WATER RESOURCES RESEARCH GRANT PROPOSAL

TITLE: Predicting the Effectiveness of High-Intensity UV Lamp Technology as a Disinfectant for Various Quality Wastewaters Using the Collimated Beam Method (Phase II)

FOCUS CATEGORIES: WQL

KEY WORDS: Water Quality, Ultraviolet Disinfection, Collimated-Beam, High-Intensity UV, Fecal Indicators, Spores, Virus

DURATION: 03/01/00 through 02/28/01 Year 2 of 2 year project

FEDERAL FUNDS REQUESTED: $30,486 Year 2

MATCHING FUNDS PROVIDED: $80,815

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CONGRESSIONAL DISTRICT: First

CRITICAL REGIONAL WATER PROBLEMS:

Sewage and other forms of wastewaters (aquaculture, animal production) have traditionally been considered an undesirable product of society that must be disposed of in the most expeditious way. To protect the environment and public health, US regulations, require the treatment of wastewater to remove its organic composition and disinfection to kill its pathogenic (bacteria, protozoans, and viruses) content before it can be discharged into the environment (rivers, lakes, oceans) or reclaimed for beneficial uses. Historically, chlorine has been the disinfectant of choice. However, continued use of chlorine is now being discouraged for two reasons. First, use, transportation and storage of chlorine are hazardous activities and have resulted in many accidents. Second, use of chlorine has been shown to be detrimental to the health of people and aquatic organisms because of the formation of chlorine by-products which are toxic or are carcinogenic. As a result, there has been search for an alternative disinfectant.

A critical regional water problem is to find a disinfectant which is not only effective but safe for people who handle the system and safe for the environment. A relatively new disinfectant process which does not have the above problems associated with chlorine is the ultraviolet radiation (UV). Its primary advantages include the fact that UV radiation will inactivate all pathogens (UVC - germicidal UV), its use does not result in the formation of carcinogenic by products nor the presence of toxic residue in the treated water. Moreover, UV is generated on site and therefore excludes the dangers associated with the shipment and storage of a dangerous disinfectant. As a result of these properties, ultraviolet light technology has been called the environmentally friendly disinfectant (Acher et al, 1997). The effectiveness of UV technology as an effective disinfectant is based on the new lamp configuration design within the disinfection unit. Thus, UV systems built by different manufacturers are not equally effective. Moreover, there are some disadvantages in the use of UV such as high costs, photoreactivation, interfering factors in water (turbidity, suspended solids, absorbing compounds), uncertainties in measuring UV dose, and no residuals to be measured to monitor effectiveness of a system. Thus, more information is required before one can predict the effectiveness of UV as a disinfectant for the various types of wastewater. This study proposes to evaluate the most recent and more powerful UV light generated from a medium-pressure, high-intensity UV lamp (low-intensity and high-intensity lamps are compared in Table 1) as a disinfectant for various wastewater types. The proposed study will use the collimated beam method to evaluate the effectiveness of the polychromatic (many UV wavelengths) high-intensity UV light as a disinfectant (additional generated wavelengths disinfection impacts are well known at this time) by comparing its effectiveness with that of the traditional monochromatic (single wavelength - 254 nm) low-intensity UV light (well known disinfection impacts). To obtain valuable data, disinfection of various classes of microorganisms in various quality of wastewater will be evaluated. In summary, the success of this study will provide a procedure to predict whether any wastewater can be effectively disinfected by low-intensity versus high-intensity light technology.

Table 1. UV Lamp Characteristics

Description	Low-intensity lamp	High-intensity lamp
Physical		
Nominal length, inches (cm)	64 (162.56)	16.5 (41.9)
Arc length, inches (cm)	58 (147.32)	14 (35.6)
Tube diameter, inches (cm)	0.59 (1.5)	0.63 (1.6)
Tube material	fused quartz	fused quartz
Internal pressure, torr	0.007 (7×10^{-3})	760 (7.6×10^{2})
Fill gas	argon (Ar)	argon (Ar)
Expected life, hr	10,000 - 13,000	5,000 - 8,000
Operating temperature, %C (%F)	40 - 50 (104 - 122)	600 - 800 (1,110 - 1,470)
Spectral		
Output, nm	185, 253.7, 577	200 - 600
Radiation at 253.7 nm, percent	86	25
Type	near monochromatic	polychromatic
Color emitted	violet	yellowish, green

Power		
Input, watts	75	4,100
UVC output, watts	26.7	430
Efficiency (UVC output/input), percent	36	10
Cathode type	hot, instant start	hot, instant start
Filament type	coiled tungsten	coiled tungsten
Ballast type	electronic/electromagnetic	electronic/electromagnetic

RESULTS, BENEFITS, AND/OR OTHER INFORMATION EXPECTED:

Traditionally, pilot scale studies were required to determine whether a wastewater could be effectively disinfected by this new UV technology because a pilot study will integrate all factors involved in the effectiveness of that lamp system including the lamp characteristics, reactor design (applied lamp intensity, hydrodynamics), and vendor assumptions for determining their dose- response characteristics as well as the quality of the water. Our laboratory has been involved in evaluating these pilot and full scale studies (Moreland et al, 1997, Moreland, 1997, Moreland et al, 1996, Rijal and Fujioka, 1994) in which UV technology has been used to disinfect wastewater. However, pilot studies require planning, are expensive, require the establishment of a full operating unit on site and the results are specific to that location. We recently compared the results of a UV pilot field study and the results of exposing the same wastewater to UV disinfection using the standard, laboratory based collimated beam method. In that study we (Moreland et al, 1997) reported that pilot units (both low-intensity and high-intensity) dose-response curve results are virtually the same as collimated beam (low-intensity lamp) dose-response curve results for enterococci and fecal coliform. Based on these results, we evaluated the effectiveness of low- intensity UV light to disinfect many types of wastewater using the collimated beam method and developed a system of predicting the effectiveness of the full scale UV system to disinfect any of the potential waste waters. However, the significance of these studies are limited to using low- intensity UV light technology. In this proposed study we will obtain comparative information when high-intensity UV light technology (collimated beam) is used. There is no published information for collimated beam studies using medium-pressure, high-intensity UV lamp as the UVC radiation source (a recent visit to a UV system manufacturer pointed out that a medium-pressure, high- intensity UV lamp collimated beam could be built providing all necessary and proper safety).

NATURE, SCOPE, AND OBJECTIVES:

In most of the previous studies, the low-intensity UV lamps were used because these lamps produce most of their UVC radiation at 254 nanometers wavelength, which has previously been determined to be the wavelength to make nucleic acid non-functional and thereby disinfect microorganisms (Figure 1). Despite the initial success of using low-intensity UV light, it is known that low-intensity UV light has poor penetrability and therefore, many lamps must be used to treat wastewater when low-intensity UV lamps are use. To address this concern, the UV industry has recently developed a high-intensity UV lamp which theoretically can use fewer high-intensity lamps to produce the same germicidal UV dose as the low-intensity UV lamps. Besides having higher intensity, this new UV lamp produces light of many wavelengths, including those at 254 nanometers (Figure 2). The germicidal effects of these other wavelengths are not known.

The nature of this study will be to compare the effectiveness of high-intensity UV lamp with that of low-intensity UV lamp using the collimated beam method to disinfect many types of wastewater. This study will determine if the high-intensity UV lamp can be used in a collimated beam apparatus to predict its capacity to disinfect wastewater from different sources. Collimated beam method is the only method which can truly measure UV dose. As a result, the method allows for reproducible doses and can determine its affect on various wastewater with different quality. If an operating UV system has been properly designed and sufficiently tested, the results based on the pilot unit should closely approximate collimated beam results using the same treated wastewater. We have determined that such an operating UV system exist. Therefore, collimated beam results is an accurate and economical way of obtaining data which can be used to predict the effectiveness of applying UV systems to treat wastewater from different treatment plants. Animal and aquaculture wastewaters have relatively low ultraviolet transmittance (ability to allow UV radiation to pass through the liquid), as a consequence low-intensity lamp system (not very practical below 45 - 50 percent UV transmittance) would not be successful in disinfecting these wastewaters. High-intensity systems could be very successful in their disinfection.

The scope of this study will determine whether the many other wavelengths of UV light produced in the high-intensity UV lamp play a significant role in the disinfection of different types of microorganisms with different resistance to UV disinfection. The microorganisms to be tested include the traditional fecal bacterial indicators (enterococci, fecal coliform), one spore-forming bacteria (*Clostridium perfringens*), and one virus (FRNA bacteriophage). These microorganisms were selected because they are structurally and genetically different and represent groups of microorganisms with various sensitivities and resistance to UV disinfection.

The objectives of Phase I and Phase II are: (1) To determine the differences in the effectiveness of high-intensity and low-intensity UV lamp in their ability to disinfect different classes of microorganisms. (2) To determine the contributing effect of different radiation wavelengths on disinfecting different microorganisms. (3) To determine how the quality of wastewater impacts on the effectiveness by which low-intensity and high-intensity UV light disinfects microorganisms. (4) To determine whether the results of collimated beam method using high-intensity UV light can reliably predict the success of applying high-intensity UV technology to disinfect various different types of wastewater. For Phase II, an additional objective to address UV disinfection of emerging new pathogens, especially different kinds of viruses, has been determined.

METHODS, PROCEDURES, AND FACILITIES (PHASE I):

The collimated beam apparatus is shown in Figure 3. The advantage of the collimated beam method is that the apparatus is small, can be operated safely in a laboratory setting and the many variables such as dose and quality of the effluent can be controlled and measured. Thus, results of comparing one sample from another is reliable when this method is used.   As this figure shows, a measured amount of UV light is collimated down to the sample. By controlling the distance of the sample and the time of exposure, the UV dose applied to a sample can be controlled. Any sample to be tested can be placed in the petri plate which will be well mixed to achieve ideal exposure of UV to the microorganisms. The quality of the wastewater and the concentrations of the various microorganisms can be measured as well as the intensity of the light at the sample source. The water quality parameters to be measured are summarized in Table 2. The methods to be used to assay for the different classes of microorganisms are shown in Table 3.

In addition, selective wavelength filters will be used to block out some wavelengths (other than 254 nm) generated by the high-intensity lamp collimated beam apparatus, while measuring the 254 nm with a radiometer, in order to determine disinfection impacts from the other wavelengths (compare organism grow for samples exposed [dose-response curve] with and without the selective filter).

Physical characteristics: The following wastewater physical properties will be used for characterization of the treated wastewaters for the listed facilities in Table 4.

Table 2. Physical Parameters

Tests	Units
Mean particle size	m
Total suspended solids	mg/l
Volatile suspended solids	mg/l
UV Transmittance at 254 nm	percent
Turbidity	NTU

All tests to be performed in accordance with *Standard Methods*

Microbiological characteristics. The following wastewater microbial characteristics will be analyzed by dose-response curves for the treated wastewater from the listed facilities in Table 4.

Table 3. Microbial Organisms

Bacteria	Virus
Clostridium perfringens[1]	FRNA bacteriophage[2]
Enterococci	
Fecal coliform	

All tests to be performed in accordance with *Standard Methods,* except
1 - Bisson 1979, 2 - Debartolomeis 1991

Table 4 shows the facilities where wastewater samples will be obtained. These wastewater samples represent different treatment and different final wastewater quality.

Table 4. Wastewater Facilities on Oahu. Abbreviations and Sample Points

Facility	Abbreviation	Sample points
CITY AND COUNTY		
Honouliuli WTP	HO	SE
Kahuku WTP	KU	SE, FE
Kailua Regional WTP	KI	SE
Paalaa Kai WTP	PK	SE
Wahiawa WTP	WH	SE
Waianae WTP	WN	SE
Waimanalo WTP	WL	SE
MILITARY		
Kaneohe MCBH WTP	KM	SE, HPE
Schofield Barracks WTP	SB	PE, SE
PRIVATE		
Hawaii Kai WTP	HK	SE
Laie WRF	LA	SE, FE
Turtle Bay WTP	TB	SE

Note: SE = secondary effluent, FE = filtered effluent, HPE = holding pond effluent

RESULTS (PRELIMINARY PHASE I):

After receiving approval for this project, we proceeded to survey the methods for obtaining a medium-pressure, high-intensity collimated beam. Calgon Company (UV vendor) had this type of collimated beam for sale at over $10,000, far exceeding our budget ($4,000). We contacted Trojan Technologies (UV vendor) about purchasing the components to build our own collimated beam or if we could purchase an assembled collimated beam for the budgeted dollars available. Later, we were able to have a newly assembled collimated beam loaned to WRRC for the next two years from Trojan Technologies. The recently acquired water jacket cooled medium-pressure, high-intensity collimated beam has currently been burning (100 hours) in the lamp, developing safety protocol and training research personnel in all aspects of the operating the system. Several secondary effluents and filtered secondary effluents have been evaluated. It has been shown in the evaluation results that there are differences between the secondary processes (suspended- growth versus attached-growth) microbial populations. Suspended-growth (activated sludge processes and stabilization ponds), attached-growth (trickling filters), and combined processes (trickling filter aerated solids contact - TFSC) inactivation rates (k) and 90 percent reductions (D_{90}) or one log reductions as shown in Table 5.

Table 5. Enterococci and Fecal coliform k and D_{90} Values for Various Processes

	Enterococci		Fecal coliform	
Process	k	D_{90}	k	D_{90}
Activated sludge	0.28	8.3	0.55	4.2
Trickling filter	0.25	9.2	0.43	5.4
TFSC	0.29	8.1	0.53	4.4
Stabilization pond	0.34	6.7	0.60	3.8

As can be seen in the table, there are organism differences between the various processes. The attached-growth process has the lower k value for both the gram-positive (enterococci) and gram-negative (fecal coliform) organisms. Therefore, the D_{90} values are higher as shown.

METHODS, PROCEDURES, AND FACILITIES (PHASE II):

The collimated beam apparatus is shown in Figure 3. The advantage of the collimated beam method is that the apparatus is small, can be operated safely in a laboratory setting and the many variables such as dose and quality of the effluent can be controlled and measured. Thus, results of comparing one sample from another is reliable when this method is used. As this figure shows, a measured amount of UV light is collimated down to the sample. By controlling the distance of the sample and the time of exposure, the UV dose applied to a sample can be controlled. Any sample to be tested can be placed in the petri plate which will be well mixed to achieve ideal exposure of UV to the microorganisms. The wastewater quality and microorganism densities can be measured as well as the light intensity at the sample source.

In addition, selective wavelength filters will be used to block out some wavelengths (other than 254 nm) generated by the high-intensity lamp collimated beam apparatus, while measuring the 254 nm with a radiometer, in order to determine disinfection impacts from the other wavelengths (compare organism grow for samples exposed [dose-response curve] with and without the selective filter).

Table 4 shows the facilities where wastewater samples (for natural virus - FRNA phage) will be obtained. These wastewater samples represent different treatment and different final wastewater quality.

Microbiological characteristics. The microorganisms to be tested are shown in Table 6, the first virus is naturally occurring and the last five are laboratory strains. These organisms were selected (along with Phase I microorganisms) because they are structurally and genetically different and represent groups of microorganisms with various sensitivities and resistance (vegetative bacteria < viruses < prozotoa < bacterial spores) to UV disinfection. The laboratory strains will be seeded in phosphate buffer and in some of the secondary and filtered effluents.

Table 6. Virus Evaluations

Organism	Description	Water-borne pathogen (example)
FRNA phage	single-stranded RNA bacterial virus	Poliovirus, Norwalk virus, Astrovirus, Hepatitis A,
MS2 phage		and human enteric virus
Poliovirus	single-stranded RNA human virus	Norwalk virus, Astrovirus, and Hepatitis A
.6 phage	double-stranded RNA bacterial virus	Human Reovirus
.X174 phage	single-stranded DNA bacterial virus	Human Parvovirus
T4 phage	double-stranded DNA bacterial virus	Adenovirus

RELATED RESEARCH:

The Water Resources Research Center (WRRC) has been involved in many research studies to assess the effectiveness of treating wastewater and determining their affect on the quality of environmental waters. Many types of disinfectant of wastewater have been previously determined. These include chlorine, chloramine, chlorine dioxide, bromine chloride and ultraviolet light. This study fits in with the mission of WRRC which is to evaluate the cutting edge technology by assessing the effectiveness of high-intensity UV light.

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