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DESIGN STANDARDS FOR
WASTEWATER ULTRAVIOLET LIGHT
DISINFECTION SYSTEMS

STATE OF VERMONT
AGENCY OF NATURAL RESOURCES
DEPARTMENT OF ENVIRONMENTAL CONSERVATION
WASTEWATER MANAGEMENT DIVISION
OPERATIONS AND MANAGEMENT SECTION

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TABLE OF CONTENTS

INTRODUCTION:

In 1995 the Vermont Department of Environmental Conservation received a grant from the United States Environmental Protection Agency (USEPA), Region I to study open channel ultraviolet light disinfection in Vermont and some New Hampshire wastewater treatment facilities. A dye study was conducted and effluent sampling was performed on each of the three facilities in Vermont, and on two facilities in New Hampshire, which utilize an open channel ultraviolet light disinfection system for disinfection of the final effluent. The purpose of the evaluation was to obtain information for use in determining whether the Vermont Design Guidelines for UV Disinfection Systems were too stringent when applied to an open channel design, in light of the purported improved hydraulic characteristics of open channel designs over that of enclosed units. The existing Vermont Design Guidelines had been developed primarily around the performance of some of the 'early' enclosed-type UV disinfection units.

The results of the 1995/1996 evaluation on the open channel ultraviolet light disinfection systems substantiated that the Vermont Design Guidelines for such systems needed to be revised in several areas. The results of the evaluation were discussed in a separate October 1996 report prepared by the Vermont Department of Environmental Conservation. In follow-up to the 1995/1996 evaluation, the Vermont Department of Environmental Conservation received a second grant in 1996 from EPA Region I for the purpose of rewriting the Vermont Design Guidelines for UV Disinfection Systems. The revisions to the guidelines pertain primarily to open channel UV disinfection systems, although the guidelines for enclosed UV disinfection units were also revised slightly.

The most significant change to the Design Guidelines involves the establishment of minimum length-to-width, and depth-to-width ratios for UV channels, and the incorporation of design features, such as perforated baffles to promote 'plug flow' conditions through the UV units and to prevent short-circuiting. The hydraulic design criteria for open channel UV systems were derived from the results of the five plant evaluations and were based on generally accepted hydraulic principles.

SPECIFICATIONS FOR ULTRAVIOLET LIGHT DISINFECTION SYSTEMS

A. PERFORMANCE STANDARDS

1. All Ultraviolet Light Disinfection Systems shall have the capability to continuously disinfect the peak flow rate from a secondary or tertiary treatment process, in order to obtain a residual *Escherichia coli* (E. coli) bacteria count not greater than the limit established by the most current version of the Vermont Water Quality Standards. The Vermont Water Quality Standards are periodically reviewed and updated, which may result in the establishment of a different limit for E. coli in the future.

Ultraviolet light disinfection is a physical process; the light striking a cell is absorbed and disrupts the cell's processes, causing death. Unlike chemical disinfection, a cell which is encapsulated in a particle and is shielded from the UV light will not be affected. The ability of a UV disinfection system to provide effective disinfection is therefore highly dependent on the Total Suspended Solids (TSS) concentration of the final effluent being discharged from the wastewater treatment facility. The number of organisms protected from UV radiation by encapsulation in TSS particles can be described by the expression $N_p = cSS^m$, where N_p is the number of organisms, SS is the Total Suspended Solids concentration in mg/l, and c and m are coefficients determined by linear regression of actual TSS vs. E coli results for a particular UV system. A more restrictive E. coli limit will necessitate that the treatment facility have the capability to consistently produce a higher quality final effluent (lower TSS concentration).

From the above discussion the necessary level of treatment prior to UV disinfection is ultimately established by the E. coli limit specified in the Vermont Water Quality Standards. The current Water Quality Standard for E. coli is 77 colonies/100 mls as an instantaneous maximum. For a proposed UV system to consistently and reliably achieve such an E. coli limit the wastewater treatment facility needs to be capable of producing a final effluent with a daily maximum TSS concentration of 10.0 mg/L or less, which necessitates that chemical precipitation and/or effluent filtration be provided as the final treatment steps prior to UV disinfection.

Alternatively it may be appropriate to establish a 200 foot mixing zone in the receiving stream through the Water Quality Division, wherein the in-stream dilution can be factored in and by calculation a higher E. coli limit can be determined for the point of discharge. A higher E. coli limit value would enable the UV disinfection system to remain effective at a higher TSS concentration in the final effluent from the treatment process.

If a mixing zone for E. coli is approved by the Department, the following table will be used to establish the necessary level of treatment and in-stream dilution.

Treatment Level vs. In-Stream Dilution

Treatment Process Type	Max Daily TSS Conc, mg/l	E. coli Level[1], col/100 ml	In-Stream Dilution Factor[2]
tertiary/filtration	10	77	---
advanced/chemical precipitation	20	120	1.5:1
secondary	30	160	2.05:1

1) Based on a 90th percentile confidence level at point of discharge
2) At end of mixing zone and at 7Q10 flow in the receiving stream

2. The ability to provide compliance with the E. coli limit in Section A.1. shall be demonstrated by the design engineer and approved by the Vermont Department of Environmental Conservation prior to installation. For enclosed and open channel units, conformance of the system design can be demonstrated by applying the Design Criteria For Ultraviolet Light Disinfection Systems established herein, so as to show the system will provide a minimum UV dose of at least 30,000 microwatt-seconds per square centimeter ($\mu ws/cm^2$) at peak flow. Peak flow is defined as a facility's established peak hourly flow rate or 2.0 ADF, whichever is greater; or the maximum decant rate of a batch treatment process such as a sequencing batch reactor; or the maximum discharge rate of an influent or effluent pumping system upstream of the UV system.

3. Alternatively, the manufacturer may, at its own expense, conduct a pilot demonstration test on a constructed disinfection system at an existing wastewater treatment facility to determine compliance with the standards prescribed in Section A.1. This test shall consist of grab samples of the disinfection system influent and final effluent, which shall be analyzed for concentrations of TSS and the number of colonies of E.coli. The sampling shall be conducted under peak flow conditions for 14 consecutive days and shall take place during a period of no less than 240 days, or more than 360 days following inspection and approval of the installation by the manufacturer's representative.

   Flow conditions during the sampling period shall be maintained as close as possible to the"design" peak flow. (Artificial peak flow conditions may be created). The test shall be conducted under conditions ordinarily existing in the system and at the treatment facility; i.e. the hydraulic and organic loading to the treatment facility shall be typical for that facility, no "enhancements", such as polymer addition or bioaugmentation shall be implemented to improve facility performance during the test period, and the replacement of lamps or extensive cleaning of the units shall not be permitted solely for the purpose of preparing for the test .

The results of all tests must meet the coliform limits specified in Section A.1. before the system will be accepted. The manufacturer shall be responsible for any modifications or replacements necessary to bring the disinfection system into compliance with the standards noted in Section A.1. After such modifications or replacements, the testing shall be repeated to determine if the non-compliance was corrected, and to demonstrate that the system consistently reduces the E. coli concentration to the level which conforms with the Vermont Water Quality Standards in the receiving water.

4. All Ultraviolet Light Disinfection Systems shall consist of multiple units. For enclosed units, each unit shall be capable of continuously disinfecting the peak flow from the treatment facility (200% capacity). For open channel units, whether of vertical or horizontal lamp orientation, at least two banks of lamps shall be provided, which operate in series. The multiple open channel units shall cumulatively provide at least the minimum required dosage at the facility's peak flow rate.

All sampling and analyses shall be conducted in conformance with the most current edition of Standard Methods for the Examination of Water and Wastewater prepared by the American Public Health Association, the American Water Works Association and the Water Environment Federation, and the Vermont Laboratory Procedures Manual.

Pilot demonstration testing in accordance with this section is also appropriate and necessary when evaluating and introducing new equipment or a new technology involving UV disinfection, such as medium pressure/high intensity lamps, not specifically covered herein.

B. GENERAL CONSTRUCTION CRITERIA

1. The emission of each low pressure mercury arc lamp shall be a minimum of 90% in the wavelength between 2,525 and 2,550 angstroms. Each lamp shall have a rated output at 100 hours of no less than 190 μw/cm^2 at one meter.

2. The fused quartz sleeves which protect the lamps from contact with the wastewater shall be General Electric Company Type 214 or equal with a minimum transmission of 90% at 2,537 angstroms. The quartz sleeves shall be sealed with easily removable compression fittings.

3. All electronic and electrical components in the disinfection system shall be designed, constructed and installed in accordance with the most current edition of the National Electrical Code

4. Each ultraviolet disinfection unit shall be equipped with a cover interlock switch, and an automatic safety device to disconnect electrical power to the lamps when the access panels to the disinfection chamber are opened.

5. For ease of maintenance and repair of the UV disinfection system during periods of inclement weather, particularly during the winter months, as a minimum all components should be located in a roofed enclosure.

6. All wastewater treatment facilities utilizing ultraviolet light for disinfection of the final effluent shall be equipped with an alternate source of electric power, such as an engine-driven generator, unless sufficient storage volume is provided upstream of the UV disinfection system. The storage volume must be sufficient to accommodate the flow that would be discharged from the facility for the duration of the longest power outage which would have affected the treatment facility in the past five years, or for four hours, whichever is greater. An engine-driven generator must be equipped with automatic start and load transfer capabilities. The generator must have sufficient capacity to provide power for the entire treatment process so that the TSS concentration of the final effluent is maintained at a level which assures effective disinfection through the UV system.

7. a. Enclosed Units

1. The disinfection chamber shall be constructed of type 304 stainless steel. In addition, all wetted surfaces other than quartz sleeves and o-rings shall be type 304 stainless steel.

2. Provision shall be made for easy removal and inspection of the ultraviolet lamps without draining the disinfection chamber.

3. A cabinet shall be provided for protection of the disinfection chamber and electrical wiring against dirt and accidental spray water.

4. The disinfection chamber shall withstand a test pressure of 50 psi and a vacuum of 2 psi.

5. In the interest of promoting laminar flow, internal perforated flow alignment baffling shall be provided at the inlet and outlet of the chamber.

b. Open Channel Units

1. The lamp configuration shall be a uniform array with all lamps parallel to each other. The lamps may be positioned either parallel or perpendicular to the flow depending on the configuration of the system design. The lamps shall be evenly spaced across the entire lamp array.

2. In designs incorporating horizontal lamp placement, the UV channel shall be designed such that the liquid depth and channel width are approximately the same dimension (H:W= 1:1), and the ratio of the length of the effective contact area to the width of the channel (L:W) shall be at least 6 to 1. In designs incorporating vertical lamp placement the channel shall be designed to maximize the length to width ratio of the UV channel, while providing the prescribed minimum UV dosage. All channel designs shall be configured so as to maximize the aspect ratio (aspect ratio is defined as length / hydraulic radius).

3. The inlet to the UV channel shall be designed to reduce the potential for short-circuiting through the primary UV unit. In designs incorporating a horizontal inlet pipe corner, 'fillets' may be appropriate at the upstream end of the channel to minimize turbulence and eddying created in the transition from closed pipe flow to open channel flow. An upflow inlet pipe should be incorporated, if possible, to reduce the potential for short circuiting.

4. The system shall be designed for complete immersion of the UV lamps including the electrodes and the full length of the lamp tube in the effluent. Both lamp electrodes shall operate at the same temperature and shall be cooled by the effluent. The channel shall be designed such that the UV lamps remain immersed at all times during normal operation. Outlet structures, weirs or automatic level controllers should be sized to maintain a constant head above the lamp surfaces, allowing maximum fluctuation of no more than ± 1 inch from the control level.

5. The UV lamp module support rack shall be type 304 stainless steel and shall be suspended above the effluent in the channel so as to allow adjustment to the precise height of the channel and requiring no fastening of the individual UV lamp modules.

6. It is recommended that the downstream end of the channel be equipped with a sump to collect and concentrate solids. This sump should be equipped with a valved drain to enable the accumulated solids to be flushed from the channel.

7. The UV channel shall be designed to provide unobstructed straight line approach and exit conditions. A distance of at least two times the channel depth or a minimum of five feet, whichever is greater, shall be provided between the inlet pipe and the primary UV unit, and the same distance shall be provided between the final UV unit and the level control device. The exit channel length for vertical lamp designs will most likely need to be extended so as not to create a hydraulic constriction at the level control device, due to the increased channel depth to accommodate the lamp assemblies.

8. The UV channel shall be designed to provide laminar flow through the units, and the flow shall be uniformly dispersed across the overall depth and width of the entire channel cross section. The channel shall be designed to include removable, full cross sectional, perforated flow alignment baffles at the upstream and downstream ends of the channel. The upstream baffle shall be installed at a location at least four feet upstream of the primary UV unit.

C. MONITORING

1. Each ultraviolet disinfection unit shall be equipped with a lamp monitoring system which utilizes L.E.D. displays for each individual lamp. A visual warning light shall signal immediately upon the failure of any single lamp. The display of the lamp monitoring system shall immediately identify the failed lamp.

2. An elapsed time indicator shall be provided for each bank of ultraviolet lamps to maintain proper chronological lamp replacement schedules.

3. The results of the E. coli sampling required by the discharge permit shall be used to monitor the effectiveness of the disinfection system. In conjunction with this the quartz sleeves for the UV lamps shall be cleaned at a frequency that assures that effective disinfection is maintained and the UV lamps shall be replaced as necessary to maintain compliance with the E. coli effluent limit.

D. CLEANING SYSTEMS

1. Each ultraviolet disinfection system shall be equipped with a convenient method of cleaning all surfaces in contact with the wastewater, including the quartz sleeves and on enclosed units, the sight glass and internal walls.

2. In designs incorporating vertical lamp placement, at least one additional module (cluster of UV lamps) must be provided to facilitate the replacement of the lamps and the cleaning of the quartz sleeves in each of the other lamp modules (one at a time), unless the capability exists to terminate the discharge from the treatment facility (i.e. storage provided upstream of the disinfection system), or the discharge is intermittent (i.e. Batch Treatment Processes).

3. On enclosed systems, units employing wiper-type cleaning systems shall be equipped with the appurtenances necessary for a supplementary cleaning method, such as acid cleaning.

4. If the disinfection system has an automatic cleaning system, it shall also be designed to operate in a manual mode.

E. SUBMITTALS/WARRANTY

1. The contractor shall submit complete fabrication and complete shop drawings for the system installation, including plumbing and electrical schematics.
2. The contractor shall submit an operation and maintenance manual for the system and its components. The level of detail discussed therein shall enable the operators to install, service, operate, troubleshoot, and maintain the system.

3. The contractor shall arrange for the UV system manufacturer to provide at least 8 hours of field service to inspect the installation and instruct the owner's personnel on the operation and maintenance of the system. The manufacturer shall provide to the owner a written approval of the installation.

4. The contractor shall provide extra parts normally replaced during one year of continuous operation. Such extra parts shall include the lamps necessary for one complete change-out of all of the lamps in a system. In the case of an open channel system, the extra lamps are in addition to the replacement lamps called for in Item #6 of the Design Criteria For Open Channel UV Light Disinfection Systems.

5. The manufacturer shall guarantee the performance of the disinfection system for one year following acceptance of the installed system. During this performance year, any failure to meet the requirements of Section A.1. (Performance Standards), while being operated according to the manufacturer's instructions, shall be corrected by the manufacturer.

6. The manufacturer shall in addition to the warranty described in Section E.5. (Submittals/Warranty), post a performance bond on any disinfection system subject to the pilot demonstration testing criteria as described in Section A.3. The performance bond shall be equal in value to 200% of the cost of the complete disinfection system.

DESIGN CRITERIA FOR ENCLOSED UV DISINFECTION SYSTEMS

1. All enclosed UV disinfection systems shall be designed to provide a minimum dosage of 30,000 μws/cm^2 at peak flow through the units. The dosage of a system is determined by multiplying the "minimum intensity" of an array by the minimum detention time in the system at peak flow.

2. The "minimum intensity" is the calculated intensity at the point of interest (location of maximum distance from the lamps, based on the geometry of the treatment unit) when:

   a. The lamps are at 70% of the new lamp intensity;

   b. The transmittance of the wastewater flow is not greater than 60%, thus the absorbance is 0.222 absorbance units/cm (a.u./cm), (% T = % Transmittance = 100 x 10^{-a}); and

   c. The transmittance of the quartz sleeves is 90% of nominal (new).

   The formula outlined below may be used in calculating the "minimum intensity" under these criteria (See attached Design Example).

   $$I = I_o\, e^{-(\propto)x}$$

   Where I = intensity at point of interest

   I_o = lamp intensity at end of design life, μw/cm^2

   a = absorbance = 0.222 a.u./cm

   $\propto$ = absorbance coefficient (cm^{-1}) = 2.3a = 0.51

   x = distance, cm.

   e = 2.7183

3. The minimum detention time shall be either the time in seconds from the addition of dye, to first dye out, in a standard dye dispersion study at design peak flow, or calculated as 50% of the theoretical detention time through the UV unit(s) at peak flow. The volume occupied by the UV lamp quartz sleeves shall be deducted from the contact volume when completing this calculation.

4. All enclosed UV disinfection systems shall be equipped with a minimum of two units (200% capacity), each with the capability to continuously disinfect the peak flow rate from the treatment process. If multiple units operating in series or parallel are needed for effective treatment, then one or more back-up units of equal capacity shall be provided, ready for immediate service. Under this scenario all UV units shall have the capability for independent operation. This arrangement will allow for any unit to be taken out of service for maintenance or repair, while enabling a sufficient number of units to remain in operation for effective disinfection.

5. If a disinfection system is designed with multiple UV units operating in parallel, the

configuration of the units and the interconnecting piping shall be hydraulically balanced to provide an equal flow rate through each unit under all operating modes.

6. The design criteria specified above is based on the utilization of low pressure mercury arc lamps with a rated UV output at 100 hours of 26.7 watts at 254 nanometers and an arc length (effective length) of 147 cm.

DESIGN CRITERIA FOR OPEN CHANNEL U V DISINFECTION SYSTEMS

1. All open channel UV disinfection units shall be designed to provide a minimum dosage of 30,000 $\mu ws/cm^2$ at peak flow through the UV system. The dosage of the system is determined by multiplying the "minimum intensity" of an array by the minimum detention time through the system at peak flow.

2. The "minimum intensity" is the expected intensity at the point of interest (location of maximum distance from the lamps, based on the lamp array) when:
   1) The lamps are at 70% of new lamp intensity,
   2) The transmittance of the wastewater flow is not greater than 60%, thus the absorbance is 0.222 absorbance units/cm (a.u./cm), (% T = % Transmittance = 100×10^{-a}), and
   3) The transmittance of the quartz sleeves is 90% of nominal.

   The formula given below may be used in calculating the minimum intensity under these criteria (see attached design example).

   $I = I_0 e^{-(\propto)x}$

   where I = intensity at point of interest
   I_0 =lamp intensity at end of design life, $\mu w/cm^2$
   a = absorbance = 0.222 a.u./cm
   $\propto$ = absorbance coefficient (cm^{-1}) = 2.3a = 0.51
   x = distance, cm.
   e = 2.7183

   For vertical lamp configurations the lamp array is staggered, which necessitates that the expected intensity be calculated for two points of interest, and the results averaged to establish the "minimum intensity" for the array.

3. The minimum detention time shall be either the time in seconds from the addition of dye, to first dye out at downstream end of each UV unit, in a standard dye dispersion study at design peak flow, or calculated as 85% of the theoretical detention time within the effective contact area at peak flow. For UV systems incorporating vertical lamp orientation, the calculation shall be completed at 75% of the theoretical detention time.

   The effective contact area is the channel volume provided between the upstream end of the primary UV unit and the downstream end of the final UV unit, less the channel volume between the UV lamp banks. The volume occupied by the UV lamp quartz sleeves shall be deducted from the channel volume when completing this calculation.

4. All channel designs shall be configured so as to maximize the aspect ratio. The aspect ratio is determined by dividing the length of the contact area (in feet) by the hydraulic radius of the channel (ft.). The hydraulic radius is determined by dividing the channel cross sectional area (ft^2) by the wetted perimeter (ft.). An aspect ratio of at least 15 is desirable.

5. All open channel UV systems shall utilize at least two banks of lamps operating in series; the distance between the UV banks shall not exceed four feet. Multiple unit installations shall cumulatively provide the required UV dosage at the facility's peak flow rate. Parallel channel configurations of multiple series units must have accurate means of flow split to each set of UV units.

6. A number of replacement lamps equaling at least 15% of the total provided in the system, or the total number of lamps in an individual module, whichever is greater, shall be available for immediate installation, along with one spare module, one replacement quartz sleeve and one electronic ballast for each UV bank provided in the system.

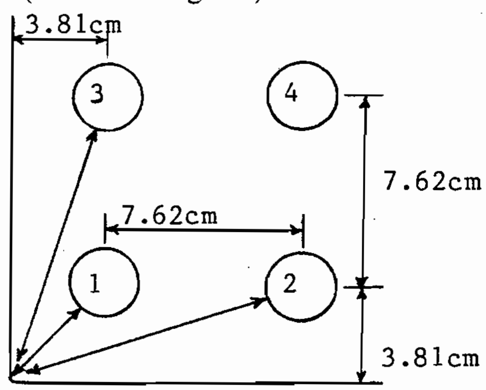
7. The design criteria specified above is based on the utilization of low pressure mercury arc lamps with a rated UV output at 100 hours of 26.7 watts at 254 nanometers and an arc length (effective length) of 147 cm.

DESIGN EXAMPLE FOR OPEN CHANNEL UV SYSTEM
Horizontal Lamp Configuration

GIVEN:
Design Average Daily Flow Rate = 0.50MGD
Design Peaking Factor 2.0

DESIGN CRITERIA:
Minimum Dosage 30,000 μws/cm^2
6:1 Length to Width Ratio
1:1 Depth to Width Ratio
Aspect Ratio >15

1. Determine the location of the unit's point of minimum intensity ("point of interest"). (Refer to diagram)



Quartz sleeve dia=1" = 2.54cm
Distance to point of interest
Lamp #1
$$x = \sqrt{3.81^2 + 1.81^2} = 5.38\text{cm}$$
$$5.38 - \frac{2.54}{2} = 4.11\text{cm}$$
Lamps # 2 & 3
$$x = \sqrt{3.81^2 + 11.43^2} = 12\text{cm}$$
$$12 - \frac{2.54}{2} = 10.73\text{cm}$$

2. Calculate the intensity of each lamp at the point of interest:

$I = I_o e^{-(\alpha)x}$
I = INTENSITY AT POINT OF INTEREST, μw/cm^2
I_o = LAMP INTENSITY AT END OF DESIGN LIFE AND AS REDUCED BY QUARTZ SLEEVE
= 38,460 UW/CM^2 x 0.7 x 0.9=24,230 μw/cm^2
x = DISTANCE FROM POINT OF INTEREST IN CM
% Transmittance = 60%

$60\%T = 100X\ 10^{-a}$ $\quad$ $a = 0.222$ a.u./cm
$\alpha = 2.3a$ $\quad$ $\alpha = 0.222 \times 2.3 = 0.51\ \text{cm}^{-1}$

FOR LAMP 1 $\quad$ X = 4.11 CM

$I = 24,230 \times e^{-(\alpha)x}$
$24,230 \times e^{-(0.51)4.11}$
$24,230 \times e^{-2.1}$
$24,230 \times 0.123$
$= 2979\ \mu\text{w/cm}^2$

FOR LAMPS 2 & 3 $\quad$ X = 10.73 CM

$I = 24,230 \times e^{-(\alpha)x}$
$24,230 \times e^{-(0.51)10.73}$
$24,230 \times e^{-5.47}$
$24,230 \times 0.0042$
$= 102\ \mu\text{w/cm}^2$

FOR LAMP 4

$I = 0.0\ \mu\text{w/cm}^2$ DUE TO LAMP INTERFERENCE .

3. Determine Total minimum intensity at point of interest:

LAMP	I in $\mu w/cm^2$
#1	2979
#2	102
#3	102
#4	0
TOTAL	$3183 \mu w/cm^2$

4. Determine required minium detention time:
Minimum Dosage = Minimum Intensity x Minimum Detention Time
$30{,}000\ \mu ws/cm^2 = 3183\ \mu w/cm^2 \times$ Detention Time
Minimum Detention Time $= \dfrac{30{,}000\ \mu ws/cm^2}{3183\ \mu w/cm^2} = 9.43$ seconds

Adjusting For Theoretical Detention Time $\dfrac{9.43 \text{ sec}}{0.85} = 11.1$ sec.

5. Determine required effective contact volume:
Effective Contact Volume = Peak Flow Rate x Detention Time
Peak Flow Rate $= \dfrac{500{,}000 \text{ gpd} \times 2.0 \text{ P.F.}}{1440 \text{ min/day} \times 60 \text{ sec/min}} = 11.57$ gps

Effective Contact Volume = 11.57 gps x 11.1 sec = 128.4 gallons
$\dfrac{128.4 \text{ gallons}}{7.48 \text{ gal/ft}^3} = 17.17\ ft^3$ (not including volume occupied by quartz sleeves)
Assume 10% of volume occupied by quartz sleeve
$17.17\ ft^3 \times 1.1 = 18.88\ ft^3$

6. Establish cross sectional area of UV channel
Length of Effective Contact Volume = 2 UV banks x 147 cm/bank = 294cm
$\dfrac{294 \text{cm}}{2.54 \text{ cm/in} \times 12 \text{ in/ft}} = 9.65$ ft

Cross sectional area $= \dfrac{18.88\ ft^3}{9.65\ ft} = 1.956\ ft^2$
Providing 1:1 Channel Depth to Width Ratio
Channel width and depth $= \sqrt{1.956\ ft^2} = 1.4$ ft (16.78") use 18" (1.5 ft)

7. Check length to width ratio of UV channel
$\dfrac{9.65 \text{ ft}}{1.5 \text{ ft}} = 6.43{:}1 > 6{:}1$

8. Check aspect ratio of channel
aspect ratio $= \dfrac{\text{length of contact area}}{\text{cross sectional area/wetted perimeter}}$

aspect ratio $= \dfrac{9.65 \text{ ft}}{1.5 \text{ ft} \times 1.5 \text{ ft}/1.5 \text{ ft} + 1.5 \text{ ft} + 1.5 \text{ ft}}$

$= \dfrac{9.65}{2.25/4.5} = \dfrac{9.65}{0.5} = 19.3 > 15$

9. Determine # of lamps required at 3" o.c. array pattern

$$\frac{18\text{" channel width/depth}}{3\text{"}} = 6 \text{ lamps horizontal and vertical;}$$

6 x 6 x 2 banks = 72 lamps

10. Check Actual Detention Time and Dosage Provided

a. Determine Volume Occupied by Quartz Sleeves for Lamps

$$\frac{\pi\, dia^2}{4} \text{ x sleeve length x number of lamps}$$

$$\frac{3.1416\,(1.0 \text{ inch})^2}{4} \text{ x } 58\text{"/lamp x 72 lamps} = 3280 \text{ in}^3$$

$$\frac{3280 \text{ in}^3}{1728 \text{ in}^3/\text{ft}^3} = 1.90 \text{ ft}^3$$

b. Determine net contact volume

Gross Effective Contact Volume

1.5 ft x 1.5 ft x 9.65 ft = 21.7 ft^3

Net contact volume (less quartz sleeve volume)

21.7 ft^3 - 1.9 ft^3 = 19.8 ft^3

19.8 ft^3 x 7.48 gal/ft^3 = 148.2 gal

c. Determine Actual Detention Time

Theoretical Detention Time

$$\frac{148.2 \text{ gal}}{11.57 \text{ gps}} = 12.8 \text{ sec}$$

Actual Detention Time

12.8 sec x 0.85 = 10.9 sec

d. Determine dosage provided by system

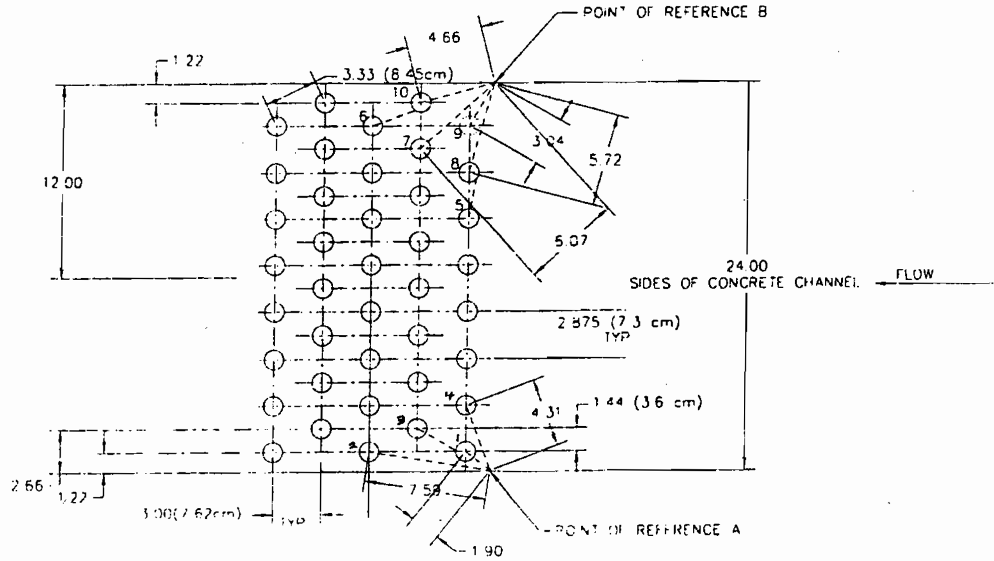
3183 μw/cm^2 x 10.9 sec = 34,695 μws/cm^2 > 30,000

DESIGN EXAMPLE FOR OPEN CHANNEL U V SYSTEM
Vertical Lamp Configuration

GIVEN:
Design Average Daily Flow Rate = 0.875 MGD
Design Peaking Factor 2.0

DESIGN CRITERIA:
Minimum Dosage 30,000 μws/cm^2

1. Determine the location of and distances to the points of minimum intensity ("points of reference") in the staggered lamp array. (Refer to diagram.)



2. Calculate the intensity of each lamp at the points of reference:

$I = I_0 e^{-(\alpha)x}$
I = Intensity at Point of Reference, μw/cm^2
I_o = Lamp Intensity at End of Design Life and as Reduced by Quartz Sleeve
= 38,460 μw/cm^2 x 0.7 x 0.9=24,230 μw/cm^2
x = Distance from Point of Reference in cm
% Transmittance = 60%

$60\%T = 100x10^{-a}$ $\quad$ a = 0.222 a.u./cm
$\alpha = 2.3a$ $\quad$ $\alpha = 0.222 \times 2.3 = 0.51$ cm^{-1}
Quartz Sleeve Diameter = 1" = 2.54 cm

a. Point of Reference A

Lamp #1 $\quad x = (1.9 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 3.56$ cm

$I = 24{,}230 \times e^{-(\alpha)x}$
$= 24{,}230 \times e^{-(0.51)3.56}$
$= 24{,}230 \times e^{-1.82}$
$= 24{,}230 \times 0.163$
$= 3943$ μw/cm^2

Lamp #2 $x = (7.58 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 18 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)18}$
$= 24{,}230 \times e^{-9.18}$
$= 24{,}230 \times 0.0001$
$= 2.5\ \mu w/cm^2$

Lamp #3 $I = 0.0\ \mu w/cm^2$ Due to Lamp Interference

Lamp #4 $x = (4.31 \text{in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 9.68 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)9.68}$
$= 24{,}230 \times e^{-4.94}$
$= 24{,}230 \times 0.0072$
$= 174\ \mu w/cm^2$

b. Point of Reference B

Lamps #5 and #6 $I = 0.0\ \mu w/cm^2$ Due to Lamp Interference

Lamp #7 $x = (6.07 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 14.1 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)14.1}$
$= 24{,}230 \times e^{-7.22}$
$= 24{,}230 \times 0.00074$
$= 17.8\ \mu w/cm^2$

Lamp #8 $x = (5.72 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 13.26 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)13.26}$
$= 24{,}230 \times e^{-6.76}$
$= 24{,}230 \times 0.0012$
$= 28\ \mu w/cm^2$

Lamp #9 $x = (3.04 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 6.45 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)6.45}$
$= 24{,}230 \times e^{-3.29}$
$= 24{,}230 \times 0.037$
$= 903\ \mu w/cm^2$

Lamp #10 $x = (4.66 \text{ in} \times 2.54 \text{ cm/in}) - \frac{2.54 \text{ cm}}{2} = 10.57 \text{ cm}$

$I = 24{,}230 \times e^{-(0.51)10.57}$
$= 24{,}230 \times e^{-5.39}$
$= 24{,}230 \times 0.0046$
$= 110.7\ \mu w/cm^2$

3. Determine "minimum intensity" of staggered lamp array by averaging the expected intensities of the points of reference.

a. Point of Reference A

Lamp #		I in μw/cm^2
# 1		3943
# 2		2.5
# 3		0.0
# 4		174
	Total	4119.5

b. Point of Reference B

Lamp #		I in μw/cm^2
# 5		0.0
# 6		0.0
# 7		17.8
# 8		28
# 9		903
#10		110.7
	Total	1059.5

"Minimum Intensity" of array $= \frac{4119.5 + 1059.5}{2} = 2589.5\ \mu\text{w/cm}^2$

(An additional module may be needed to facilitate the replacement of lamps and cleaning of the quartz sleeves in each of the other modules.)

4. Determine Required Minimum Detention Time:

Minimum Dosage = Minimum Intensity x Minimum Detention Time
30,000 μws/cm^2 = 2589.5 μw/cm^2 x Detention Time

Minimum Detention Time $= \frac{30{,}000\ \mu\text{ws/cm}^2}{2589\ \mu\text{w/cm}^2} = 11.6$ seconds

Adjusting for Theoretical Detention Time $\frac{11.6 \text{ sec}}{0.75} = 15.4$ sec

5. Determine Required Effective Contact Volume:

Effective Contact Volume = Peak Flow Rate x Detention Time

Peak Flow Rate $= \frac{875{,}000 \text{ gpd x } 2.0 \text{ P.F.}}{1440 \text{ min/day x } 60 \text{ sec/min}} = 20.25$ gps

Effective Contact Volume = 20.25 gpd x 15.4 sec = 312 gal

$\frac{312 \text{ gallons}}{7.48 \text{ gal/ft}^3} = 41.7\ \text{ft}^3$ (not including volume occupied by quartz sleeves)

6. Determine Effective Contact Volume of Each Lamp Module:

Channel Width	24 inches
Channel Depth	60 inches
Effective Length of Array (parallel to flow)	15 inches

Total Volume/Module = $\dfrac{24 \text{ in} \times 60 \text{ in} \times 15 \text{ in}}{1728 \text{ in}^3/\text{ft}^3} = 12.5 \text{ ft}^3$

Volume Occupied by Quartz Sleeves for Lamps

$\pi \dfrac{\text{dia}^2}{4} \times$ sleeve length x number of lamps

$\dfrac{3.1416 \, (1.0 \text{ inch})^2}{4} \times 58 \text{ in} \times 40 \text{ lamps} = 1822 \text{in}^3$

Net Contact Volume of Each Module

$12.5 \text{ ft}^3 - \dfrac{1822 \text{ in}^3}{1728 \text{ in}^3/\text{ft}^3} = 11.45 \text{ ft}^3$

7. Determine Number of Modules Required:

$\dfrac{41.7 \text{ ft}^3}{11.45 \text{ ft}^3/\text{Module}} = 3.64$ modules, use 4 modules

8. Check Actual Detention Time and Dosage Provided:

a. Determine Actual Detention Time

$11.45 \text{ ft}^3/\text{Module} \times 4 \text{ modules} \times 7.48 \text{ gal/ft}^3 = 342.6 \text{ gal}$

Theoretical Detention Time

$\dfrac{342.6 \text{ gal}}{20.25 \text{ gps}} = 16.92 \text{ sec} > 15.4$

Actual Detention Time

$16.92 \text{ sec} \times 0.75 = 12.7 \text{ sec} > 11.6$

b. Determine Dosage Provided by System

$2589.5 \, \mu\text{w/cm}^2 \times 12.7 \text{ sec} = 32{,}858 \, \mu\text{ws/cm}^2 > 30{,}000$