- flow rate, ozone concentration, temperature, and pressure monitors of ozone gas line
- ozone monitor for plant ambient air (in case of leaks)
- ozone monitoring for exhaust gas
- separate power input monitors for ozonator and air preparation units

14-9 UV DISINFECTION

The use of ultraviolet (UV) radiation for disinfection of wastewater is an emerging technology. It was first introduced almost 2 decades ago. This process has been described in the EPA Task Force Report as potentially advantageous over conventional disinfection by chlorination and ozonation.[12] In addition, it is a physical process, whereas all others are chemical processes, which leave chemical residuals. In this section the current state of knowledge on the design of the UV disinfection process is presented. Being a relatively new technology, the process design procedures are still being developed, and field data on the operation and maintenance are limited. More information will be available in the future as new plants come on-line.

14-9-1 Mechanism of UV Disinfection

Disinfection by UV radiation is a physical process that relies on the transfer of electromagnetic energy from a source (lamp) to the cellular material (protein and nucleic acids) of an organism. The basic premise of the UV disinfection process is that radiation must be absorbed by the organisms so that the energy can have a damaging effect. The UV light that is absorbed by the organisms is measured by *reflectance*, or *transmittance*. The DNA molecule of an organism is the principal target of UV photons. When UV energy is absorbed by the genetic material (DNA) of an organism, structural changes or damage occur that may prevent the propagation of the organisms. The absorbance of UV radiation by DNA molecules depends on the wavelength of the radiation. It has been shown that the most effective spectral region for germicidal effect is in the range of 250–265 nm with an optimum absorbance by nucleic acid around 254 nm.[12]

Repair of the damaged DNA molecules occurs when injured organisms are exposed to the visible range (primarily blue spectrum) subsequent to their UV exposure. This repair phenomenon has been described as *photoreactivation* and has been detected in many organisms.[20] The repair is enzymatic and requires light in the wavelength of 310–500 nm to complete the repair of damage caused by UV exposure. Among the species most often addressed by wastewater discharge permitting, the *E. coli* will photorepair while *Enterococci* cannot. Viruses do not have this ability except when in a host cell that can repair. Maximum repair occurs during summer months. A maximum of 1.5 log increase in total coliform count may occur in receiving waters after UV exposure.[21]

14-9-2 The Source of UV Light

The primary source of UV energy, at present, is the low-pressure mercury lamp. It is almost universally accepted as the most efficient and effective source of UV radiation for

disinfection systems. The primary reason for its acceptance is that approximately 85 percent of its energy output is nearly monochromatic at the wavelength of 253.7 nm. This is within the optimum wavelength for germicidal effects. The lamps are tubes, typically 0.75–1.5 m in length and 1.5–2.0 cm in diameter. Some manufacturers supply shorter, thicker and high-pressure lamps. The radiation is generated by striking an electric arc through mercury vapor, which results in the emissions of UV light. Approximately 35 to 40 percent of the energy is converted to light, and approximately 85 percent of the light has a wavelength of 253.7 nm.

14-9-3 Types of UV Reactors

UV reactors are of two basic types: contact and noncontact. In both types the liquid flow may be parallel or perpendicular to the lamp. Different types of UV reactors are compared in Table 14-6. The lamp arrangement and technical details are shown in Figure 14-13.

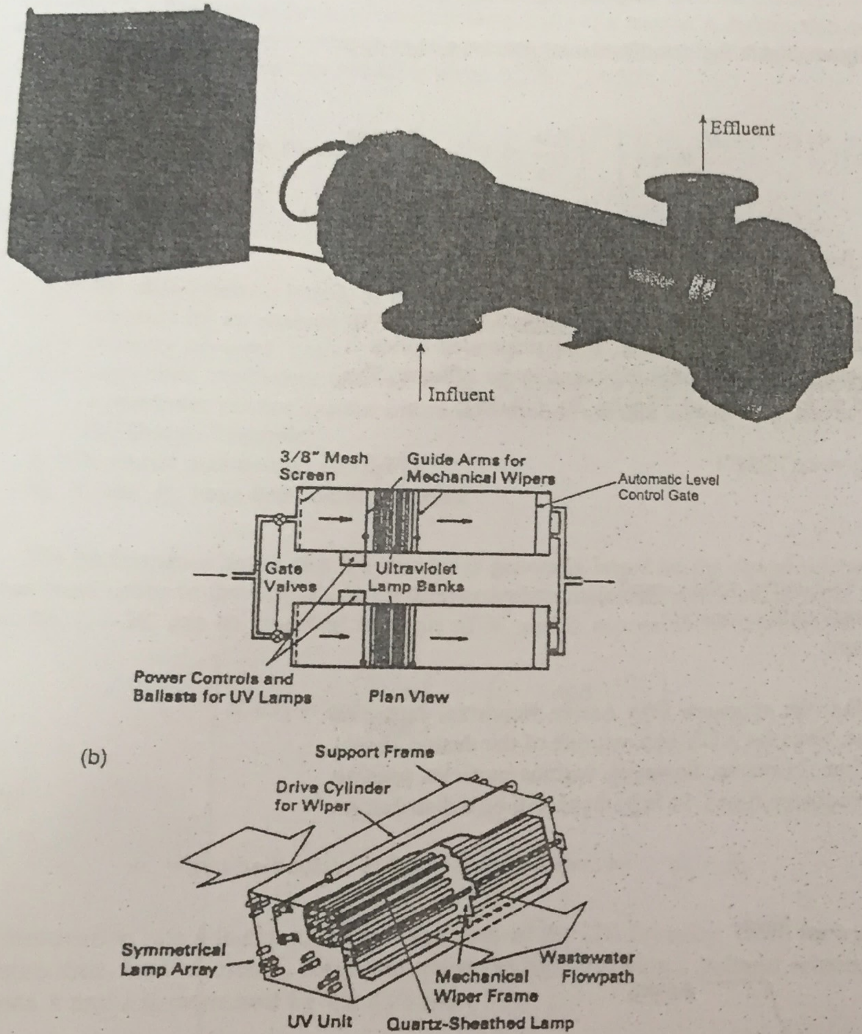
14-9-4 General Description of UV Process

Several mathematical models have been proposed to estimate the inactivation of bacteria caused by UV radiation. These models are mostly based on first-order kinetics. The ideal

TABLE 14-6 Comparison of Contact and Noncontact UV Reactors

Reactor Type	Description	Flow Direction	Flow Type
Contact	The lamps are submerged at all times in wastewater. The lamps are encased in quartz sleeves that are slightly larger in diameter than the lamps. The lamp module or rack is encased in a sealed shell.	Parallel to lamps or perpendicular to lamps	Pressure or open channel
Noncontact	Lamps or quartz sleeves do not come in contact with the liquid. The lamps are suspended above the liquid or surround the Teflon® conduits that carry the liquid. These Teflon® conduits are transparent to UV light. The lamps are placed outside and parallel to the conduits or as an inserted removable rack (either vertically or horizontally) between the tubular rows.	Parallel to lamps or perpendicular to lamps	Pressure or gravity flow

(a)



(b)

Figure 14-13 System Components of UV Disinfection Reactors: (a) example of closed vessel UV reactor, with flow parallel to lamps (courtesy of Trojan Technologies Inc.); (b) contact-type reactor with flow direction perpendicular to the lamps, and open channel flow (from Ref. 21).

(c)

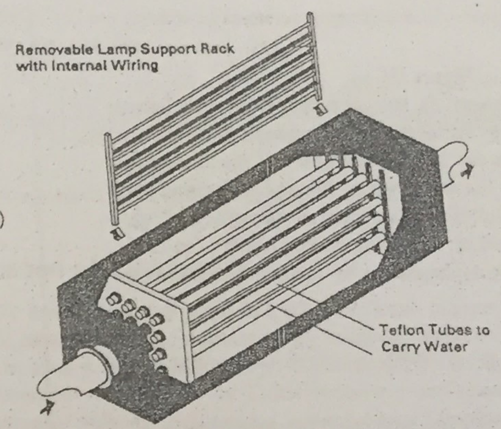


Figure 14-13—cont'd (c) example of UV system utilizing Teflon® tubes (from Ref. 12).

UV disinfection model is expressed by Eq. (14-30). The logarithmic expression of this equation yields a linear relationship [Eq. (14-31)].

$$N_t = N_0 e^{-kIt} \tag{14-30}$$

$$\ln (N_t/N_0) = -kIt \tag{14-31}$$

where

N_t = bacterial density remaining after exposure to UV and often after photorepair, numbers per unit volume of liquid
N_0 = initial bacterial density, numbers per unit volume of liquid
I = intensity of UV radiation, $\mu W/cm^2$. A procedure to determine UV intensity is covered in Sec. 14-9-5.
t = exposure time, min
k = rate constant, t^{-1}

The intensity I is the rate at which the energy is delivered to the liquid. The product of UV intensity and time of exposure is called UV dose. The rate constant k is the slope of the line [Eq. (14-31)]. The above equations represent the idealized situations. In practice, however, deviation from the ideal model may occur because of many interfering effects, such as the following:

- Tailing effect is attributed to occulation or shadowing of bacteria by suspended particles. Filtration prior to UV disinfection is recommended to increase the efficiency.
- There is minimal or no response below a threshold dose (shoulder).

The tailing and shouldering effects are shown in Figure 14-14.

The intensity of UV radiation will attenuate as the distance from the lamps increases. This is caused by dissipation of energy in increasing surrounding volume or space. A second attenuation mechanism involves the actual absorption of the energy by physical, chemical, and biological constituents in the wastewater. This is *UV demand* and is analogous to *chlorine demand.* The UV demand of a wastewater is quantified by absorption of energy per unit depth. This is expressed by absorbance units per cm (au/cm). The au/cm is related to transmittance of UV light as measured by a spectrophotometer and is expressed by Eq. (14-32):

$$\% \text{ Transmittance} = 100 \times 10^{-(\text{au/cm})} \qquad (14\text{-}32)$$

In most designs, a coefficient α is used to express UV absorbance. The coefficient α is to the base e and is directly related to au/cm. This relationship is expressed by Eq. (14-33):

$$\alpha = 2.3 \text{ (au/cm)} \qquad (14\text{-}33)$$

The unit of α is cm^{-1}.

The suspended solids in the liquid reduces the efficiency of UV radiation. Experiments with mixed culture have shown that, as the UV dose is increased, the efficiency of inactivation is also increased but in a reduced proportion. The main reason is the aggregation or occulation of bacteria in particulate matter.[22-26] As a result the UV light is unable to penetrate aggregated material, and inactivation of the trapped bacteria does not occur. Thus, continued increase in the UV dose shows a reduced efficiency of inactivation.

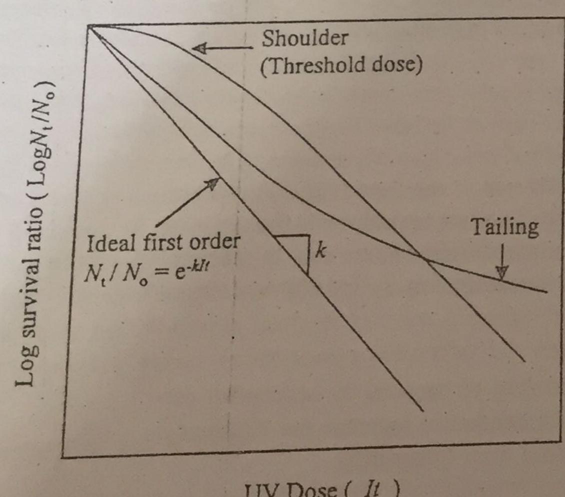


Figure 14-14 Illustration of UV Model and the Interfering Effects (from Ref. 12).

This phenomenon is shown in Figure 14-15. Eq. (14-30) is modified to include this effect:

$$N_t = N_0\, e^{-kIt} + N_p \qquad (14\text{-}34)$$

where

N_p = particulate bacterial density that is unaffected by UV light

The particulate bacterial density N_p is generally expressed as a function of some measurable index, such as total suspended solids (TSS) or turbidity. Total suspended solids is generally used because it is the parameter most commonly regulated in the effluent. The value of N_p is conveniently expressed as a function of TSS by Eq. (14-35):

$$N_p = c_1 (\text{TSS})^{m_1} \qquad (14\text{-}35)$$

where

TSS = total suspended solids, mg/L
c_1 = proportionality constant
m_1 = constant

From Eq. (14-34), it is apparent that the exposure time t is an important factor to achieve the desired level of inactivation. Thus for a UV system, one of the design objectives is to achieve a typical exposure time. In reality, however, various particles passing through the reactor will have different exposure times. In fact, there will be a distribution

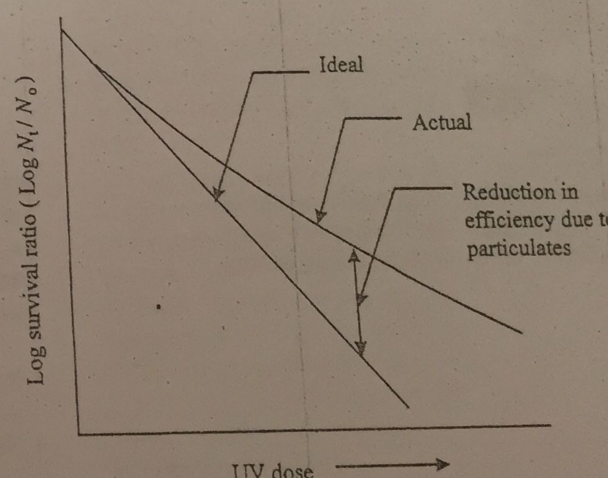


Figure 14-15 Effect of Particulate Matter on UV Disinfection Efficiency (from Ref. 12).

of time around the ideal time, which is known as the residence time distribution (RTD). The RTD is a function of the dispersion characteristics of a reactor. A disinfection model that incorporates dispersive properties of a reactor was developed by Scheible et al.[24] A generalized expression of this model is given by Eq. (14-36):

$$N_t = N_0 \exp\left[\frac{ux}{2E}\left\{1-\left(1+\frac{4kE}{u^2}\right)^{1/2}\right\}\right] + N_p \qquad (14\text{-}36)$$

where

x = the characteristic length of the reactor, defined as the average distance traveled by an element of water while under direct exposure to UV, cm
u = velocity of water, cm/s
E = dispersion coefficient (cm^2/s). E can be estimated from the RTD curve of a particular reactor system (more information on this subject is given in the Design Example)
k = bacterial inactivation rate, s^{-1}
N_t, N_0 and N_p have been defined earlier.

The performance curve of a UV reactor is generally based on the nonparticulate effluent fecal coliform density, N'. Since the particulate fecal coliform density N_p is additive, Eq. (14-36) can be modified in terms of N' and is expressed by Eq. (14-37):

$$N'/N_0 = \exp\left[\frac{ux}{2E}\left\{1-\left(1+\frac{4kE}{u^2}\right)^{1/2}\right\}\right] \qquad (14\text{-}37)$$

where

N' = nonparticulate effluent coliform density = $N_t - N_p$

The inactivation rate k is expressed as a function of the UV intensity. Thus, for a given exposure time, k will increase, depending upon the light intensity I. A linear relationship between k and I is expressed by Eq. (14-38):

$$k = a\,(I_{avg})^b \qquad (14\text{-}38)$$

where

a and b = slope and intercept of the linear regression developed from log function of the equation
I_{avg} = average intensity of light in the reactor, $\mu W/cm^2$

Eqs. (14-36) and (14-38) are combined to give a generalized UV design model. This model is expressed by Eq. (14-39):

$$N_t = N_0 \exp\left[\frac{ux}{2E}\left\{1-\left(1+\frac{4Ea(I_{avg})^b}{u^2}\right)^{1/2}\right\}\right] + c_1(\text{TSS})^{m_1} \qquad (14\text{-}39)$$

All terms in Eq. (14-39) have been defined earlier.

14-9-5 Determination of UV Intensity

Determination of UV intensity at any point in a complex lamp reactor is not straightforward. At the present time there is no commercially available detector that can measure the true intensities in such a system. Moreover, different lamp configurations will yield different nominal intensities in the reactor. Calculations are performed for a number of designs and subsequently reduced to show the intensity as a function of UV density of the reactor and UV energy absorbed.

The UV density, D is defined as the total nominal UV power (at 253.7 nm) available within a reactor divided by the liquid volume of the reactor (D = total UV output/liquid volume). The density is directly related to the spacing of the lamps; the closer the spacing, the higher is the UV density in the reactor. Typical spacing configurations are as follows:

- uniform array: The lamps are arranged in even, horizontal rows and vertical columns. The centerline spacings are generally equal in both directions [Figure 14-16(a)].
- staggered uniform array: The array is similar to uniform array, except that the alternating vertical rows are offset by one-half of vertical spacing. The staggered effect is designed to induce turbulence [Figure 14-16(b)].
- centric array: The lamps are arranged in concentric circles [Figure 14-16(c)].
- tubular array: The lamps are suspended outside and parallel to a Teflon® conduit. The lamps and tubes are stacked vertically in alternating rows. The equivalent vertical and horizontal centerline spacing between lamps is generally kept equal [Figure 14-16(d)].

Generalized graphical relationships have been developed for four arrangements of tubes to obtain average nominal intensity from UV absorbance coefficient and UV density for different lamp arrangements. These relationships are given in Figure 14-17. It is important to note that, in Figure 14-17, the intensity of UV radiation is calculated by assuming that the quartz sleeve or Teflon® tube transmits 100 percent of the energy emitted by the lamps. That is why it is expressed as calculated nominal average intensity. Under actual operation and for design purposes, the nominal average intensity of lamps must be adjusted to account for the aging of the lamps and consequent reduction of UV output caused by losses of energy as it passes through the quartz sleeves or Teflon® walls. These losses are caused by fouling of the inner side of the Teflon® tubes and the outer surface of the quartz sleeves because of the contact with wastewater. Thus, to es-

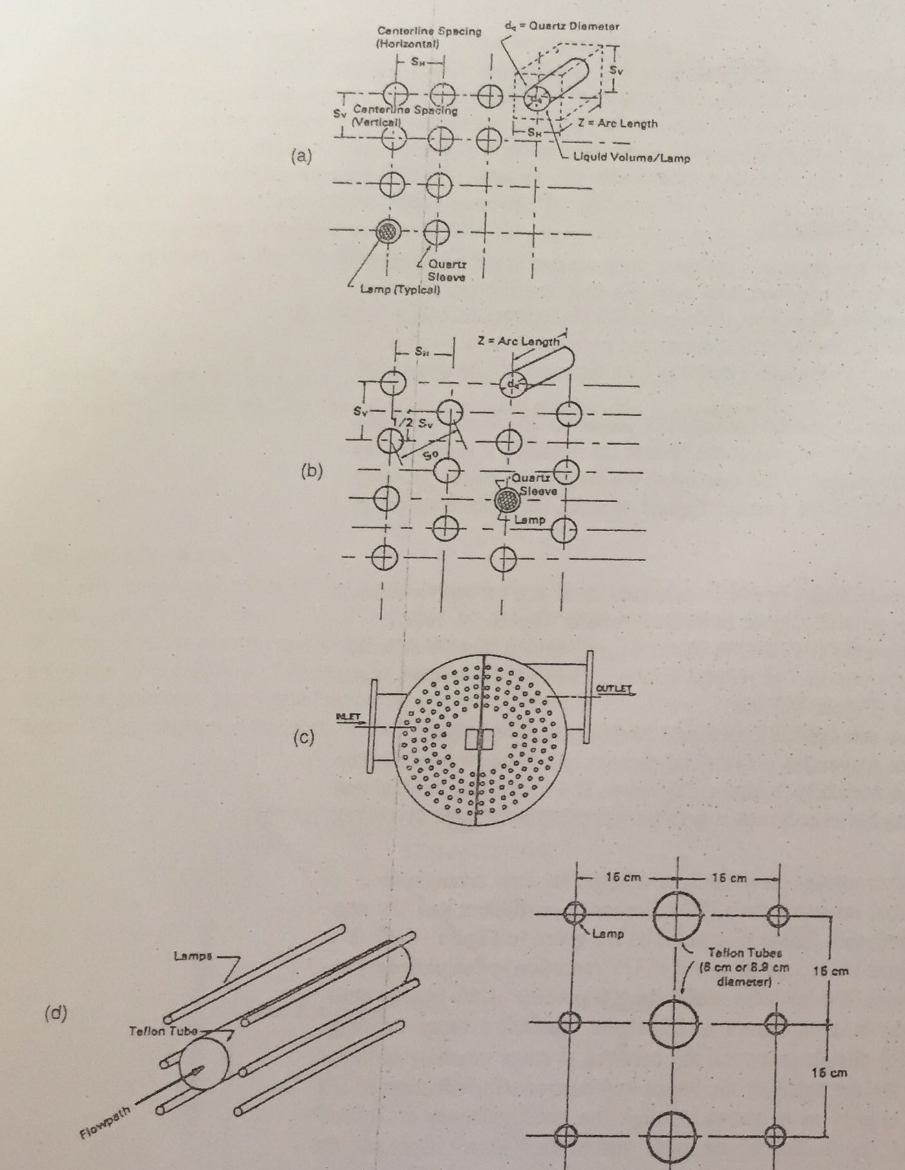


Figure 14-16 Schematic of Different Lamp Arrangements (from Ref. 12): (a) uniform array, (b) staggered uniform array, (c) concentric array, and (d) tubular array.

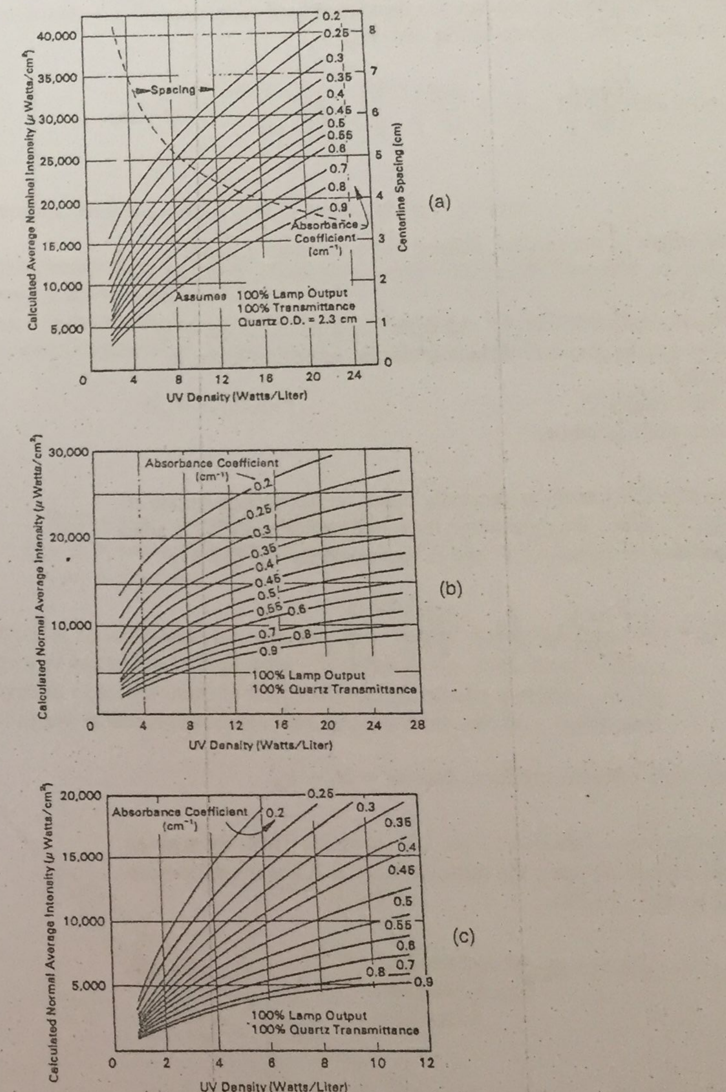


Figure 14-17 The Average Nominal Intensity as a Function of the Reactor UV Density and UV Absorbance Coefficient for Different Lamp Arrangements (from Ref. 12): (a) uniform array, (b) staggered uniform array, (c) concentric array.

Continued

(d)

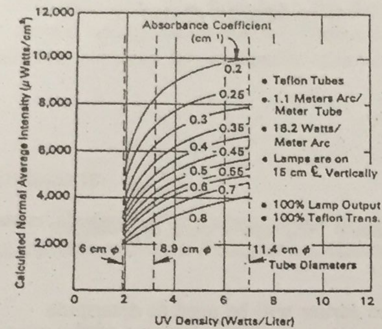


Figure 14-17—cont'd (d) tubular array.

timate the actual intensity under a given set of field conditions, it is necessary to adjust the nominal intensity. Eq. (14-40) is normally used for this purpose.

$$I_{avg} = (\text{Nominal } I_{avg}) \times F_p \times F_t \tag{14-40}$$

where

F_p = ratio of the actual output to the nominal output of the lamps
F_t = ratio of the actual transparency of the quartz sleeve or Teflon® tubes to the nominal transparency (100%) of the enclosures

When designing a new unit, the system should be designed at an average F_p of 0.8, which represents a lamp inventory output at approximately one-half of its operating life. An F_p of 0.65 is expected at the end of the operating life. A reasonable minimum F_t would be 0.7 for a quartz system and 0.6 for a Teflon® system.

14-9-6 Hydraulic Design of UV Reactor

There are three basic design objectives of an effective UV disinfection reactor: (a) the unit should be a plug flow reactor (PFR), and (b) the flow motion should be turbulent radially from the direction of flow. This allows each element to receive the same overall average intensity of radiation in the nonuniform intensity field that may exist in the reactor. The trade-off in this requirement is that some axial dispersion will be introduced, yielding a dispersive or nonideal plug flow reactor, and (c) maximum use must be made of the entire volume of the reactor. Dead spaces must be minimized so that the effective volume is very close to the actual volume available. The basic factors for a UV reactor design are discussed below.

Residence Time Distribution (RTD). The RTD provides key information on the actual or anticipated hydraulic behavior of a reactor. Dye-tracer study should be conducted to establish the actual residence time.

Dispersive Characteristic. A key goal of hydraulic design of the UV reactor is to minimize the dispersion and maximize the contact time. Therefore, the average velocity profile should be established at different flow conditions.

Turbulence and Head Loss. An important consideration in the hydraulic design of a UV reactor is fluid turbulence. Some turbulence is desired for uniform distribution of UV energy in the nonuniform intensity field of the reactor. But turbulence is associated with head loss, which is a function of velocity. Head loss is the controlling factor in the design of a reactor. This topic is discussed in the Design Example.

Effective Volume. Maximum use of the reactor volume is another important design consideration. The lamp battery volume is the portion of the total vessel volume that is occupied by UV lamps. It is therefore important that the reactor is designed to utilize the maximum vessel volume. Dead zones or short-circuited areas would also mean ineffective use of lamp power. Both components of the system (reactor and lamp battery) comprise a major portion of the capital and operating costs.

14-10 EQUIPMENT MANUFACTURERS OF A UV DISINFECTION FACILITY

A number of equipment manufacturers supply UV disinfection systems. Names and addresses of many manufacturers are given in Appendix D. The design engineer should work closely with the local representatives of the equipment suppliers. A good performance record of UV disinfection equipment at other installations should be reviewed before equipment selection is made. Responsibilities of the design engineer for proper equipment selection are given in Sec. 2-10.

14-11 INFORMATION CHECKLIST FOR DESIGN OF A UV DISINFECTION FACILITY

The following information must be obtained and decisions made before the design engineer should proceed with the design of a UV disinfection facility:

1. Effluent TSS (must be typically less than 20 mg/L)
2. Peak wet weather, peak dry weather, average design, and minimum initial flows
3. Treatment plant design criteria prepared by the concerned regulatory agency
4. Specified contact time and corresponding flow condition (peak or average)
5. UV absorbance or transmittance of the effluent to maintain the desired level of germicidal effect; color caused by industrial wastes can be serious.
6. Equipment manufacturers and equipment selection guide
7. Information about existing facility if plant is being expanded
8. Head loss constraints through the unit; the automatic level control gate requires a minimum of 0.4 m of head loss.
9. Existing site plan with contours and location of the disinfection system
10. Influent and effluent seasonal coliform count for specific flows (annual average,

maximum 7-day average, maximum 30-day average, peak dry weather, and peak wet weather)

11. Amount of redundancy required
12. Attitude and capability of operating and maintenance staff towards cleaning the lamps and providing continued operation under adverse conditions
13. Likely future expansion of the plant and anticipated design changes such as module size, number of banks, and number of channels

14-12 DESIGN EXAMPLE

14-12-1 Design Criteria Used

The following design criteria shall be used for the design of the UV disinfection system.

Step A: General

1. The plant's permit calls for year-round disinfection.
2. The influent to the UV disinfection system is the effluent from the secondary clarifiers. Many manufacturers recommend a coarse screen in the channel ahead of the UV disinfection facility.
3. Provide a Parshall flume ahead of the UV disinfection facility to measure the flow. The flow data are necessary to operate the required number of channels and lamp modules.
4. The following flow shall be used for the design of the UV system:
   - average daily wastewater flow = 0.440 m^3/s (26,400 Lpm) (Table 6-9)
   - maximum 7-day average flow = 0.660 m^3/s (39,600 Lpm). This flow is based on 1.5 × (avg. daily flow)
   - maximum 30-day average flow = 0.484 m^3/s (29,040 Lpm). This flow is based on 1.1 × (avg. daily flow)
   - peak dry weather flow = 0.917 m^3/s (55,000 Lpm) (Table 6-9)
   - peak wet weather flow = 1.321 m^3/s (79,300 Lpm) (Table 6-9)
5. The following TSS values shall be used for the influent to the plant:
   - average daily TSS = 10 mg/L
   - maximum 7-day average TSS = 20 mg/L
   - maximum 30-day average TSS = 10 mg/L
6. Influent fecal coliform density:
   - average daily = 5×10^5 org[d]/100 mL
   - maximum 7-day = 2×10^6 org/100 mL
   - maximum 30-day = 1×10^6 org/100 mL
   - peak dry weather = 1×10^6 org/100 mL
   - peak wet weather = 0.5×10^6 org/100 mL
7. Required effluent fecal coliform density:
   - average daily = 100 org/100 mL
   - maximum 7-day average = 200 org/100 mL
   - maximum 30-day average = 100 org/100 mL
   - peak dry weather flow = 200 org/100 mL
   - peak wet weather flow = 400 org/100 mL
8. UV transmittance (at 253.7 nm wavelength of UV)
   - daily average flow = 70%
   - maximum 7-day average flow = 60%
   - maximum 30-day average flow = 65%
9. Assume UV transmittance at peak wet weather flow = 70% and at peak dry weather flow = 65%.

[d]Organisms.

Step B: Reactor. The disinfection models presented earlier will be used to determine the optimum design for the stated application. Several design scenarios and unit configurations will be evaluated to maximize the loading to the system while still meeting the performance goals.

The basic assumptions for the reactor design are

1. Provide uniform lamp array.
2. The center to center spacing of the lamps shall be 6.0 cm.
3. The lamps shall be 1.5 m long with an effective arc length of 1.47 m; the nominal UV output is approximately 18.2 W (watts)/m arc.
4. Each lamp is sheathed in a quartz enclosure with an outer diameter of 2.3 cm.
5. The lamps shall be configured axially parallel to one another, and the flow path will be parallel to the lamps.
6. The values of the energy loss factors, F_p and F_t [Eq. (14-39)], are 0.8 and 0.7, respectively.
7. The coefficient a, b, c_1, m_1, and E in Eqs. (14-35), (14-36), and (14-38) are generally developed experimentally because they are site-specific. The typical values of these coefficients for disinfection of secondary effluent from a POTW are used here.[12] These typical values are

$$a = 1.45 \times 10^{-5}$$
$$b = 1.3$$
$$c_1 = 0.25$$
$$m_1 = 2.0$$

E varies in the range of 120–1300 cm^2/s in proportion to the flow.

14-12-2 Reactor Type and Arrangement

The UV system designed in this example utilizes four open channels arranged in parallel. Each channel has two banks of UV lamps in series. Each bank contains several UV modules in a *uniform array*. The flow is parallel to the UV lamps. The flow from a Parshall flume enters a common influent division channel that divides the flow into the UV disinfection channels. A sluice gate and identical rectangular weir at the head of each disinfection channel divide the flow equally into each channel. The entire system consists of UV modules, power distribution centers, and all necessary interconnecting cables, along with a host of accessory components. The effluent structure has an automatic control flap gate level controller. The flow from the flap drops into a common collection channel. The system configuration for the Design Example and layout of other UV system installation supplied by equipment manufacturers are shown in Figure 14-18.

14-12-3 Design Calculations

Step A: Disinfection Reactor Design. The reactor design involves UV lamp selection, arrangement and cleaning, module and bank arrangement, channel sizing, and head loss calculations.

1. Calculate the UV density of the reactor.
   The UV density is calculated from the volume of liquid exposed to light. Two banks of the UV module are placed in series in each channel.
   a. Calculate the volume of liquid (V_v) exposed per lamp.
      The lamp spacings in both vertical and horizontal directions are 6 cm (Figure 14-19). The volume of liquid exposed per lamp is calculated from Eq. (14-41):

$$V_v/\text{lamp} = (S^2 Z) - (\pi d_q^2/4)Z \qquad (14\text{-}41)$$

where

S = center to center spacing between the lamps = 6 cm
Z = arc length of the lamp = 147 cm
d_q = diameter of quartz sleeve = 2.3 cm

$$\text{Therefore, } V_v/\text{lamp} = \{(6.0\text{ cm})^2 \times (147\text{ cm})\} - \{\tfrac{\pi}{4}(2.3\text{ cm})^2 \times 147\text{ cm}\}$$
$$= 4700\text{ cm}^3 \text{ or } 4.7\text{ L}$$

   b. Calculate the UV density.

$$\text{The UV density, } D = \text{total UV output per lamp/liquid volume per lamp}$$
$$= (1.47\text{ m arc} \times 18.2\text{ W/m arc})/4.7\text{ L}$$
$$= 5.7\text{ W/L}$$

   c. Calculate the absorbance unit (au/cm), absorbance coefficient α, nominal UV intensity (nominal I_{avg}), and adjusted UV intensity (adjusted I_{avg}).
      (i) At average daily flow
      The absorbance unit (au/cm) is calculated from Eq. (14-32). At average daily flow, the UV transmittance at 253.7 nm = 70% (see Design Criteria)

$$70 = 100 \times 10^{-\text{au/cm}}$$
$$\text{au/cm} = 0.155$$

The absorbance coefficient α is calculated from Eq. (14-33):

$$\alpha = 2.3 \times (0.155/\text{cm})$$
$$= 0.35/\text{cm}$$

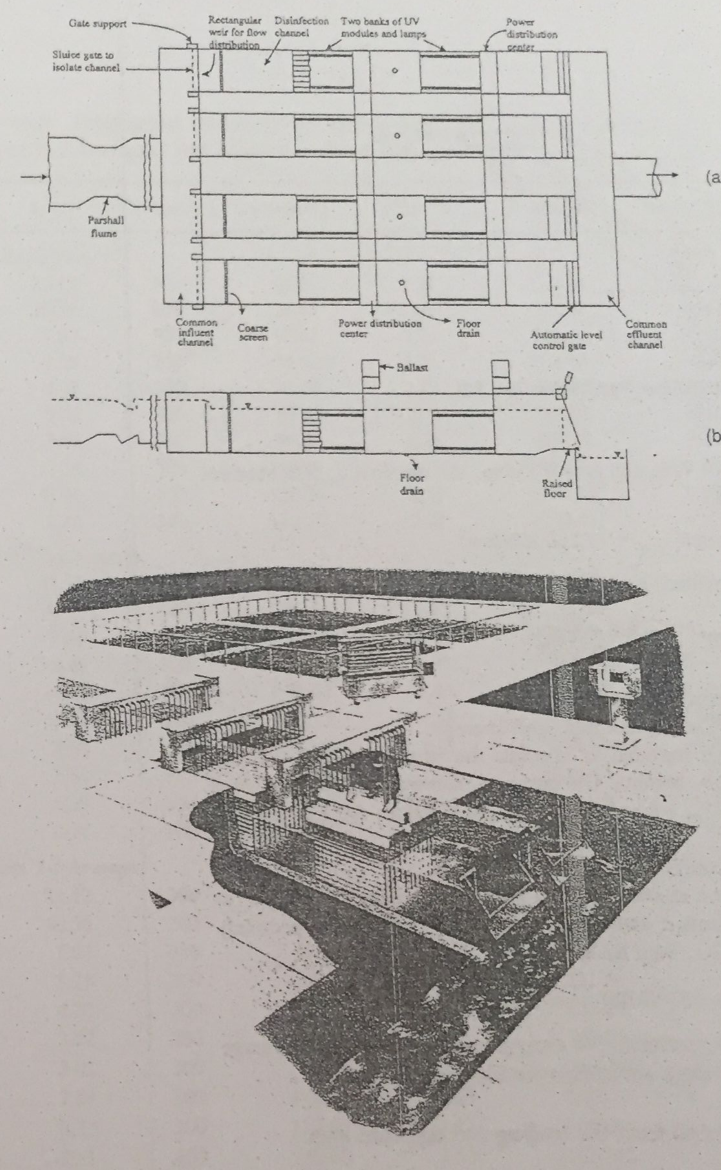


Figure 14-18 UV Disinfection System Layout: (a) plan view, (b) longitudinal section of proposed facility for the Design Example, and (c) a photograph of UV system with two channels and three banks (courtesy Trojan Technologies, Inc.).

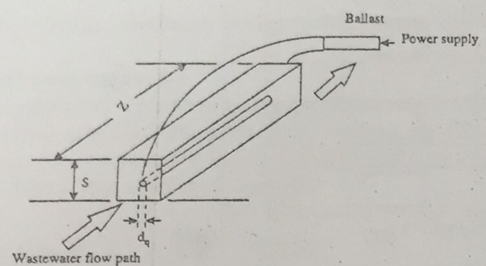


Figure 14-19 One UV Lamp and Flow Path (from Ref. 12).

At UV density = 5.7 W/L and α = 0.35/cm, the nominal I_{avg} is obtained from Figure 14-17(a):

$$\text{Nominal } I_{avg} = 17{,}300\ \mu W/cm^2$$

Adjusted I_{avg} is calculated from Eq. (14-40):

$$\text{Adjusted } I_{avg} = 17{,}300\ \mu W/cm^2 \times 0.8 \times 0.7 = 9700\ \mu W/cm^2$$

These results are summarized in Table 14-7.

(ii) Maximum 7-d average and maximum 30-d average.
The above procedure is repeated to calculate the absorbance unit (au/cm), absorbance coefficient α, nominal UV intensity (nominal I_{avg}), and adjusted UV intensity (adjusted I_{avg}) for above flows. These values are also summarized in Table 14-7.

d. Calculate the inactivation coefficient k at different flows.
The inactivation coefficient k at average daily flow is calculated from Eq. (14-38). The values of coefficients a and b are 1.45×10^{-5} and 1.3, respectively (Design Criteria, Sec. 14-12-1, Step B, 7):

$$k = 1.45 \times 10^{-5}(9700)^{1.3} = 2.21\ s^{-1}$$

Similarly, the k values for the maximum 7-d average and maximum 30-d average flows are calculated. These values are summarized in Table 14-7.

2. Develop the performance curve.
The performance curve is developed from UV loading and exposure time.
a. Calculate the UV loading.
UV loading is defined as the volume of water exposed to the nominal UV wattage:

$$\text{UV loading} = \frac{4.7\ \text{L/lamp}}{1.47\ \text{m arc/lamp} \times 18.2\ \text{W/m·arc}} = 0.176\ \text{L/W}$$

TABLE 14-7 Adjusted Average UV Intensity and Inactivation Coefficients at Different Flow Conditions

Design Conditions	UV Transmittance at 253.7 nm (%)	UV au/cm	UV Absorbance Coefficient α (cm^{-1})	Nominal I_{avg} (μW/cm^2)	Adjusted I_{avg} (μW/cm^2)	Inactivation coefficient k (s^{-1})
Average daily flow	70[a]	0.155	0.35	17,300	9700	2.21
Maximum 7-d avg	60[a]	0.220	0.51	13,000	7300	1.53
Maximum 30-d avg	65[a]	0.190	0.43	15,100	8450	1.85

[a]Values obtained from the Design Criteria (Sec. 14-12-1 Step A, 7).

b. Calculate nominal exposure time.
The nominal exposure time t_n is the average time the water is exposed to UV light.
For each lamp t_n is calculated from volume of water exposed per lamp (V_v) and flow rate per lamp (q):

$$t_n = \frac{\text{volume of water exposed/lamp}}{\text{flow rate/lamp}} = \frac{V_v, \text{liter (L)}}{q, \text{liter per min (Lpm)}}$$

Divide numerator and denominator by W_n (watt):

$$t_n = \frac{V_v/W_n}{q/W_n}$$

To develop the UV performance curve, assign different values to variable q/W_n. For each assigned value of q/W_n, calculate the corresponding value of t_n. As an example, at $q/W_n = 0.5$ Lpm/W.

$$t_n = \frac{0.176 \text{ L/W}}{0.5 \text{ L/min}\cdot\text{W}} \times 60 \text{ s/min} = 21.12 \text{ s}$$

Similarly, calculate t_n for other assigned values of q/W_n (q/W_n = 1.0, 2.0, 3.0, and 4.0 L per min per Watt). These values are summarized in Table 14-8.

c. Calculate the velocity through UV lamps in the channel.
The velocity through the UV banks is obtained from the nominal exposure time and the liquid exposure length under the UV lamps. There are two UV banks per channel, and flow is parallel to the lamps. The length of each lamp is 150 cm. Therefore, total length of UV exposure is 300 cm. The nominal exposure time t_n for q/W_n = 0.5 Lpm/W is 21.12 s. The corresponding velocity u is calculated below:

$$u = 300 \text{ cm}/21.12 \text{ s} = 14.20 \text{ cm/s}$$

Similarly, the u values for other assumed g/W_n values are calculated and summarized in Table 14-8.

d. Calculate the dispersion coefficient.
The dispersion coefficient E relates to the hydraulic regime, mixing, or the residence time distribution in a reactor. Experimental determination of RTD using a conservative (nonreactive) dye tracer is the most reliable technique. Dispersion models are used to evaluate or diagnose the flow regime in a specific reactor. Equation (14-42) is generally used to define the dispersion behavior in a reactor:

$$d = \frac{E}{ux} \tag{14-42}$$

where

d = dispersion number
E = dispersion coefficient, cm²/s

TABLE 14-8 Calculated Performance Values log N′/N₀ at Daily Average, Maximum 7-d Average, and Maximum 30-d Average Flows

q/W_n	t_n (s)	x (cm)	u (cm/s)	k[a] (s^{-1})	E (cm²/s)	log N'/N_0
Average Daily Flow						
0.5	21.12	300	14.20	2.21	127.84	−11.37
1	10.56	300	28.41	2.21	255.68	−6.88
1.5	7.04	300	42.61	2.21	383.52	−5.02
2	5.28	300	56.82	2.21	511.36	−3.98
2.5	4.22	300	71.02	2.21	639.20	−3.31
3	3.52	300	85.23	2.21	767.05	−2.83
3.5	3.02	300	99.43	2.21	894.89	−2.48
4	2.64	300	113.64	2.21	1022.73	−2.20
4.5	2.35	300	127.84	2.21	1150.57	−1.98
5	2.11	300	142.05	2.21	1278.41	−1.80
Maximum 30-d Average						
0.5	21.12	300	14.20	1.85	127.84	−10.04
1	10.56	300	28.41	1.85	255.68	−6.01
1.5	7.04	300	42.61	1.85	383.52	−4.35
2	5.28	300	56.82	1.85	511.36	−3.43
2.5	4.22	300	71.02	1.85	639.20	−2.84
3	3.52	300	85.23	1.85	767.05	−2.43
3.5	3.02	300	99.43	1.85	894.89	−2.12
4	2.64	300	113.64	1.85	1022.73	−1.88
4.5	2.35	300	127.84	1.85	1150.57	−1.69
5	2.11	300	142.05	1.85	1278.41	−1.54
Maximum 7-d Average						
0.5	21.12	300	14.20	1.53	127.84	−8.76
1	10.56	300	28.41	1.53	255.68	−5.18
1.5	7.04	300	42.61	1.53	383.52	−3.73
2	5.28	300	56.82	1.53	511.36	−2.92
2.5	4.22	300	71.02	1.53	639.20	−2.41
3	3.52	300	85.23	1.53	767.05	−2.05
3.5	3.02	300	99.43	1.53	894.89	−1.79
4	2.64	300	113.64	1.53	1022.73	−1.58
4.5	2.35	300	127.84	1.53	1150.57	−1.42
5	2.11	300	142.05	1.53	1278.41	−1.29

[a]These values are taken from Table 14-7.

The variables u and x are defined earlier.

True plug-flow and complete-mix reactor regimes are reached when d approaches 0 and ∝, respectively. Performance of a disinfection system is high under plug flow conditions. At $d = 0.03$, low to moderate dispersion exists, and E values are calculated for different flow velocities. Sample calculations for $q/W_n = 0.5$ are given below:

$$0.03 = \frac{E}{14.2 \text{ cm/s} \times 300 \text{ cm}}$$

$$\text{or } E = 27.8 \text{ cm}^2\text{/s}$$

Similarly, the values of E for other assumed q/W_n values are calculated and are summarized in Table 14-8.

e. Calculate UV performance values, log N'/N_0.

The UV performance values log N'/N_0 for average daily, maximum 7-d average, and maximum 30-d average flow conditions are calculated from Eq. (14-37). Sample calculations for $q/W_n = 0.5$ and average daily flow are shown below. It may be noted that if the effect of photoreactivation in the effluent or receiving water is considered, then the procedure for developing the performance goal should be modified.

$$N'/N_0 = \exp\left[\frac{ux}{2E}\left\{1 - \left(1 + \frac{4kE}{u^2}\right)^{1/2}\right\}\right]$$

The values of u and E are given in Table 14-8, $x = 300$ cm, and $k = 2.21 \text{ s}^{-1}$.

$$N'/N_0 = \exp\left[\frac{14.2 \text{ cm/s} \times 300 \text{ cm}}{2 \times 127.8 \text{ cm}^2\text{/s}}\left\{1 - \left(1 + \frac{4 \times 2.21 \text{ s}^{-1} \times 127.8 \text{ cm}^2}{(14.2 \text{ cm})^2}\right)^{1/2}\right\}\right]$$

$$= \exp(-26.17)$$

$$\ln N'/N_0 = -26.17$$

$$\log N'/N_0 \times \ln 10 = -26.17$$

$$\log N'/N_0 = -26.17/2.3 = -11.37$$

Similarly, the performance values for the three flow conditions are calculated and arranged in Table 14-8. The performance curves (log N'/N_0 versus q/W_n) for the three flow conditions are developed and are shown in Figure 14-20.

3. Establish the performance goals.

The performance goals of the UV disinfection facility are developed from the permit requirements of the fecal coliform. The values of N_p are calculated from Eq. (14-35), with the coefficient c and m_1 equal to 0.25 and 2.0, respectively (see Design Criteria). These values are then subtracted from the permitted effluent fecal coliform densities to yield the design performance goals (N'org/100 mL). This value is then used to compute log (N'/N_0) for the design purposes. The goals are established for

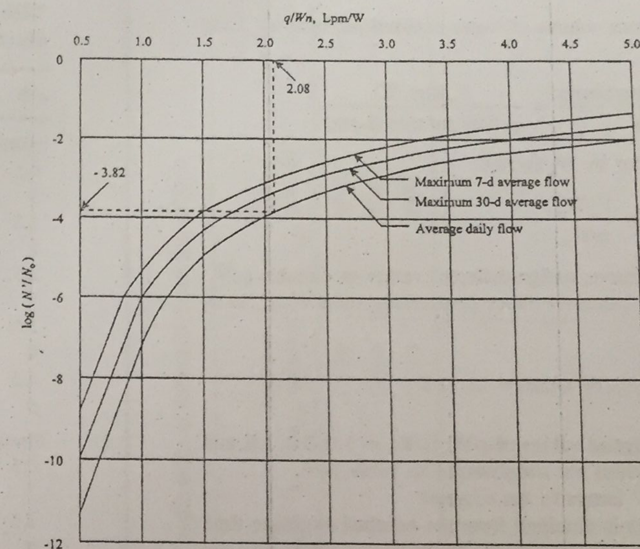


Figure 14-20 Performance Curves.

daily average flow, maximum 7-d average, and maximum 30-d average. Various values are summarized in Table 14-9.

4. Determine UV-loading (q/W_n) to achieve performance goals.

The performance curves are used to obtain the required UV-loading (q/W_n) to achieve the performance goals. The UV-loading (q/W_n) for average day, maximum 7-d average, and maximum 30-d average are read directly from the corresponding performance curves in Figure 14-20, to achieve the performance goals established in Table 14-9. For example, for average day flow and the required removal of log $(N'/N_0) = -3.82$, the UV-loading (q/W_n) is obtained from Figure 14-20. This value is 2.08. Similarly, the values for maximum 7-d average and maximum 30-d average are also obtained from Figure 14-20. These values are summarized in Table 14-10. The performance curves for design peak dry weather and design peak hour flows are not developed. The UV-loadings q/W_n for these flows are estimated from the closest performance curves (Figure 14-20). The UV-loading values for these flows are also summarized in Table 14-10.

5. Calculate the nominal exposure time t_n.

The value of nominal exposure time t_n is the time required to achieve the required disinfection. It is obtained from the equation,

$$t_n = \frac{0.176}{q/W_n} \times 60 \text{ s}$$

TABLE 14-9 *Estimate of Reactor Performance Requirement for the Design Example*

	Daily Average	Maximum 7-Day Average	Maximum 30-Day Average	Peak Dry Weather	Design Peak Hour
Initial fecal coliform density,[a] N_0 (org/100 mL)	5×10^5	2×10^6	1×10^6	1×10^6	0.5×10^6
Total suspended solids (mg/L)	10	20	10	20[b]	20[b]
Particulate coliform density, N_p (org/100 mL)	25[c]	100	25	100	100
Effluent coliform density, N (org/100 mL)	100[d]	200[d]	100[d]	200[d]	400[b]
Performance goals N' (org/100 mL)	75[e]	100	75	100	300
Required UV performance value log (N'/N_0)	−3.82[f]	−4.3	−4.12	−4.0	−3.22

[a]Values are given in the Design Criteria (Sec. 14-12-1, Step A, 5)
[b]Assumed values.
[c]$N_p = c(\text{TSS})^m$
$= 0.25\,(10)^{2.0}$
$= 25$
[d]Obtained from effluent standards (Table 6-6).
[e]$N' = N - N_p$
$= 100 - 25$
$= 75$
[f]$\log (N'/N_0) = \log \left(\dfrac{75}{5 \times 10^5}\right)$
$= -3.82$

The values of nominal exposure time for different flow conditions to achieve the required performance levels are given in Table 14-10.

6. Calculate the number of lamps required.
The number of lamps required is calculated from Eq. (14-43):

$$\text{Number of lamps} = \frac{\dfrac{Q}{q/W_n}}{W/\text{Lamp}} \qquad (14\text{-}43)$$

The required UV loading q/W_n for different flow conditions and for needed performance are provided in Table 14-10.

TABLE 14-10 *The Maximum UV Loading and Number of Lamps Required as Different Flow Conditions to Achieve the Required Performance Levels*

	Daily Average	Maximum 7-Day Average	Maximum 30-Day Average	Peak Dry Weather	Design Peak Hour
Required UV performance value, log (N'/N_0)	−3.82[a]	−4.3	−4.12	−4.0	−3.22
Maximum q/W_n (Lpm/W), from performance curve	2.08[b]	1.28[b]	1.58[b]	1.40[c]	1.83[c]
Nominal exposure time t_n, s	5.1	8.3	5.9	8.3	5.8
Flow (Lpm)	26400	36900	29040	55000	79300
Lamp requirement	475	1078	687	1468	1620

[a]For daily average flow the required performance, log $(N'/N_0) = -3.82$ is obtained from Table 14-9.
[b]The maximum UV-loading, q/W_n is obtained from performance curves (Figure 14-20).
[c]The performance curve for maximum 7-d average flow is used.

$$\text{Number of lamps at average daily flow} = \frac{\dfrac{26{,}400 \text{ Lpm}}{2.08 \text{ Lmp/W}}}{\dfrac{1.47 \text{ m.arc}}{\text{Lamp}} \times \dfrac{18.2 \text{ W}}{\text{m.arc}}}$$

$$= 475 \text{ lamps}$$

Similarly, the number of lamps at all other flow conditions are calculated and summarized in Table 14-10.

7. Design the UV disinfection channel.
The maximum number of UV lamps (1620 lamps) are needed for design peak hour flow. There are four disinfection channels and each channel has two banks.

Number of lamps per channel = 405 lamps
Number of lamps per bank = 203
Provide 12 lamps per module.
Number of modules per bank = 16.9 or 17
Total number of lamps per bank = 204
Total number of lamps provided = 1632
Water depth in the channel = 12 lamp × 6 cm spacing/lamp
= 72 cm or 0.72 m
Provide a free board = 0.6 m
Width of the channel = 17 modules × 6 cm spacing/lamp
= 102 cm or 1.02 m

This arrangement gives lamp spacings 6 cm center to center in vertical and horizontal directions, 3 cm from the bottom and sides of the channel to the center of the lamp, and 3 cm from the free water surface to the center of the lamp. Different manufacturers may specify different spacings. Designers must work closely with the manufacturer for proper clearance requirements in the channel. The design details and lamp arrangement is shown in Figure 14-21. This arrangement gives a total of 408 lamps per channel.

8. Location of UV bank in the channel
The placement of influent and effluent structures relative to lamp arrays is critical to achieve uniform flow. Measurement of velocity profiles in full-scale systems show that a minimum of 2 m (6 ft) should be allowed between inlet/outlet structures and the closest lamp array.[27]

9. Select the head loss equation.
The head loss through a UV bank causes a drop in the free water surface in the channel. This may cause serious operational problems in the disinfection process. If the liquid level is set such that the downstream free surface is coincident with the top of the irradiated zone, then some liquid on the upstream end will pass through a region of low intensity. Conversely, if the free surface is set in accordance with the upstream lamps, then the portions of the lamps in the lower end of the bank may not be immersed. With diurnal fluctuations in the flow, some lamps may experience alternate immersion and dryness, which may cause fouling of quartz sleeves and irregular heat distribution that may shorten the life of the lamps. Some designers have used the sloping bottom of the channel to step down the subsequent banks.

The head loss through the UV banks depends on the number and arrangement of the UV lamps, system geometry, and velocity through the channel. Most manufacturers of the UV system have experimentally developed a relationship between head loss and velocity through the net section of UV bank. The functional relationship between the head loss and velocity may be expressed by Eq. (14-44):

$$\Delta h/L = au + b\rho u^2 \qquad (14\text{-}44)$$

where

Δh = head loss, cm
L = length of chamber over which Δh is expressed, cm
u = approach velocity, cm/s
ρ = liquid density, g/cm^3
a, b = empirical constants measured by field test

Under laminar flow conditions, only the first term in the equation is important. Under turbulent conditions, only the second term is important. Experimental results have shown that in a UV system the second term accounts for most of the head loss.

The designers are more familiar with Eq. (7-9) for calculation of head loss through valves, fittings, elbows, contractions, expansions, and so on. Blatchley experimented head loss across UV banks arranged in series in a UV channel. He reported the experimental results as head loss per bank as a function of approach ve-

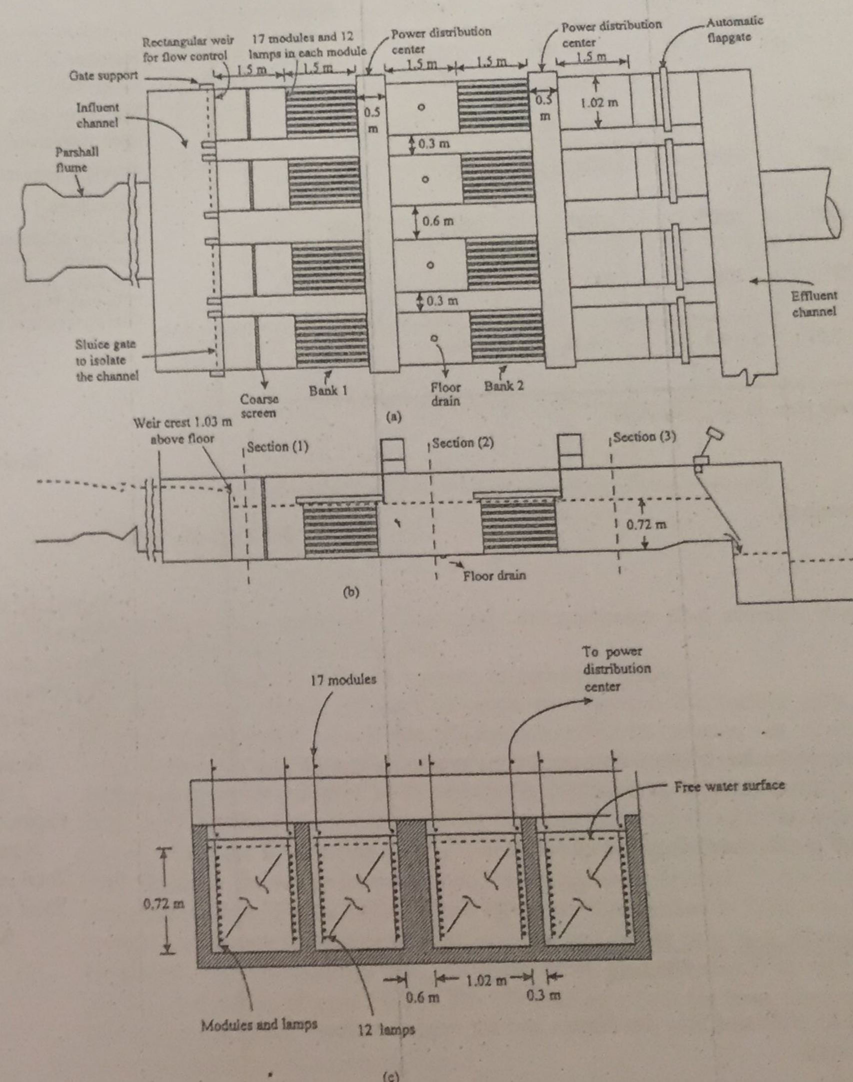


Figure 14-21 Design Details of the UV System: (a) plan, (b) longitudinal section, (c) cross section.

Continued

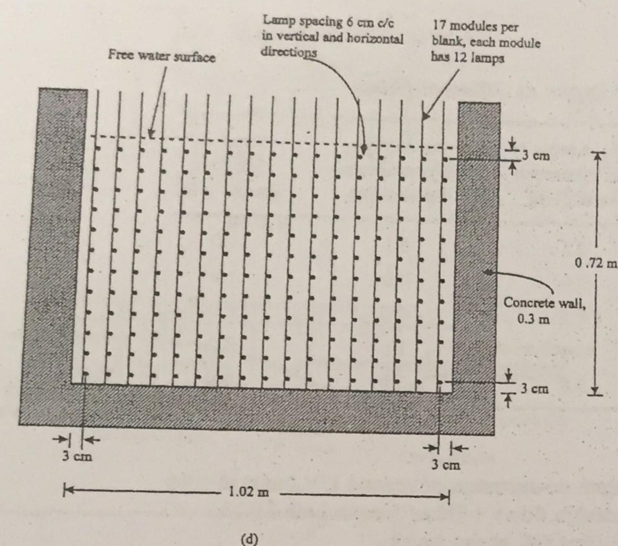


Figure 14-21—cont'd (d) details of modules and lamp arrangement.

locity.[27] From these experimental data the head loss coefficients K for each bank as a function of approach velocity are calculated. These K values are shown in Figure 14-22. These K values shall be used in Eq. (7-9) to determine head loss across each UV bank in series. Eq. (7-9) for UV application is given below:

$$h_L = Kv^2/2g$$

10. Calculate the head loss through the UV system at average daily flow.
The procedure for calculating head loss through the UV system involves the use of the energy equation at downstream and upstream sections of the UV bank. Apply the energy equation at section (3) and (2) as shown in Figure 14-21(b).
a. Calculate head loss across the downstream bank.

$$\text{Flow per channel}^{e} = 0.11\ \text{m}^3/\text{s}$$

The depth of liquid above the top of UV lamp at the downstream end of the second bank

[e]Average flow = 0.440 m³/s. Flow per channel = $\frac{0.44}{4}$ m³/s = 0.11 m³/s.

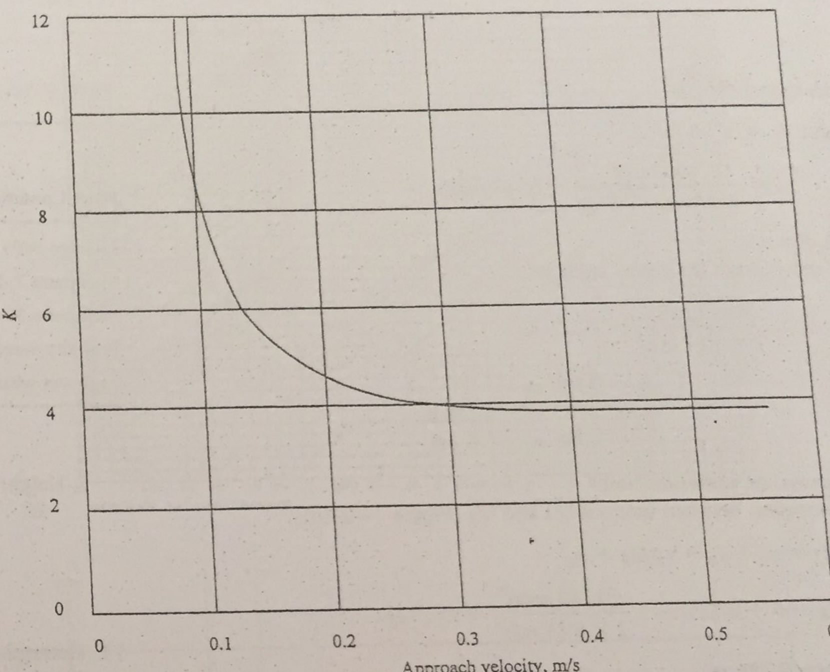


Figure 14-22 The Head Loss Coefficient through Two Banks Arranged in Series.

$$\text{section (3)}^{f} = \left(\frac{6\ \text{cm}}{2} - \frac{2.3\ \text{cm}}{2}\right) = 1.85\ \text{cm}$$

$$\text{Channel width} = 1.02\ \text{m}$$

$$\text{Liquid depth in the channel at section (3)} = 0.720\ \text{m}$$

$$\text{Velocity of flow, } v_3 \text{ at section (3)} = 0.11\ \text{m}^3/\text{s}/\ (1.02\text{m} \times 0.72\ \text{m}) = 0.150\ \text{m/s}$$

Applying energy equation between sections (2) and (3) [Figure 14-21(b)]

$$z_2 + d_2 + v_2^2/2g = z_3 + d_3 + v_3^2/2g + h_L$$

$$0 + d_2 + v_2^2/2g = 0 + 0.72\ \text{m} + \frac{(0.150\ \text{m/s})^2}{2 \times 9.81\ \text{m/s}^2} + Kv_2^2/2g$$

$$d_2 + (1 - K)\, v_2^2/2g = 0.721\ \text{m}$$

[f]The center-to-center spacing of the lamps is 6 cm, and the outer diameter of quartz sleeve is 2.3 cm.

Using the trial-and-error method,

Assume $d_2 = 0.725$ m

$$v_2 = \frac{0.11\ \text{m}^3/\text{s}}{0.725\ \text{m} \times 1.02\ \text{m}} = 0.149\ \text{m/s}$$

From Figure 14-21, $K = 4.6$.
Solving for d_2 and v_2 from the above equation,

$$d_2 + (1 - 4.6) \times \frac{(0.149\ \text{m/s})^2}{2 \times 9.81\ \text{m/s}^2} = 0.721\ \text{m}$$

$$d_2 = 0.725\ \text{m}$$
$$h_L = 0.725\ \text{m} - 0.720\ \text{m} = 0.005\ \text{m or } 0.5\ \text{cm}$$

b. Calculate head loss across the upstream bank.
Applying the energy equation between sections (1) and (2) [Figure 14-21(b)]

$$z_1 + d_1 + v_1^2/2g = z_2 + d_2 + v_2^2/2g + h_L$$

$$0 + d_1 + v_1^2/2g = 0 + 0.725\ \text{m} + \frac{(0.149\ \text{m/s})^2}{2 \times 9.81\ \text{m/s}^2} + Kv_1^2/2g$$

$$d_1 + (1 - K)\, v_1^2/2g = 0.726\ \text{m}$$

Using the trial-and-error solution, $d_1 = 0.730$ m, $v_1 = 0.148$ m/s, and $K = 4.61$.

Head loss across the upstream bank $= 0.730\ \text{m} - 0.725\ \text{m}$
$= 0.005$ m or 0.5 cm

Total head loss $= 0.730\ \text{m} - 0.720\ \text{m}$
$= 0.01$ m or 1.0 cm

c. Calculate the head loss across upstream and downstream banks for different flow conditions. These head losses are summarized in Table 14-11.

11. Determine the head loss through the influent structure.
The influent structure to the UV channel is controlled by a rectangular weir. The length of the weir is the same as the width of the UV channel. A free fall of 0.08 m at average design flow is provided in the UV channel. The head over weir at average and peak design flows are calculated below:

$$H_{avg} = \left[\frac{3}{2} \times \frac{0.11\ \text{m}^3/\text{s}}{0.6 \times 1.02\ \text{m} \times \sqrt{2 \times 9.81\ \text{m/s}^2}}\right]^{2/3} = 0.16$$

$$H_{peak} = \left[\frac{3}{2} \times \frac{0.33\ \text{m}^3/\text{s}}{0.6 \times 1.02\ \text{m} \times \sqrt{2 \times 9.81\ \text{m/s}^2}}\right]^{2/3} = 0.32$$

12. Determine the height of influent weir above the floor of UV channel.

TABLE 14-11 Head Loss across UV Banks at Different Flows

Flow Condition	Flow (m^3/s)	h_L Across for Upstream Bank (cm)	h_L Across Downstream Bank (cm)	Total h_L for Two Banks (cm)
Average daily	0.11	0.5	0.5	1.0
Maximum 7-d average	0.17	0.9	0.9	1.8
Maximum 30-d average	0.12	0.5	0.5	1.0
Peak dry weather	0.23	1.4	1.6	3.0
Peak wet weather	0.33	3.0	3.0	6.0

Height of influent weir = (water depth downstream of second UV bank at average design flow) + (head loss in both UV banks) + (free fall at the weir)
= 0.72 m + 0.01 m + 0.08 m
= 0.81 m

13. Determine the head loss in the influent channel.
The head losses in the influent channel will be encountered because of excessive turbulence, friction, flow distribution, and change in direction. Therefore, a total of 0.37-m head loss is assumed in the influent channel.
14. Determine the head loss at the effluent structure.
The effluent structure has a raised floor on which an automatic flap gate level control structure is installed. The flap-type gate with counterweights keeps the liquid level near the effluent structure at the exact depth. A free fall at the downstream of the gate is necessary for proper operation of the flap gate. As a result, the entire head because of channel depth is lost at the gate. In this design, the channel floor is raised 0.3 m to conserve some head. Therefore, a total of 0.42 m (0.72 m − 0.30 m) head will be lost at the gate. Provide a free fall of 0.20 m downstream of the gate.

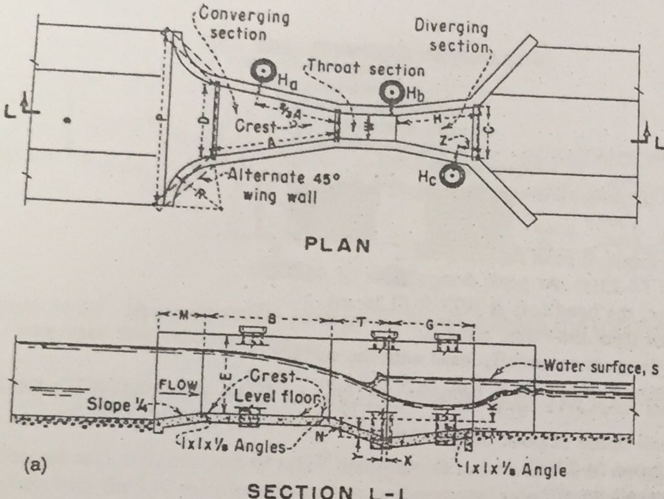
Step B: Parshall Flume Design. A standard Parshall flume is designed as an integral part of the UV disinfection system. The flow measured at the Parshall flume will be divided into the operating UV disinfection channels equally. The design details of the Parshall flume are shown in Figure 14-23.

1. Select the dimensions of the channel upstream of the Parshall flume.

Channel section = rectangular

Width of the channel = 2.0 m

Depth of flow at peak design flow, y_1 = 0.8 m



Standard dimensions of 1.22 m (4ft) Parshall flume

W	1.22m
A	1.83m
B	1.79m
C	1.52m
D	1.94m
E	0.91m
T	0.61m
G	0.91m
H	-
K	0.08m
M	0.46m
N	0.23m
P	2.66m
R	0.61m
X	0.05m
Y	0.08m
Z	-
Capacity,min.	36.81l/s
Capacity,max.	1922.71l/s

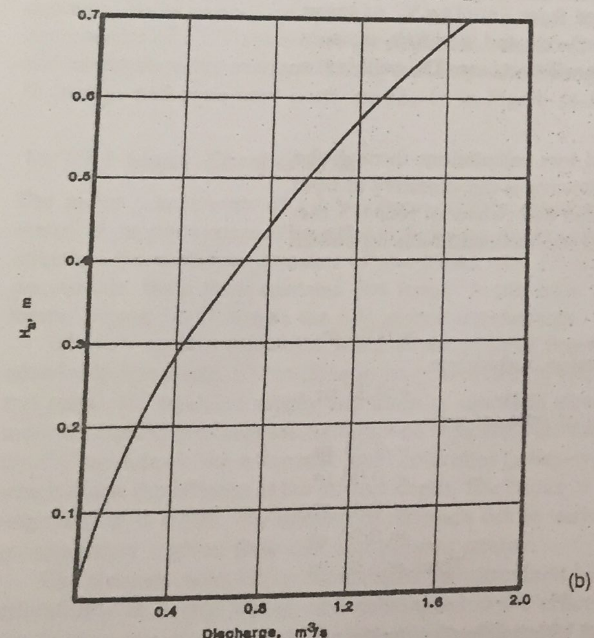
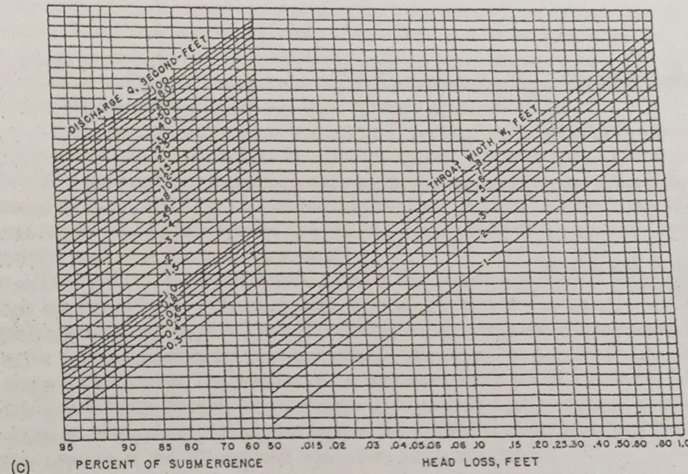


Figure 14-23 Design Details of Parshall Flume Used for Flow Measurement in the Design Example: (a) standard dimensions of Parshall flume (from Refs. 28 and 29); (b) calibration curve of 1.22 m (4 ft) Parshall flume.



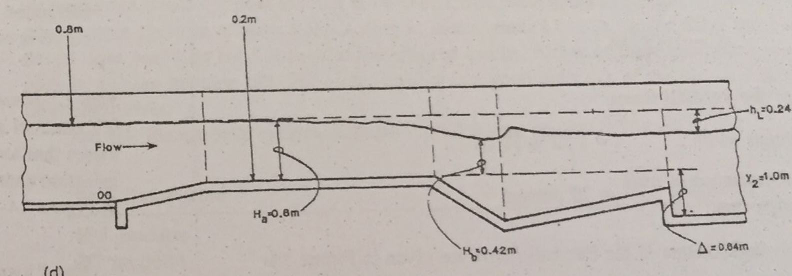


Figure 14-23—cont'd (c) head loss through Parshall flume, second-ft = ft³/s. (from Refs. 28 and 29); and (d) water surface profile through Parshall flume at peak design flow.

The slope of the channel is obtained from the Mannings Equation [Eq. (7-1)].

$$\text{Cross-sectional area} = 2.0\ \text{m} \times 0.8\ \text{m} = 1.60\ \text{m}^2$$

$$R = \frac{\text{area}}{\text{perimeter}} = \frac{1.60\ \text{m}^2}{\text{width} + 2\ \text{depth}}$$

$$= \frac{1.60\ \text{m}^2}{2.0\ \text{m} + 2 \times 0.8\ \text{m}}$$

$$= 0.44\ \text{m}$$

$$1.321\ \text{m}^3/\text{s} = 1.60\ \text{m}^2 \times \frac{1}{0.013} \times (0.44\ \text{m})^{2/3}\ S^{1/2}$$

$$S = 0.000344$$

2. Select the dimensions of the rectangular channel downstream of the Parshall flume.

Width	= 2 m
Depth of flow at peak design flow y_2	= 1 m

The slope of the channel is obtained from Eq. (7-1).

$$\text{Cross-sectional area} = 2.0\ \text{m} \times 1\ \text{m} = 2.0\ \text{m}^2$$

$$R = \frac{2.0\ \text{m}^2}{2\ \text{m} + 2 \times 1\ \text{m}} = 0.5\ \text{m}$$

$$1.321\ \text{m}^3/\text{s} = 2.0\ \text{m}^2 \times \frac{1}{0.013} \times (0.5\ \text{m})^{2/3} \times S^{1/2}$$

$$S = 0.000186$$

3. Select the dimensions of the Parshall flume.

Throat width	= 1.22 m (4 ft)
Submergence at peak design flow	= 70 percent

The dimensions of various components of the Parshall flume are given in Figure 14-23(a).

4. Select the discharge equation for the Parshall flume.
At submergence below 70 percent, the flow through a 1.22-m Parshall flume is essentially the same as for free flow conditions.[28,29] Free flow discharge for a Parshall flume is given by Eq. (14-45):

$$Q = 4WH_a^{1.522W^{0.026}} \qquad (14\text{-}45)$$

where

Q = free flow, cfs
W = throat width, ft
H_a = depth of water at upstream gauging point, ft (Figure 14-23)

5. Compute H_a and H_b (depth of water at upstream and downstream gauging points).
H_a at peak design flow of 1.321 m³/s (46.7 cfs) is calculated from Eq. (14-45):

$$46.7\ \text{cfs} = 4 \times 4\ \text{ft} \times H_a^{1.522(4\ \text{ft})^{0.026}}$$

Solving this equation,

$$H_a = 1.97\ \text{ft}\ (0.6\ \text{m})$$

$$H_b \text{ at 70 percent submergence} = 0.7 \times 1.97\ \text{ft} = 1.38\ \text{ft}\ (0.42\ \text{m})$$

6. Compute head loss H_L through Parshall flume at peak design flow.
The head loss is computed from Figure 14-23(c). At peak design flow of 46.7 cfs (1.321 m³/s) and 70 percent submergence, the head loss is 0.77 ft (0.24 m).
7. Compute the downstream channel bottom from the flume crest Δ.
The water surface in the flume at the H_b gauge is essentially level with the surface in the downstream channel. Therefore, $\Delta = y_2 + H_L - H_b = 1.00\ \text{m} + 0.24\ \text{m} - 0.60\ \text{m} = 0.64\ \text{m}$.
8. Prepare water surface through the Parshall flume at peak design flow.
The water surface profile is shown in Figure 14-23(d).
9. Prepare the calibration curve for the Parshall flume.
The calibration curve for the Parshall flume is prepared from Eq. (14-45). At lower flows the water depth in the contact chamber will be reduced, and therefore, the submergence at the downstream side of the Parshall flume will increase. The calibration curve is shown in Figure 14-23(b).

Step C: Head Losses and Hydraulic Profile. The head loss calculations through the UV channel and Parshall flume were provided earlier. Following is the summary of head losses that are encountered through each unit at peak design flow when all four UV disinfection chambers are in service. The hydraulic profile for such a condition is illustrated in Figure 14-24.

Head loss through Parshall flume	= 0.24 m
Head loss in the influent channel due to free fall friction, turbulence, entrance, etc. (assume)	= 0.37 m
Differential head between upstream and downstream of influent weir of UV disinfection channel	= 0.35 m
Head loss through UV disinfection channel	= 0.06 m
Head loss through level control gate	= 0.42 m
Free fall downstream of gate	= 0.20 m
Total	= 1.64 m

A total head loss of 1.64 m at the Parshall flume and UV disinfection facility is disproportionately large; however, such head losses are not uncommon. In situations where adequate head is not available, free fall allowances could be reduced, and further raising the channel floor at the level control gate may be considered.

Step D: Design Details. The design details of the UV disinfection facility and Parshall flume are provided in Figures 14-21, and 14-23.

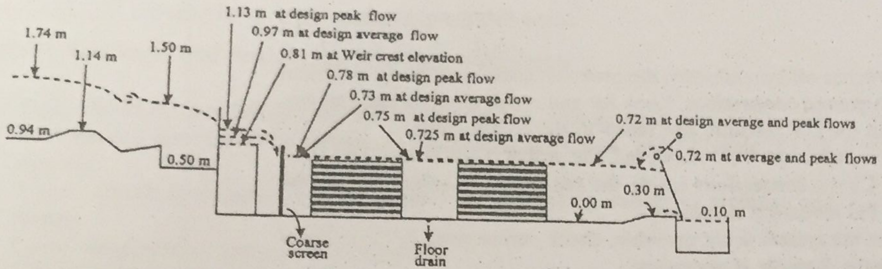


Figure 14-24 Hydraulic Profile Through the Parshall Flume and UV Disinfection Channel at Peak Hour Wet Weather Flow.

14-13 OPERATION AND MAINTENANCE AND TROUBLESHOOTING AT UV DISINFECTION FACILITY

Operation and maintenance of a UV disinfection system requires well-trained operators familiar with the UV disinfection system and personal safety. It is also important that the operators know various components of the UV system. Therefore, a summary of major components of a UV system are presented first, followed by operation and maintenance and troubleshooting sections. The hydraulic profile through the UV disinfection channel at average and peak hour flows are shown in Figure 14-23.

14-13-1 Major Components

The major components of a UV system include disinfection channel, UV banks, and electrical supply system. The effluent flows by gravity into four open channels for disinfection. Each channel consists of two banks with 17 modules per bank and 12 lamps per module. Each bank contains 204 lamps. In all, eight banks contain a total of 1632 lamps. Figure 14-21 shows the UV system components.

The UV system disinfects water as the effluent flows through the banks. A power cord leads from each UV module to its power control (PC) module, located in the control panel. PC modules supply and monitor electrical power to the UV lamps. The UV modules and PC modules can be removed separately for maintenance. Downstream from the UV modules is the automatic level controller (a flap-type gate with counterweights), which keeps the effluent at the correct depth. The banks of UV modules can be operated singularly or in series. The number of channels can be varied to meet the disinfection requirements of a given flow rate and effluent quality.

The stainless steel UV modules hold the ultraviolet lamps. The lamps are enclosed individually in quartz sleeves and submerged in the effluent channel. UV modules are held in the support frame with the module handle above the water. Each UV module is connected to a power cable that leads through the wireway to a PC module in the control panel. The lamps are 147 cm long, and there are 12 lamps in each module.

The PC Modules are located in the control panels. Each PC module contains the ballasts for the UV lamps and a printed circuit board that monitors current to the lamps.

Attached to the circuit board and visible on the front of the PC module are light emitting diodes (LEDs). They indicate the status of each lamp and are arranged in the same order as the lamps they monitor. One additional LED monitors the power to the PC module. The number and type of ballast, type of circuit board, and power requirements of the PC module depend on the number and type of lamps in the UV module.

A total of eight control panels house the PC modules. A power cable leads from each PC module to the UV module in the effluent channel. The monitoring LEDs are visible through a window in the lockable front door. The PC modules connect to the main power supply through ground fault circuit interrupters. Lamp ballasts are kept at operating temperature by cooling fans located near the ballasts. The service entrance for the control panel is located at the main disconnect.

The automatic level controller is a device that keeps the effluent at the proper depth. It is positioned in the effluent channel downstream from UV modules. It consists of a baffle balanced by weights. The baffle automatically swings partially open in proportion to the flow and releases the excess discharge. This keeps the effluent level constant, regardless of flow rate. The position of the balance weights can be adjusted to control the liquid level in the channel. The automatic level controller can be opened completely and rested on a stop chain to lower the depth in the channel to a minimum level. This permits maintenance of the UV modules while they are in the channel.

The UV sensor probe measures the intensity of UV light at 254 nm and converts this measurement into a UV dose reading at the meter. The meter is also equipped with a UV dose remote alarm or running light. A drop in meter reading can be caused either by reduced light output or by a change in the effluent quality. Either of these conditions results in a lower bacteria kill. The meter reading is a good indicator of the system's disinfecting power.

The UV disinfection system includes the following equipment items:

Item Description	Quantity
UV modules	136
PC modules	136
Stainless steel control panel	8
Stainless steel UV rack assembly	8
Automatic level controller	4
Cable wireway tray stainless steel	4
Elapsed time meters	8
UV module cleaning rack, cleaning basins and jib crane	2

14-13-2 Routine Operation and Maintenance

Routine operation consists of operating the UV disinfection channels in parallel. During a peak design wet weather flow of 1.32 m^3/s, all four channels and eight banks must be in operation. During the average flow condition, only two channels or one bank in four channels will provide the required degree of disinfection. One UV bank may be removed for cleaning and maintenance any time except during peak wet weather flow condition.

The following operation and maintenance steps are necessary to keep a trouble-free operation:

1. Start up: To start up a UV channel, turn on the lamps for that channel. Then start the water flow through the channel by operating the gate over the weir. Verify that the drain valves are closed. Lamps require approximately 20 minutes to warm up.
2. Shut down: To shut down a channel, close the slide gate to that channel and open the drain valve. After the channel is drained, turn off the UV lamps.
3. Operation: Check daily and record the meter reading of UV dose. Also check the LED display on the UV control cabinet. If the lamps or ballasts are burned out, replace them.
4. Dirty quartz sleeves and lamps can reduce disinfection efficiency. Turn off the lamp module and electric supply before removing the module or bank. Do not overtighten the sensor clamp on the quartz sleeves because this may break the sleeve.
5. Do not operate near UV lamps without proper eye, face, and body protection. Monitor the water surface and effluent gate to keep the top of the lamp near the gate completely submerged and to keep the water surface about 2 cm above the lamp.
6. Clean the UV module as needed in accordance with the manufacturer's instructions.
7. Regularly monitor the fecal coliform in the influent and effluent of the UV disinfection channel. Also record the number of banks and modules on-line and the flow rate. This information is used to determine the actual dose being applied. Additionally, the information is useful over time, to identify trends, predict cleaning intervals, and provide design information for future expansions.
8. Measure TSS and turbidity in the effluent. Both TSS and turbidity affect the performance of the UV system. If TSS or turbidity is higher than normal, all standby modules should be utilized to maintain the required degree of disinfection.
9. Insects are generally attracted by the UV light. Vacuum the area daily around the UV disinfection channels if an insect problem occurs.
10. Replace lamps after 8700 hours of actual operation.

14-13-3 Troubleshooting

The following troubleshooting guide should be utilized:

1. If power LED is on but two or more LEDs are out, the probable cause may be
   a. Malfunctioning of one or more lamps: A single faulty lamp can cause more than one LED to go out. Replace the appropriate lamps one at a time.
   b. If the LED is still off, check the connections in the PC module. The problem may be caused by a malfunctioning ballast. Identify the faulty ballast by the lamp number written on it and replace the ballast. If necessary, replace the circuit board of the entire module.
2. If all LEDs are on but the PC module is out, make sure that the main switch is on and the PC module and related UV module are properly connected. Press the RESET switch located on the ground fault receptacle. If it does not solve the problem, plug the PC module into a different ground fault receptacle and press the RESET switch. The following troubleshooting guide may apply:
   a. If the receptacle switches off immediately, the probable cause may be an electrical leak (short) through ground connections. Look for and repair any cracked sleeves, loose connections in the UV module, and faults in the power cable.
   b. If the receptacle stays on but the LED is still out, the probable cause may be a fault in the PC module. Check connections inside the receptacle. Replace the circuit board or the entire PC module if necessary.
   c. If LEDs come on but the system is not operable, check connections to the original ground fault receptacle. Replace if necessary.
3. If the sensor indicates that the UV dose is below the desired level, the probable causes of the problems and solutions are as follows:
   a. A sudden drop in measured dose may be caused by dirt or debris on the sensor window. Clean if necessary.
   b. A low measured dose reading may be caused by a faulty lamp being monitored. Try a different lamp.
   c. Decrease in effluent quality may cause low readings in other sensors. If readings of other sensors are acceptable, the sensor in question may be faulty.
   d. A gradual drop in sensor reading may be caused by a coating on the sleeve. Clean the sleeve.
   e. A low measured dose after elapse of a reasonable amount of time since installation of the lamp may be caused by normal depreciation of the lamp output. If sufficient time has not been elapsed, the lamp is faulty. Replace the lamp in both cases. Follow the instructions for lamp replacement.

14-14 SPECIFICATIONS

Specifications on a UV facility are briefly presented in this section. The purpose of these specifications is to describe many components that could not be fully covered in the design. The design engineer should use these specifications only as a guide. Detailed specifications for each unit or component should be prepared in consultation with the equipment manufacturers.

14-14-1 General

The contractor shall provide all labor, materials, tools, and equipment required to furnish and install a complete, tested, and ready-for-continuous-service ultraviolet disinfection system in an open channel as shown on the design plans.

14-14-2 Channels and Housing

The contractor shall provide four UV disinfection channels complete with foundations, concrete channels, handrails and stairs, piping, channel drains and valves, solid metal grating over the UV banks to confine light exposure within the banks (to minimize the insect attraction), walkway grating, channel isolation gates, lifting hoist, and main electrical power systems.

14-14-3 UV Equipment

The UV equipment shall include the following components:

1. Eight UV banks, two banks in series in each channel, with uniform array in horizontal rows, and flow parallel to lamps, 17 modules in each bank, and 12 lamps in each module
2. Power distribution center, control panel, interconnecting cables to modules and alarms
3. Lamp identification and monitoring system
4. UV intensity monitoring systems
5. Module cleaning station liner
6. Energy conservation flow pacing system
7. Automatic level control
8. UV eye shields and safety equipment
9. Spare parts
10. Startup, testing, and personnel training

14-14-4 Quality Assurance

1. The UV disinfection system shall be capable of disinfecting the specified flows based on the minimum effluent quality.
2. Provide a 5-year history of successful installations. Evidence of previous performance shall include the operational data documented by a laboratory independent of the manufacturer.
3. Provide a reference list of a minimum of five wastewater treatment plants in which similar UV disinfection systems have been installed. The list shall include operator names and current telephone numbers.

14-14-5 Performance Requirements

1. The lamp output must be at least 65 percent of initial levels after 1 year of operation and with no fouling on the lamp sleeves.
2. The head loss through two series banks at peak design flow shall not exceed 6 cm, this being confirmed by measurements in the field after startup.
3. The system shall be designed for energy conservation and partial system shutdown by automatic flow pacing of modules in a manner that minimizes any loss of disinfection capacity. The system specified shall be able to continue providing disinfection of at least 90 percent of peak design flow when the largest single bank of lamps are out of service for cleaning or while replacing UV lamps, quartz sleeves, ballasts, or electronic circuit boards.

14-14-6 UV Module

1. Each horizontal UV module shall consist of 12 UV lamps, each enclosed in an individual quartz sleeve. The sleeve shall be sealed with a UV-resistant double seal with stainless steel backup. The closed end of the quartz sleeve shall be held in place by means of a UV-resistant retaining cup. The quartz sleeve shall not come into contact with any stainless steel in the frame. The quartz sleeve shall provide a minimum of 90 percent transmission at a 254-nm wavelength and shall have a nominal wall thickness of 1.0 mm.
2. Each module shall be labeled with the module number permanently attached to the module and shall be constantly visible without requiring the grating to be removed. The module enclosure shall be suitable for continuous outdoor operation.
3. Each module shall include an integral air scrub system during the cleaning process. Provision for compressed air shall be provided.
4. Wiring exposed to UV light shall be Teflon® coated.
5. Each UV lamp module shall include a safety interlock that shall automatically disconnect the power to the UV lamps when the module enclosure is opened for service.
6. Each module shall be protected by a panel-mounted thermal magnetic circuit breaker. The rating of each individual circuit breaker shall not exceed 30 amps. The circuit breakers shall be located adjacent to the UV channel in a proper load center.
7. Ultraviolet lamps and individual electronic lamp controllers shall be arranged so that each may be easily and safely tested in place.

14-14-7 Ultraviolet Lamps

Lamps shall meet the following requirements:

1. The lamp shall be low-pressure, mercury vapor UV lamps. Each lamp shall produce UV light with 90 percent of the UV emission at a 253.7-nm wavelength.
2. The UV lamp output shall not be less than 26.7 UV watts. Maximum power consumption per lamp shall be 70 watts. The UV lamp intensity at a distance of 1 m in air shall be 190 microwatts/cm^2.
3. Minimum UV lamp arc length shall be 147 cm.
4. Lamps shall be rated not to produce ozone.
5. The lamp base shall be of a durable construction resistant to UV. The lamp design shall prevent electrical arcing between connections in moist conditions.

14-14-8 Instrumentation and Controls

The power distribution center (PDC) shall be of type NEMA 3R and wall-mounted for indoor/outdoor installation. It will be provided with necessary LED displays, alarms, and controls.

14-14-9 Automatic Flap Gate Level Controller

An automatic level control shall be placed at the discharge end of the channels to ensure that the UV lamps are properly submerged, regardless of the plant flows. The level of the water shall be maintained at an appropriate level at all design flow conditions by simple adjustment to a counterbalance tank. The level control gates shall include a hinged baffle with a counterbalance.