effluent at flowrates to 500 gal/d	Disinfection of wastewater effluent with BOD and TSS < 30 mg/L at flows up to 3 gal/min	Disinfection of drinking water with iron < 0.3 mg/L, hardness <120 mg/L, UV transmittance > 75%, and TSS < 5 mg/L	Ozonation of pool water to volume of 7000 gal following initial super chlorination and adjustment of pH and alkalinity. Chlorine residual of 0.5 to 1 mg/L during normal operation.
Approximate equipment and chemical cost	Unit cost $150; chlorine tablets $100/year	Unit cost $700; replacement lamp $75	Unit cost $330; replacement lamp $75	Unit cost $300, including venturi and fittings
Energy usage of disinfection unit	None	35 Watts or 306.6 kWh/y if operated continuously	23 Watts or 201.5 kWh/y if operated continuously	3.6 Watts or 32 kWh/y, not including required pump
Manufacturer recommended service frequency	Inspection and replacement of chlorine tablets on a semi-annual basis	Inspection every six months, annual cleaning, and 2 year lamp replacement	Annual lamp replacement and cleaning of quartz sleeve as needed	Replacement of the ozone generator unit after 15,000 h (1.7 y) of use

(a)

(b)

Figure 1. Images of packed bed filter unit used for treatment of septic tank effluent prior to disinfection (a) outside view of filter housing situated above anoxic recirculation tank for nitrogen reduction and (b) interior view showing packing used for biomass attachment and growth

Sampling and Analytical Methods

Samples were taken approximately once per week and only when the conditions were considered to be characteristic of expected field operation. Water quality parameters sampled, including total coliform, fecal coliform, MS2 coliphage, BOD_5, TSS, and turbidity, were measured in the laboratory within 2 hours of obtaining samples. Temperature, pH, and ORP were measured at the research site when the samples were obtained. Total and free chlorine were measured 10 min (contact time) after taking samples. Ozone was measured immediately after taking samples. Undisinfected and disinfected effluent grab samples were obtained approximately once per week in sterilized Pyrex containers. Measurements for BOD_5 and TSS were conducted in accordance with Standard Methods (1998). Turbidity was measured with a Model #2100A Turbidimeter from HACH (Loveland, CO). Temperature, pH, and ORP were measured using a combination handheld Ultrameter 6P from Myron L (Carlsbad, CA). Total and free chlorine were measured using the DPD method with reagents and photometer from HF Scientific (Ft. Meyers, FL). Ozone was measured using the indigo method with low-range reagents and a Model 2021 spectrophotometer from HACH. Total and fecal coliform were enumerated using the membrane filtration technique and MS2 coliphage was enumerated using an agar overlay plating technique with E. coli #15597 as a host (Standard Methods, 1998).

Characteristics of Influent to Disinfection Systems

During the first 13 weeks of operation of the disinfection systems, the biological filters were operated to obtain an influent to the disinfection systems with BOD_5 and TSS less than 30 mg/L. This level of performance is the standard used for secondary treatment processes by the U.S. EPA and also represents the expected effluent quality resulting from many onsite aerobic biological treatment processes. For the following 24 weeks, the biological filter performance was optimized to obtain effluent BOD_5 and TSS less than 5 mg/L, to simulate effluent that would be obtained from an intermittent sand filter or similar process. Details on the water quality used for testing of the disinfection systems during the study are summarized in Table 6.

Table 6
Characteristics of influent to the disinfection systems

	Period of operation

		12/15/04 to 3/16/05		3/16/05 to 9/1/05	
Parameter	Unit	Mean	Range	Mean	Range
BOD_5	mg/L	14.3	5.7 – 31.0	1.2	0.8 – 1.9
TSS	mg/L	17.6	6.2 – 24.9	2.2	0.5 – 4.8
Turbidity	NTU	14.2	7.4 – 33.8	2.2	0.5 – 2.9
pH	unitless	7.5	7.29 – 7.67	7.6	7.10 – 7.91
Temperature	°C	14	10.5 – 18.4	24	18.0 - 28.8
Total coliform	CFU/100 mL	1.9E6	7.4E4 – 3.8E6	1.7E5	4.7E4 – 5.5E5
Fecal coliform	CFU/100 mL	5.5E5	5.3E4 – 1.2E6	5.4E4	2.4E4 – 1.5E5
MS2 coliphage[a]	PFU/mL	1.8E5	8.6E4 – 3.8E5	5.0E5	1.5E5 - 2.3E6

[a] Seeded into influent to disinfection systems

Effluent from the biological filtration modules was collected in a common basin. A timer and normally-closed float switch were used to activate a pump in the collection basin and automatically fill a batch mix tank for the UV and chlorination systems on demand (see Fig. 2). The timer was set to allow the pump to operate and fill the batch mix tank during a three hour period in the morning and four hour period in the evening. When the batch mix tank was filled, the filter effluent would flow by gravity to the UV and chlorine disinfection systems. The flow to each disinfection system was controlled with a gate valve, which was recalibrated twice per week to 1 gal/min. It was observed that the actual flow would fluctuate during the unattended loading periods, and ranged from 0.25 to 1 gal/min. The estimated daily loading to each disinfection unit was 187 gal/d. Wastewater flow to the disinfection systems was stopped on 2/3/2005 and resumed on 2/26/2005 to simulate a vacation stress period. During the period of non-operation the UV lamps remained on while there was no flow through the unit. The ozone unit was evaluated separately using an independent batch recirculation and contact tank, also shown on Fig. 2. Before sampling, the flowrate to each disinfection system was set to 1 gal/min. Additional details on the evaluation procedure are presented in the following sections.

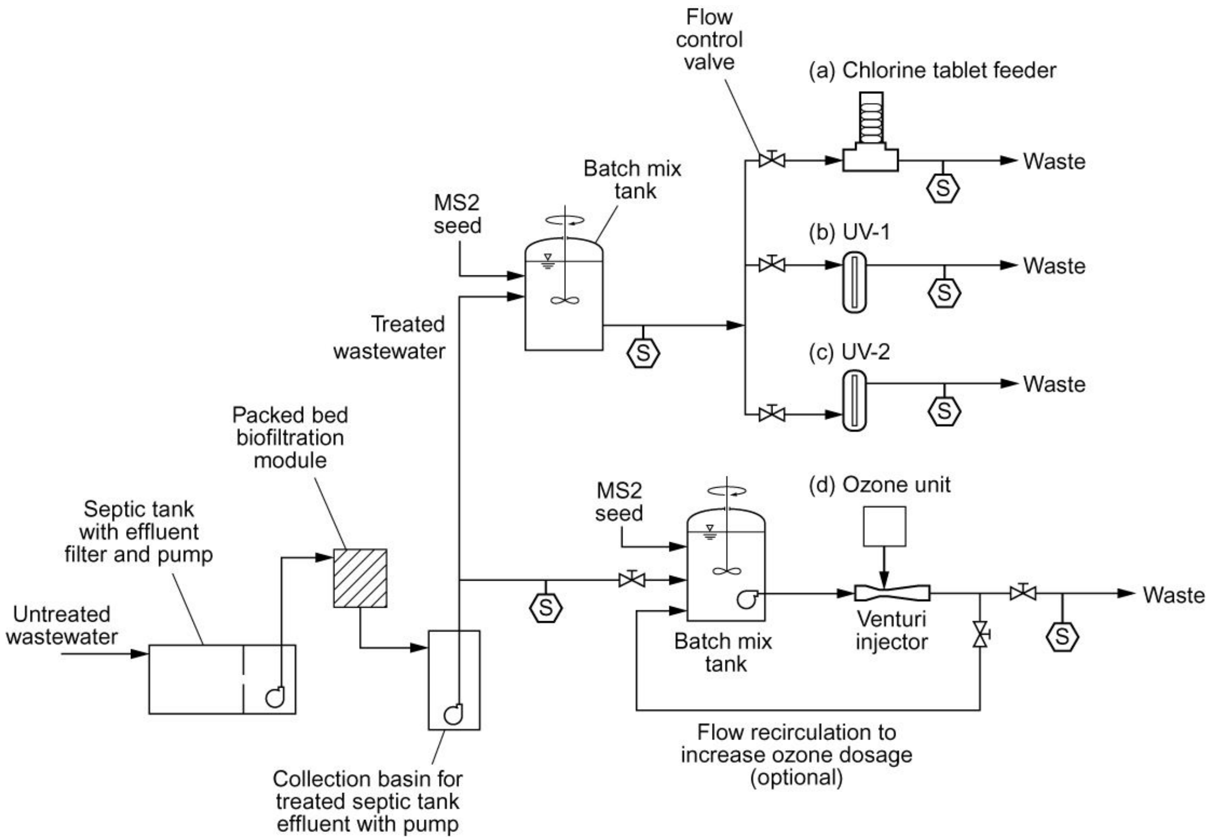


Figure 2. Schematic diagram of the disinfection study configuration. Treated septic tank effluent was processed using a (a) chlorine tablet feeder, (b) UV-1 unit, (c) UV-2 unit, and (d) ozonation unit.

Description and Configuration of Disinfection Systems for Testing

Each of the disinfection units was configured according to manufacturer guidelines, while additional accommodations were made for flowrate control and sampling. Difficulties that were encountered with setup, operation, and maintenance are described for the relevant system. For each process, treated septic tank effluent was collected in a batch mix tank and inoculated with MS2 coliphage to obtain a high concentration (>10^5 phage/mL). A flow control valve was used to obtain a flowrate of 3.8 L/min (1 gal/min). After a sufficient time to ensure that the system was at equilibrium (at least three volumes flushed through each disinfection system), an influent and effluent sample were withdrawn and taken to the lab for analysis. Details on performance are presented in Chap. 4, Experimental Results and Discussion.

Chlorine Tablet Feeder The dry chlorine tablet feeder, consisting of a flow through chamber fitted with a single tablet feed tube, is designed for long-term operation with minimal maintenance. The calcium hypochlorite tablets (70 percent available chlorine) are designed to dissolve slowly as water flows through the tablet contact chamber. The tablet feeder is typically installed inline, but could also be used to treat a side stream that would then be blended with the bulk flow. The manufacturer states that the unit is acceptable for disinfecting septic tank effluent, effluent from a secondary treatment process, or drinking water. There can be large variability in the chlorine dose required for untreated wastewater and drinking water; however there is little capacity for dose control using this type of chlorination system. The tablet feeder is typically installed subsurface, for example in the effluent line of a septic tank. A schematic diagram of the chlorination systems and images are shown on Fig. 3.

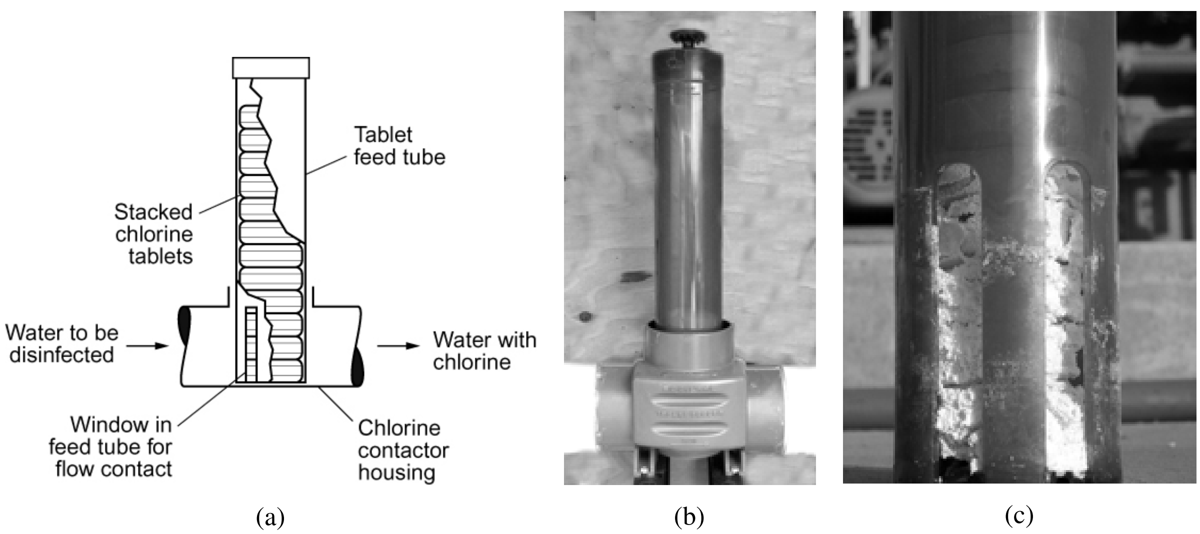
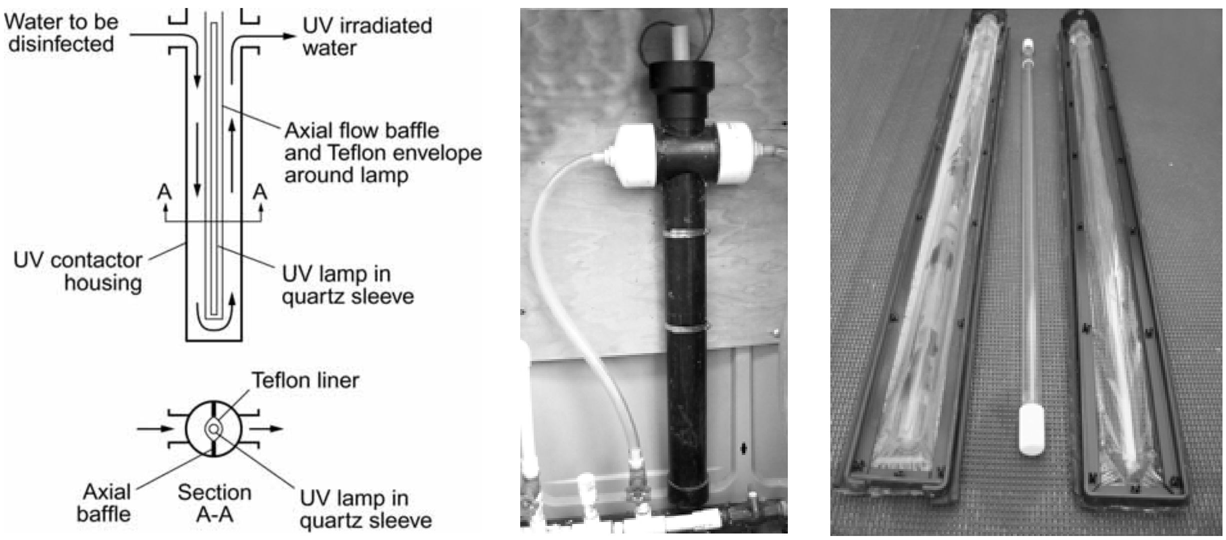


Figure 3. Chlorine tablet feeder used for disinfection study (a) diagram of tablet feeder, (b) image of unit as installed for testing purposes, and (c) with tablet holder removed showing non-uniform dissolution of chlorine tablets. Note: water flow was only in direct contact with bottom tablet.

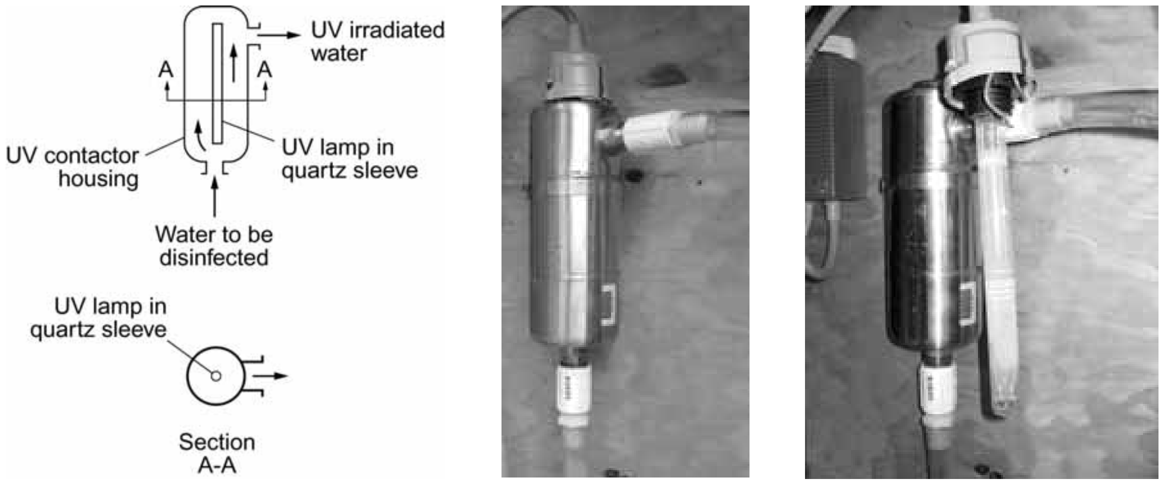
UV-1 The UV-1 irradiation unit is an assembly consisting of a tubular ABS pipe reactor with an axial germicidal lamp. The lamp housing is divided along the axis of the lamp such that water entering at the top of the unit flows downward past one side of the lamp, around the bottom of the lamp, and then upwards across the other side of the lamp before exiting at the outlet. The lamp is protected by a quartz sleeve, enveloped with a Teflon liner to inhibit surface fouling. The UV-1 unit is marketed for onsite and decentralized wastewater treatment systems and is typically installed following a secondary treatment device. The maximum flowrate recommended by the manufacturer is 3 gal/min. Additional units may be added in series or parallel to accommodate higher flowrates or higher UV dosages. The recommended influent water quality for both BOD and TSS is less than 30 mg/L, while a maximum turbidity value is not specified. A schematic diagram of the UV-1 system and images are shown on Fig. 4.



(a) (b) (c)

Figure 4. System UV-1 used for disinfection study (a) diagram of UV-1 unit (b) image of UV-1 unit as installed for testing purposes, and (c) with fouled Teflon sleeve on left, UV lamp in center, and new Teflon sleeve to the right.

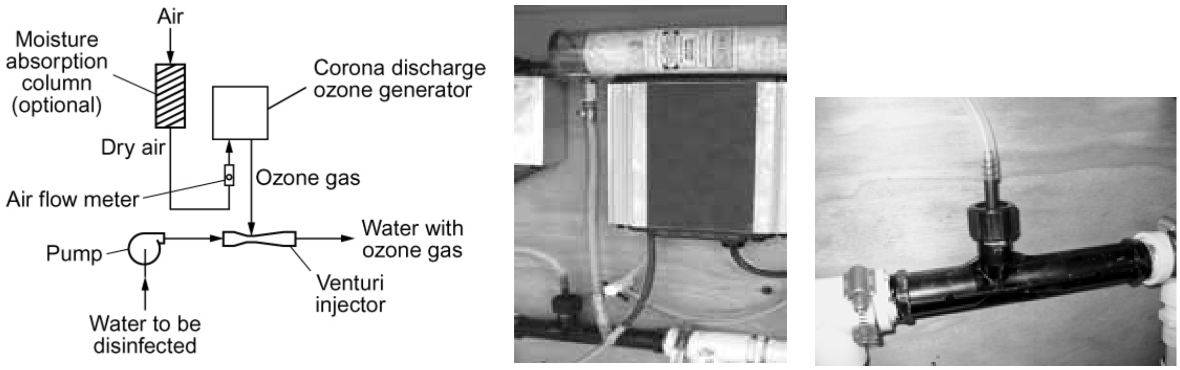
UV-2 The UV-2 irradiation unit is an assembly consisting of a stainless steel housing with an axial germicidal lamp. A spring inside of the housing holds the lamp in place. Water enters at the bottom of the unit and flows around the lamp, before exiting the unit. The unit is designed to be operated at flow rates of 2 to 5 gal/min and is designed for the disinfection of drinking water. For purposes of this study, the UV-2 system was evaluated using wastewater. The manufacturer recommends water with hardness less than 120 mg/L, iron less than 0.3 mg/L, and TSS less than 5 mg/L. The water used in the study had iron less than 0.1, however, the hardness value was 150 mg/L and TSS was occasionally higher than 5 mg/L. A schematic diagram of the UV-2 system and images are shown on Fig. 5.



(a) (b) (c)

Figure 5. System UV-2 used for disinfection study (a) diagram of UV-2 unit, (b) image of UV-2 unit as installed for testing purposes, and (c) with quartz sleeve and lamp removed, note presence of surface fouling on quartz sleeve.

Ozone The ozone unit is composed of a corona discharge ozone generator and a venturi injector. An external pump capable of supplying sufficient flow and pressure to maintain the correct amount of vacuum at the venturi gas inlet is also required for operation of the ozone unit. Using this configuration, the system was wired such that the ozone generator would turn on automatically whenever the pump was activated. The pump must be operating for ozone to be injected into the water. The flow of water through the venturi injector pulls air through the attached corona discharge ozone generator. According to the manufacturer, the ozone model tested is capable of generating 300 mg/h of ozone. The corona discharge ozone generator tested is designed for pools (up to 7000 gal) and spas and it is suggested to be used in combination with another disinfectant, such as chlorine or bromine to help maintain a residual. For pools, the manufacturer recommends a chlorine residual of 0.5 to 1.0 mg/L in addition to ozone injection. For this study, a supplemental disinfectant was not used so that the effect of the ozonation unit could be evaluated independently. A schematic diagram of the ozone system and images are shown on Fig. 6.



(a) (b) (c)

Figure 6. Ozonation system used for disinfection study (a) diagram of ozonation system, (b) ozonation unit as installed for testing purposes with air drying column, and (c) venturi injector used to inject ozone into wastewater.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained for each disinfection unit are presented and discussed in this section. In addition to the performance measurements, reliability and constraints, maintenance requirements, and estimated cost of implementation and operation are also discussed.

Chlorine Tablet Feeder

The chlorine tablet feeder had the lowest cost of the units evaluated and did not require electricity for operation. The tablet chlorination unit was easily installed and maintained. A few minor problems were encountered during use of the unit related to differential tablet erosion, as discussed below.

Performance The performance of the tablet chlorinator, evaluated at a flowrate of 1 gal/min is presented on Fig. 7. Total and free chlorine were measured following a 10 min contact time. Sodium bisulfite ($NaHSO_3$) was added at this time (10 min) to stop the chlorine oxidation reactions. The free chlorine dose ranged from 0.14 mg/L to 390 mg/L (see Fig. 7a). As shown on Figs. 7b, 7c, and 7d, about 90 percent of the sampling events resulted in no coliphage or coliform organisms detected in the chlorinated effluent. There were three separate events where an organism was detected in the influent, for these three events the corresponding free chlorine concentration was less than 1 mg/L. The performance results are summarized in Table 7. While the manufacturer did not specify a contact chamber design, the 10 min contact time resulted in high rates of disinfection due to the high free chlorine concentrations present. However, a contact basin with residence time greater than 10 min may provide better performance by moderating the variability in the chlorine concentration. A longer contact time may also be required if high concentrations of organic matter or ammonia are present in the effluent.

Reliability and Constraints The primary issues related to reliability for the tablet chlorinator are (1) the dissolution rate of the hypochlorite tablets and (2) the ability to consistently apply a chlorine dose sufficient to cause disinfection. A summary of findings related to chlorine tablet usage and dose are presented on Fig. 8. As shown in Fig. 8a, periodic events with flowrates up to 2 gal/min resulted in tablet decay at a rate of 0.4 tablet/d, while at a maximum flowrate of 1 gal/min, the rate of tablet decay was about 0.08 tablet/d. Therefore, without flow equalization it would be difficult to predict the rate of tablet decay. Further, the manufacturer installation manual suggested the use of adapters for inline plumbing; however, the suggested installation caused the tablets to be submerged and rapid dissolution of the tablets.

Table 7
Summary of performance characteristics of tablet chlorination disinfection system

Parameter	Unit	Parameter	Performance value for indicated free chlorine concentration range, mg/L [a] 0 to 1	>1
MS2 coliphage	PFU/mL	Maximum	154,333	0
		Mean	96,514	0
		Log reduction[c,d]	0.8	>5.4
Total coliform	CFU/100 mL	Maximum	21,700	0
		Mean	12,400	0
		Log reduction	1.4	>5.6
Fecal coliform	CFU/100 mL	Maximum	1670	0
		Mean	853	0
		Log reduction	2.1	>5.2

[a] All values reported after 10 minute contact time

[b] Events with free chlorine concentration less than 1 mg/L are estimated to have occurred 10 percent of the time during the experiment. Organisms were only detected in the effluent when the free chlorine was less than 1 mg/L

[c] Log reduction = -log(effluent concentration / influent concentration)

[d] Reported as mean log reduction

The results of several consecutive measurements made to characterize the chlorine dose as related to flowrate are shown on Fig. 8b. The chlorine dose applied was related to flowrate, duration and variability in flowrate, and age and condition of tablets. When new tablets were used, the free chlorine dose gradually decreased from 46 to 13 mg/L after 90 min of continuous operation. An identical chlorine dose test using tablets that had been in use for 3 months resulted in a higher initial free chlorine concentration (311 mg/L), followed by a rapid decline to 3.8 mg/L after 60 min of continuous operation. Although water only contacts the bottom tablet, it was observed that several tablets located above those also began to dissolve. The dissolution of the elevated tablets was caused by condensation and may have contributed to some of the extreme measurements. It was also found that the chlorine tablets did not dissolve uniformly, and sometimes only a small amount of the chlorine tablet was actually in contact with the water, as the bottom tablets had eroded and formed a channel where water could pass through with little contact. On other occasions, large amounts of particulate calcium hypochlorite were washed out of the reactor with the effluent. Stopping and restarting of flow caused chlorine concentration peaks followed by a rapid decline.

A summary of all chlorine concentrations measured while obtaining samples is shown on Fig. 8c using a probability distribution. As shown, the average concentrations measured were 11 and 20 mg/L, for free and total chlorine, respectively. The free chlorine concentration exceeded 200 mg/L 10 percent of the time and was less than 1 mg/L 10 percent of the time.

The chlorination unit was not affected by the three-week vacation period (i.e., no flow conditions). In addition, the chlorination performance was not affected by variations in water quality that occurred during the study. However, the effect of high residual chlorine in the effluent on the ability of the soil bacteria to provide advanced treatment is not known. Dechlorination facilities (also tablet feed) following contact basins, are recommended to control the discharge of chlorine to the environment.

Maintenance Requirements and Frequency Maintenance for the tablet chlorination unit consisted of periodically refilling the tablet feed tube with new tablets. About 20 tablets can be loaded into the feed tube. Assuming flow equalization and uniform tablet erosion, it is estimated that the unit would not require servicing for 10 to 12 months. The ease of maintenance is a key advantage for this technology.

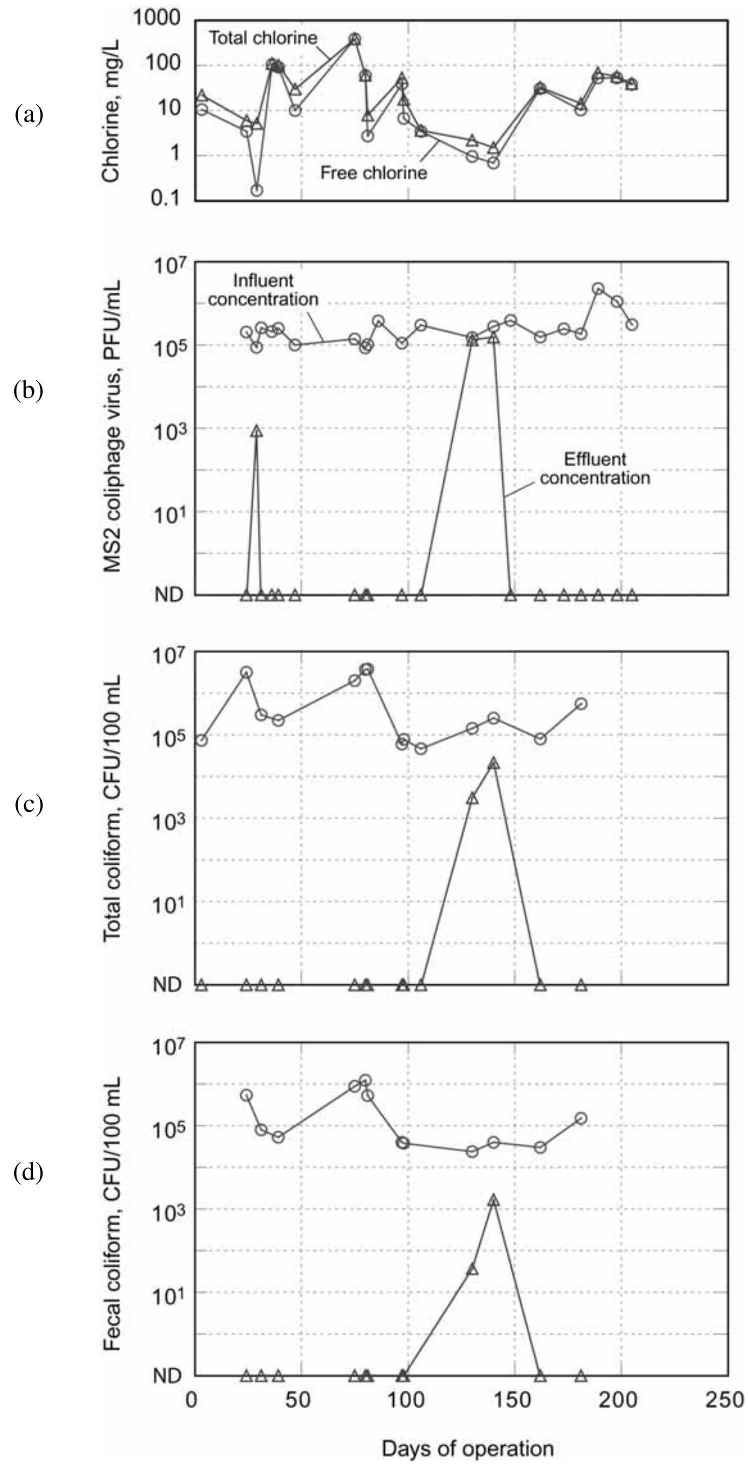
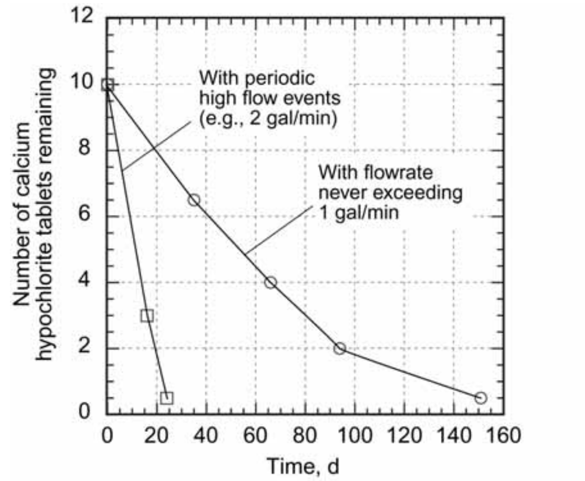
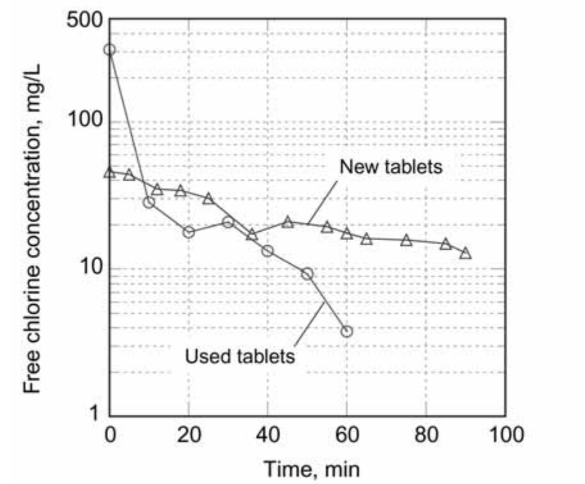


Figure 7. Performance of the chlorination unit (a) chlorine concentration, (b) MS2 coliphage removal, (c) total coliform removal, and (d) fecal coliform removal.

(a)



(b)



(c)

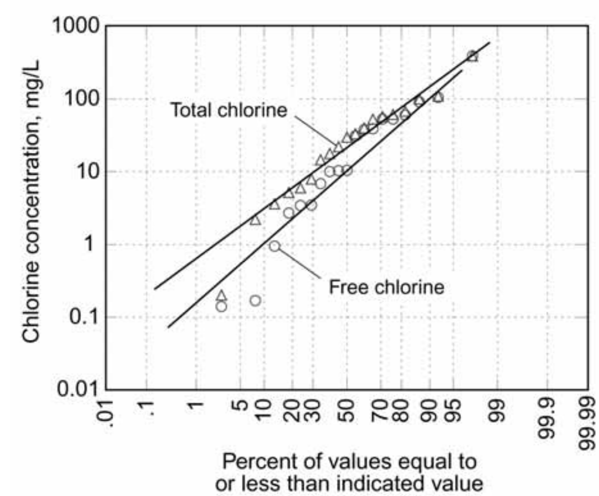


Figure 8. Characteristics of the chlorine dose applied to water (a) tablet erosion characteristics, (b) example of continuous measurement of chlorine dose at flowrate of 0.6 gal/min, and (c) probability analysis of chlorine dose. Note that chlorine tablets were present in feeder and undisturbed for all measurements.

Estimated Cost of Installation and Operation The capital cost for the tablet chlorinator was $150 and the cost of a year supply of calcium hypochlorite tablets (a 10 lb supply, about 30 tablets) with shipping is $100. However, the additional costs of proper contacting and dechlorination facilities would increase both the capital and operating costs. The installation cost would include excavation for inline installation, including equalization, contact, and dechlorination facilities. Unlike the other disinfection technologies, the chlorination facilities may not require the expenses associated with a power supply.

UV-1 and UV-2

The UV units that were evaluated were both self contained and easy to install. The increased contact time and UV dose for UV-1 resulted in better disinfection performance compared to UV-2. Both of the UV units were subject to fouling over time that affected performance. Characteristics of performance, reliability, maintenance, and cost are discussed below.

Performance The performance of both UV units for inactivation of MS2 coliphage, total coliform, and fecal coliform is shown on Fig. 9 and summarized in Table 8. The performance of both UV units was affected by the quality of effluent from the pretreatment system, with best performance occurring when the pretreatment process was producing effluent with TSS less than 5 mg/L and TSS less than 3 NTU. The three-week period with no flow (2/3/05 to 2/26/05) severely impacted performance, reducing removal rates for MS2 and coliform bacteria. After several sampling events between 2/26/05 and 3/11/05, the UV units were inspected to determine the cause of the reduced performance. For UV-1, it was found that water had entered into the space between the quartz sleeve and Teflon lining. According to the manufacturer of UV-1, water was not supposed to enter the space inside of the Teflon lining, therefore the entry occurred due to a manufacturing or handling defect. Two types of surface fouling were also identified for UV-1 during the 3/11/05 inspection. The first type of surface fouling was present on the outside of the Teflon lining and consisted of a powdery white substance, concluded to be precipitated carbonate hardness minerals. The carbonate precipitate evenly covered the entire length of the Teflon liner in all areas that were submerged and exposed to UV light. This white precipitate coating was easily removed by wiping the Teflon lining with a towel. The second type of fouling was present on the inside of the Teflon lining and was brown in color, covering about 25 percent of the area exposed to UV. It was concluded that the brown discoloration was due to a reaction between humic substances in the water, increased water temperature, and the UV radiation. It was observed that both instances of fouling were only present in areas on the liner that were submerged and exposed to UV radiation, and not present in areas that were out of direct exposure, e.g., the area around the cap on the end of the lamp. The brown surface fouling on the interior of the Teflon lining was due to the water intrusion, but the time and manner of water intrusion was not known. It was not possible to remove the brown fouling in the field, thus a new lamp housing assembly was acquired and installed on 3/16/05. The UV-2 unit also had a carbonate precipitate on the quartz sleeve. An acid cleaning product was needed to remove the precipitate from the quartz sleeve of UV-2 and the lamp assembly was reinstalled.

On 3/16/05 through 3/22/05, the performance of the pretreatment systems was optimized to improve the influent water quality to the disinfection systems (see Table 3). As shown on Fig. 9, the performance of both UV units improved following the optimization of the pretreatment system and lamp maintenance events. After 3/22/05, the mean removal of MS2 coliphage was 5 log (99.999 percent) and 1.7 log (98 percent) for UV-1 and UV-2, respectively, during the testing with high quality effluent at 1 gal/min. Using data on MS2 inactivation from U.S. EPA (2003), the estimated applied UV dose was 105 and 30 mJ/cm^2 for UV-1 and UV-2, respectively. The UV dose applied by the UV-2 unit was less than the UV-1 dose by a factor of 3.5 due to a lower lamp output and reduced contact time in the UV-2 reactor.

Table 8
Summary of performance characteristics of UV-1 and UV-2 disinfection systems

			Performance value during given time period		
Parameter	Unit	Parameter	12/15/04 - 2/3/05[a]	2/26/05 - 3/11/05[b]	3/22/05 - 8/19/05[c]

MS2 coliphage	PFU/mL	Maximum	150	7400	264
		Mean	58	4900	21
		Log reduction[d,e]	3.6	1.5	>5.0
Total coliform	CFU/100 mL	Maximum	117	13,133	240
		Mean	48	7522	24
		Log reduction	4.0	2.7	>4.8
Fecal coliform	CFU/100 mL	Maximum	17	1200	13
		Mean	9	757	1
		Log reduction	4.3	3.1	>4.4
		UV-2			
MS2 coliphage	PFU/mL	Maximum	70,000	70,667	31,800
		Mean	28,406	60,556	10,684
		Log red.[d,e]	0.95	0.25	1.7
Total coliform	CFU/100 mL	Maximum	53,667	550,000	4400
		Mean	16,679	413,000	823
		Log red	1.7	0.93	2.8
Fecal coliform	CFU/100 mL	Maximum	19,333	184,000	900
		Mean	6778	115,667	269
		Log red.	1.9	0.90	2.5

[a] Loading was discontinued on 2/3/2005 and resumed on 2/26/05; lamp remained on during the entire period of no flow

[b] Severe fouling occurred during the 23 d without flow, lamp maintenance occurred on 3/11/05

[c] Lamp maintenance occurred on 6/6/05

[d] Log reduction = -log(effluent concentration / influent concentration)

[e] Reported as mean log reduction

There was a gradual decrease in the removal of MS2 coliphage for both UV units following the first lamp maintenance event. The lamp assemblies were removed from both UV units on 6/6/05, 75 days after the first lamp maintenance. The carbonate precipitate was present on the Teflon lining of UV-1 and on the quartz sleeve of UV-2. In addition, the Teflon liner was once again found to have a small tear and water inside of the liner, however, the brown fouling was not present. It was concluded that the water intrusion was not inhibiting the effectiveness of the unit. The precipitate was removed from the Teflon liner of UV-1 and the quartz sleeve of UV-2, and both lamp assemblies were replaced and flow restarted.

(a)

(b)

(c)

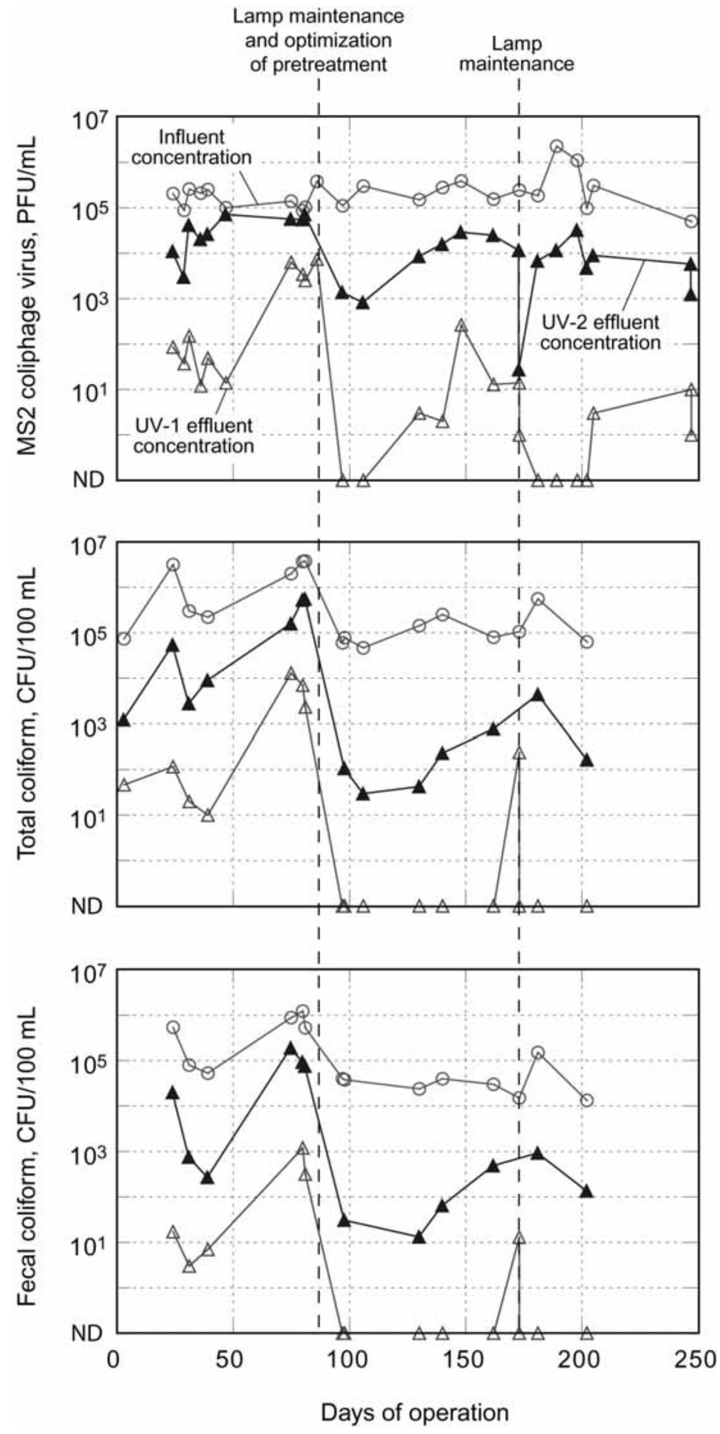


Figure 9. Performance of the UV-1 and UV-2 units (a) MS2 coliphage removal, (b) total coliform removal, and (c) fecal coliform removal. The vertical dashed line indicated removal and cleaning of precipitates from the lamp housing

Cleaning of the lamp had a positive effect on the performance of both UV units. Without frequent measurement of indicator organisms it would not have been possible to determine the effectiveness of disinfection. While the precipitate was visible when the lamp was removed, the relationship between the observed fouling and disinfection performance is not known. Therefore, visual inspection for fouling is not considered to be an adequate measure of disinfection efficacy. Some UV units are equipped with a sensor to monitor UV output. This type of device may be used to alert a user that the lamp performance has been compromised and initiate lamp maintenance or lamp replacement.

During normal operation of the UV-1 unit it was noted that suspended solids accumulated in the bottom of the reactor during extended periods of low flow. Increases in the flowrate through the reactor caused these solids to be flushed out of the system with the effluent. The solids accumulation and flushing was most noticeable when the influent TSS was elevated. The effect of the solids flushing is expected to reduce the performance by shielding organisms, and possibly providing a habitat for biological growth within the reactor. While performance measurements were not made during the solids flushing events, a pretreatment process capable of producing effluent with low TSS is considered to be an important factor in UV disinfection performance.

The UV-2 unit was specified for treatment of drinking water containing TSS less than 5 mg/L and flowrate of 2 to 5 gal/min. Although the water used for testing met the TSS criteria and the unit was loaded at only 1 gal/min, high levels of disinfection were not achievable. Therefore, a UV process cannot be assumed to be effective based on manufacturer specification or in the absence of actual testing. Additional testing should be conducted to evaluate the potential of a given UV disinfection system for the unique conditions encountered with onsite and small flows disinfection. For example, the turbidity and TSS in the water are considered to be the primary factors inhibiting the performance of UV-2, as demonstrated by the better performance following improvement to the influent water quality (i.e., after 3/22/05). It should be noted that the addition of a small pump could be used to recirculate water through the UV unit. The resulting increase in contact time would make it possible to obtain higher levels of disinfection, however, this option was not evaluated. In addition, reducing the flowrate to increase the contact time or using multiple units in series would also improve performance.

Reliability and Constraints Several constraints were identified that affected the reliability of the UV units. The constraints were the mineral characteristics of the water supply used, the influent water quality from the pretreatment systems, and the period while the lamp was left on without flow.

Under optimum conditions, the UV-1 unit was able to reduce MS2 coliphage and coliform bacteria concentration effectively. The manufacturer's recommended inspection interval is every six months, however, maintenance may be required more frequently depending on the influent water quality and the level of disinfection desired. The high carbonate hardness present in the water supply used for testing was implicated in the increased maintenance needs. Therefore, the specified maintenance interval should be based on water quality parameters and disinfection requirements.

The type and performance of the pretreatment system needs to be taken into consideration with respect to the effectiveness of the UV unit. When operated with a lower water quality, performance of the UV unit was reduced and additional lamp fouling may have occurred from the presence of increased organic matter present in the water. The accumulation of solids in the bottom of the UV-1 reactor was also a consequence of using water with moderate levels of residual TSS. Therefore, the type and reliability of the pretreatment system are important factors for the implementation of UV disinfection.

The flow variability from onsite and decentralized treatment systems may have a negative impact on UV disinfection systems. For example, the process would be subjected to both periods of high flow and no flow. At high flowrate events the UV unit will not provide an adequate dose for effective disinfection, while the no flow condition will result in the stagnant water being heated by the lamp, resulting in increased precipitation of some water constituents (if present). Therefore, flow equalization and water quality should both be considered for implementation of UV disinfection.

Maintenance Requirements and Frequency Maintenance of the UV units consisted of (1) stopping flow through the unit, (2) disconnecting the power supply, (3) removal of the lamp assembly, and (4) cleaning of the Teflon liner or quartz sleeve. The precipitate was removed easily from the Teflon liner using a cloth, whereas the quartz sleeve required the use of acidic chemicals. In addition, any solids deposited in the bottom of a flow through reactor should be removed by flushing with water. During this study, punctures were found in the Teflon liner (UV-1) that allowed water to come into contact with the quartz sleeve. The intrusion of high quality water did not adversely impact performance of the unit, while intrusion of water with partial treatment caused fouling inside of the Teflon liner. Therefore, the Teflon liner, if present, should be inspected carefully for punctures and replaced if necessary.

The maintenance frequency depends on several factors, including (1) the organisms to be inactivated, (2) the required degree of inactivation, (3) background water quality related to potential for precipitation of minerals, and (4) reliability and performance of the pretreatment system. Under the test conditions for this study, it was found that the UV-1 unit could operate for 32 d after lamp maintenance without detection of MS2 in the effluent, and 75 d before detection of coliform bacteria. However, if the permissible concentrations are higher than none-detected, extended periods of operation may be acceptable. Determination of maintenance intervals should therefore be determined according to the factors cited above and site specific information. For reference, the UV disinfection system used at the UC Davis wastewater treatment plant (2×10^6 gal/d) requires monthly cleaning for precipitates.

Estimated Cost of Installation and Operation The capital cost of the UV-1 unit, which is marketed for secondary wastewater flowrates up to 3 gal/min, is about $700. The cost of replacing the lamp every two years (manufacturer recommendation) is estimated to be $75. The energy usage during operation was 35 W or 306.6 kWh/y. The estimated cost of the UV-2 unit, which was recommended for point-of-use drinking water flowrates from 2 to 5 gal/min and a TSS concentration less than 5 mg/L is about $330. The cost of an annual replacement lamp, is estimated to be $75. The energy usage during operation was 23 Watts or 201.5 kWh/y. Additional costs would be required for the initial installation, which is usually below grade for subsurface systems with gravity flow, and the cost of system maintenance. A power supply would need to be provided where the unit is installed.

Ozone

The ozonation unit was installed with a batch recirculation tank and operated according to the manufacturer recommendations for flowrate, but without pre-chlorination. The ozone output was not sufficient for purposes of disinfection, as discussed below. Characteristics of performance, maintenance, and cost are discussed below.

Performance The ozone generator did not provide an ozone concentration in the water capable of causing a measurable level of disinfection, as shown on Fig. 10 and summarized in Table 9. The use of a moisture absorption column to prepare the air stream did not result in any measurable ozone concentration in the water. In several batch ozonation experiments, water was recirculated through the ozonation unit for 24 to 72 h, however no measurable ozone was detected. Possible reasons for the lack of detectable ozone in the water include (1) presence of organic matter in water, (2) insufficient ozone output, and (3) no ozone transfer into the water. Many ozonation processes utilize high oxygen, particle free feed gas, pressurized ozone contact tanks, and excess ozone gas destruction. The implementation of an ozone system with these accessories will significantly increase cost.

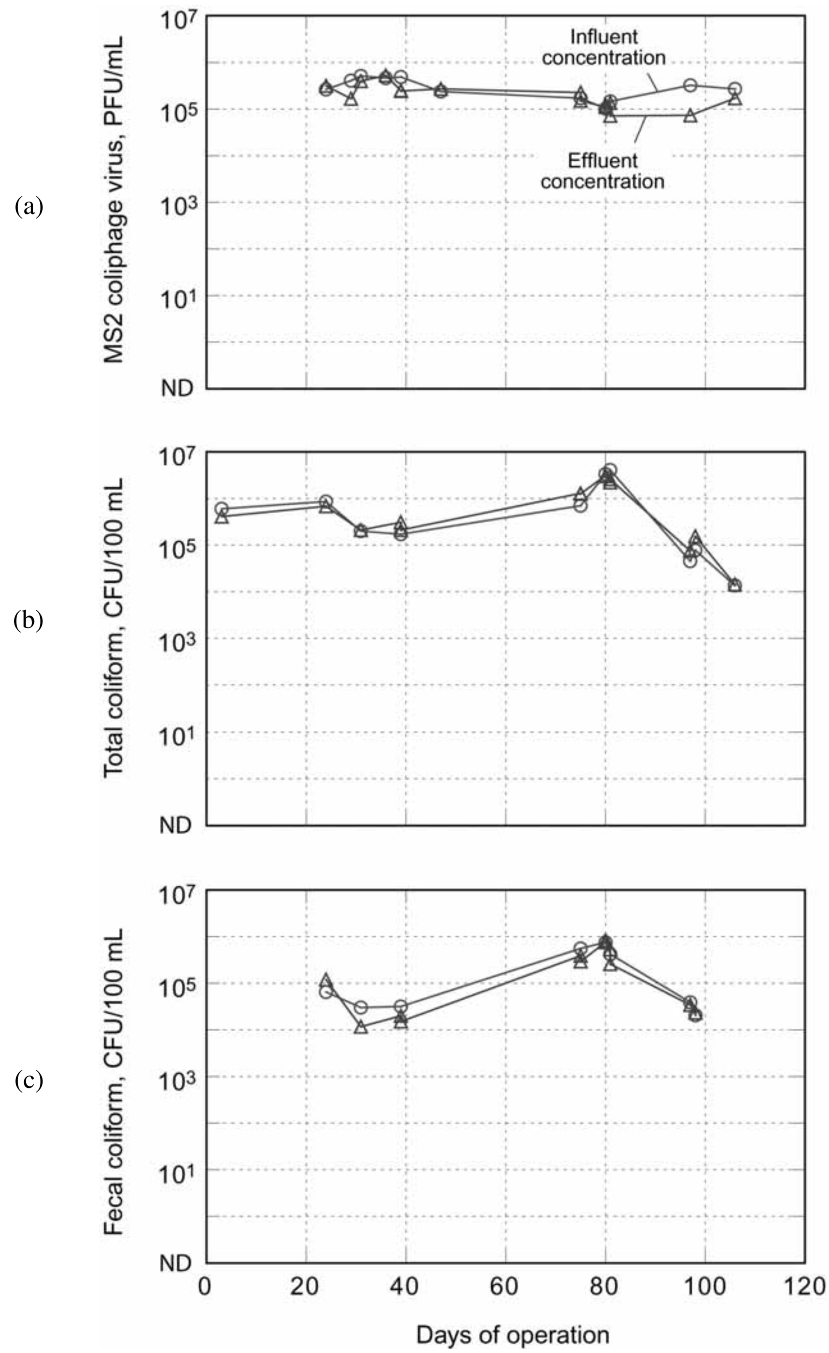


Figure 10. Performance of the ozonation unit (a) MS2 coliphage removal, (b) total coliform removal, and (c) fecal coliform removal.

Table 9
Summary of performance characteristics of pool ozonation unit

Item	Unit	Parameter	Performance value [a]
MS2 coliphage	PFU/mL	Maximum	536,667
		Mean	220,500
		Log red.[b,c]	0.1
Total coliform	CFU/100 mL	Maximum	3,100,000
		Mean	1,111,976
		Log red	0.1
Fecal coliform	CFU/100 mL	Maximum	833,333
		Mean	274,750
		Log red.	0.1

[a] Ozonation times ranged from 10 to 60 min, all values are considered together because longer ozonation times did not improve performance

[b] Log reduction = -log(effluent concentration / influent concentration)

[c] Reported as mean log reduction

Maintenance Requirements and Frequency The ozone unit appeared to require little or no maintenance. A properly operating system would require maintenance for a feed gas preparation and supply system. The ozone unit itself was specified to last for 15,000 h of use, however, a correlation between operating time and disinfection capacity was not determined.

Estimated Cost of Installation and Operation The ozonation system had a cost of $300, including the venturi injector and the necessary fittings. The actual ozone generator only consumed about 3.6 W, however a pump is required to pressurize the flow and can be expected to use 100 to 500 W.

5. CONCLUSIONS

Proper design, installation, and monitoring are necessary to ensure that any disinfection system will operate properly. The systems tested in this study failed in a number of ways that would not have been apparent without monitoring for indicator organisms. Periodic care and maintenance are essential to ensure these systems are functioning properly after installation. The manufacturer recommended maintenance schedule may not be adequate, given the amount of variability in water quality and water use patterns from diverse applications.

Other key findings from this research:

- The frequency of maintenance for each disinfection technology will depend on site-specific conditions.
- The tablet chlorination system is susceptible to episodic failure due to non-uniform erosion of tablets, while the UV systems are subject to progressive failure as fouling occurs on the lamp housing (e.g., quartz or Teflon liner).
- The chlorine dose from erosion of calcium hypochlorite tablets is difficult to predict and is not related to water quality. Similarly, the rate of tablet erosion can be variable if flow equalization is not used.
- The chlorination system is expected to generate toxic byproducts with an unknown fate in the soil while the UV system is not expected to generate byproducts at the UV dose applied.
- The chlorination system for an individual residence is expected to have a capital cost in the range of $400 to 600 if appropriately sized chlorination, contact facilities, flow equalization, and dechlorination are provided. The annual cost of chlorine tablets is approximately $100, dechlorination tablets will increase the annual cost by $110. Effective UV disinfection systems are expected to have a capital cost of $750 to $1000 with an annual lamp replacement cost of $40 to $80 for an individual residence.

- UV and ozonation systems will require an electrical connection, while the tablet chlorination system may not require an onsite electrical supply.
- UV systems designed for water disinfection can be used successfully for wastewater, but should be tested using wastewater to determine capacity.
- UV systems are sensitive to water mineral content, periods of no flow while the lamp remains on, flowrate through the unit, and reliability of the pretreatment system to provide adequate water quality. The chlorination system is not sensitive to these factors.
- A small pool ozonation system was found to have negligible capacity to disinfect high quality treated wastewater under the test conditions.
- All disinfection systems should be used in conjunction with flow equalization to minimize the peak flows expected from small wastewater systems.

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