2001 Ghausi Hall
University of California
1 Shields Avenue
Davis, CA 95616
(530) 752-0586

10 June 2019

Courtney Hall, Assoc. Civil Engineer
UC Davis Utilities 740 Garrod Drive
Davis, CA 95616
(530) 754-4970

Dear Ms. Hall:

Enclosed is the final report, entitled *UC Davis Watewater Treatment Plant Ultraviolet Disinfection System Replacement Design*, pHlux Engineering was contracted to produce on behalf of the UC Davis Utilities Division on 11 January 2019.

As requested, the report evaluates the feasibility of lowering the ultraviolet transmissivity requirement in the UC Davis wastewater treatment plant's NPDES permit in addition to recommending a replacement UV disinfection system design. The primary goal was to ensure all effluent meets Title 22 standards for recycled water under the maximum design flow and lowest permissible ultraviolet transmissivity: 5.7 mgd at 55% UVT.

Considering the reduction in treatment capacity necessary to operate at a UVT lower than the NPDES permit currently allows, pHlux engineering recommends that no changes be made to the permit. Additionally, pHlux engineering recommends a replacement disinfection system consisting of TrojanUV3000Plus lamps with three-inch on-center spacing.

My colleagues and I at pHlux Engineering hope that this report answers all questions you have regarding the proposed recommendations for addressing the UVT violations and the design of a replacement disinfection system. Please contact us with any concerns you may have regarding the contents of this report.

Sincerely,

Charles Hammond

Jaime Luo

Jacob Newman

pHlux Engineering
Encl.: *Final Report*

UC Davis Wastewater Treatment Plant Ultraviolet Disinfection System Replacement Design

Final Report

pHlux Engineering
Team 20

Prepared by: Charles Hammond
Jaime Luo
Jacob Newman

Prepared for: UC Davis Utilities Division

Submitted on: 10 June 2019

Executive Summary

On January 11th, 2019, the UC Davis Utilities Division (UD) contacted pHlux Engineering to request assistance in solving two problems affecting the UC Davis Wastewater Treatment Plant (WWTP). The WWTP treats its effluent with ultraviolet (UV) disinfection, but may violate the minimum UV transmissivity (UVT) of 55% required by the WWTP's National Pollutant Discharge Elimination System (NPDES) permit during rainfall events. The UD requested pHlux Engineering investigate the recurring UVT violations and potentially recommend the Central Valley Regional Water Quality Board (CVRWQCB) modify the UVT requirement in the WWTP's NPDES permit. Additionally, the current UV disinfection system is approaching the end of its useful life, and the UD has requested a replacement design. This report provides background on the unique challenges faced by the WWTP, details the technical approach used to design the replacement disinfection system, and recommends a replacement disinfection system consisting of TrojanUV3000Plus lamps.

An analysis of UVT and local rainfall data from the past three years revealed a positive correlation between the cumulative rainfall in a 72-hour period following a 72-hour dry spell and the likelihood of a UVT violation during that period. The analysis revealed a near 100% probability of violation for a cumulative rainfall of two or more inches following a 72-hour dry spell. Additionally, the UVT fell below 55% for only 2.4% of all operating hours in the last three years.

A bioassay performed by Carollo Engineers demonstrated the current UV disinfection system is capable of delivering the NPDES-required 100 mJ/cm^2 dose at a UVT as low as 42%. However, in order to adequately disinfect the wastewater under such conditions, all banks must be operational and the influent must be reduced to 56% below capacity. This is unacceptable considering the projected growth of UC Davis. Additionally, operating with no redundant treatment capacity is irresponsible and increases the risk of violating the NPDES permit. Thus, pHlux Engineering does not recommend lowering the UVT requirement in the NPDES permit. Instead, an oxidizing agent or coagulant could be added upstream of the UV disinfection system, thereby increasing the UVT to acceptable levels before disinfection occurs. The requested technical memorandum can be found in Appendix E of this report.

Alternative UV disinfection system designs were produced using lamp specifications provided by the manufacturers for the TrojanUV3000Plus and Calgon C^{3}500 lamps. The Line Source Integration Method was used to produce a fluence rate distribution model for each alternative. Assuming laminar flow, dose distributions were generated by multiplying the contact time by the fluence rate distribution. Computational fluid dynamics analysis supported the assumption of laminar flow. The acceptable fraction of doses below 100 mJ/cm^2 was set at approximately 5% to reflect uncertainty regarding actual flow conditions and mixing in the channel.

The recommended replacement disinfection system utilizes TrojanUV3000Plus lamps spaced three inches apart. Three channels will operate simultaneously during peak flow with two online banks and one redundant bank per channel. The system requires 972 total lamps, with 18 modules per bank and 6 lamps per module. No alteration of the existing infrastructure will be required for installation and the system is expected to cost a total of $3.2 million, which includes operating and capital costs. TrojanUV does not currently provide the TrojanUV3000Plus lamps with three-inch spacing. However, our analysis shows that this configuration is necessary to ensure compliance under all permissible operating conditions.

Contents

Nomenclature

Symbol/Initialism	Meaning
CFD	Computational Fluid Dynamics
CVRWQCB	Central Valley Regional Water Quality Control Board
H_2O_2	Hydrogen peroxide
LPHI	Low Pressure High Intensity
LPLI	Low Pressure Low Intensity
LSI	Line Source Integration Method
mgd	Million gallons of wastewater per day
MPHI	Medium Pressure High Intensity
MPN	Most probable number
NPDES	National Pollution Discharge Elimination System
NWRI	National Water Resources Institute
O&M	Operations and maintenance
UD	UC Davis Utilities Division
UV	Ultraviolet
UVT	Ultraviolet transmissivity
WWTP	UC Davis Wastewater Treatment Plant

1 Introduction

1.1 Problem Statement

This project aims to solve two problems for the UC Davis Wastewater Treatment Plant (WWTP). First, during large rainfall events the WWTP sometimes violates the minimum ultraviolet transmissivity (UVT) requirement of 55% in its National Pollution Discharge Elimination System (NPDES) permit. These violations are undesirable because 1) they result in fines, 2) erode the public's trust in the WWTP, and 3) could lead to legal action requiring the WWTP to halt operation [1]. To resolve these issues, the UC Davis Utilities Division (UD) has requested a memorandum addressed to the Central Valley Regional Water Quality Control Board (CVRWQCB) that justifies, based on data and rigorous testing, the reduction or removal of the UVT limit. The goal of the memorandum is to demonstrate that the current ultraviolet (UV) system is capable of achieving the required disinfection efficiency at a UVT less than the standard 55% [2].

Second, the UV disinfection system is nearing the end of its planned service life and must soon be replaced. Because the WWTP's effluent is sent to Putah Creek, the UC Davis Arboretum, and the UC Davis Thermal Energy Storage Plant, the safety and compliance of the recycled water is of the utmost importance. Failure to maintain or replace an aging disinfection system could result in outbreaks of disease, fines, and even legal action. Thus, the primary goal of this project is to design a replacement UV disinfection system.

1.2 Project Objectives

This project has two major objectives:

1. Craft a technical memorandum addressed to the CVRWQCB that uses data from a site-specific UV bioassay to justify the reduction or removal of the UVT requirement in the WWTP's NPDES permit.
2. Design a replacement disinfection system that satisfies Title 22 and the NPDES permit, fits within the current UV disinfection system footprint, utilizes existing infrastructure, performs well under all hydraulic conditions, and minimizes cost.

Success in completing these objectives will be measured by how well the goals detailed in the objectives are satisfied.

2 Background

Wastewater treatment is usually divided into three main stages: primary, secondary, and tertiary. Primary treatment involves the removal of suspended solids and organic matter, secondary treatment typically includes the biological oxidation of organics remaining in the primary effluent, and tertiary treatment employs filters and/or disinfection processes to produce recycled water [3].

Disinfection is the process of destroying or inactivating pathogenic organisms. Considering the potential for human exposure to recycled wastewater, proper disinfection is extremely important. Of particular concern are bacteria, protozoan oocysts and cysts, viruses, and helminth ova, all of which can cause serious illness [3]. Although many bacteria are harmless or beneficial, some present serious human health risks; for example, *Legionella pneumophila* can cause malaise, myalgia, fever, headache, and respiratory illness [3].

Wastewater is usually disinfected with either chemical agents, such as chlorine or ozone, or non-ionizing radiation, most commonly UV light [3]. Chlorine and ozone function by oxidizing and destroying cell walls, while UV works primarily by dimerizing adjacent thymine and cytosine DNA/RNA molecules, so pathogens with thymine-rich genetic material (e.g., *C. parvum* and Adenovirus) are more sensitive to UV disinfection [3]. Combined UV-chemical treatments are known as UV-based advanced disinfection processes; research has suggested that combining UV treatment with hydrogen peroxide (H_2O_2) could enhance viral deactivation [4]. Each method has strengths and weaknesses and each treatment plant should tailor its disinfection process to its particular needs. For example, using chlorine or ozone can result in toxic disinfection byproducts and some viruses are resistant to UV irradiation [3], [5]. For the reasons outlined in Table 2.1, UV was chosen as the disinfection method for the replacement disinfection system.

Table 2.1: Selected considerations of UV, chlorine, and ozone disinfection systems [5].

Characteristic	**UV**	**Chlorine**	**Ozone**
Disinfection by-products	None	Trihalomethanes	Brominated and nonhalogenated
Existing infrastructure	Yes	No	No
Staff retraining	No	Yes	Yes
Chemical:			
Transport	No	Yes	No
Generation	No	No	Yes
Storage	No	Yes	No
Handling	No	Yes	No
Space required	Least		

UV light is electromagnetic radiation with wavelengths between 100-400 nm, which is divided into longwave (UV-A), middlewave (UV-B), and shortwave (UV-C). The wavelength used for disinfection (254 nm) is most commonly generated by striking an electric arc between two electrodes in a lamp containing mercury [5]. UV lamps come in three general categories, 1) low-pressure, low-intensity (LPLI), 2) low-pressure, high-intensity (LPHI), and 3) medium-pressure, high intensity (MPHI) [3]. Among the three types, LPLI and LPHI lamps are the most efficient, with 30-50% and 35-50% of their energy output in the form of monochromatic 254 nm wavelength light, respectively. MPHI lamps produce more intense light, but much less efficiently, with only 15-20% of their energy output in the germicidal range [3].

The effectiveness of a given UV disinfection system depends on the chemical characteristics of the wastewater, presence of particulate matter, the target organisms, and the system design [3]. These factors all influence the UV "dose," which is defined as

$$D = I_{avg} \times t \tag{2.1}$$

Where $D = dose[mJ/cm^2]$

I_{avg} = average UV intensity $[mW/cm^2]$

t = exposure time, s

Constituents in wastewater can influence the dose by reducing the average UV intensity. Typically these effects are measured via absorbance and transmissivity, which is why the National Water Resources Institute (NWRI) recommends a general minimum of 55% UVT for a UV dose of 100 mJ/cm^2 [2]. Dissolved iron and organic compounds with double bonds and aromatic functional groups are the most influential constituents, as they can directly absorb UV light [3]. Particles can reduce disinfection performance by shielding harmful organisms from irradiation, reflecting and/or refracting light, and by harboring microorganisms [3].

Contact basins can be either open channels or closed reactors and, due to the relatively short contact time, they must be carefully designed to ensure complete disinfection [3]. Hydraulic design of a UV disinfection system is extremely important, as non-ideal hydraulics can lead to longitudinal mixing, which leads to a distributed, rather than uniform, exposure time [3]. Two important challenges when designing a UV disinfection system are 1) ensuring uniform velocity fields approaching and exiting the UV banks and 2) ensuring equal flow between channels; both issues could result in over or underdosing [3]. Optimization models have suggested that dose distributions and flow characteristics for open-channel reactors are most dependent on the lamp configuration [6]. Alternatively, closed vessel UV reactors offer several advantages, including improved hydraulics, reduced construction costs, and lower power requirements [7].

The required dose is most commonly determined via a collimated beam bioassay in which a known UV dose is applied to a small batch reactor and correlated to the organism inactivation results, which is typically reported in most probable number (MPN) and must fall between quality-control limits set by the United States Environmental Protection Agency [3]. Organisms used for determining the required dose include Bacteriophage MS2 and *B. subtilus* [3].

2.1 Site History

The existing WWTP replaced its 52 year old predecessor in 1999 for $15.3 million [8]. The WWTP serves over 40,000 students and 20,000 faculty and staff, and is rated for 3.6 million gallons of wastewater per day (mgd), though it averages about 1.2 mgd [9]. The WWTP discharges tertiary treated recycled water (as defined in Title 22) to the south fork of Putah Creek and the UC Davis Arboretum as well as the UC Davis Thermal Energy Storage Plant [2], [10]. A third UV disinfection channel was added in 2007 when the WWTP underwent a major expansion. The wastewater source profile at the WWTP is challenging, as UC Davis has many animal teaching facilities that produce low-transmittance runoff, especially during large rainfall events.

2.2 Precedents

TrojanUV, whose technology the current UV disinfection system utilizes, claims that UV treatment can be used on wastewater with a transmissivity as low as 15% [11]. TrojanUV provides a case study where effective disinfection was achieved in a 54.3 mgd combined wastewater and stormwater treatment plant with as low as 30% UVT using the TrojanUV4000Plus lamps [11]. They claim the key to effective disinfection is to optimize the “effective water layer” by manipulating the reactor hydraulics, lamp output, and lamp spacing [12].

3 Constraints

3.1 Regulations

The 1969 Porter-Cologne Water Quality Control Act provides the legal framework for water recycling in California [13]. Title 22, the state's most recent legislation regarding water recycling, requires the Department of Health Services to set water and bacteriological treatment standards for recycled water [13]. The CRWQCB is one of nine regional boards in California that sets water quality standards with help from the Department of Public Health and issues individual discharge permits, known as NPDES permits [13]. Recycled water can be used for irrigation, landscaping, air conditioning, commercial laundry, decorative fountains, and toilets in commercial buildings [13]. The minimum 55% UVT required by the WWTP's NPDES permit comes from the NWRI's recommendation and is mandated by Title 22.

3.2 Criteria

The replacement disinfection system alternatives shall be designed to 1) treat the full 5.7 mgd capacity of the WWTP at at UVT of 55%; 2) require minimal new construction; 3) remain within the existing system footprint; 4) deliver approximately 95% of all doses above the NPDES required value of 100 mJ/cm^2; and 5) comply with the Title 22 standards for recycled water.

4 Technical Approach

As per the NWRI guidelines, the performance of each alternative was evaluated at the most challenging operating conditions for the maximum design flow: 55% UVT and 1.9 mgd per channel [14]. A model incorporating refraction, reflection, and absorbance was used to simulate each configuration. All MATLAB code used to perform this analysis can be found in Appendix B.

4.1 Assumptions

Four major assumptions were used to simplify the analysis: 1) flow through the channel is laminar, 2) lamp shading effects are negligible, 3) height of flow is constant at one-half the inter-lamp spacing above the highest lamp, and 4) UV intensity does not vary along the length of the lamp.

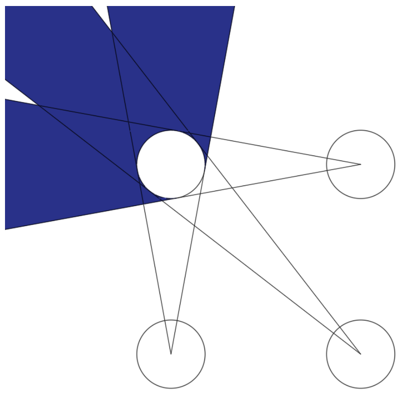
Laminar Flow

Computational fluid dynamics (CFD) software was used to determine the flow regime through the UV lamps in each bank of the existing system. A 3-D computer model of one of the UV banks was run through a commercially available CFD solver under peak design flow conditions (1.9 mgd per channel).

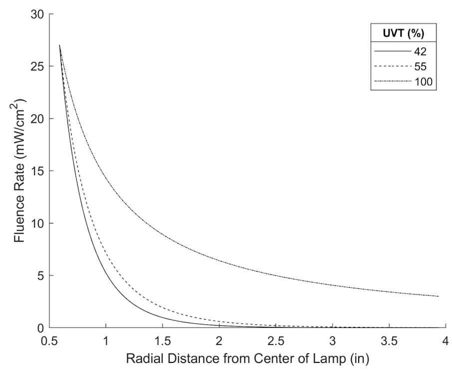
A representational cross-section of the flow velocity through the bank demonstrated that the radial velocities in the bank were practically zero, meaning the water flows nearly parallel with the lamps. This analysis supports the assumption of laminar flow through each UV bank. Details regarding the CFD analysis can be found in Appendix A.

Lamp Shading

As Figure 4.1a shows, lamps can block light emitted from their neighbors. The assumption that these effects can be safely neglected is supported by Figure 4.1b, which shows that for a UVT of 55%, the intensity of light from a lamp is effectively zero at approximately three inches from the center of the lamp. Since each alternative was evaluated at 55% UVT for an on-center spacing of three inches or greater, the assumption is valid.



(a)



(b)

Figure 4.1: (a) Schematic of the effects of lamp shading; shaded area represents the area shielded from light emitted from other lamps; (b) plot of UV intensity as a function of radial distance from lamp.

Range of Influence

Each alternative was designed such that the maximum distance between a particle of water and a lamp is one-half the inner-lamp spacing. This is to ensure all wastewater flowing through the banks experiences sufficient UV intensity.

Uniform Lamp Intensity

The UV intensity produced by a given lamp is not uniform along its entire length. While the intensity drops off dramatically at either end of the lamp, as shown in Figure 4.2, the intensity is uniform for most of the lamp. Therefore, this analysis assumes a uniform intensity profile of a given lamp along its entire length.

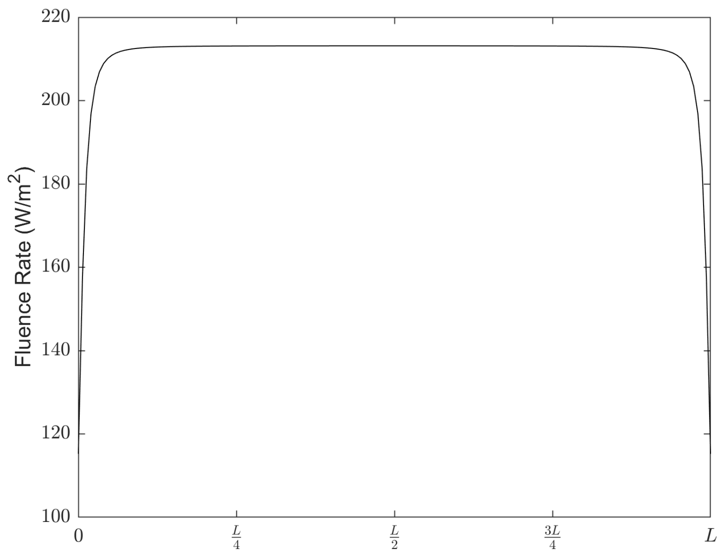


Figure 4.2: Fluence rate at a radial distance from a lamp as a function of axial distance along a lamp of length L.

4.2 Methods

A model of each alternative was created in MATLAB using the Line Source Integration (LSI) method [15]. The LSI method models the intensity at a point located radially from a single UV lamp and accounts for refraction, reflection, and absorption in the air, quartz, and water and at their interfaces. This radial model was manipulated to produce a 2-D Cartesian model of a single lamp, which was overlapped appropriately to model the entire channel. The LSI model is given by Equation 4.1.

$$I = \frac{P}{4\pi LR}\left(arctan\left(\frac{L/2+H}{R}\right) + arctan\left(\frac{L/2-H}{R}\right)\right) \times atten \tag{4.1}$$

where P = Power output at 254 nm (W)
L = Length of lamp (m)
R = Radial distance from center of lamp (m)
H = Longitudinal distance from center of lamp (m)

The attenuation factor corrects for absorption, reflection, and refraction, and is given by Equation 4.2. For the purposes of this analysis the "focus factor" as defined in [15] has been omitted, as its implementation resulted in anomalous and unusual results.

$$atten = \frac{\Sigma_{n=1}^{N}\left[\frac{\Phi/N}{4\pi(d_1+d_2+d_3)^2}(1-R_{12})(1-R_{23})\,T_2^{d_2/0.01}\,T_3^{d_3/0.01}cos(\theta_1)\right]}{\Sigma_{n=1}^{N}\left[\frac{\Phi/N}{4\pi(l^2+r^2)}\right]} \tag{4.2}$$

where Φ = Power output at 254 nm (W)

$R_{12,23}$ = Fraction of light reflected by air-quartz and quartz-water interface, respectively

$T_{2,3}$ = 10 cm transmissivity of quartz and water, respectively

$d_{1,2,3}$ = Optical path length through air, quartz, and water, respectively, to point of evaluation (m)

θ_1 = Angle of d_1 with perpendicular line from lamp

N = Chosen number of point sources along lamp length

$r = r_1 + r_2 + r_3$(defined in Figure 4.3)

$l = \Delta x$(defined in Figure 4.3)

The lamp is broken up into N number of point sources and the light intensity contribution of each is combined for a single evaluation point. To eliminate axial oscillations in the fluence rate, a minimum N of 200 is required. The light reflected at the interfaces between materials can be calculated using the Fresnel Law and the index of refraction of each material (n), given by Equation 4.3 from Buchner [15].

$$R = \frac{1}{2}\left(r_{\parallel}^2 + r_{\perp}^2\right) \tag{4.3}$$

where

$$r_{\parallel} = \frac{n_1 cos(\theta_1) - n_2 cos(\theta_2)}{n_1 cos(\theta_1) + n_2 cos(\theta_2)}$$

$$r_{\perp} = \frac{n_2 cos(\theta_1) - n_1 cos(\theta_2)}{n_2 cos(\theta_1) + n_1 cos(\theta_2)}$$

The key to evaluating these expressions is finding θ_1, which is defined in the schematic of the optics found near the surface of a lamp found in Figure 4.3. Through trigonometry, θ_1 can be determined from Equation 4.4 given by Buchner [15]. The expression must be evaluated numerically with an initial bracket that reflects the physical limits of what θ_1 can be; the MATLAB function *fzero* with a bracket of [0,89.99] (degrees) was used for this analysis. Once θ_1 is obtained, the other angles can be easily calculated using Snell's Law.

$$f(\theta_1) = r_1 tan(\theta_1) + n_1 sin(\theta_1)\left(\frac{r_2}{\sqrt{n_2^2 - n_1^2 sin^2(\theta_1)}} + \frac{r_3}{\sqrt{n_3^2 - n_1^2 sin^2(\theta_1)}}\right) - \Delta x \tag{4.4}$$

Once a radial distribution of intensities was obtained, a 2-D Cartesian model of the intensity around a single lamp was generated by rotating the radial intensities 360 degrees around an axis and converting to Cartesian coordinates. Because of the irregularity in the data and the need for consistency to facilitate overlapping the models, the MATLAB function *scatteredInterpolant* was used to map the irregular 2-D model onto a regularly spaced meshgrid. A distance of 0.01 inches between each index in the meshgrid was determined to be the optimal balance between resolution and performance.

A meshgrid of a front-elevation cross section of the entire channel was generated and the individual lamp intensity distributions superimposed upon it. The meshgrid allows for the observation of the boundary conditions and the interactions between the lamps. Because the interior of the lamps contain interpolated values but do not come in contact with water, logical indexing is required to remove these points from all dose distribution considerations.

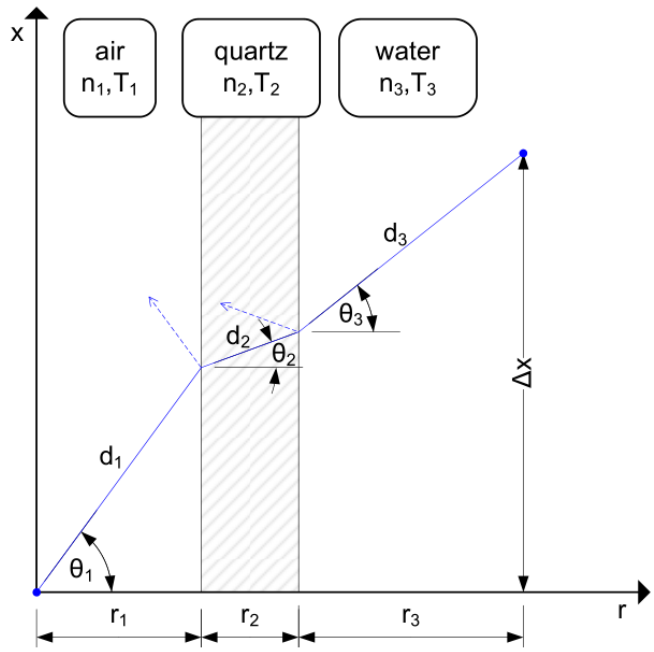


Figure 4.3: Optics around a UV lamp; taken from [15].

The LSI model gives the fluence rate at a point in space, in watts per meter squared. To find the dose, or fluence (mJ/cm^2), experienced by a particle, the fluence rate is multiplied by the particle's exposure time. Because laminar flow is assumed, the dose distribution for a given design is found by multiplying the contact time of the water with the lamps by the fluence rate distribution. A cumulative probability distribution of the delivered doses, as shown in Figure 4.4, was produced for each alternative to evaluate what fraction falls below the minimum of 100 mJ/cm^2 required in the NPDES permit.

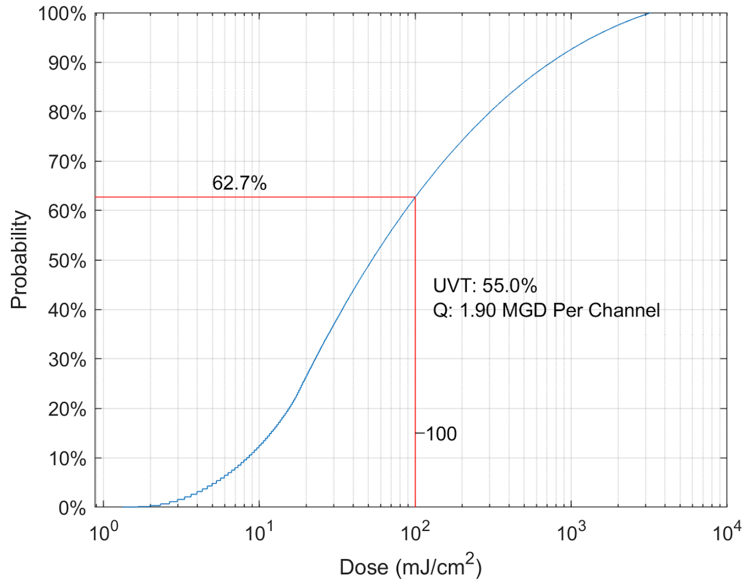


Figure 4.4: Cumulative probability distribution of delivered doses for the Calgon $C^3$500 lamps with 6 inch on-center spacing at 55% UVT and 1.9 mgd per channel.

5 Alternatives Analysis

Lamps from two UV manufacturers, Calgon Carbon and TrojanUV, were considered for the UV disinfection design. Each manufacturer provided quotes and specifications, which can be found in Appendix D, for their recommended design. A total of four alternative designs were analyzed: two manufacturer recommended designs and two custom designs created by varying lamp spacing. The specifications for each alternative are summarized in Table 5.1.

Table 5.1: Specifications for the considered alternatives.

Parameter	Trojan		Calgon	
On-center lamp spacing (in.)	3	4	4	6
Total channels	3	3	3	3
Total banks	9	12	12	12
Redundant banks	3	3	3	3
Modules per bank	18	13	13	9
Lamps per module	6	6	6	4
Total lamps	972	936	702	432

The alternatives analysis was conducted in two stages. Each alternative was first evaluated for Title 22 compliance using the LSI method to evaluate a design's ability to deliver approximately 95% of its doses above the NPDES required minimum of 100 mJ/cm^2. This initial screening disqualified both the Calgon Carbon recommended design using Calgon $C^3$500 lamps with 6-inch spacing and the TrojanUV recommendation using TrojanUV3000Plus lamps with 4-inch spacing. The two alternatives with modified lamp spacing had significantly lower probabilities of non-compliance, as shown in Figure 5.1.

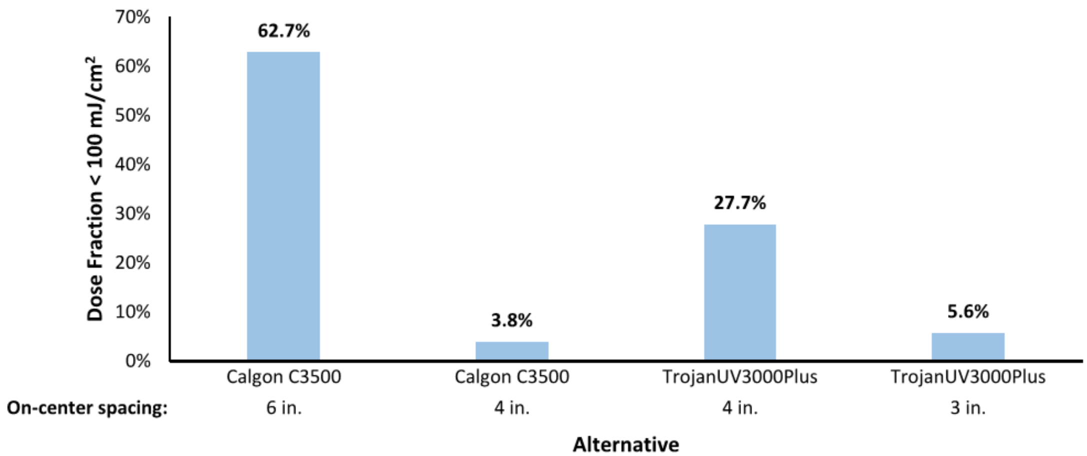


Figure 5.1: Comparison of percentage of delivered doses less than the NPDES required minimum for four alternative UV disinfection system designs.

The second stage was to evaluate the cost and operating characteristics of the two remaining alternatives. The capital costs were calculated using the lamp pricing specifications provided in Calgon Carbon's quote. The annual operations and maintenance (O&M) costs were estimated using the lamp replacement costs from each manufacturer and assuming approximately 12% of the lamps will be replaced each year. It is estimated that annual labor costs to maintain the lamps are equal to 0.2% of the capital cost, as per Calgon's quote. The annual O&M costs were then converted to a net present value (NPV) in 2019 dollars using an annual interest rate of 7.0% and a system lifespan of 20 years. The calculated costs of the final alternatives are shown in Figure 5.2. The detailed cost calculations for these alternatives are available in Appendix C.

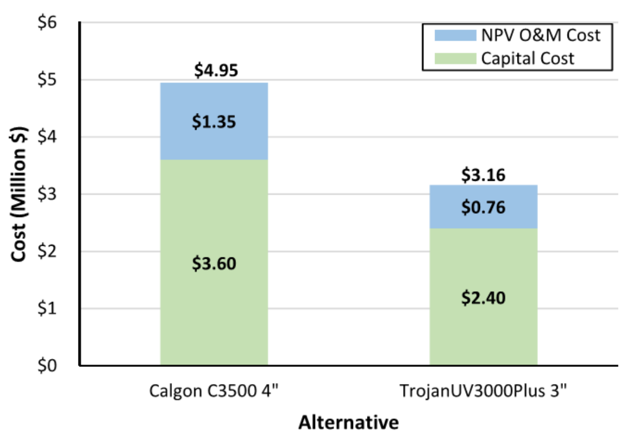


Figure 5.2: Cost comparison of final alternatives.

The final design was selected by ranking each alternative according to its satisfaction of key design parameters. These criteria included cost, maintenance requirements, operational hazards, and power consumption. Each criterion was assigned a weight of importance based on the engineers' own judgment. The two alternatives were ranked on a scale of one to two, where two was the more optimal design. The weighted rankings were then summed for each alternative. The alternative with the higher score was chosen as the final design. Table 5.2 summarizes the results of the alternative analysis.

Table 5.2: Weighted criteria analysis of final design alternatives.

Criteria	Weight	Calgon C3500 4"	TrojanUV3000Plus 3"
Capital cost	10	1	2
Annual O&M cost	10	1	2
Maintenance required	6	2	2
Operational hazards	10	2	2
Title 22 compliant	10	2	2
Within existing footprint	10	2	2
System capacity	9	2	2
No new construction	5	1	2
Power consumption	8	1	2
Permissible UVT	8	2	2
	Total	**139**	**172**

6 Recommendations

6.1 UVT Violations

Based on the assessment described in the technical memorandum addressed to the CVRWQCB found in Appendix E, no modifications to the NPDES permit are recommended. Reducing the treatment capacity to operate at a UVT below 55% is not practical, especially given current plans to increase the campus population and facilities.

Rather than modifying the NPDES permit, the UD should consider pre-treating the wastewater before it enters the UV disinfection system. Chemical pre-treatment is ideal as it can be on-demand and requires no major upgrades to the WWTP. The addition of a strong chemical oxidizer or coagulant upstream of the UV reactors could remove color from the wastewater, thereby increasing the UVT [16]. The chosen chemical could easily be injected into the clarifiers preceding the sand filters to allow time for the oxidizer to bleach the water or the particles to settle.

6.2 Risk Management

Public safety was a key consideration in designing the final disinfection system. Operating risks were identified and addressed throughout the design process. The final design recommendation includes a redundant UV bank in each channel should any of the other banks malfunction or require maintenance. Should a lamp break and spill mercury into the effluent, the channels are equipped with gates at either end that can be shut to isolate the system from the rest of the WWTP. The gates may also be shut in the event of a system-wide failure. If any effluent is deemed unsafe for discharge, a bypass valve may be opened to divert the wastewater to a holding pond until it can be further disinfected to safe levels. The bypass valve may also be used in the event of a malfunction upstream of the UV system.

In addition to reducing public exposure to unsafe effluent, the proposed UV design includes mechanisms to protect the safety of the WWTP operators and maintenance staff. It is advised that the operators be provided with proper personal protective equipment, including ANSI-Z87 rated wrap-around eyeglasses, pants, and long-sleeve clothing to minimize exposure to UV light when working around the UV reactors.

6.3 Replacement Design

The proposed replacement UV disinfection system consists of nine banks evenly distributed across the three existing concrete channels. A rendering of one of the proposed UV banks is depicted in Figure 6.1. Each bank consists of 108 TrojanUV3000Plus lamps with three-inch on-center spacing, arranged in 18 modules of 6 lamps each. Only two out of three banks per channel are required to be online at any given time, giving a 33% system redundancy. By comparison, the NWRI guidelines require a minimum redundancy of only 20% [14]. The complete list of lamp specifications is summarized in Table 6.1.

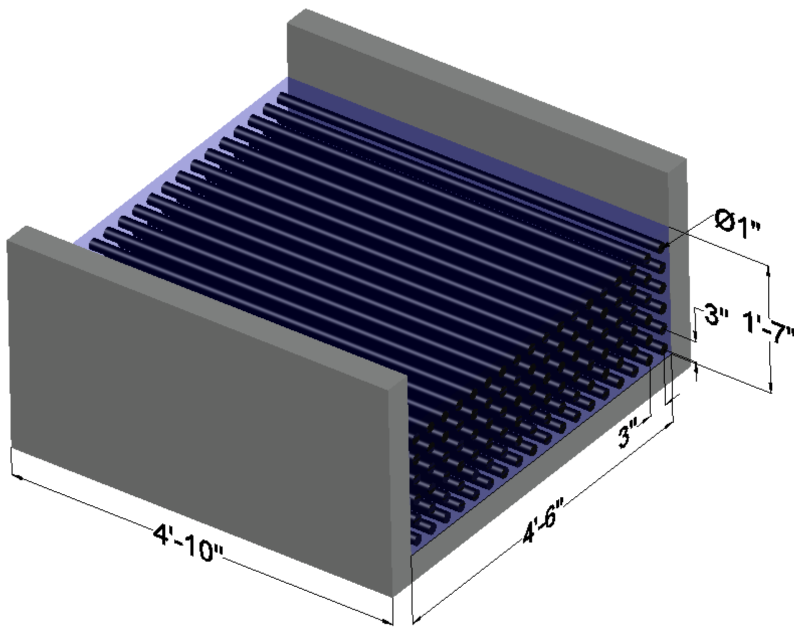


Figure 6.1: Proposed UV bank (not to scale).

TrojanUV does not currently manufacture a three-inch spacing variety of their TrojanUV3000Plus lamps. However, the LSI model demonstrated that this configuration is ideal to ensure compliance under all permissible operating conditions. pHlux Engineering would work closely with TrojanUV to manufacture the lamp arrangement described in this report or an equivalent design.

Table 6.1: Design specifications for replacement UV system.

Parameter	Design
On-center lamp spacing (in)	3
Total channels	3
Total banks	9
Redundant banks	3
Modules per bank	18
Lamps per module	6
Total lamps	972

The recommended UV system is certified for the WWTP's peak design flow of 1.9 mgd per channel, allowing the system's treatment capacity to remain unchanged. The LSI model results provide strong evidence of the system's compliance with Title 22. The implementation of the new system will require no major modifications to the existing concrete channels, thereby leaving the existing footprint unchanged and reducing the project's capital cost. The proposed system includes TrojanUV's trademark combination mechanical and chemical cleaning mechanism for removing grime that has built up on the lamp sleeves. These chemicals are food-grade and therefore harmless for operators should they be exposed. Additionally, compared to Calgon Carbon's lamps, the TrojanUV lamps consume half as much electricity per unit, thus reducing operating costs.

Based on the LSI model, 5.6% of the system's delivered doses fall below the required dose of 100 mJ/cm^2 at peak flow for the minimum permissible UVT. However, in operation the system should perform better because of additional mixing not accounted for in the LSI model. The capital cost to install the recommended design is $2.4 million, with an NPV of $760,000 in O&M costs. In total, the proposed design will cost the UD $3.16 million.

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Appendix A - Computational Fluid Dynamics Analysis

A commercially available CFD software was used to validate the laminar flow assumption for the LSI model. CFD refers to a variety of numerical methods for computing analytical solutions to fluid mechanics problems of complex geometry. The CFD software used in this analysis employs a proprietary numerical method to solve the Navier-Stokes equations, which govern the fluid motion observed in the UV system.

Modeling a UV Bank

A 3-D model of one of the existing UV banks was created using commercially available computer aided design software. For simplicity, some features of the bank were excluded from the model, including the structural elements that hold the lamps in place. However, the lamps and channel were properly sized according to the manufacturer's specifications for TrojanUV3000 lamps and as-built drawings of the existing UV system. Once the 3-D model was imported into the CFD software, the water and lamps were each assigned their respective materials, as in Figure A.1. Due to software limitations, the quartz-sleeved lamps were assigned a material of glass. This modification should not have affected the analysis greatly as glass and quartz have a similar characteristic surface roughness.

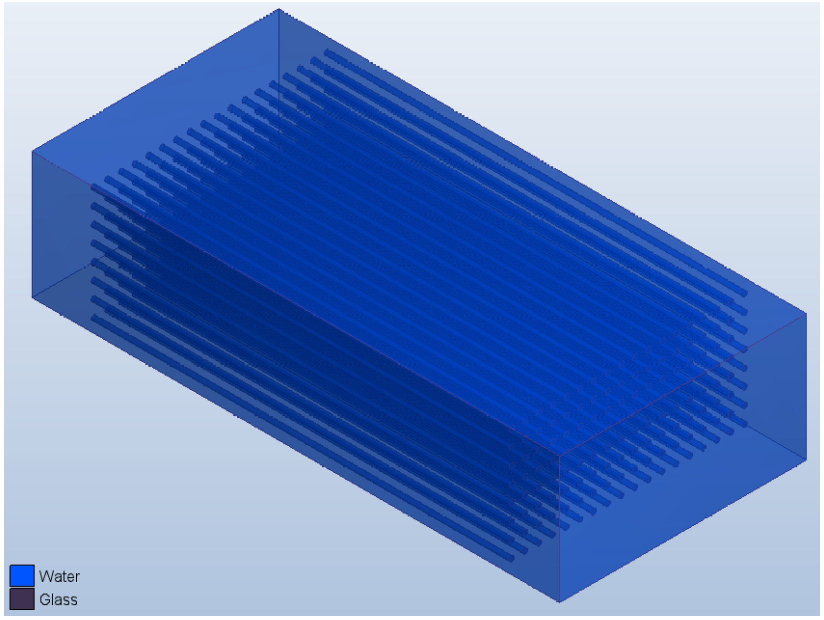


Figure A.1: 3-D model of the UV bank with assigned material properties.

CFD Analysis

The flow regime through the UV bank was analyzed for the peak design flow condition of 1.9 mgd per channel. The boundary conditions were defined accordingly assuming steady state conditions. Next, the 3-D model was discretized into points using the software's automatic mesh sizer (see Figure A.2).

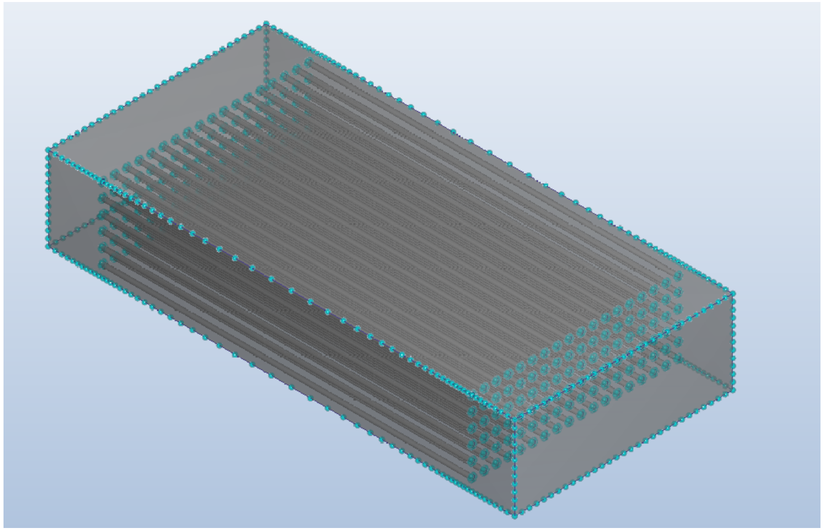


Figure A.2: Mesh sizing the 3-D model into discrete points.

The CFD solver was then ran for 78 iterations until the software converged upon a solution. A cross-sectional plane midway through the bank was analyzed to interpret the results of the analysis, as shown in Figure A.3. The velocity vectors in this plane revealed that the radial flow velocities were negligible. Because the direction of flow was primarily parallel with the lamps, this analysis verified that the laminar flow assumption was valid. This assumption made it possible to multiply the intensity distribution from the LSI model by a singular contact time as computed using the cross-sectional area of the channel and the discharge rate. The CFD analysis was repeated for the final recommended design to verify the laminar flow assumption held true for that lamp configuration as well.

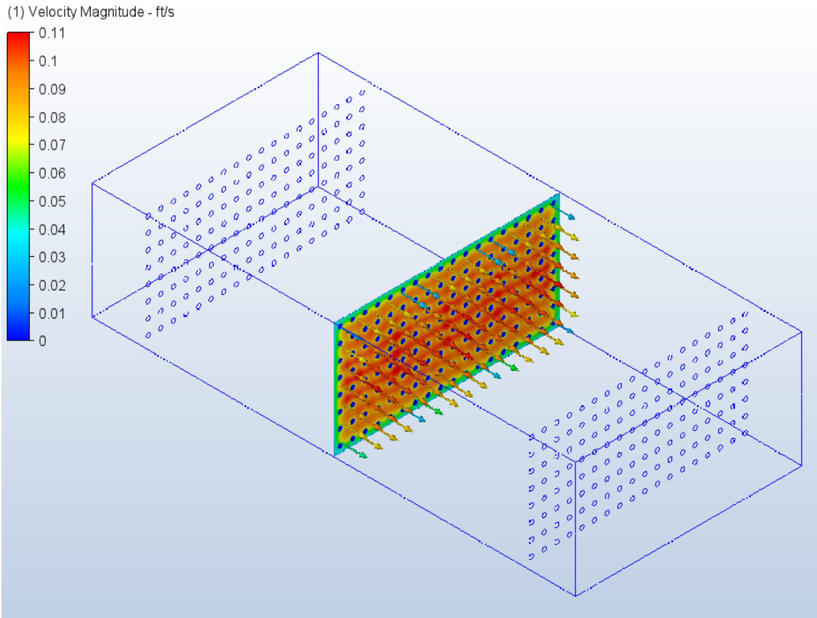


Figure A.3: Results plane showing flow velocity vectors midway through the UV bank.

Limitations

Due to the limited computational power of the computer used to run the CFD solver, the 3-D model of the UV system had to be greatly simplified. To save computational effort and time, the UV system was reduced to a single UV bank. Consequently, the CFD analysis did not account for turbulence induced by gates or weirs at either end of each channel. The software was also unable to solve for flows through a series of UV banks, meaning any turbluence between UV banks was neglected. It was therefore assumed that all the banks had the same flow regime.

Appendix B - Line Source Integration Model Code

Fluence Rate Function

```
function [I] = FluenceRateCalc(r, r1, r2, H1,UVT,L,P)

Phi=P; % total UV power ouput of the system - need real VALUE

N=200; % # of point sources/segments, Buchner justifies this number

n1=1; % index of refraction of air from Buchner
n2=1.506; % index of refraction of quartz or other panel material
n3=1.376174; % index of refraction of water

T1=1; %transmittance of air, 0.01m
T2=0.8208; %transmittance of quartz, 0.01m
T3=UVT/100 ; %transmittance of water, 0.01m

%L=L; % (m) length of lamp


k=1;

I=nan(length(r),1);
H=nan(length(r),1);
I_MSSSF=nan(length(r),1);
I_MPSS=nan(length(r),1);
Atten=nan(length(r),1);


for R=r

    %r1=0.013; % radial distance of air m
    %r2=0.002; % outer radius of quartz sleeve m
    r3=r-r1-r2; % radial distance of water m

    % All lengths are in m

    %%%%% Preallocation %%%%

    for H=H1%abs(-L/2:dH:L/2) % longitudinal distance from the center of the
        ↪ lamp to the point of interest

        MPSS=nan(N+1,1);
        MSSSF=nan(N+1,1);
        d1=nan(N+1,1);
        d2=nan(N+1,1);
```

```
    d3=nan(N+1,1);
    theta1=nan(N+1,1);
    theta2=nan(N+1,1);
    theta3=nan(N+1,1);
    Focus=nan(N+1,1);
    r_perp12=nan(N+1,1);
    r_parallel12=nan(N+1,1);
    R12=nan(N+1,1);

    r_perp23=nan(N+1,1);
    r_parallel23=nan(N+1,1);
    R23=nan(N+1,1);

    j=1;

    for ΔX=abs((-L/2+H):L/N:(L/2+H)) % (cm) length along the lamp to point of interest from source point

        l=ΔX;

        theta0=[0,89.99]; % initial guess interval, degrees needs to be a function of position! atand(ΔX/(r1+r2+r3))
        %lower bound of guess is direct line to point from radiation source , upper
        %is approaching 90 degrees

        fun= @(theta1)...
            r1.*tand(theta1)+n1.*sind(theta1).*(r2./(sqrt(n2.^2-n1.^2.*sind(theta1).^2))...
            +r3./(sqrt(n3.^2-n1.^2.*sind(theta1).^2)))...
            -ΔX;

        theta1(j)=fzero(fun,theta0); % deg
        theta2(j)=asind(n1*sind(theta1(j))/n2); % deg
        theta3(j)=asind(n1*sind(theta1(j))/n3); % deg
        %
        % ΔX=ΔX
        % checkDeltaX=tand(theta1(j))*r1+tand(theta2(j))*r2+tand(theta3(j))*r3
        % good to go, same result


        r_perp12(j)=(n1*cosd(theta1(j))-n2*cosd(theta2(j)))/(n1*cosd(theta1(j))+n2*cosd(theta2(j)));
        r_parallel12(j)=(n2*cosd(theta1(j))-n1*cosd(theta2(j)))/(n2*cosd(theta1(j))+n1*cosd(theta2(j)));
        R12(j)=0.5*(r_perp12(j)^2+r_parallel12(j)^2);

```

```
            r_perp23(j)=(n2*cosd(theta2(j))-n3*cosd(theta3(j)))/(n2*cosd(theta2(j))+n3*cosd(theta3(j)));
            r_parallel23(j)=(n3*cosd(theta2(j))-n2*cosd(theta3(j)))/(n3*cosd(theta2(j))+n2*cosd(theta3(j)));
            R23(j)=0.5*(r_perp23(j)^2+r_parallel23(j)^2);

            d1(j)=r1/cosd(theta1(j)); % optical path length of air (cm)
            d2(j)=r2/cosd(theta2(j)); % optical path length of quartz (cm)
            d3(j)=r3/cosd(theta3(j)); % optical path length of water (cm) % when Δx=0,
            % d values approach r values! validation

            Focus(j)=((d1(j)+d2(j)+d3(j))^2/((r1+r2+r3)*cosd(theta3(j))*n1))*((r1)/(n1*cosd(theta1(j))^3)+(r2)/(n2*cosd(theta2(j))^3)+(r3)/(n3*cosd(theta3(j))^3));


            % Ignore focus for now, should be 1.0 at ΔX=0... but isn't...

            MSSSF(j)=((Phi/N)/(4*pi*(d1(j)+d2(j)+d3(j))^2))*(1-R12(j))*(1-R23(j))*T2^(d2(j)/0.01)*T3^(d3(j)/0.01)*cosd(theta1(j));%*Focus(j);


            % the equation in Buchner shows dividing by 0.01, but I think he is  doing
            % it in meters, my d3 values are in cm, so it should be /1
            % from EQ 1.32 in Buchner !

            MPSS(j)=((Phi/N)/(4*pi*(l^2+R^2)));

            j=j+1;
        end

        I_MSSSF(k)=sum(MSSSF);
        I_MPSS(k)=sum(MPSS);

        Atten(k)=sum(MSSSF)/sum(MPSS);

        I(k)=(P/(4*pi*L*R))*(atan((L/2+H)/(R))+atan((L/2-H)/(R)))*Atten(k); % Fluence Rate, W/m^2
    end
    k=k+1;
end
I;

% yyaxis left
% plot(Focus)
```

```
% hold on
% yyaxis right
% plot(theta1)
% pause
end
```

Full Channel Model

```
%% Full Channel - TrojanUV3000Plus three-inch on-center spacing
clc,clear
% Notes: all inputs are SI, so m, W, s, etc.
%%%%% Inputs - SINGLE LAMP %%%%%
P_in=250; %W
n=0.5; % Efficiency
P_254nm=n*P_in;
phi=P_254nm;
L=1.4732;
H=0;

UVT=55; %percent

r1=0.028/2; % radial thickness of air
r2=0.003/2; % radial thickness of quartz
r_start=r1+r2;
r_end=0.1;
dr=0.001;

%%%%% Inputs - SINGLE CHANNEL %%%%%
NumChan=3;
NumBank=2;
NumRow=6;
NumMod=18;
NumLampPerBank=NumMod*NumRow;
Width=54; % in
Height=54; % in
Spacing=3; % in-on-center
Q=5.7/NumChan; %mgd
LampDiam=2*(r1+r2)*39.37; % in
AreaChannel=Width*NumRow*Spacing/144
AreaLamps=pi/4*LampDiam^2/144*NumLampPerBank % ft2
Area=AreaChannel-AreaLamps
Velo=Q*0.1337*10^6/24/60/60*12/Area % in/second
SecPerBank=L*39.37/Velo % s, velo from CFD
FoulingFactor=0.95;
LampAgingFac=.9;

```

```
ET=SecPerBank*NumBank; % Exposure Time Total

dx=0.01; % 0.01 inches between indices for ALL arrays
dy=0.01;
Sp=3/dx; % (inches)/(inches per index) gives number of indices between lamps

Channel=zeros(Height/dy+1,Width/dx+1);

% cannot still be tied to the meshgrid used to create the intensity dist
% is intead a meshgrid for the channel in the same increments as the dist
% is generated
xspace=0:0.01:Width;
yspace=0:0.01:Height;
[Xspace,Yspace]=meshgrid(xspace,yspace); % used for generating contours of full channel


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%% SINGLE LAMP CALCS %%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

theta=(0:1:360)';
j=1;
for r=r_start:dr:r_end
    x(j:j+length(theta)-1)=r.*cosd(theta);
    y(j:j+length(theta)-1)=r.*sind(theta);
    z(j:j+length(theta)-1)=ones(length(theta),1)*FluenceRateCalc(r,r1,r2,H,UVT,L,P_254nm);
    j=j+length(theta);
end

%%%% FRDOP=1 for producing the fluence rate drop-off plot %%%%
FRDOP=0
for b=1
if FRDOP==1

    j=1;
    r=r_start:dr:r_end;
    I=nan(length(r),1);
    for r=r_start:dr:r_end
        I(j)=FluenceRateCalc(r,r1,r2,H,42,L,P_254nm);
        j=j+1;
    end

    j=1;
    r=r_start:dr:r_end;
    I2=nan(length(r),1);
```

```
    for r=r_start:dr:r_end
        I2(j)=FluenceRateCalc(r,r1,r2,H,55,L,P_254nm);
        j=j+1;
    end

    j=1;
    r=r_start:dr:r_end;
    I3=nan(length(r),1);
    for r=r_start:dr:r_end
        I3(j)=FluenceRateCalc(r,r1,r2,H,100,L,P_254nm);
        j=j+1;
    end

    figure
    hold on
    r=r_start:dr:r_end;
    plot(r*39.37,I/10,'k')
    plot(r*39.37,I2/10,'k--')
    plot(r*39.37,I3/10,'k-.')
    leg=legend('42','55','100')
    title(leg,'UVT (%)')
    xlabel('Radial Distance from Center of Lamp (in)')
    ylabel('Fluence Rate (mW/cm^2)')

end
end

Mat=[x; y; z];

[¬,idx] = sort(Mat(1,:)); % sort just the first column
Mat = Mat(:,idx); % sort the whole matrix using the sort indices

Mat1=Mat; % at (x1,y1)
Mat1(:,1)=Mat(:,1); Mat1(:,2)=Mat(:,2);

X1=round(Mat1(1,:),2);
Y1=round(Mat1(2,:),2);

x = round(Mat1(1,:)/0.0254,2); %converting grid to inches
y = round(Mat1(2,:)/0.0254,2);
z = Mat1(3,:);

xlin = -3.00:0.01:3.00; % needs to be 0.01 for good resolution
ylin = -3.00:0.01:3.00; % reducing by factor of 10: squares computation time

% The stepsize of 0.01 is very important and is needs to be
% consistent with other aspects of the code
% like the overlapping calculations
```

```
[X,Y] = meshgrid(xlin,ylin);
f = scatteredInterpolant(x',y',z');
Z = f(X,Y); % X and Y are in inches
Z(Z<0)=0;

figure
contour(X,Y,Z,15)
c = colorbar;
colormap(jet)
c.Label.String = 'UV-Fluence (W/m^2)';
axis tight square; hold on
xlabel('inches')
ylabel('inches')
hold off

save('XYZ.mat','X','Y','Z')

Inten=Z(Z>0)*1000/100^2; % 1000 mJ/J and 1m2/10000cm2
Inten=round(Inten,2);
Inten=Inten(Inten<max(max(Inten)));
Inten=Inten(Inten>0);
DoseDist=ET*Inten; % 1000 mJ/J and 1m2/10000cm2

figure
histogram(DoseDist,100,'Normalization','Probability')
yt = get(gca, 'YTick'); % Get Y-Tick Values
set(gca, 'YTick',yt, 'YTickLabel',yt*100) % Since Data Vector Is (1x25),
    ↪ Multiply yt By 4 To Get Percent
ylabel('Percent')
xlabel('Dose (mJ/cm^2')

SingleLampAverageIntensity=mean(Inten) % mW/cm2
SingleLampAverageDose=mean(DoseDist) % mW/cm2



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%% FULL CHANNEL CALCS %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% corners %%%
Lz=length(Z);
W=Width/dx; % converting length to indices
H=Height/dy;

C=length(Z)-1.5*Sp;


```

```
% Channel(rows,columns) = Z(rows,columns)

Channel(1:Lz-C,1:Lz-C)=Z(C:end-1,C:end-1); % lower left

Channel(1:Lz-C,W-(Lz-C):W)=Z(C:end-1,1:end-C+1); % lower right

% bottom lamps

    for i=0:1:Width/Spacing-3
        Channel(1:Lz-C+1,(C)+i*Sp:(C+Lz-1)+i*Sp)=Channel(1:Lz-C+1,(C)+i*Sp:(C+Lz-1)+i*Sp)+Z(C:end,:);
    end

% left lamps

    for i=0:1:NumRow-2
        Channel((C)+i*Sp:(C+Lz-1)+i*Sp,1:Lz-C+1)=Channel((C)+i*Sp:(C+Lz-1)+i*Sp,1:Lz-C+1)+Z(:,C:end);
    end

% right lamps

    for i=0:1:NumRow-2
        Channel((C)+i*Sp:(C+Lz-1)+i*Sp,W-(Lz-C):W)=Channel((C)+i*Sp:(C+Lz-1)+i*Sp,W-(Lz-C):W)+Z(:,1:end-C+1);
    end

% interior lamps

    for i=0:1:NumRow-2
        for k=0:1:Width/Spacing-3

        Channel((C)+i*Sp:(C+Lz-1)+i*Sp,(C)+k*Sp:(C+Lz-1)+k*Sp)=Channel((C)+i*Sp:(C+Lz-1)+i*Sp,(C)+k*Sp:(C+Lz-1)+k*Sp)+Z(:,:);

        end
    end

RC=Channel(1:NumRow*3/dy,:)*1000/100^2; % Relevant channel indices to account for water depth mW/cm2
Inten=RC(RC<max(max(Z*1000/100^2))); % mW/cm2
Inten2=Inten(Inten>0);
DoseDist=FoulingFactor*LampAgingFac*ET*Inten2; % 1000 mJ/J and 1m2/10000cm2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

FullChannelAverageIntensity=mean(Inten2);
FullChannelAverageDose=mean(DoseDist);
```

```
figure

ylabel('Intensity (mW/cm^2)')
%yticks(0:50:500)
xlabel('Inches')
hold on
plot(([1:601+450]/100),RC([1:601+450],151),'k-')
plot(([1:601]+150)/100,Z(:,300)/10,'k--','LineWidth',2)
plot(([1:601]+450)/100,Z(:,300)/10,'k--','LineWidth',2)
legend('Combined In-Channel','Single Lamp')
% ylim([0,max(Z)+50])
% ytick([0:50:max(Z)+50])
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
histogram(DoseDist,100,'Normalization','Probability')
yt = get(gca, 'YTick'); % Get Y-Tick Values
set(gca, 'YTick',yt, 'YTickLabel',yt*100);
ylabel('Percent')
xlabel('Dose (mJ/cm^2)')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

hold on
figure
cdfDD=ecdf(DoseDist);
% DoseDist=sort(DoseDist);
% find(DoseDist≥100,1);
cdfplot(DoseDist)
title('')
set(gca,'XScale','log');
%set(gca,'YLabel','Cumulative Probability of Achieving Specified Dose');

a=[cellstr(num2str(get(gca,'ytick')'*100))];
pct = char(ones(size(a,1),1)*'%');
new_yticks = [char(a),pct];
set(gca,'yticklabel',new_yticks)

y100=0.0558
y80=0.05
line([100 100],[0,y100],'Color',[1 0 0]);
%line([80 80],[0 ,y80],'Color',[1 0 0]);

%text(115,0.05, '80')
%line([80 115],[.05,.05],'Color',[0 0 0]);
```

```
text(115,y100/2, '100')
line([100 115],[y100/2,y100/2],'Color',[0 0 0]);

text(5,y100+0.03,sprintf('%.1f%%',100*y100) )
%text(5,y80+.03, sprintf('%.1f%%',100*y80))

line([1 100],[y100,y100],'Color',[1 0 0]);
%line([1 80],[y80,y80],'Color',[1 0 0]);

text(5,.8,sprintf('UVT: %.1f%%',UVT ) )
text(5,.75,sprintf('Q: %.2f mgd Per Channel',Q ) )

h.Color = [0 0 0];
xlabel('Dose (mJ/cm^2)')
ylabel('Probability')


%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


figure
ChannelX=0:0.01:Width;
ChannelY=0:0.01:Height;
[X,Y]=meshgrid(ChannelX,ChannelY);
contour(ChannelX,ChannelY,Channel,50)

c = colorbar;
colormap(parula)
c.Label.String = 'Ultraviolet Fluence Rate (W/m^2)';
c.FontSize=18;
set(gca,'FontSize',18)
grid on
axis tight square
xlabel('inches','FontSize',21)
ylabel('inches','FontSize',21)
xticks(0:3:54)
yticks(0:3:54)
ax.DataAspectRatio = [1 1 1];


Wm=mean(log(DoseDist(DoseDist>0)));
Wv=var(log(DoseDist(DoseDist>0)));
DD_lognormal_mean=exp((Wm+Wv^2/2))

INm=mean(log(Inten(Inten>0)));
INv=var(log(Inten(Inten>0)));
```

```
IN_lognormal_mean=exp((INm+INv^2/2))
```

Longitudinal Variation

```
%% Fluence Rate Along Length of Lamp

P_in=250; %W
n=0.5; % Efficiency
P_254nm=n*P_in;
phi=P_254nm;
L=1.5;
H=L/4;

UVT=55; %percent

r1=0.028/2; % radial thickness of air
r2=0.003/2; % radial thickness of quartz
r_start=r1+r2;
r_end=0.1;
dr=0.001;
dh=0.01
r=r1+r2+0.01

I=nan(length(-L/2:dh:L/2),1)

i=1
for H=abs(-L/2:dh:L/2)
I(i)=FluenceRateCalc(r, r1, r2, H,UVT,L,P_254nm);
i=i+1;
end

plot(0:dh:L,I,'k-')
ylabel('Fluence Rate (W/m^2)')
xticks([0 L/4 L/2 3*L/4 L ])
xticklabels({'$0$','$\frac{L}{4}$','$\frac{L}{2}$','$\frac{3L}{4}$','$L$'})
set(gca,'TickLabelInterpreter','latex')
```

Appendix C - Economic Analysis of Final Alternatives

	Calgon C3500 4"	TrojanUV3000Plus 3"
Lamp spacing	4"	3"
Number of channels	3	3
Number of banks/channel	4	3
Number of modules/bank	13	18
Number of lamps/module	6	6
Total number of lamps	936	972
Lamp manufacturer	Calgon	Trojan
Cost per lamp	$250	$160
Capital cost	**$3,600,000**	**$2,392,615**
Power/lamp (W)	575	88
Electrical consumption (kW)	269.1	38.0
Annual power consumption (kWh)	523324	73930
Power cost per kWh	$0.10	$0.10
Annual electrical power cost	**$52,332**	**$7,393**
Price per replacement lamp	$250	$160
Lamp life (hours)	16000	12000
Lamp required per year (12.15%)	114	119
Annual lamp replacement cost	**$28,500**	**$19,040**
Price per replacement ballast	$400	$400
Ballast life (years)	10	10
Total number of ballasts	936	972
Ballasts per year	93.6	97.2
Annual ballast replacement cost	**$37,440**	**$38,880**
Price per replacement quartz sleeve	$90	$90
Number of quartz sleeves total	936	972
Number broken per year (2%)	18.72	19.44
Annual replacement quartz sleeve cost	**$1,685**	**$1,750**
Annual labor cost (0.2% of capital)	**$7,200**	**$4,785**
Summary of O&M costs for UV system		
Annual electrical power cost	$52,332	$7,393
Annual lamp replacement cost	$28,500	$19,040
Annual ballast replacement cost	$37,440	$38,880
Annual replacement quartz sleeve cost	$1,685	$1,750
Annual labor cost	$7,200	$4,785
Total annual O&M for UV system	**$127,157**	**$71,848**

Net present value of O&M		
Interest Rate	7.0%	7.0%
Amortization period (years)	20	20
Net present value of O&M	**$1,347,105**	**$761,157**
Total net present value	**$4,947,105**	**$3,153,773**

Appendix D - Quotes from Manufacturers

C^{3}500™ ULTRAVIOLET LAMP

Description

The C^{3}500™ Ultraviolet (UV) low-pressure, high-output lamp meets or exceeds the specifications listed below.

Lamp Specifications

Lamp Type:	Amalgam, 254 nm, pre-heat type
Lamp Diameter:	32 mm (T10)
Arc Length:	1448 mm (57.0 inches)
Lamp Power:	515 W, nominal
Lamp Operating Current:	5.1 A at full power
UV Output at 254 nm:	205 W, average
Lamp Envelope Material:	Quartz Glass with Internal Coating
Lamp Base:	4-Pin Ceramic Connector
Base Face to Base Face Length:	1570 mm (61.8 inches)
Rated Average Life:	12,000 hours, minimum
UV Output at Rated Average Life:	average of 90 % of 100 hour lamp

Operating Conditions

Environment:	Operating under water in a quartz sleeve
Quartz Sleeve Diameter:	O.D. 40 mm, I.D. 37 mm
Variable Output	The output of the lamp is varied to match the effluent conditions so the lamp must be capable of being varied to 58% of the full power current
Water Temperature:	1 – 30 ^{o}C
ON/OFF Cycles per Day:	4 – 6 cycles per day

EXECUTIVE SUMMARY

Proposal # QW-1811-11
Revision: 2

UC Davis WWTP, CA - C3500D UV Disinfection System

Calgon Carbon proposes to supply our C3500D Ultraviolet Disinfection System to treat effluent at the above site. This system will include 288 UV lamps to treat the peak flow of 4.8 MGD. The system will be configured into 3 channels, 3 banks per channel, 8 racks per bank each with 4 lamps. One channel is provided for redundancy.

The main advantages of the C3500D system are as follows:

- The C3500D uses the highest power low pressure horizontal lamps available. The UV lamp emits 204 W of UV light at 254 nm. This means our system will have fewer lamps, resulting in less maintenance.
- The $C^3$500D system includes automatic, in-place cleaning as a key feature. This reduces the need for operators to remove lamp racks and manually clean them, significantly reducing maintenance. The Calgon Carbon automatic cleaner is mechanical only – no chemicals are required.
- The patented mixing devices dramatically improve the hydraulic and germicidal efficiency of the UV reactor providing unparalleled performance.

Calgon Carbon is a world leader in granular activated carbon solutions. We are also one of the world's foremost providers of ultraviolet light (UV) disinfection and oxidation technologies for water. From the initial introduction of our UV advanced oxidation systems to the continued development of drinking water and wastewater disinfection technologies, we've been delivering proven UV water treatment solutions for more than 25 years. Combined we have over 500 installations in operation or under construction.

This proposal includes system sizing and a bill of materials. If you need any further information, please feel free to contact David DesRochers at 519.824.8318.

PROJECT SPECIFICATIONS

Proposal # QW-1811-11
Revision: 2

UC Davis WWTP, CA - C3500D UV Disinfection System

1. Design Conditions

Peak Flow	4.8	MGD
Average Flow	1.32	MGD
Minimum UV Transmittance	55 %	
Total Suspended Solids	5 mg/L	
Total Coliform at Inlet	50000 CFU/100mL	
Total Coliform Permit Limit	2.2 CFU/100mL, based on 7-day median	
Target UV Dose	100 mJ/cm2 Title 22	

2. $C^3$500D Specifications

Lamp UV Radiation at 254 nm	204
Lamp Life	16,000 Hours
Lamp Life Factor	0.90
Quartz Transmission Factor	0.92
Quartz Fouling Factor	0.95
MS2 T22 RED	102.3 mJ/cm2 validated

3. System Configuration

Number of Channels	3	One channel is provide for redundancy
Number of Banks/Channel	3	
Number of Racks/Bank	8	
Number of Lamps/Rack	4	
Total Number of Lamps	288	
Number of UV Sensors	9	
Number of Power Distribution Centers	9	
Number of System Control Centers	3	
Number of Weirs	3	

4. Hydraulic Considerations

Peak Velocity in Channel	5.57 inches/s
Headloss per UV Bank	0.17 inches
Headloss across Level Control Device	6 inches
Total Headloss across UV System	6.5 inches
Retention Time	28.43 seconds

5. Electrical Requirements

Input Voltage	480/277 VAC, 3Ph, 4-wire	
Peak Loading per PDC	70.3 FLA	
Power Consumption per PDC	55.9 kW	(all lamps at 100% power)
Total System Power Consumption	503 kW	(all lamps at 100% power)

6. Approximate Channel Dimensions

Length	473 inches
Width	54 inches
Width with Reduction Baffle	48 inches
Width at Level Control Weir	54 inches
Channel Height	54 inches
Channel Height at Level Control Weir	50 inches
Effluent Depth in Channel	24 inches, nominal

BILL OF MATERIALS

Proposal # QW-1811-11
Revision: 2

UC Davis WWTP, CA - C3500D UV Disinfection System

Item No.	Qty.	Model Number C3500D3308041WP	
1.	3	Channel Equipment	
		Qty. 1	Level Control Weir
		Qty. 12	Bank Support Brackets
		Qty. 6	Lamp Rack Support Brackets
		Qty. 1	Point Ultrasonic Level Sensor with Mounting Bracket
		Qty. 3	UV Sensors with Mounting Bracket and Scrapers
		Qty. 3	Channel Reduction Baffles, Precast Concrete
2.	72	Lamp Rack Assemblies	
		Qty. 4	Low Pressure High Intensity Amalgam Lamps
		Qty. 4	Quartz Sleeves
		Qty. 1	Cable Assemblies
		Qty. 1	Cleaning System Motor
		Qty. Lot	Cleaning System Mechanism and Accessories
		Qty. 4	Scrapers
3.	9	Power Distribution Centers	
		Qty. 32	Electronic Ballasts
		Qty. 1	Main Breaker
		Qty. 8	Earth Leakage Circuit Breakers
		Qty. Lot	Control & Monitoring Equipment with Operator Station
4.	3	System Control Center	
		Qty. 1	Main Breaker
		Qty. Lot	Allen Bradley CompactLogix L30ER PLC Equipment and Accessories
		Qty. 1	Allen Bradley PanelView 1000 Plus Operator Interface
5.	Lot	Spare Parts	
		Qty. 1	UV Face Shield
6.	Lot	Accessories	
		Qty. 1	Service Trolley
		Qty. 1	Rack Lifting Sling
		Qty. 1	Mercury Spill Kit
		Qty. 1	Reference UV Sensor
7.	Lot	Equipment Documentation	
8.	Lot	Start-up and Commissioning Services	
9.		One (1) Year Warranty Period	

Terms and Conditions

Payment Terms: CCUV Standard Terms
Freight: Jobsite
Delivery: 20 to 24 weeks after receipt of approved shop drawings

CCUV Standard Terms & Conditions Will Apply

Budgetary Price (USD): $1,101,000

Project Name: **UC Davis WWTP, CA**
Project Number: **QW-1811-11**

General Parameters		*Peak Conditions*	*Average Conditions*
Operating Flow Rate	MGD	4.80	1.32
MS2 T22 RED	mJ/cm2	100	100
UV Transmittance	%T	55	61
Combined ELL/FF		0.855	0.928
Annual operating hours	hours	8760	8760

System Configuration	*Design*	*Average*
Number of channels	2	1
Number of standby channels	1	0
Total number of channels	3	1
Number of banks/channel	3	2
Number of racks/bank	8	8
Number of lamps/rack	4	4
Total number of lamps	288	64

Electrical Power Cost Calculations			
Power per lamp (including ballast)	W/lamp		575
Electrical consumption with all lamps at full power	kW		335.3
Electrical consumption @ operating flow	kW		76.36
Annual power consumption	kWh		668,884
Power cost per kWh	per kWh		$0.10
Annual Electrical Power Cost		$	66,888

Replacement Lamp Cost Calculations		
Price per replacement lamp		$250
Lamp life (hours)		16,000
Number of lamps operating at average flow		64
Lamps required per year		35.0
Annual Replacement Lamp Cost	$	8,760

Replacement Ballast Cost Calculations		
Price per replacement ballast		$400
Ballast life (years)		10
Number of ballasts total		288
Ballasts required per year		28.8
Annual Replacement Ballast Cost	$	11,520

Replacement Quartz Sleeve Cost Calculations		
Price per replacement quartz sleeve		$90
Number of quartz sleeves total		288
Number broken per year (2%)		1.3
Annual Replacement Quartz Sleeve Cost	$	115

Replacement Scraper Cost Calculations		
Price per replacement scraper		$70
Scraper life (years)		5
Number of scrapers total		288
Scrapers required per year		57.6
Annual Replacement Scraper Cost	$	4,032

Labor Requirement		
Estimated manhours for replacing one lamp		0.5
Annual manhours for lamp replacement		17.5
Estimated manhours for replacing one ballast		0.25
Annual manhours for ballast replacement		7.2
Estimated manhours for replacing one quartz sleeve		0.5
Annual manhours for quartz sleeve replacement		0.6
Estimated manhours for replacing one wiper		0.5
Annual manhours for wiper replacement		28.8
Total annual manhours		54.2
Labor cost per hour		$40
Annual Labor Cost	$	2,166

Summary of O&M Costs for UV System		
Annual Electrical Power Cost	$	66,888
Annual Replacement Lamp Cost	$	8,760
Annual Replacement Ballast Cost	$	11,520
Annual Replacement Quartz Sleeve Cost	$	115
Annual Replacement Scraper Cost	$	4,032
Annual Labor Cost	$	2,166
Total Annual O&M for UV System	**$**	**93,482**
Net Present Value of O&M		
Interest Rate		7.00%
Amortization Period (years)		20
Net Present Value of O&M	**$**	**990,349**

Terms and Conditions for
UV Equipment / System Purchase (the "Terms and Conditions")

1) DEFINITIONS:

(a) Seller:	Calgon Carbon UV Technologies LLC, a Delaware limited liability company
(b) Buyer:	The buyer named in the Documentation
(c) Documentation:	The Proposal, Confirmation or Acknowledgement, as applicable, for the sale of the System/Products to which these Terms and Conditions are attached
(d) System/Products:	The system and/or equipment described in the Documentation
(e) Agreement:	The Documentation, these Terms and Conditions and any attachments referenced in the Documentation

2) GENERAL: Seller hereby offers for sale to Buyer the Products on the express condition that Buyer agrees to accept and be bound by the terms and conditions set forth herein. To the extent of a conflict between these Terms and Conditions and the express terms set forth in the Documentation, the terms set forth in the Documentation shall control. Any provisions contained in any document issued by Buyer are expressly rejected and if the terms and conditions set forth herein differ from the terms in any document issued by Buyer, this document shall be construed as a counter offer and shall not be effective as an acceptance of Buyer's document. In ordering and delivery of the Products, the parties may employ their standard forms; provided, however, that nothing in those forms shall be construed to modify or amend the terms of this Agreement. In the event of a conflict between this Agreement and either party's standard forms, this Agreement shall govern.

3) PRICE AND PAYMENT: The price shall be as stated in the Documentation, subject to these Terms and Conditions and other terms and conditions as may be stated in the Documentation. Unless otherwise stated in the Documentation:
(a) The price is exclusive of any taxes, tariff, and duties of any kind which either party may be required to pay with respect to the sale of goods described in the Documentation, and Buyer shall be responsible for the payment of all taxes, tariffs and duties related hereto, except for income taxes imposed on Seller;

(b) Sales Tax will be added to the price based upon the Product destination unless tax exemption or direct pay documentation is provided;

(c) Billing terms are (i) twenty percent (20%) when Seller submits design drawings to Buyer for review and approval, (ii) seventy percent (70%) when the System is ready for shipment, and (iii) ten percent (10%) when the System is delivered and installed (if applicable);

(d) Payment terms shall be net thirty (30) days, or net forty-five (45) days if paid by Electronic Funds Transfer (EFT). A late payment fee of 1.25% per month, or the highest lawful rate, whichever is less, will apply to all amounts past due, and will be prorated per day. Retainage may only be applied on the final invoice.

4) PRICING CONDITIONS:
(a) Pricing Limitations: Unless otherwise indicated within the Documentation, all pricing quoted in connection with the Documentation is valid for purchase for a sixty (60) day period beginning with the date of the Documentation.

(b) Pricing Escalations: Buyer acknowledges that the price for raw materials may increase unexpectedly. Therefore, unless otherwise specified in the Documentation, in the event that fabrication of the System is delayed for a period beyond three (3) months from the date of the Documentation, Buyer agrees to pay all surcharges and price increases as they are incurred by Seller. Pricing escalations for raw materials will be based upon the percent change in the Producer Price Index for such raw materials from the date of the Documentation to the date fabrication has begun. In addition all prices are subject to adjustment on account of changes in specifications, quantities, shipment arrangements and other terms or conditions which are not part of Seller's original price quotation set forth in the Documentation.

5) SALE AND DELIVERY: Sale terms and pricing, unless otherwise specified in the Documentation, are Ex Works Seller's point of shipment (INCOTERMS 2010). Seller will have the right, at its election, to make partial shipments of the Products and to invoice each shipment separately. Seller reserves the right to stop delivery of any Product in transit and to withhold shipments in whole or in part if Buyer fails to make any payment to Seller when due or otherwise fails to perform its obligations hereunder or under any other outstanding payment obligations of Buyer to Seller, whether related to the Documentation or otherwise.

6) TITLE AND RISK OF LOSS. Notwithstanding the trade terms indicated above and subject to Seller's right to stop delivery of any Product in transit pursuant to Section 5 above, title to and risk of loss of the Products will pass to Buyer upon delivery of the Products by Seller to the carrier at Seller's point of shipment; provided, however, that title to any software incorporated within or forming a part of the System shall at all times remain with Seller or the licensor(s) thereof, as the case may be. Notwithstanding the foregoing or the provisions of the UCC or INCOTERMS, title to the goods, and all accessions to or products of the goods, shall remain with Seller until the later of (a) payment in full of the purchase price and of other amounts owing by Buyer and (b) delivery to Buyer, if Buyer is located outside the United States.

7) AVAILABILITY: Shipment dates (and delivery and installation dates if included in the System/scope of work description in the Documentation) are not guaranteed, and Seller will not be liable for any loss or damage resulting from any delay in delivery or failure to deliver which is due to any cause beyond Seller's reasonable control. In the event of a delay due to any cause beyond Seller's reasonable control, Seller reserves the right to reschedule the shipment within a reasonable period of time, and Buyer will not be entitled to refuse delivery or otherwise be relieved of any obligations as the result of such delay. If any delivery is delayed for more than thirty (30) days beyond the originally scheduled delivery date and such delay is caused by Buyer, Buyer will be subject to storage charges from the scheduled shipment date of two percent (2%) of the sale price per month; and such storage charge shall be due monthly on the first day of each month. Storage by Seller shall be at Buyer's risk and expense.

8) ON-SITE SERVICES: All orders which include on-site services (including installation supervision, startup, training, testing, etc.) as stated in the Documentation (On-Site Services), will require the completion of the Pre-Visit Checklist and Service Request Form prior to scheduling the visit. If there are delays, cancellations, or failures by Buyer to meet service personnel at designated times, then fees will be assessed to the customer accordingly on a per hour rate of $160 per hour of delay per person. For domestic travel, additional on-site services not specified in the Documentation shall be provided at a per diem rate of $1,280 per person inclusive of all travel and living expenses per eight (8) hour day (or partial day not pro-rated), or as specified in the Documentation. For international travel, an additional fee will apply. Buyer shall make the premises, where On-Site Services are to be performed (the "Premises"), available to Seller at all reasonable times as Seller may request, such that Seller shall be able to perform the On-Site Services in a timely manner. Buyer shall bear all risk and liability associated with its inability to make the Premises available to Seller to perform the On-Site Services. Prior to the commencement of On-Site Services, Buyer shall insure that the Premises are in good repair and in safe condition for the performance of Seller's On-Site Services, and shall, prior to the commencement of work, notify Seller of any dangerous, unsafe or hazardous conditions associated with the Premises, such that Seller can take the appropriate safeguards. Prior to the commencement of any work, Buyer shall notify Seller of any special workplace requirements, safety standards, operating procedures or other conditions imposed on persons performing work at the Premises.

9) PERMITS, LICENSES AND FEES: Buyer shall be responsible, at its sole expense, for all environmental permits, applications, regulatory approvals, and other permits or licenses that may be required for installation and/or operation of the System.

10) CHANGES: Any changes requested by Buyer after signing the Documentation will be separately designed and priced by Seller. No change will be made without receipt of a written change order accepted in writing by Seller.

11) ACCELERATION: Buyer agrees that Seller, at its discretion, may accelerate and make due and payable all remaining payments if Buyer shall fail to perform any of its obligations hereunder or under the Documentation, including without limitation Buyer's failure to pay any amount when due, subject to any applicable cure periods provided for herein.

12) CANCELLATION; TERMINATION:

(a) In the event that Buyer cancels its order under the Documentation prior to approving the design drawings submitted by Seller, Buyer shall pay to Seller as liquidated damages ten percent (10%) of the total purchase price of the Products, in addition to any progress payments invoiced. Following the acceptance of the design drawings by Buyer, Buyer shall not be permitted to cancel its order without Seller's written consent, and then only upon payment of Seller's cancellation charges which shall be equal to Seller's direct costs of goods sold, plus direct labor costs and fixed charges relating to the design and manufacturing of the Products, plus ten percent (10%) of the total purchase price as liquidated damages.

(b) Seller may cancel this Agreement if any of the following occurs: (i) Buyer becomes insolvent; (ii) Buyer ceases to conduct its operations in the normal course of business; (iii) Buyer is unable to meet its obligations as they mature, or admit in writing such inability or fails to provide adequate assurances of its ability to perform its obligations hereunder; (iv) Buyer files a voluntary petition in bankruptcy; (v) Buyer suffers the filing of an involuntary petition in bankruptcy and the same is not dismissed within thirty (30) days after filing; (vi) a receiver, custodian or trustee is appointed for Buyer or for a substantial part of its property; (vii) Buyer fails to make payment on the terms and within the time specified in this Agreement, or breaches any other obligations under this Agreement; or (viii) Buyer executes an assignment for the benefit of its creditors. In the event of such cancellation, Seller shall have all rights and remedies set forth in the UCC of any applicable jurisdiction and all other remedies available at law or in equity. The following provisions shall survive termination or expiration of this Agreement: Sections 2 (General), 12 (Cancellation; Termination), 13 (Limited Warranties), 15 (Limitation of Liability), 17 (Export Controls), 18 (Confidentiality), 19 (Security Interest), 22 (Applicable Law and Jurisdiction), 23 (Miscellaneous) and 24 (Entire Agreement).

13) LIMITED WARRANTIES: Unless otherwise specifically provided for in the Documentation, Seller warrants that the (i) System shall be free from defects in material and workmanship, and shall be manufactured in accordance with the specifications agreed to in writing by the parties in the Documentation or any subsequent written change order, for a period of twelve (12) months from startup or eighteen (18) months from the date of shipment, whichever is earlier, and (ii) any On-Site Services provided for hereunder shall be performed in a workman-like manner, and in accordance with industry standards. Corrosion or other chemical action is specifically excluded as a defect covered hereunder. Seller agrees during the respective warranty periods specified above, (i) to repair or replace, at Seller's option, defective Products so as to cause the same to comply materially with the agreed to specifications, and (ii) to provide corrective On-Site Services so as to cause such On-Site Services to be performed in accordance with the terms hereof; provided that Buyer shall (a) promptly notify Seller in writing upon the discovery of any defect, which notice shall include the product model and serial number (if applicable) and details of the warranty claim; and (b) after Seller's review, Seller will provide Buyer with service data and/or a Return Material Authorization ("RMA"), which may include biohazard decontamination procedures and other product-specific handling instructions. Then, if applicable, Buyer may return the defective Products to Seller with all costs prepaid by Buyer. Replacement parts may be new or refurbished, at the election of Seller. All replaced parts shall become the property of Seller. Shipment to Buyer of repaired or replacement Products shall be made in accordance with the delivery provisions of these Terms and Conditions, freight charged to Seller.

In no event shall Seller have any obligation to make repairs, replacements or corrections required, in whole or in part, as the result of (i) normal wear and tear, (ii) accident, disaster or event of force majeure, (iii) misuse, fault or negligence of or by Buyer, (iv) use of the Products in a manner for which they were not designed, (v) external causes such as, but not limited to, power failure or electrical power surges, (vi) improper storage and handling of the Products or (vii) use of the Products in combination with equipment or software not supplied by Seller. If Seller determines that Products for which Buyer has requested warranty services are not covered by the warranty hereunder, Buyer shall pay or reimburse Seller for all costs of investigating and responding to such request at Seller's then prevailing time and materials rates. If Seller provides repair services or replacement parts that are not covered by this warranty, Buyer shall pay Seller therefor at Seller's then prevailing time and materials rates. ANY INSTALLATION, MAINTENANCE, REPAIR, SERVICE, RELOCATION OR ALTERATION TO OR OF, OR OTHER TAMPERING WITH, THE PRODUCTS PERFORMED BY ANY PERSON OR ENTITY OTHER THAN SELLER WITHOUT SELLER'S PRIOR WRITTEN APPROVAL, OR ANY USE OF REPLACEMENT PARTS NOT SUPPLIED BY SELLER, SHALL IMMEDIATELY VOID AND CANCEL ALL WARRANTIES WITH RESPECT TO THE AFFECTED PRODUCTS.

Notwithstanding the foregoing, Products supplied by Seller that are obtained by Seller from an original manufacturer or third party supplier are not warranted by Seller, but Seller agrees to assign to Buyer any warranty rights in such Product that Seller may have from the original manufacturer or third party supplier, to the extent such assignment is allowed by such original manufacturer or third party supplier.

THE OBLIGATIONS CREATED BY THIS WARRANTY STATEMENT TO REPAIR OR REPLACE A DEFECTIVE PRODUCT OR TO PROVIDE CORRECTIVE ON-SITE SERVICES SHALL BE THE SOLE REMEDY OF BUYER IN THE EVENT OF A DEFECTIVE PRODUCT OR ON-SITE SERVICES. THERE ARE NO WARRANTIES MADE WITH REGARD TO THE GOODS OR SERVICES TO BE PROVIDED PURSUANT TO THIS AGREEMENT OTHER THAN THOSE CONTAINED HEREIN. ALL OTHER WARRANTIES, EITHER EXPRESS OR IMPLIED, ARE HEREBY DISCLAIMED, INCLUDING, WITHOUT LIMITATION, THE WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE AND ALL WARRANTIES ARISING FROM COURSE OF DEALING OR USAGE OF TRADE. SELLER DOES NOT WARRANT THAT THE PRODUCTS ARE ERROR-FREE OR WILL ACCOMPLISH ANY PARTICULAR RESULT. ANY ADVICE OR ASSISTANCE FURNISHED BY SELLER IN RELATION TO THE PRODUCTS PROVIDED FOR HEREUNDER AND UNDER THE DOCUMENTATION SHALL NOT GIVE RISE TO ANY WARRANTY OR GUARANTEE OF ANY KIND, AND SHALL NOT CONSTITUTE A WAIVER BY SELLER OF ANY PROVISIONS OF THIS AGREEMENT, UNLESS OTHERWISE AGREED TO IN WRITING.

This warranty does not cover any charges for replacement of parts, adjustments or repairs, or any other work unless such charges shall be assumed or authorized in advance in writing by the Seller.

14) SHORTAGE, LOSS, DAMAGES and NON-CONFORMITY: It is Buyer's responsibility to notify the freight carrier of any shortages, losses, or damage. This notification must be noted on the Bill of Lading at time of delivery. Claims will be disallowed if not reported within fifteen (15) calendar days of receipt of the respective Products and the responsibility for repairs/replacement will be on Buyer. Without expanding the limited warranties set forth in Section 13, Buyer shall have (i) thirty (30) days after delivery to its destination of use to inspect and test the System for any apparent non-conformity, and (ii) fifteen (15) days after the performance of any On-Site Services to inspect and test such On-Site Services for any apparent non-conformity. Failure to so inspect and test, or to give notice to Seller of any claim during the respective periods above, shall constitute an irrevocable acceptance of the Products and/or On-Site Services, and a waiver of any defect or warranty claim that could have been discovered by inspecting and testing. Buyer shall have the right to reject, refuse acceptance and revoke acceptance of any non-conforming Products or On-Site Services during the respective periods.

15) LIMITATION OF LIABILITY: Notwithstanding any provision to the contrary herein, the parties hereto agree that in no event shall either party be liable to the other party for any indirect, special, consequential, incidental or punitive damages, or lost profits, as a result of a breach of any provision of this Agreement or for any other claim of any kind arising out of or relating to this Agreement, whether in contract, in tort or otherwise. Notwithstanding any provision to the contrary herein, for all losses, damages, liabilities or expenses (including attorney's fees and costs), whether for indemnity or negligence, including errors, omissions or other acts, or willful misconduct, or based in contract, warranty (including any costs and fees for repairing, replacing or re-performing services or curing a breach hereof), or for any other cause of action (individually, a "Claim"; collectively, "Claims"), Seller's liability,

including the liability of its insurers, employees, agents, directors, and officers and all other persons for whom Seller is legally responsible, shall not, to the maximum extent permitted by law, exceed in the cumulative aggregate with respect to all Claims arising out of or related to this Agreement, the lesser of (a) the total amount of compensation paid to Seller hereunder, and (b) One Million Dollars ($1,000,000). All Claims of whatsoever nature shall be deemed waived unless made in writing within ninety (90) days of the occurrence giving rise to the Claim. Moreover, any failure of Buyer to notify Seller of unsatisfactory operation or any improper or unauthorized installation, maintenance, use, repair, adjustment or attempts to operate the System outside of the design limits shall relieve Seller of any further responsibilities hereunder.

16) **FORCE MAJEURE:** Notwithstanding any provision to the contrary herein, Seller shall have no liability to Buyer or its affiliates, and shall have the right to suspend performance (including, without limitation, shipments) hereunder, in the event of war, riot, terrorism, accident, explosion, sabotage, flood, acts of God, fire, court order, strike, labor disturbance, work stoppage, national defense requirements, act of governmental authority, extraordinary failure of equipment or apparatus, inability to obtain electricity or other type of energy, raw material, labor, equipment or transportation, or other causes beyond Seller's reasonable control. It is understood and agreed that settlement of strikes, lockouts and other labor disputes shall be entirely within the discretion of Seller and that nothing in this Agreement shall require the settlement of strikes, lockouts and labor disputes when such course is inadvisable in the sole discretion of Seller.

17) **EXPORT CONTROLS:** Buyer acknowledges that the Products and related technology are subject to U.S. export controls and economic sanctions, which may include the International Traffic in Arms Regulations (ITAR), the Export Administration Regulations (EAR) and regulations promulgated by the U.S. Department of the Treasury Office of Foreign Assets Control (OFAC). Buyer further acknowledges that the reexport of the Products and/or related technology to a third country or retransfer to an unapproved end user may require a license or other authorization from the Government of the United States. Such licenses or other authorizations may impose further restrictions on the reexport or retransfer of the Products and/or related technology. U.S. law also restricts the reexport or retransfer of U.S.-origin goods, technology, or services to countries or persons subject to U.S. sanctions or embargoes. Buyer represents and warrants that it is in compliance with and agrees to comply with all such applicable export control and economic sanctions laws and regulations. It is the sole responsibility of Buyer to apply for and obtain any necessary licenses or other authorizations prior to any reexport or retransfer of the Products and/or related technology. Seller makes no warranty that any such licenses or other authorizations will be granted, and shall have no liability for Buyer's inability to obtain such licenses or other authorization or for any violation by Buyer of any applicable export control and/or economic sanctions laws and regulations. Buyer will indemnify Seller and hold it harmless from any liability resulting from Buyer's violation of this provision or applicable export laws or regulations. Notwithstanding any other provision in this Agreement, Seller shall have the right to terminate this Agreement immediately upon the determination by Seller, in Seller's sole discretion, that Buyer has breached, intends to breach, or insists upon breaching any of the provisions in the above clauses.

18) **CONFIDENTIALITY:** Other than in the performance of the terms of this Agreement, neither Buyer nor its agents, employees, or subcontractors shall use or disclose to any person or entity any confidential information of Seller (whether written, oral, electronic or other form) that is obtained or otherwise prepared or discovered in connection with this Agreement. Buyer agrees that all pricing, discounts, design drawings and technical information that Seller provides to Buyer are the confidential and proprietary information of Seller, whether or not otherwise identified as such. The obligations under this section continue perpetually and survive the termination or expiration of any underlying agreement between the parties. The provisions of this section relating to use and disclosure shall not apply to any information that: (a) is or becomes generally available to the public other than as a result of a disclosure by Buyer under this Agreement; (b) becomes available to Buyer from a source other than Seller without breach of any obligation of confidentiality; (c) was independently developed by Buyer without violation of Seller's rights and without reference to the confidential information, as evidenced by written records, maintained in the ordinary course of business by Buyer; (d) is used or disclosed with the prior written approval of Seller; (e) is information previously known to Buyer as evidenced by written records maintained by Buyer in the ordinary course of business, and not otherwise subject to any confidentiality restrictions; or (f) Buyer becomes legally compelled (by oral questions, interrogatories, requests for information or documents, subpoenas, investigative demands or similar process) to disclose. If Buyer becomes legally compelled (by oral questions, interrogatories, requests for information or documents, subpoenas, investigative demands or similar process) to disclose any of the confidential information, Buyer shall provide Seller with prompt written notice so that Seller may seek a protective order or other appropriate remedy or waive compliance with the provisions of this Agreement. If such protective order or other remedy is not obtained, or if Seller waives compliance with the provisions of this Agreement, Buyer shall furnish only that portion of the confidential information which Buyer is legally required to disclose and shall exercise its reasonable efforts to obtain reliable assurance that confidential treatment shall be accorded the confidential information. Buyer shall not undertake any qualitative or quantitative analysis, reverse engineering or replication of any of Seller's products, samples or prototypes without Seller's specific written authorization.

19) **SECURITY INTEREST:** Buyer hereby grants Seller a security interest in the System to secure the payment of the purchase price and shall not sell, lease, transfer or encumber the System and will keep it free from any and all liens and security interests until Seller has been paid in full. Buyer shall execute any and all documents reasonably requested by Seller to protect such security interests.

20) **MODIFICATION OF PROVISIONS:** This Agreement cannot be modified except by agreement in writing signed by Seller.

21) **MANAGEMENT OF CHANGE:** Seller is constantly striving to improve its products and capabilities and to provide the best product to its customers. Seller may from time to time develop product improvements or alterations with respect to the Products hereunder (the "Product Improvements"), and Seller may implement such Product Improvements without notice to Buyer so long as the performance of the Products will not be materially diminished, as determined in Seller's sole discretion, and so long as Seller has not separately agreed in writing to provide such notification to Buyer. In the event that Seller has agreed in writing to provide notice of Product Improvements to Buyer (the "Notice"), then Seller shall provide such Notice in accordance with the terms set forth in the separate writing.

22) **APPLICABLE LAW AND JURISDICTION:** This Agreement shall be governed by, construed and enforced in accordance with the laws of the Commonwealth of Pennsylvania, without regard to its conflict of law principles. The UN Convention on Contracts for the International Sale of Goods shall not apply to the transaction(s) represented hereby. The parties consent and submit to the exclusive jurisdiction and service of process of any state or federal court located in Allegheny County, Pennsylvania.

23) **MISCELLANEOUS:**

(a) Neither party may assign this Agreement, including without limitation any of its rights or obligations hereunder, without the express written consent of the other party hereto; provided that Seller may, without Buyer's consent (i) assign this Agreement, including without limitation any of its rights or obligations hereunder, to any of its parents, subsidiaries or affiliates or to any third party which merges with Seller or acquires all or substantially all of its business and assets or a substantial part of its assets or business relating to the Products and (ii) use subcontractors (for which Seller shall be responsible).

(b) In the event of any legal proceeding between Seller and Buyer relating to this Agreement, neither party may claim the right to a trial by jury, and both parties waive any right they may have under applicable law or otherwise to a trial by jury.

(c) In the event that any one or more provisions (or portions thereof) contained herein shall be held by a court of competent jurisdiction to be invalid, illegal or unenforceable in any respect, the validity, legality and enforceability of the remaining provisions (or portions thereof) contained herein shall remain in full force and effect, unless the revision materially changes the bargain.

(d) Seller's failure to enforce, or Seller's waiver of a breach of, any provision contained in this Agreement shall not constitute a waiver of any other breach or of such provision.

(e) Seller reserves the right to correct clerical, arithmetical, or stenographic errors or omissions in the Documentation, quotations, order acknowledgments, invoices or other documents.

(f) Any notice or communication required or permitted hereunder shall be in writing and shall be deemed received when personally delivered or three (3) business days after being sent by certified mail, postage prepaid, to a party at the address specified in this Agreement, or at such other address as either party may from time to time designate to the other.

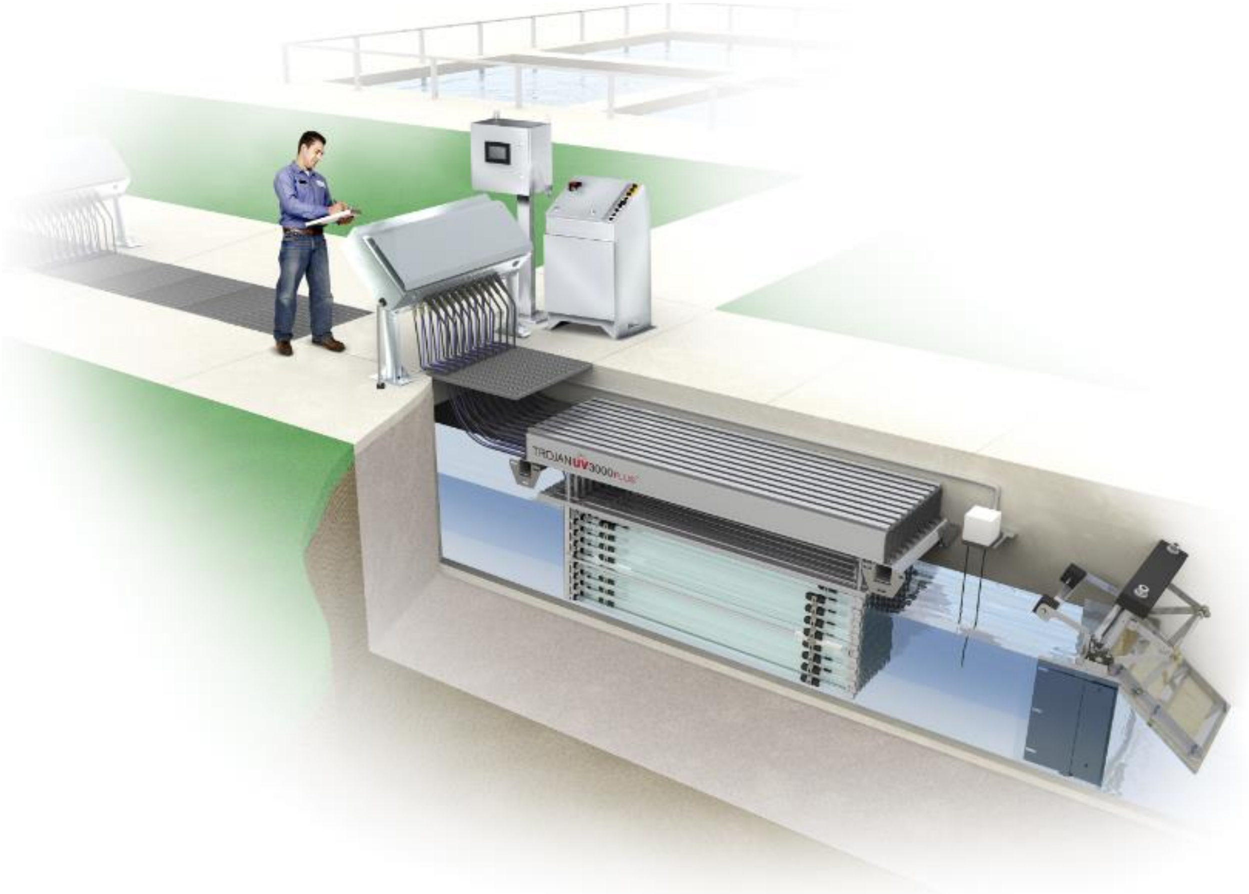
(g) Buyer agrees that it will not use Seller's name(s), logo(s) or mark(s) in any public communication or press release, or for any other marketing or promotional purpose, without Seller's prior written consent.

(h) Terms used in this Agreement which are not defined herein and which are defined by the Uniform Commercial Code of the Commonwealth of Pennsylvania shall have the meanings contained therein.

24) ENTIRE AGREEMENT: With respect to the subject matter hereof, this Agreement constitutes the complete and exclusive statement of the contract between Seller and Buyer. No waiver, consent, modification, amendment or change of the terms contained in this Agreement shall be binding unless made in writing and signed by Seller and Buyer. Seller's failure to object to terms contained in any subsequent communication from Buyer (whether in a purchase order or other communication) will not be a waiver or modification of the terms set forth herein.

TROJANUV3000PLUS™

PROPOSAL FOR THE UC DAVIS - REPLACEMENT, CA
QUOTE: 218487
11/14/2018



The TrojanUV3000Plus™ is operating in **over 2000** municipal wastewater plants around the world. Disinfecting **over 17 billion** gallons a day, the TrojanUV3000Plus™ has become the reference standard in the industry.

November 14, 2018

In response to your request, we are pleased to provide the following TrojanUV3000Plus™ proposal for the **UC DAVIS - REPLACEMENT** project.

The TrojanUV3000PlusTM has been shown in over 2000 installations to provide dependable performance, simplified maintenance, and superior electrical efficiency. As explained in this proposal, the system incorporates innovative features to reduce O&M costs, including variable output electronic ballasts to provide dimming capability and Trojan's revolutionary ActiClean-WWTM system – the industry's only online chemical and mechanical quartz sleeve cleaning system. All Trojan installations are supported by a global network of certified Service Representatives providing local service and support.

Please do not hesitate to call us if you have any questions regarding this proposal. Thank you for the opportunity to quote the TrojanUV3000Plus™ and we look forward to working with you on this project.

With best regards,

Jordan Fournier
Regional Manager
Trojan Technologies
3020 Gore Road
London, Ontario N5V 4T7
Canada
(519) 457 – 3400 ext. 2193
jfournier@trojanuv.com

DESIGN CRITERIA
UC DAVIS - REPLACEMENT

Peak Design Flow:	**5.7 MGD**
UV Transmittance:	**57 %** (minimum)
Total Suspended Solids:	**5 mg/l** (30 Day Average, grab sample)
Disinfection Limit:	**2.2 Total Coliform per 100 ml,** based on a day 7 of consecutive daily grab samples
Design Dose:	**102 mJ/cm2** (bioassay validated per NWRI protocol)
Validation Factors:	**0.9** end of lamp life factor **0.95** fouling factor
Redundancy:	1 Channel

DESIGN SUMMARY
QUOTE: 218487

Based on the above design criteria, the TrojanUV3000Plus™ proposed consists of:

CHANNEL (Please reference Trojan layout drawings for details.)	
Number of Channels:	**3**
Approximate Channel Length Required:	**46 ft**
Channel Width Based on Number of UV Modules:	**52 in**
Channel Depth Recommended for UV Module Access:	**54 in**
UV MODULES	
Total Number of Banks:	**12 (8 Duty, 4 Redundant)**
Number of Modules per Bank:	**13**
Number of Lamps per Module:	**6**
Total Number of UV Lamps:	**936 (Including Redundancy)**
Maximum Power Draw:	**234 kW (Including Redundancy)**
UV PANELS	
Power Distribution Center Quantity:	**12**
System Control Center Quantity:	**1**
MISCELLANEOUS EQUIPMENT	
Level Controller Quantity:	**3**
Type of Level Controller:	**Motorized Weir Gate**
Automatic Chemical / Mechanical Cleaning:	**Trojan ActiClean-WW™**
UV Module Lifting Device:	**Lifting Sling**

On-line UVT Monitor:	**Hach UVAS sc Sensor**
Standard Spare Parts / Safety Equipment:	**Included**
Other Equipment:	
ELECTRICAL REQUIREMENTS	
1. Each Power Distribution Center requires an electrical supply of one (1) 480/277V 60Hz, 19.9kVA **2.** The Hydraulic System Center requires an electrical supply of one (1), Powered by PDC, 2.5 kVA. **3.** The System Control Center requires an electrical supply of one (1) 120V 60Hz , 15 Amps. **4.** The Online UVT Monitor requires an electrical supply of one (1) 120 Volts, 1 Ph, 2 wire (plus ground), 1 Amp. **5.** Electrical disconnects required per local code are not included in this proposal.	

COMMERCIAL INFORMATION

Total Capital Cost: $ 2,295,000 (USD)

This price excludes any taxes that may be applicable and is valid for 90 days from the date of this letter.

EQUIPMENT WARRANTEES

1. Trojan Technologies warrants all components of the system (excluding UV lamps) against faulty workmanship and materials for a period of 12 months from date of start-up or 18 months after shipment, whichever comes first.
2. UV lamps purchased are warranted for 9,000 hours of operation or 3 years from shipment, whichever comes first. If a lamp fails prior to 9,000 hours of use, a new lamp is provided at no charge.
3. Electronic ballasts are warranted for 5 years, pro-rated after 1 year.

Appendix E - Technical Memorandum to the Water Board

MEMORANDUM

To: Central Valley Regional Water Quality Control Board
From: pHlux Engineering on behalf of UC Davis Utilities Division
Subject: UC Davis NPDES Permit Violations
Date June 9, 2019

Introduction

The UC Davis Wastewater Treatment Plant (WWTP) is a Title 22-certified facility that produces on average 2.8 million gallons per day (mgd) of tertiary treated recycled water. The ultraviolet (UV) disinfected effluent is discharged to the south fork of Putah Creek and the UC Davis Arboretum, as well as to the UC Davis Central Heating and Cooling Plant where it is used as chilling water [1], [2].

To comply with the Title 22 requirements for tertiary treated recycled water, the WWTP's National Pollutant Discharge Elimination System (NPDES) permit requires the effluent meet a minimum hourly average ultraviolet transmissivity (UVT) of 55%, an hourly average UV dose of 100 mJ/cm^2, and a 7-day median total coliform count of 2.2 MPN/100mL [1]. During large rainfall events, the effluent UVT falls below 55%, likely due to runoff intercepting inorganic and organic solids from the university's many livestock facilities. Low UVT effluent is unsafe for human contact and not permitted for beneficial reuse by Title 22 or the National Water Research Institute (NWRI) *Guidelines* [3].

As stated in the WWTP's NPDES permit, the permit may be reopened for modification pending evidence from an engineering study that identifies Title 22 compliant UV operating specifications [1]. This memorandum presents the results of a site-specific bioassay and a UV fluence rate distribution model to assess disinfection performance under low UVT conditions. For the reasons outlined in this memorandum, we do not recommend modifying the WWTP's NPDES permit, but instead propose consideration of chemical pre-treatment to increase influent UVT.

Methods

Carollo Engineers conducted a bioassay at the WWTP to determine the minimum allowable UVT at which the existing disinfection system can meet the total coliform count of 2.2 MPN/100 mL required by the NPDES permit. To simulate low-UVT conditions, Carollo injected varying amounts of humic acid into the influent stream. Non-pathogenic MS2 coliphage was added upstream of the UV reactor as a surrogate for total coliform, as recommended by the NWRI *Guidelines*. Carollo then measured MS2 coliphage and UVT in samples collected directly upstream and downstream of the UV system. An equivalent disinfection dose was calculated for each test based on the log inactivation and the standard dose-response relationship from NWRI *Guidelines*. Membrane filtration tests were also performed to enumerate the most probable number (MPN) of MS2 in the disinfected effluent.

To evaluate the UVT violation frequency, three years of UVT data were analyzed in MATLAB. The data resolution is hourly, so the violation frequency was found by dividing the number of hours with violations by the total number of operating hours. To investigate the relationship between UVT and rainfall, the concept of a first-flush event was explored via data analysis in MATLAB. Following a dry period in which material builds up on roads and surfaces, a first-flush is a large rainstorm that “flushes” this debris into the wastewater collection system via runoff. The curve in Figure 1 results from selecting only rainfall events that occur after a 72-hour dry period and is a function of minimum cumulative precipitation during the 72 hours following the dry period. This accounts for the predicted lag-time between the initiation of rainfall and the observation of low UVT at the WWTP.

A UV fluence rate model was constructed in MATLAB using the Line Source Integration (LSI) method [4]. The model estimates the fluence rate (W/m^2) of UVT light at a given radial distance from the UV lamp as a function of UVT, power output, length of the lamp, and internal lamp dimensions. It accounts for absorbance, transmittance, and refraction through the air, quartz, and water. A dose distribution ($W\text{-}s/m^2$) for each flow rate/UVT scenario was produced by multiplying the corresponding fluence rate distribution by the exposure time resulting from the linear flow velocity. The flow velocity was calculated using the computational fluid dynamics (CFD) software CFD Ultimate. Similarly, the flow was determined to be laminar based on the velocity vectors computed using CFD analysis.

A cumulative probability density function was produced from the dose distribution and evaluated to determine what percentage of doses fall below the 100 mJ/cm^2 mandated by the NPDES permit.

Results and Discussion

Table 1 summarizes the number of hourly UVT violations (i.e. less than 55% UVT) at the WWTP from 2016 to 2018. On average, the WWTP violated its UVT mandate only 2.4% of the time. Based on Figure 1, which depicts the relationship between precipitation and probability of triggering a UVT violation, there is a strong correlation between rainfall size and probability of UVT dropping below 55%. For a 0.4-inch storm there is a 50% probability of violation. However, the daily precipitation in Davis, CA, from 2016 to 2018 exceeded 0.4 inches only 5.2% per year. UVT violations are an infrequent occurrence that are largely limited to larger rainstorms in the region.

Table 1: Annual historic UVT violations.

Year	**2016**	**2017**	**2018**	**Average**
Total violation time	303 hr	267 hr	68 hr	212.7 hr

Based on the bioassay, the measured effluent total coliform complied with the maximum of 2.2 MPN/100 mL in all examined cases except for a UVT of 30% with only two banks online in the channel. To achieve compliance for a UVT as low as 30%, all four banks were required. Although this low UVT delivers sufficiently disinfected effluent, using all four banks is not ideal. This test shows that compliant total coliform count can be achieved at 52% UVT and two online banks.

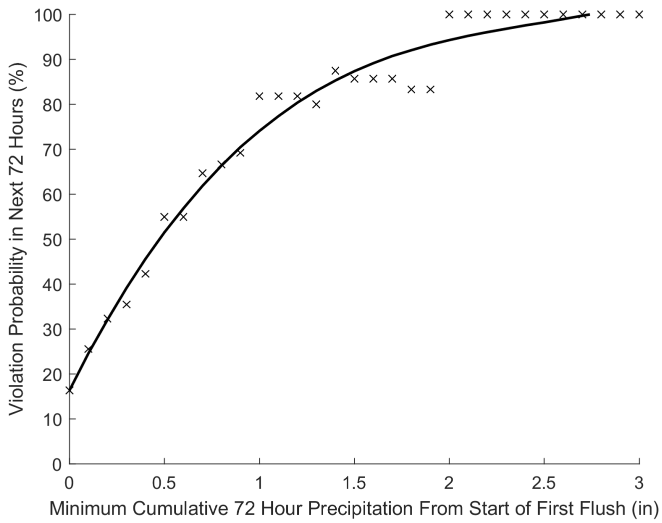


Figure 1: Probability of triggering a UVT violation in the next 72 hours following a 72-hour dry period.

As shown in Table 2, the bioassay reveals that the WWTP is able to deliver a minimum UV dose of 100 mJ/cm^2 at a UVT as low as 42%. The fluence rate distribution model (Figure 2) verified that 95.0% of the delivered doses are compliant with this minimum dose.

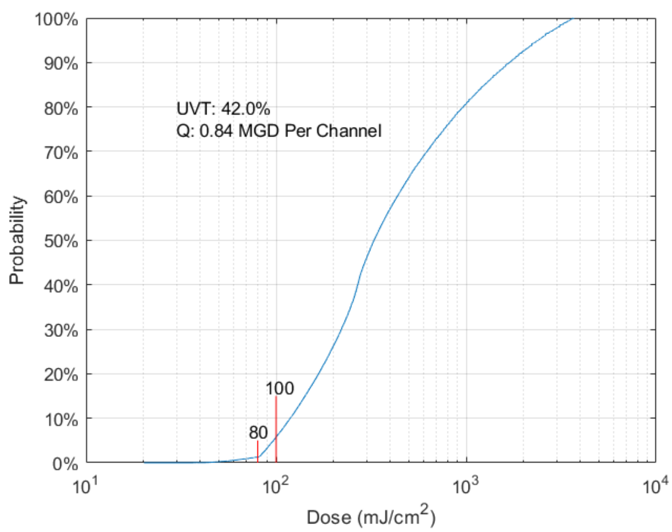


Figure 2: Cumulative probability plot showing the distribution of doses delivered with the current system operating at 42% UVT and 0.84 MGD per channel.

Nevertheless, to achieve this disinfection performance, all four UV banks must be online in two of the three channels. This requirement leaves no redundancy in either channel should one of the banks malfunction. The flow would also be reduced from a daily average capacity of 1.35 mgd per channel to 0.84 mgd per channel to accommodate the higher hydraulic retention time necessary to achieve the minimum dose. Decreased capacity is impractical as low UVT conditions occur when flows are high. Operating the UV system at a UVT lower than 55% would strain the existing UV banks and greatly reduce the system's overall capacity, neither of which are operationally prudent [3].

Table 2: Capacity of existing UV system for various operating conditions.

Operating Condition	**UVT, (%)**	**Total Flow, (MGD)**	**Channels Online**	**Flow / Channel (MGD)**	**Banks**	**Predicted Dose, (mJ/cm^2)**
Minimum UVT	42	1.68	2	0.84	4	100
Avg. Daily Flow	55	1.35	1	1.35	3	100

Recommendations

The evidence presented in this memorandum supports the recommendation that no modifications be made to the existing NPDES permit. While both the bioassay and fluence rate distribution model verified the minimum dosage compliance of the current UV system, the reduction in capacity required to treat the water at a UVT below 55% is inadvisable. Capacity reduction is especially impractical given current projections to expand the campus population and facilities in the coming years.

Instead of modifying the NPDES permit, we recommend the WWTP pre-treat its wastewater before it enters the UV disinfection system. Chemical pre-treatment is ideal as it requires no major upgrades to the WWTP and can be automatically turned on/off based on UVT monitoring. The addition of a strong chemical oxidizer or coagulant upstream of the UV reactors could remove color from the wastewater, thereby increasing the UVT [5]. The chosen chemical could easily be injected into the clarifiers preceding the sand filters to allow time for the oxidizer to bleach the water or the particles to settle out of suspension.

References

[1] California Central Valley Regional Water Quality Control Board, "Waste Discharge Requirements for the University of California, Davis Main Wastewater Treatment Plant, Solano and Yolo Counties," December 2014.

[2] Dave Jones, "The 'cool' and fast way we're saving 61 million gallons of water a year." EvoQua, `https://www.evoqua.com/en/brands/ETS_UV/Documents/ETS-UV-MUN-WW-AP.pdf`, June 2015.

[3] National Water Research Institute, "Ultraviolet disinfection: Guidelines for drinking water and water reuse," August 2012. In collaboration with the Water Research Foundation.

[4] C. Buchner, *Modelling of UV Disinfection Reactors by Means of Computational Fluid Dynamics*. PhD thesis, Atominstitut der osterreichischen Universitaten, 2006.

[5] K. Bell, J. Sánez, and M. Wells, "Optimizing disinfection pretreatment using excitation-emission matrix fluorescence spectroscopy," *Ozone: Science and Engineering*, Mar 2012.