DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
CEMP-ET Washington, D.C. 20314-1000

Engineer Technical
Letter No. 1110-3-442

24 August 1992

Engineering and Design
ULTRAVIOLET DISINFECTION AT ARMY WASTEWATER TREATMENT FACILITIES

1. Purpose: This letter provides basic criteria and information pertaining to the design of ultraviolet disinfection systems for Army wastewater treatment facilities.

2. Applicability: This letter applies to all HQUSACE elements, major subordinate commands (MSC), districts, laboratories and field operating activities (FOA) having Army military construction and design responsibility.

3. References: Required and related publications are listed in Appendix D at the enclosure.

4. Discussion: Chlorine has been the most widely used disinfectant of wastewater treatment plants (WWTP) effluent because of its germicidal effectiveness and low cost. Recently, however, concern for the environmental impact of residual chlorine and its by-products on aquatic life and human health have generated much interest in the development and use of alternative disinfection agents and techniques. One method, ultraviolet light disinfection (UV), is being used increasingly throughout the United States at municipal wastewater treatment plants, and several military installations are currently planning, designing, constructing and operating UV systems in response to concern over meeting effluent standards for preventing the discharge of chlorinated organics. Currently, UV disinfection of secondary wastewater is recognized as a viable, reliable, safe, cost effective, and economically competitive alternative to chlorination/dechlorination. Army installations must comply with regulations on levels of residual chlorine and/or indicator microorganisms discharged to the receiving stream and will be required to install equipment or change processes to meet these requirements.

5. Action to be Taken. The information attached at the enclosure to this technical letter provides guidance for planning and designing UV disinfection systems for new and existing Army domestic wastewater treatment plants.
The technology is not conclusive for industrial wastewater treatment plants and should be used with caution in

situations where industrial wastes are, or will be, the principal or major influent contribution to the plant.

6. Implementation. This technical letter will have routine application, as defined in paragraph 6c, ER 1110-345-100.

FOR THE DIRECTOR OF MILITARY PROGRAMS:

Encl

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for RICHARD C. ARMSTRONG, P.E.
Chief, Engineering Division
Directorate of Military Programs

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ULTRAVIOLET DISINFECTION AT ARMY WASTEWATER TREATMENT FACILITIES

1. INTRODUCTION

Application of chlorine for the control of disease producing organisms has been commonly practiced since the early 1900's. In recent years, attention has been given to the disadvantages of chlorine as a wastewater disinfectant since chlorination of wastewater can cause environmental and health problems. Chlorinated effluent produces residuals which are toxic to aquatic life[10,1,2] and some by-products of chlorination such as chlorinated hydrocarbons may be carcinogenic[10,3]. Also, chlorination is less effective in virus destruction than in killing bacteria[10,4]. Since chlorine-induced toxicity is becoming a serious environmental concern by the individual States with regard to the discharge of chlorinated wastewater into the surface waters, the priority given to chlorine as a wastewater disinfectant at Army installations is also being questioned.

Several methods have been developed to eliminate this toxicity problem. Residual chlorine and some chlorinated compounds have been removed from disinfected secondary effluent prior to discharge. Alternative chemical treatments have been employed involving chlorine dioxide, sulfur dioxide, iodine, bromine, and bromine chloride[10,5,6]. Use of ozone as a disinfectant has shown some promise, since ozone, in terms of biocidal efficiency is more potent than chlorine, chlorine dioxide, or chloramine[10,7]. Recently, increased attention has been given to ultraviolet disinfection. Ultraviolet radiation has been shown to be a practical, safe, effective, and cost effective disinfection alternative to both chlorination/dechlorination and ozonation of wastewater effluent[10,8,9]. Petrasek, et. al.[31] concluded that UV radiation presents a viable disinfection process for secondary effluent and that an activated sludge effluent can be adequately disinfected with UV radiation to comply with disinfection standards. Ultraviolet disinfection does not require highly toxic chemicals, does not produce harmful by-products, and requires only short contact time and low energy. Improved technology has made UV disinfection increasingly reliable.

This ETL presents background information concerning UV disinfection of secondary treated wastewater, basic design considerations and criteria, specification considerations, equipment descriptions and testing requirements. A design procedure is explained and an example problem included.

2. BACKGROUND

2.1 Disinfection of Wastewater

Wastewater disinfection processes involve specialized treatment for the destruction or removal of organisms capable of giving rise to infection[10]. Disinfection processes have been employed to destroy or inactivate disease causing microorganisms, primarily bacteria of intestinal origin. The term disinfection now has a meaning of inactivation of all microorganisms which cause disease, i.e. pathogenic bacteria, protozoa, and waterborne viruses[10,11]. Disinfection can be achieved by a variety of methods including chlorine, calcium and sodium hypochlorite, chlorine dioxide, chloramine, ozone, and ultraviolet light radiation. Other means, utilized to a lesser degree, are iodine, bromine chloride, potassium permanganate, hydrogen peroxide, metal ions, heat, ultrasonics, and electrostatic processes. This ETL deals exclusively with the ultraviolet disinfection process.

2.2 Disinfection with Ultraviolet Radiation

The disinfecting potential of ultraviolet light has been known for many years [10]. In 1877 it was discovered that the ultraviolet radiation of the sunlight spectrum could destroy bacteria and that the germicidal action was associated mainly with the short wavelength component of the solar radiation [10,11]. In 1893 it was shown that the UV radiation of the sunlight was responsible for the germicidal action. The germicidal effect of ultraviolet light is thought to be associated with its absorption by various organic molecular components essential to the functioning of cells[10,12]. Ultraviolet light has been proven effective against many microorganisms but the effectiveness varies with microbe type. A higher dose is required to inactivate bacterial and fungal spores than to destroy vegetative cells. Ultraviolet light is also effective against viruses with a two-log reduction in viral concentration shown in wastewater treatment plants using ultraviolet disinfection[10,13].

2.3 Application to Wastewater Disinfection

The application of UV light to the disinfection of wastewater has become a well established technique with installations exceeding one mgd dating back to 1967. Prior to this, and despite the widespread recognition of UV as a disinfectant, it's use was confined to treatment of potable water. However, increased knowledge of ultraviolet transmission, improved lamp and equipment design, attention to operation and maintenance, and the absence of a residual have been significant factors in the application of UV disinfection technology to wastewater. Because wastewater is considered homogeneous relative to concentrations of constituents and bacteria, an effective UV system can transmit the germicidal radiation through the entire waste stream. This has been accomplished by reducing the distance of wastewater from the UV source, by providing enough turbulence to mix the wastewater stream, and by lengthening the UV exposure time[25].

Other improvements have been made to keep the lamp surfaces clean in order to maintain maximum transmittance and the UV equipment provided is now able to compensate for water quality considerations such as turbidity, color, and suspended solids which would otherwise result in decreased light penetration and less disinfecting potential.

The two major requirements for disinfection of potable water, namely, the need to maintain residual protection during transport to the consumer and total kill of raw water sources of high turbidity, are not valid for secondary wastewater since there is no need to maintain a residual and the process only has to leave about 200 counts/100 ml fecal coliform. Both of these criteria are desirable characteristics when discharging treated wastewater to natural receiving waters.

2.4 Advantages and Disadvantages of UV Disinfection

Some advantages of UV for disinfection over alternative methods include: (a) excellent disinfection performance with bacteria and viruses; (b) short contact times required to inactivate viruses and bacteria (exposure time on the order of seconds); (c) no undesirable by-products such as assimilable organic carbon (AOC) or carcinogenic halogenated compounds created; (d) no chemical additions required, no dangerous chemicals or gases for operators to store and handle, and no chemical or physical changes to the disinfected effluent; (e) no potential harm to fish, wildlife, or humans downstream; (f) no detrimental effects produced by over-dosing as with chemical and gaseous disinfectants; and (g) lower cost than most alternative methods of disinfection.

Some disadvantages of UV disinfection include: (a) possibility of re-activation of irradiated microorganisms if exposed to energy wavelengths in the visible light range; (b) limited information on factors influencing effectiveness in practice; (c) uncertainties regarding accuracy and reliability in measuring UV dose because current systems rely on sensors and theoretical measurements; (d) frequent and expensive apparatus maintenance is necessary to ensure efficient light energy intensity application and uniform light density throughout the effective radiation area; and (e) treatment efficiency is not readily determinable because of lack of a rapid field test.

2.5 Disinfection Standards

Historically, individual states have established and controlled wastewater disinfection practices in the U.S. with emphasis on protection of public health, particularly where contact with wastewater is likely to occur[25]. An attempt was made by EPA in the Clean Water Act, PL 92-500, in October 1972 and in the Secondary Treatment Information Regulation of August 1973 by the EPA for national effluent standards including a fecal coliform standard applicable to all wastewater disinfection situations. Because of variation in impact on costs and benefits for site specific cases, the EPA withdrew the regulations and returned control of wastewater disinfection practices to the states. Today disinfection requirements are implemented through National Pollutant Discharge Elimination System (NPDES) permits issued to individual treatment plants which set effluent limitations in terms of indicators of pathogenic contamination (i.e. coliform bacteria) based on the desired use of the receiving water.

The generally accepted criteria for disinfection, based on water use, are as follows[26,27]:

a. Where shellfish are grown for human consumption, the median coliform densities should be 14 fecal coliform or 70 total coliform per 100 ml,

b. Where whole body contact of a receiving water is desired, the geometric mean over a 30-day period should not exceed 200 fecal coliform bacteria per 100 ml, with a maximum 7-day average of 400 per 100 ml,

c. Where secondary contact recreation is desired, such as boating, in-stream levels may be from 1,000 to 5,000 fecal coliform per 100 ml.

The predominant effluent criteria used in specifying performance requirements for UV systems at military facilities is that for whole body contact.

As a result of the concern associated with the dangers of chlorinated effluent and in particular the formation of trihalomethane (THM), many states have already enacted legislation limiting the amount of chlorine allowed in an effluent discharge. Limitations of 0.01 ppm require de chlorination ar an alternative method of disinfection such as UV.

2.6 Special Requirements

Several considerations should be included in the design and operation of a UV disinfection system. First, it must be simply designed and constructed, and must be provided with reliable equipment that is not labor intensive or complex in terms of maintainability, serviceability, and availability of parts. Second, the trend is toward limited operator manpower availability at Army treatment plants and this must be considered in the design. Third, operator safety must be incorporated in the design process.

3. FUNDAMENTALS OF ULTRAVIOLET DISINFECTION

3.1 Nature of Ultraviolet Light[34]

Ultraviolet light is invisible radiation within a range of the electromagnetic spectrum having a wavelength between 100 and 400 nanometers (nm). One nanometer unit wavelength equals 10 Angstroms, Å.

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As can be seen in Figure 3-1, there are three main groups within the ultraviolet spectrum, only one of which the germicidal range of 200 to 280 nm is utilized for disinfection. The peak effectiveness for inactivation of micro-organisms occurs at the wavelength of 260 nm units, which is sometimes expressed as 2,600 Å. The relationship between bactericidal effect and wavelength is shown in Figure 3-2. Fortunately, this range coincides with the resonance line of mercury vapor lamps, 253.7 nm (Figure 3-3), the almost exclusively used sources of UV light for disinfection.

3.2 UV Light Disinfection Mechanics[34]

All microorganisms contain proteins and nucleic acid as their main components. Ultraviolet light disrupts these components and destroys the ability of microorganisms to reproduce, ie. they are inactivated and as a consequence can no longer cause disease.

The inactivation of microorganisms results primarily from the absorption of UV radiation by the deoxyribonucleic acid (DNA) of the organisms and subsequent dimerization of thymine bases in DNA.

In order to be effective, the electromagnetic waves of UV radiation must actually strike the microorganism. In the process, some of the radiation energy is absorbed by the organism and some by other constituents in the medium surrounding the organisms. The germicidal effect of UV energy is thought to be associated principally with its absorption by nucleic acids essential to the replication of cells. Energy dissipation by excitation, which causes disruption of the nucleic acid molecules that are vital to both bacteria and viruses, appears to produce a progressively lethal biochemical change. UV treatment does not chemically alter water since nothing is added except energy, which produces heat resulting in a negligible temperature rise in the treated wastewater.

3.3 UV Dose and Inactivation Time

The energy required to inactivate microorganisms varies with the particular species under attack. Radiation is typically expressed as a function of intensity (energy), time and area. Thus, UV dosages are expressed as microwatt seconds per square centimeter(μw-sec/cm^2).

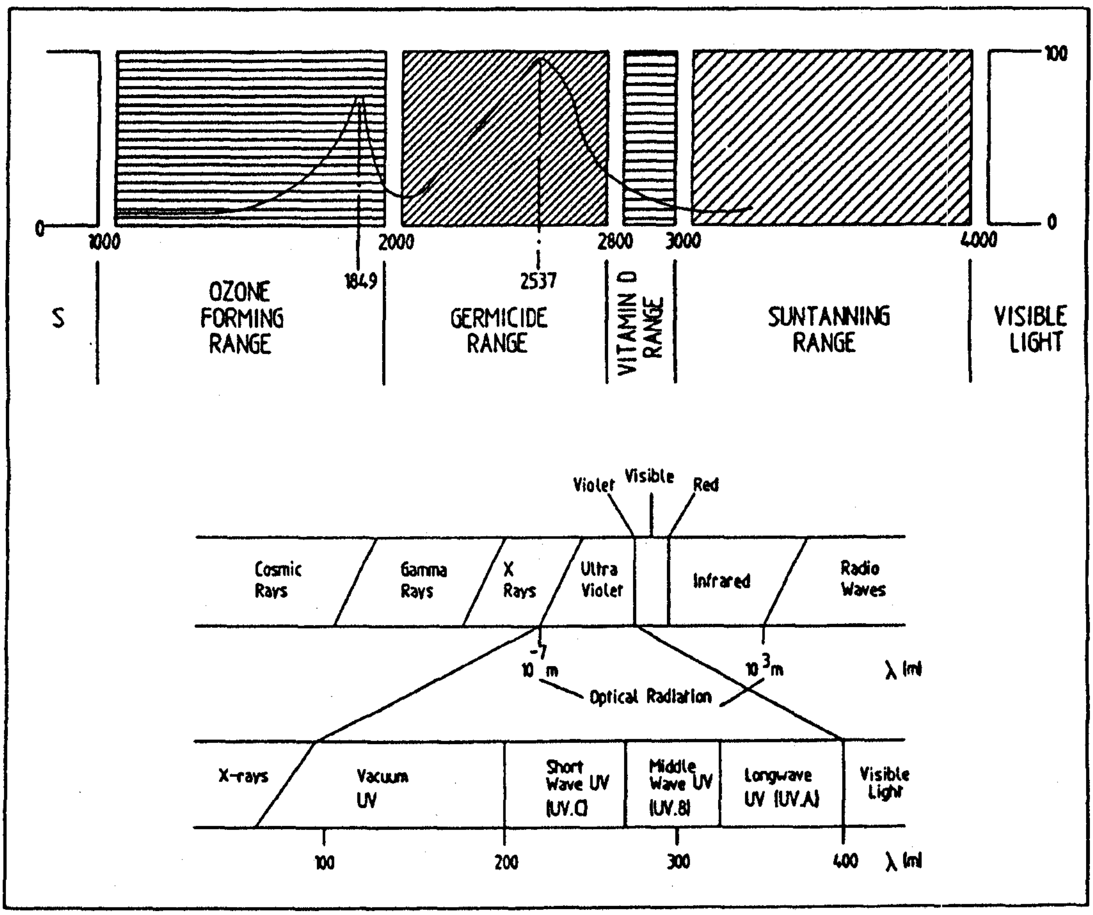

FIGURE 3-1 Electromagnetic spectrum with expanded scale of ultraviolet spectrum[34]

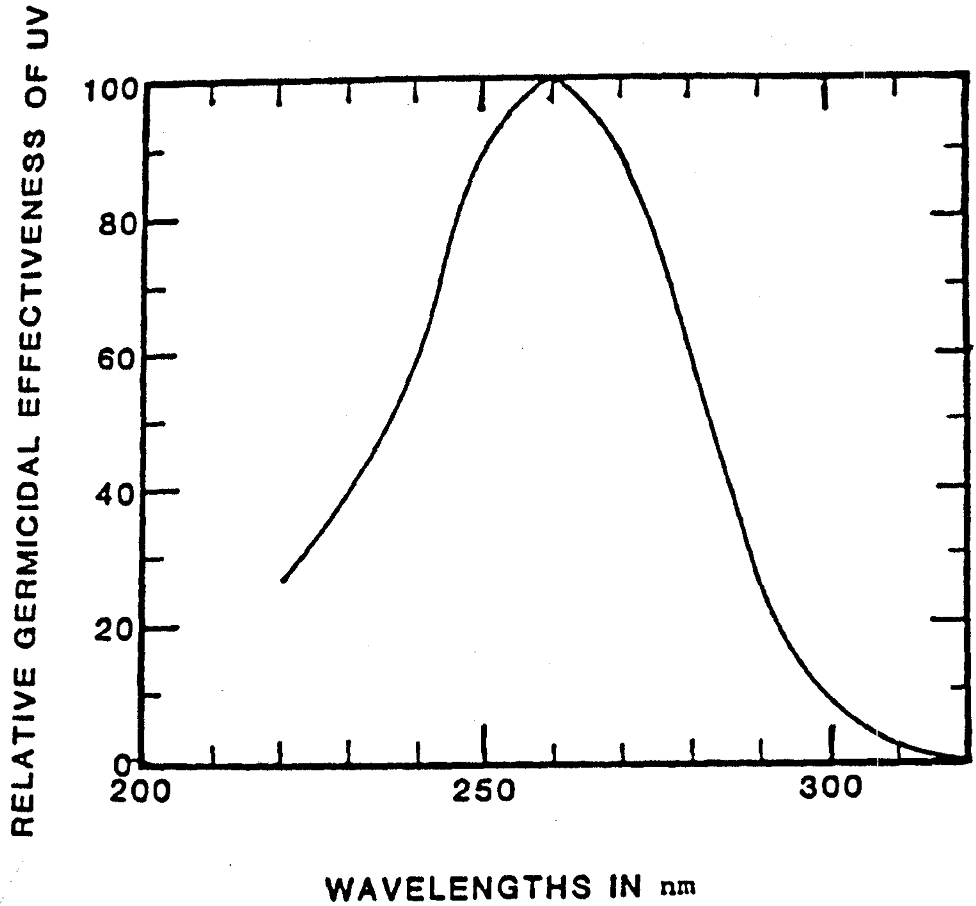

FIGURE 3-2 Relative bactericidal effectiveness of ultraviolet radiation[16]

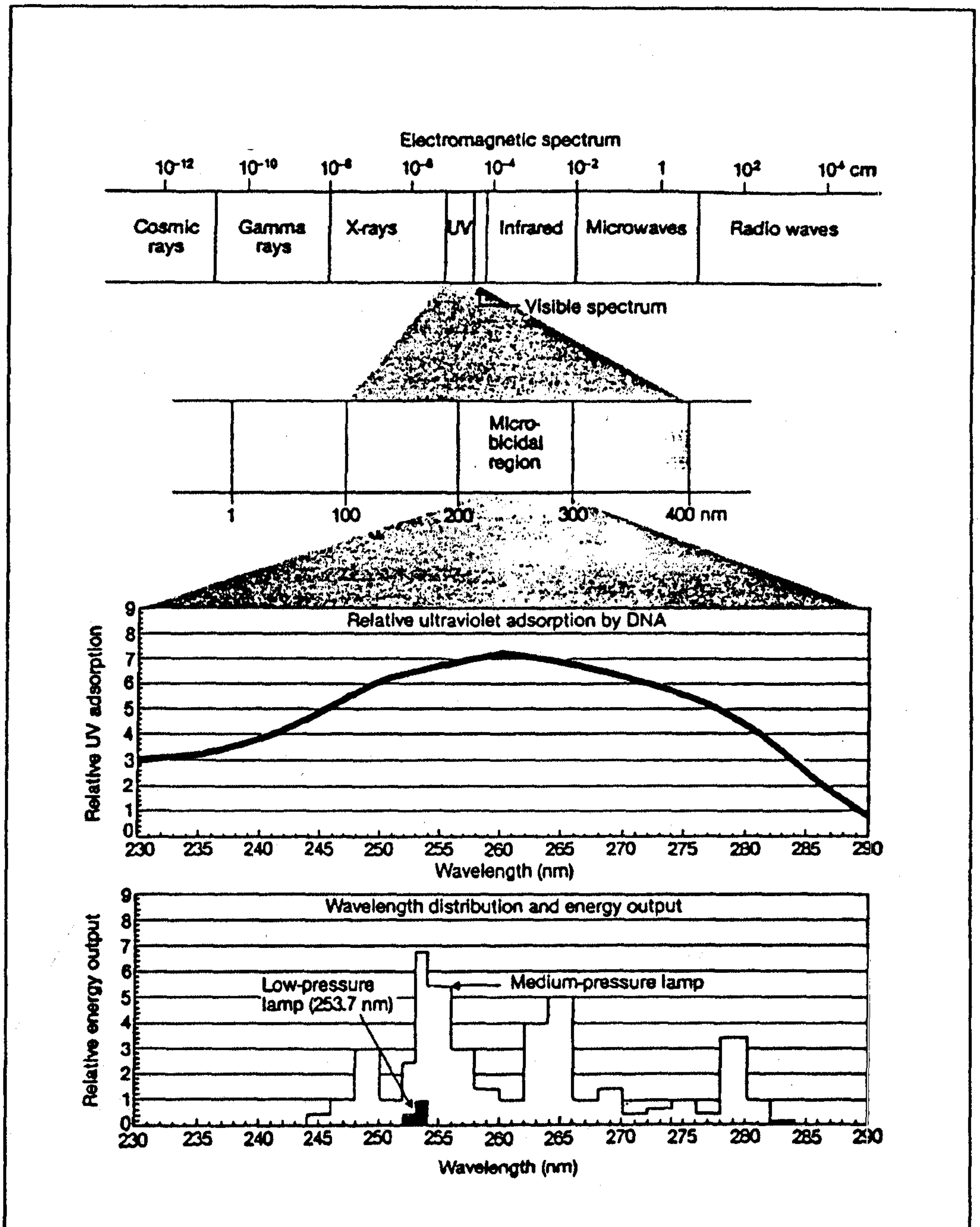

FIGURE 3-3 Microbiocidal wavelengths of UV and distribution of energy output for low and medium-pressure arc lamps(14)

The average UV light intensity, or the dose, has been measured indirectly by a bioassay technique which has been proven to be a reliable method of determining the UV dose necessary to destroy various organisms[33]. The laboratory procedure used is essentially as follows[34]:

1. A UV lamp is set up at a fixed distance from a petri dish (Figure 3-4).

2. A shield is placed over a portion of the UV lamp, and a collimating tube is positioned between the lamp and the petri dish.

3. A UV intensity meter is used to accurately measure the intensity of 253.7 nm at the point where the petri dish is located.

4. A pure strain of the microorganism to be evaluated is placed in the petri dish and mixed with a magnetic stirrer.

5. The experiment is repeated for various exposure times.

6. Each sample is then incubated, and the concentration (N_o) of the microorganisms before and after (N) exposure to UV light was determined.

7. The measured intensity multiplied by the specific exposure UV time represents the UV dosage.

8. The dose response curve is then plotted. It shows the log of the survival ratio N/N_o as a function of the UV dosage. Figure 3-5 gives an example. From Figure 3-5, the UV dosage for 90%, 99%, 99.9% etc. reduction respectively, 10%, 1%, 0.1% etc. survival ratio can be determined. If the necessary UV dosage for 90% reduction (10% survival) has the value X, it needs a UV dosage of 2X to obtain 99% reduction (1% survival), 3X for 99.9% (0.1% survival), 4X for 99.99% (0.01% survival) etc.

<u>For example</u>: If the intensity at the petri dish is 1,000 $\mu w/cm^2$, and the retention time for destruction of the organism is 5.6 seconds, the dosage to destroy the organism is 5,600 $\mu w\text{-}sec/cm^2$.

Using the collimated beam apparatus, the survival of a specific indicator organism is determined as a function of the UV dose under controlled laboratory conditions. The intensity can then be determined in an unknown system by determining the survival, reading the dose corresponding to the observed survival on the curve, an example of which is

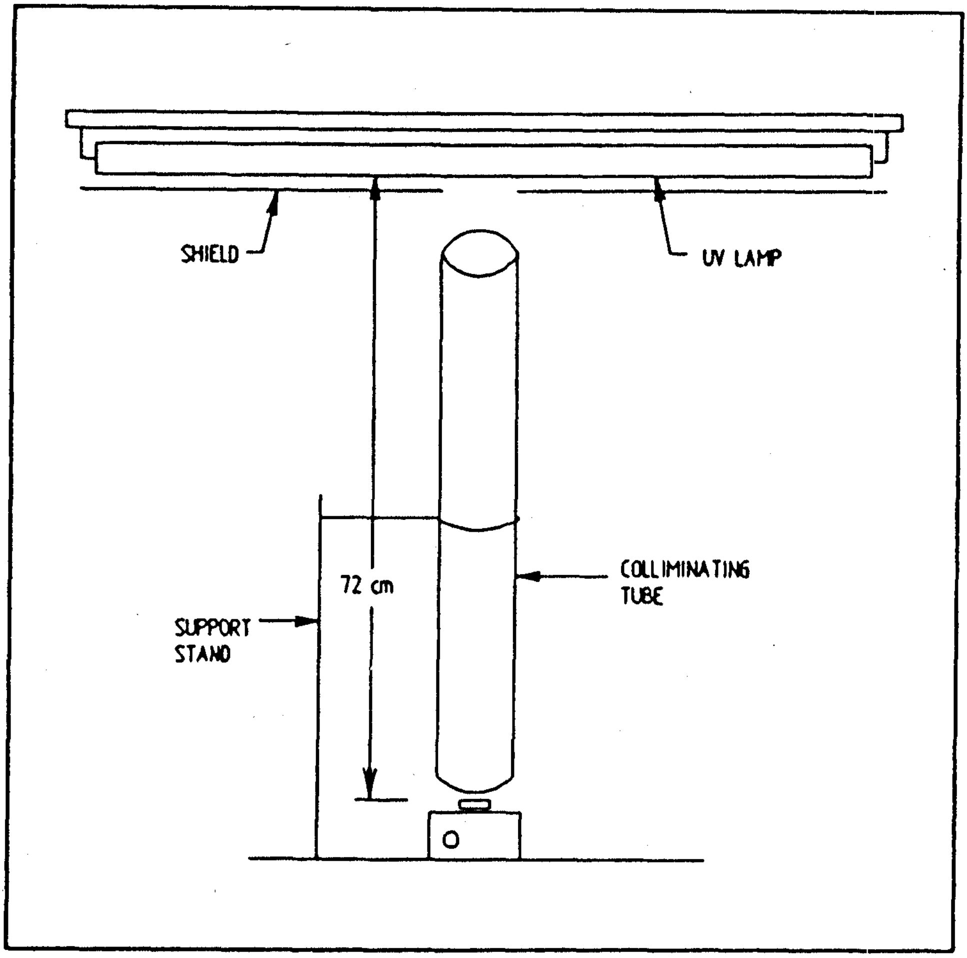

FIGURE 3-4 Collimated beam apparatus[34]

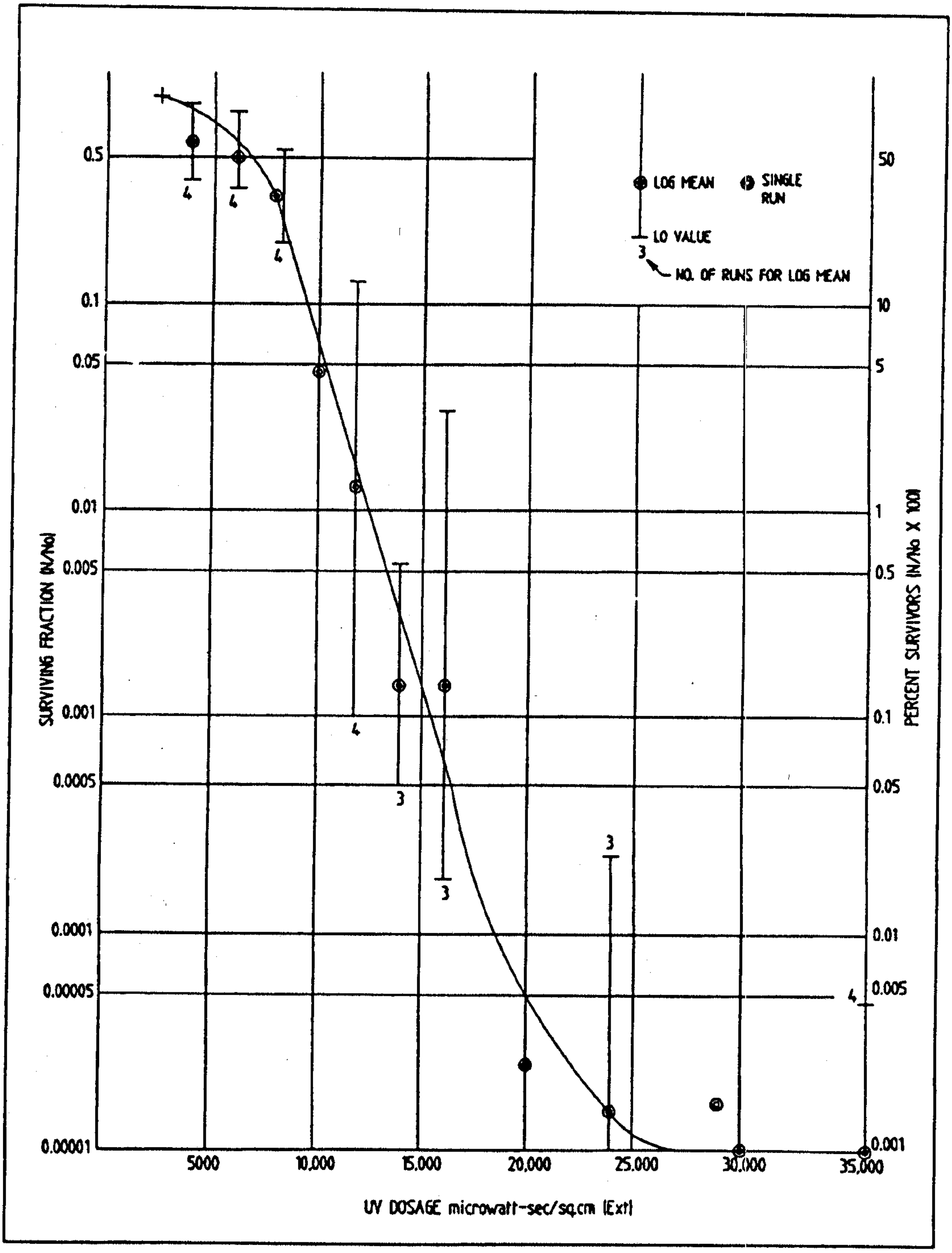

FIGURE 3-5 Dose-response reference curve(34)

shown in Figure 3-5, and using the known exposure to calculate average intensity.

3.4 E. Coli as Indicators[34]

There has been considerable discussion within the scientific community regarding the use of Escherichia Coli (E. Coli) as an indicator method. There are numerous organisms and viruses that survive standard chlorination. The absence of coliforms in a treated effluent does not indicate or guarantee the absence of these chlorine resistant organisms.

It is interesting to note that the same condition does not exist in the case of UV disinfection. Coliforms are among the most resistant of the waterborne organisms, and the absence of E. Coli in a UV treatment system is a good indication of the absence of the other significant microorganisms. Figure 3-6 shows this relationship.

UV light is a very powerful disinfectant. Comparison of doses required to inactivate various microorganisms applying different methods of disinfection is shown in Figure 3-6, where the required doses are related to a unity dose necessary to inhibit E. Coli. Figure 3-6 shows that one advantage of UV radiation over chlorine disinfection is the sensitivity of viruses to UV.

3.5 UV Disinfection Efficiency[34]

The disinfection efficiency of a UV system is primarily dependent on the UV dose. The required dose will vary as effluent quality varies. Determination of the actual dose being delivered involves defining the hydraulic detention time in the reactor throughout the expected range of flows, and defining the average intensity of the UV radiation in the reactor. These two parameters are reactor-specific. The average intensity to which the wastewater flow is exposed is a function of the total number of lamps, their types, size, and the geometry of the lamp placement in relation to the wastewater flow[15].

3.6 Factors Affecting UV Disinfection Efficiency

Because UV light must be absorbed into the microorganisms to achieve inactivation, anything that prevents the UV light from reacting with microorganisms will impair disinfection.

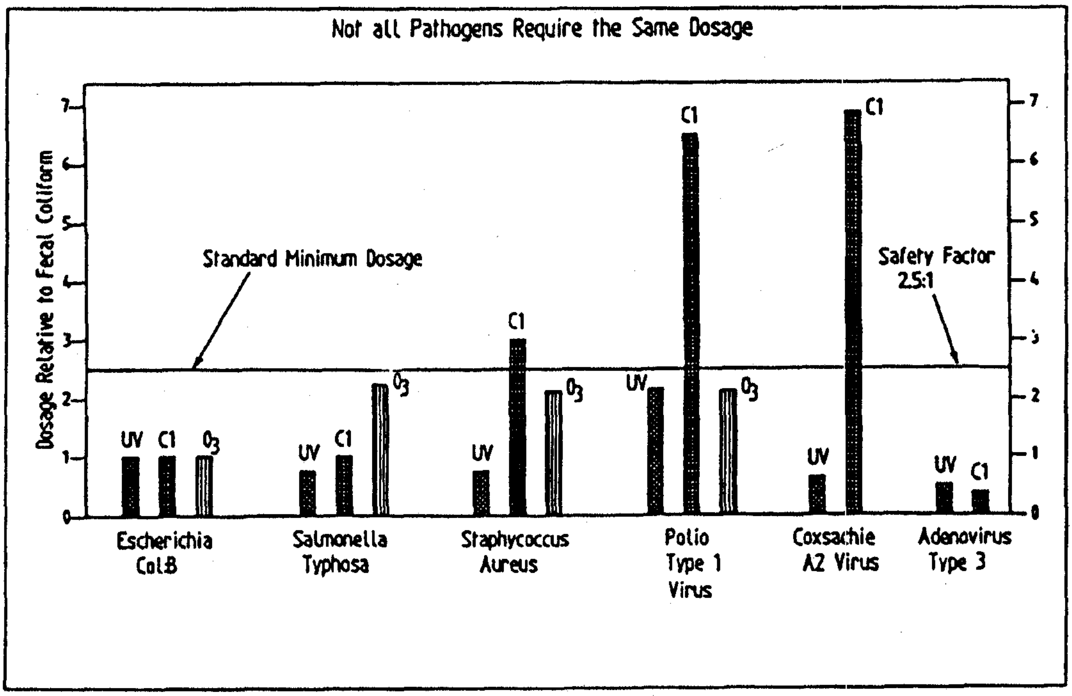

FIGURE 3-6 Comparison of relative dosages with UV, chlorine and ozone[34]

Conditions and materials that interfere with this process include chemical and biological films that develop on the surfaces of UV lamps; clumping or aggregation of micro-organisms, which has a protective effect; turbidity; color; dissolved organics and inorganics; and short-circuiting in water flowing through the exposure chamber. Disinfectant activity using UV, however, appears to be relatively independent of temperature and pH[14].

3.6.1 UV Transmittance at 254 nm

Ultraviolet light transmission through the fluid changes with the fluid density. The coefficient of absorption of the fluid is a very important factor to be considered in evaluation of UV dose. The coefficient of absorption of water or wastewater is not a constant and must be measured for each application.

Table 3-1 lists the typical UV light transmission levels for various fluids.

Table 3-1 Typical UV transmission levels
(Source: 19)

Fluid	Percent Transmission T_r	Coefficient of Absorption α (cm^{-1})
Distilled water	99	0.1
Potable water	80 - 90	0.2 - 0.1
Secondary effluent*	60 - 70	0.4 - 0.3
Liquid sugar	50 - 60	0.5 - 0.4

* Secondary effluent based on a survey of 200 random medium strength domestic secondary effluent.

The intensities of UV light reaching the irradiated bacteria change with the absorbance according to Equation 3.

In addition to the changes in ultraviolet transmission of the fluid, other factors that affect UV light intensity are:

1. depreciation of the output of the UV lamps with their age.

2. a formation of a coating on the quartz lamp jackets or fouling of the teflon tubes.

Power voltage drop also reduces lamp intensity and therefore ultraviolet disinfection efficiency.

3.6.2 Water and Wastewater Quality

To analyze the ultraviolet disinfection efficiency, several factors that affect the penetration of ultraviolet energy through water and, hence, the effective destruction of organisms should be considered[10]. Water and wastewater constituents may have a large impact on ultraviolet disinfection efficiency. The energy which kills a bacterium is only that absorbed by it, therefore, ultraviolet coefficients of absorption are affected by turbidity, iron salts and organic compounds in wastewater[20]. Compounds of calcium, magnesium, sodium, and aluminum have little effect on transmission, unless the compounds form a precipitate[20]. Water quality parameters such as temperature, pH, conductivity, alkalinity, total organic carbon (TOC), chemical oxygen demand (COD), total phosphorus, and orthophosphate, ammonia, nitrite, and nitrate affect wastewater transmittance, hence affecting ultraviolet reactor performance[10,21].

Where wastewater quality parameters do not show higher than the average for secondary effluent values, the impact of physical and chemical quality of wastewater on the overall UV disinfection efficiency is relatively low[10,22]. Huff, et al.[20], studied the effect of color on transmission and on limiting efficiency in destruction of organisms and determined that concentrations giving 30-33 units of color did not decrease intensities below the average values. Turbidities of 5 Jackson units did not reduce UV intensity and disinfection was sufficient to produce total and fecal coliform counts in the water within acceptable drinking water limits of E. coli. per 100 ml. while turbidities of 20 units sometimes reduced light intensities but the coliform counts were still within the limits of acceptance for potable water. The effect of iron on disinfection was not observed at concentrations up to 3.7 mg/1 as the UV transmittance of the solution decreased without resulting in a decrease in coliform removal. Other studies have concluded that water relatively low in turbidity, color, iron content, and organic composition could effectively be disinfected.

3.6.3 Temperature

Severin, et al.[10,23], concluded that the UV disinfection is relatively insensitive to temperature changes, since the calculated activation energies for three organisms studied were in the range of purely photochemical reactions[10].

3.6.4 Mixing

Mixing in the radial direction of an annular reactor was found to be beneficial while mixing in longitudinal direction is detrimental to reactor efficiency[10, 24].

3.6.5 Suspended Solids

The presence of particulate materials in wastewater also affects ultraviolet disinfection. Absorption of microorganisms to inorganic surfaces provides some protection against radiation. Organic particles can significantly protect organisms from disinfection and the difference between microbial survival in irradiated raw wastewater and secondary effluent has been attributed to differences in particle sizes. Bacteria inside aggregates of particulate matter are partially protected from ultraviolet light. Secondary wastewater effluent subjected to mixed media filtration and exposed to UV at different flow rates, and different lamp intensity rates showed significantly better disinfection than unfiltered effluent[10].

3.6.6 By-Products of UV Radiation

Undesirable disinfection by-products (DBP's) in water and wastewater are classified into two general categories -those which are harmful to health and to fish and those which affect the water's aesthetic quality. The literature indicates that UV disinfection does not contribute to either by-product category. UV radiation does not produce increased mutagenic activity in water, does not produce assimilable organic carbon (AOC), and produces no tastes and odors or other measurable water quality by-products[14].

4. ULTRAVIOLET DISINFECTION SYSTEM DESIGN

4.1 Salient Features of UV Systems

The following are essential elements of UV systems that should be included in the design and specifications.

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4. ULTRAVIOLET DISINFECTION SYSTEM DESIGN

4.1 Salient Features of UV Systems

The following are essential elements of UV systems that should be included in the design and specifications.

4.1.1 General:

The design should be an open channel system which provides effective wastewater disinfection through a series of UV lamp modules that fit into the plant's existing chlorine contact tank or new concrete channels. An example layout is depicted in Figure 4-1.

The number of modules in the system is determined by the delivered dosage required for disinfection of the peak flow, and the specific wastewater characteristics.

Modular lamp configurations have three advantages: first, they allow easy retrofitting (the UV modules are designed for all-weather use, so no building is required). Second, they enable the system to be enlarged without major redesigning as flow volume increases (additional capacity can be obtained simply by placing additional modules in the channel). And, third, modular systems can be easily removed for cleaning and lamp maintenance.

4.1.2 UV Reactor[17]

Currently, two reactor designs are being used. The first and most preferred is a contact (annular) reactor in which the lamps are always submerged in the pretreated wastewater and the lamps are sheathed in slightly larger quartz or teflon sleeves as depicted in Figure 4-2. The second design (coaxial) suspends the lamps around the outside of transparent conduits which carry the wastewater and therefore there is no contact between sleeves and wastewater.

Lamp spacing should not be too close since energy will be wasted when the lamps absorb most of the UV energy and overheat beyond the optimum lamp temperature, thereby reducing germicidal efficiency[17]. Designers should ensure that manufacturers utilize at least 90 percent of the useful UV energy from each lamp in multiple lamp reactors when selecting lamp spacing.

For a typical plant disinfection arrangement, each reactor lamp module containing multiple bulbs is connected in series. The modules are configured so that individual modules can be taken off-line and pulled out of the channel for maintenance purposes without interrupting plant flow. This arrangement ensures that too many lamps are not

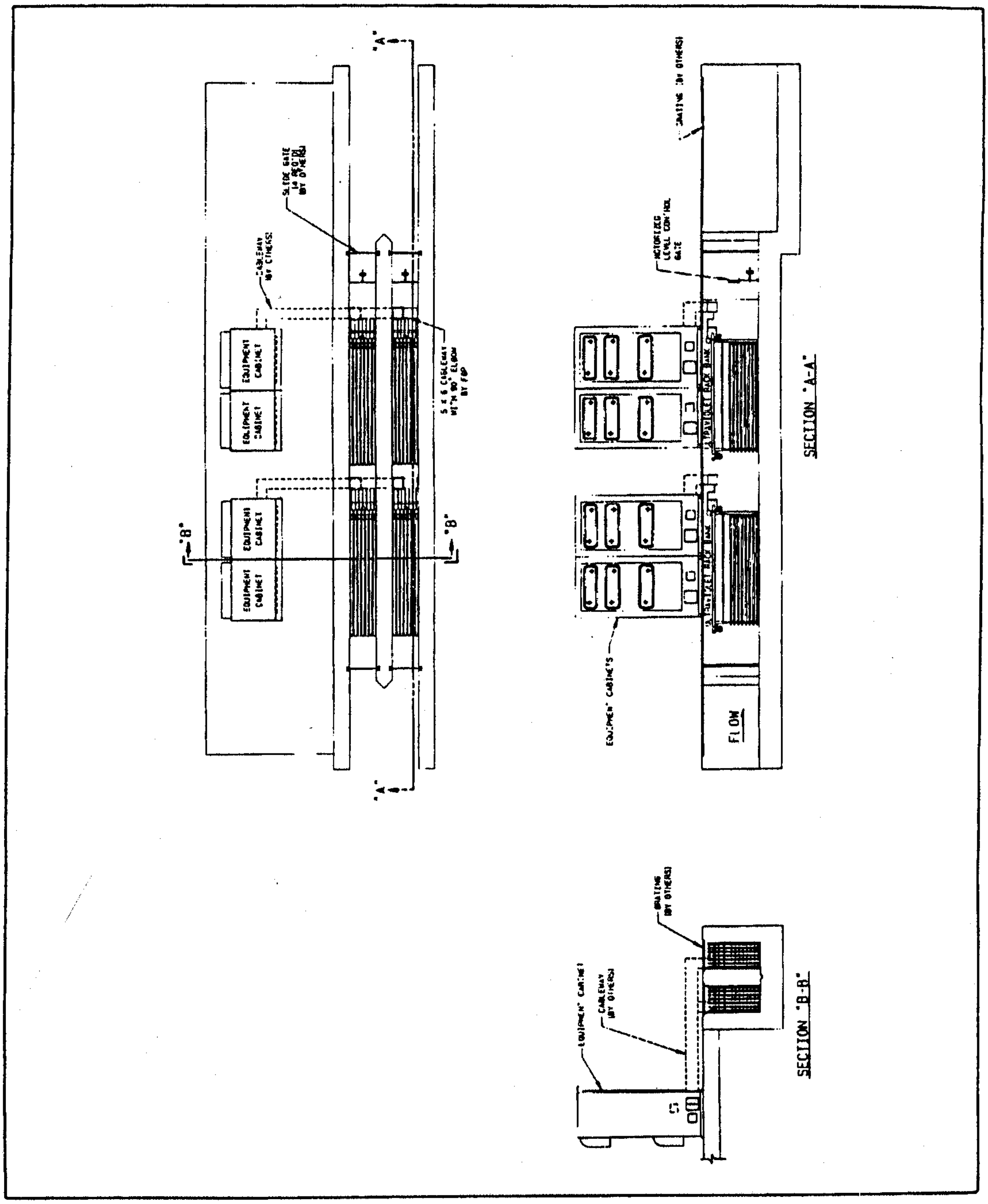


FIGURE 4-1 Typical horizontal, open channel UV disinfection system (Courtesy of Fischer & Porter Company, Westminster, Pennsylvania)

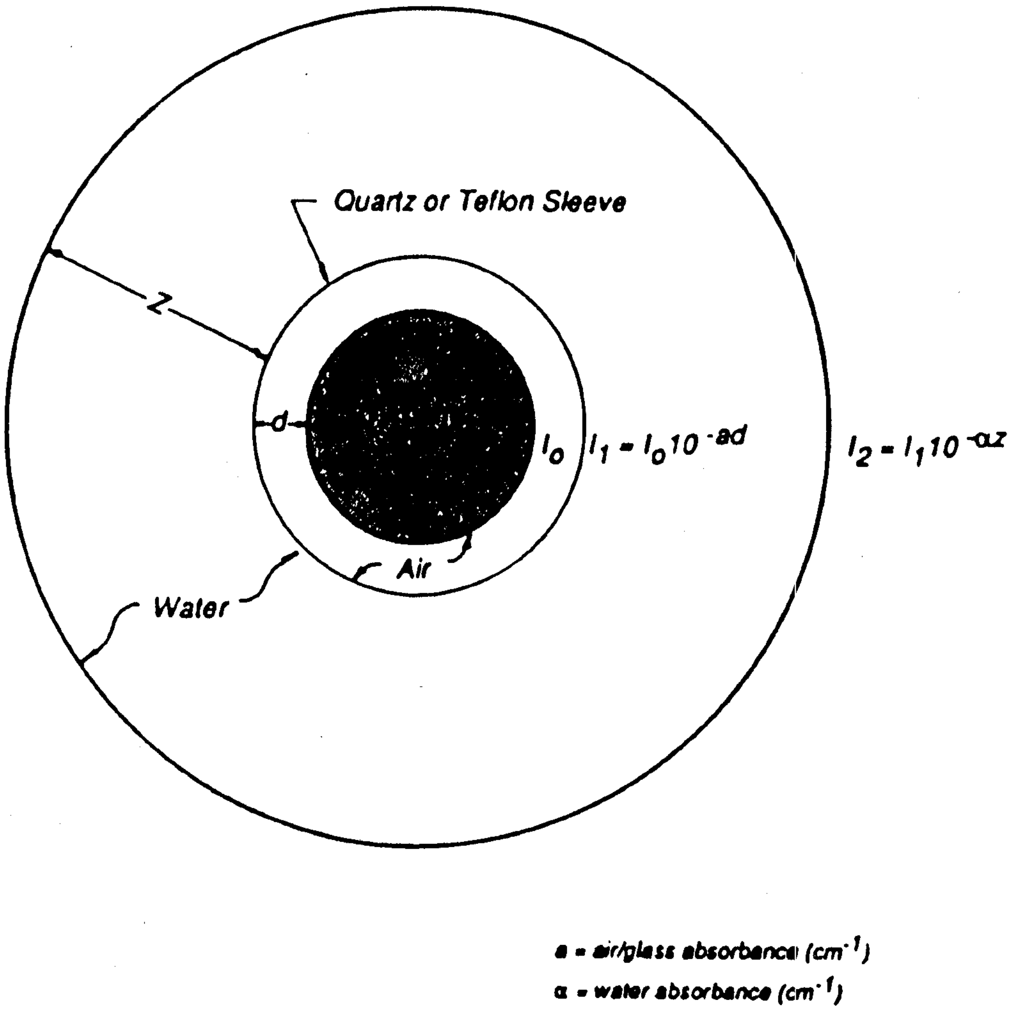


FIGURE 4-2 Single UV lamp in sleeve surrounded by concentric layer of water showing intensity attenuation through various mediums according to Beer's Law[17]

installed in one module which could create problems in cleaning and lamp replacement. The best lamp configurations are installed parallel to the flow. Reactor materials should be stainless steel for small installations or concrete and used together with UV resistant plastics and seals. Figure 4-3 shows a typical module system.

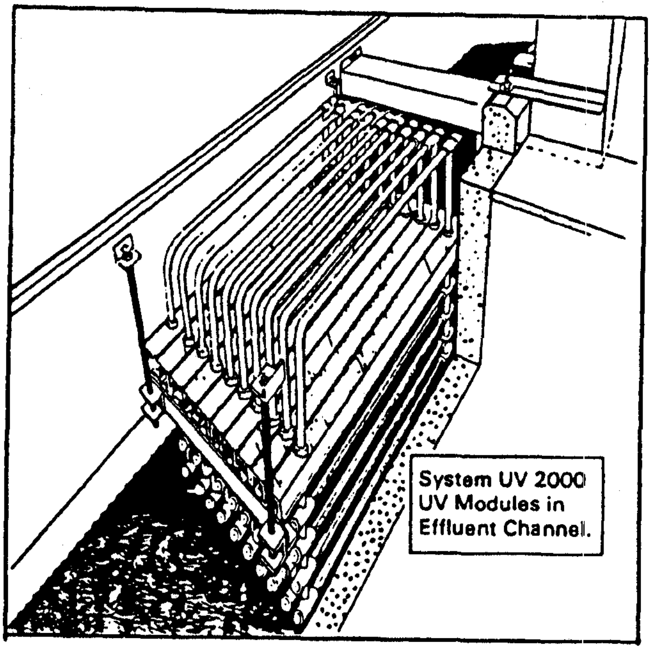
4.1.3 Lamps and Ballasts[17]

UV germicidal lamps are similar to fluorescent tubes except the UV tube is made of quartz glass and the inside surface is not phosphor coated. The lamp is filled with low pressure mercury vapor and argon and when the cathode is energized, UV radiation at 253.7 nm wavelength is emitted. The amount of germicidal radiation available from low pressure mercury vapor lamps is approximately 20 to 25 percent of the lamp rating. Manufacturers' rated literature should be consulted and average UV output after 100 hours should be used in dose intensity computations[17]. The expected useful life of low pressure UV lamps is 7,000 to 10,000 hours. Continuous operation and voltage dimming operations tend to prolong UV lamp life.

Standard single pin, slimline, UV tubes with instantaneous-start, energy-saving ballasts, certified by American National Standards Institute (ANSI) and Underwriters Laboratories Inc. (UL), should be specified. Some new applications utilize electronic ballasts which, it is claimed, tend to operate the mercury lamp close to the optimum temperature (40 C), draw less energy and last about 25 years as compared to electromagnetic ballasts which last about 15 years. Operating temperatures lower or higher thanoptimum will reduce UV output by from 1 to 3 percent per degree C.

Medium and high pressure lamps can operate at higher temperatures but useful germicidal output is lower than low pressure lamps.

One requirement of UV equipment systems is that the lamps be separated from the water flow by quartz glass or teflon-fluorinated ethylene propylene (FEP) sleeves. Extremely high lamp temperatures can enhance fouling by scale deposits on the sleeve surfaces closest to the lamps hence the preference for low pressure, low temperature bulbs.



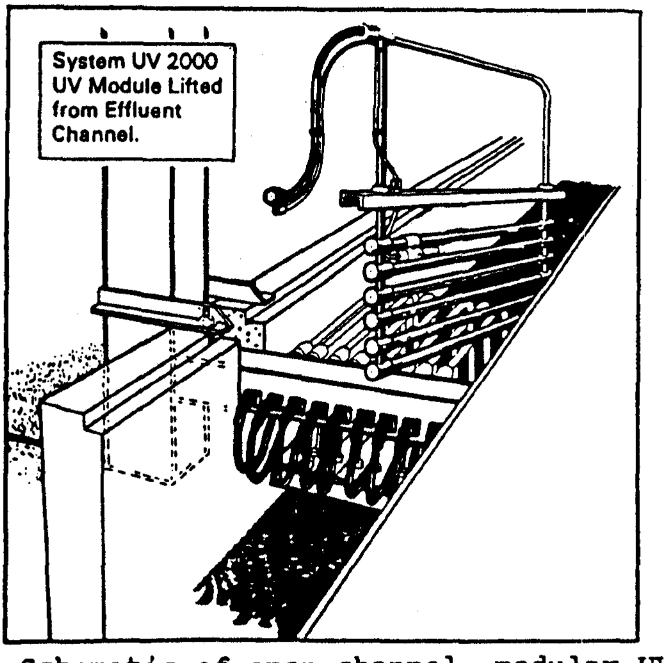


FIGURE 4-3 Schematic of open-channel, modular UV system (Courtesy of Trojan Technologies, Inc., London, Ontario, Canada)

The mercury vapor lamp was developed in 1901 and is the heart of the ultraviolet disinfection system.

Most ultraviolet system suppliers utilize low pressure mercury arc lamps which produce ultraviolet light at the 253.7 nm wavelength. This lamp was universally accepted because 86% of its energy output, in the UV range, is monochromatic at 253.7 nm which is within the optimal wavelength for germicidal effectiveness.

Ultraviolet lamps, like fluorescent lamps, are very stable and reliable operating from a 115 volt single phase electrical supply. Although a UV lamp can fail electrically and therefore require replacement, the typical reason for replacement is depreciation.

Lamp depreciation is a natural phenomenon which occurs over a period of time, typically 7,000-9,000 hours. During this period of time, which is accumulated only while the lamp is switched on, the UV lamp gradually over-exposes its quartz tube and restricts the UV emission. At the end of the lamp's life, the UV emission has been reduced to approximately 70% of its original output. To ensure adequate treatment throughout the lamp's life, all dosage calculations are made at this "end of life" output level. Having reached this low level of UV intensity, the lamps have to be removed and replaced.

Manufacturers and designers must always give consideration to the practical implications of lamp maintenance and replacement. First be aware that UV lamps are electrical components which are being utilized in a wet environment and usually at an outdoor location. Access to the lamps has to be both simple and safe with each system design. However, a universal feature is the use of a quartz jacket to house the lamp itself. This quartz jacket isolates the lamp from the wet environment while allowing intimate exposure of the water to the ultraviolet energy.

Quartz jackets are constructed with "test tube" ends so that only one end of the jacket needs to be accessed for lamp servicing. The ultraviolet lamp slides into the quartz jacket and is held centrally using spacers which also serve to prevent the lamp from rattling under the effect of water flow. See Figure 4-4.

4.1.4 Effective Treatment Zone[34] When the low pressure mercury vapor is activated, an arc is established between the electrodes and ultraviolet light radiates from the lamp. The area between the electrodes of the lamp is known as the arc of the lamp and it is the length of this arc which is referred to when lamps are identified (Figure 4-5).

For the majority of wastewater applications, lamps having 76.2 cm (30 in), or 147.3 cm (58 in), arc lengths are used with the latter lamp being the preferred size.

The ultraviolet light emitting from a UV lamp is evenly distributed along its length but, obviously, diminishes the further it gets from the source (Figure 4-6).

In fact, the effectiveness of the UV ray diminishes in proportion to the reciprocal of the distance the ray is from the lamp. Therefore, for maximum effect the water to be treated has to be directed through the area of greatest UV intensity. This is achieved by ensuring that each particle of water, passing through the reactor, follows virtually the same path and receives the same dose. This is accomplished by creating plug flow conditions with relatively high turbulence. In this way almost all the UV intensity, produced by the lamps, is absorbed by the water.

With the lamps in a submerged horizontal format (Figure 4-7), treatment is confined to the lamp arc length only, and increased dosage of UV energy can only be achieved by adjusting the flow or adding another bank of lamps.

When the vertical open channel format is used (Figure 4-8), optimum use of the ultraviolet light is achieved. Since the lamps are now suspended vertically in the water to be treated, the ultraviolet light can be allowed to radiate along the channel creating pretreatment and post-treatment zones. Also, by arranging the lamp modules with a space between them, intermediate treatment zones can be created.

All these measures serve to increase the contact time without varying the flow which improves the efficiency.

Each lamp module should contain two, four, six or eight UV lamps each, depending upon the depth of the channel. Refer to Figure 4-9 for a typical module arrangement.

4.1.5 Modular Lamp Mounting:

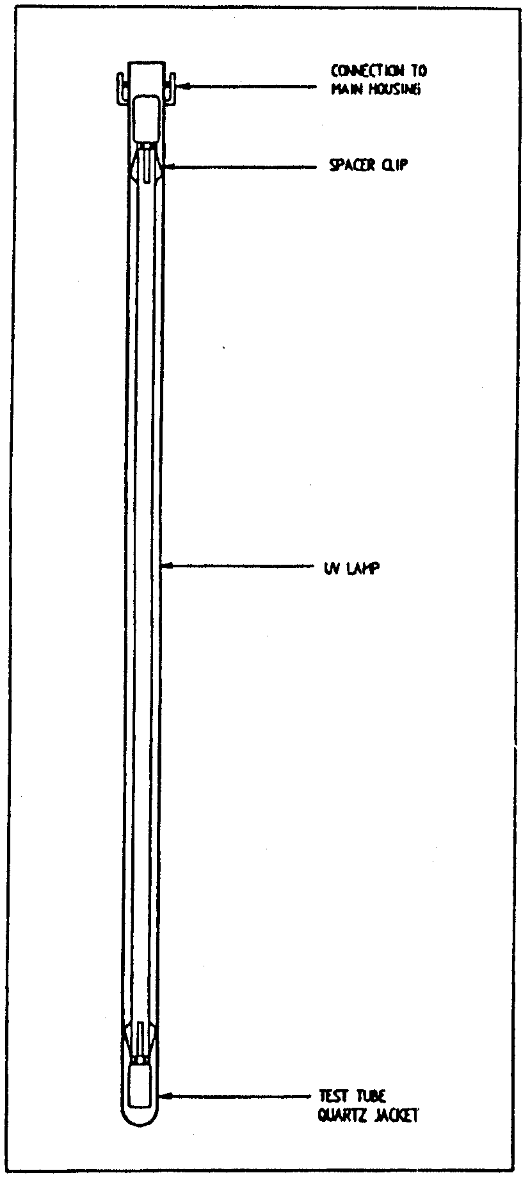


FIGURE 4-4 UV lamp in quartz jacket[34]

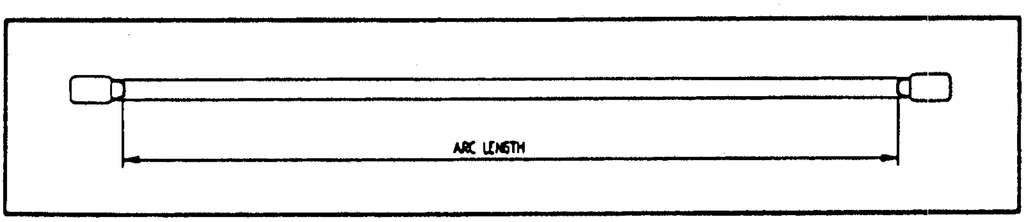


FIGURE 4-5 Definition of lamp arc length[34]

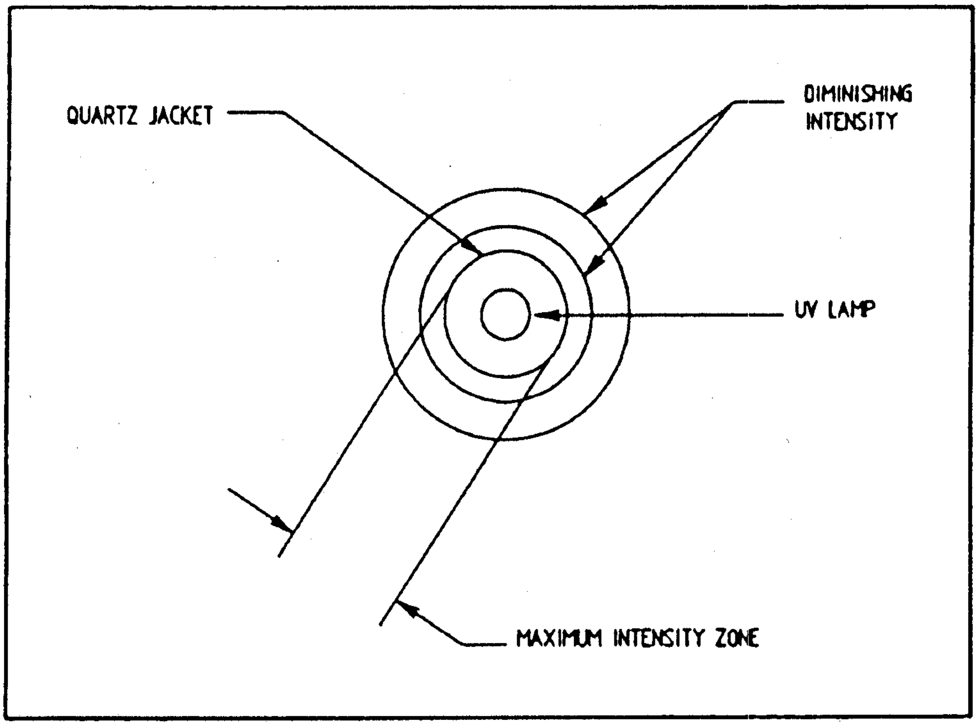


FIGURE 4-6 UV intensity relationship to distance from lamp(34)

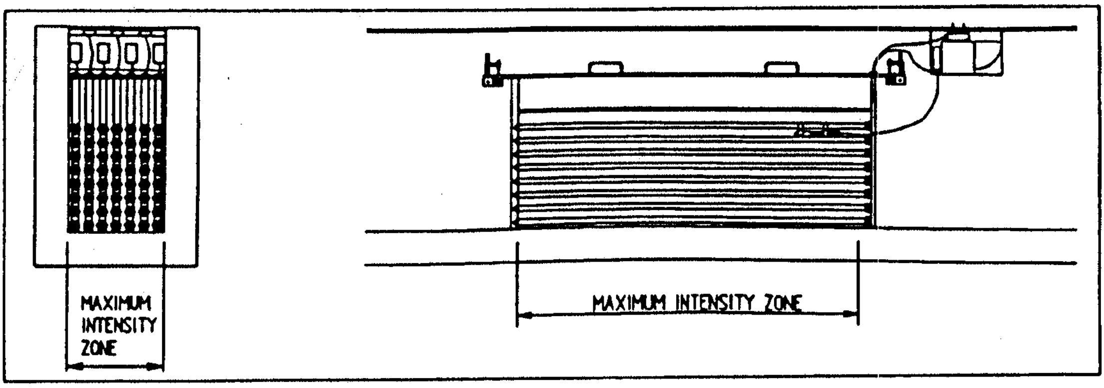


FIGURE 4-7 Maximum intensity zones in submerged horizontal reactor(34)

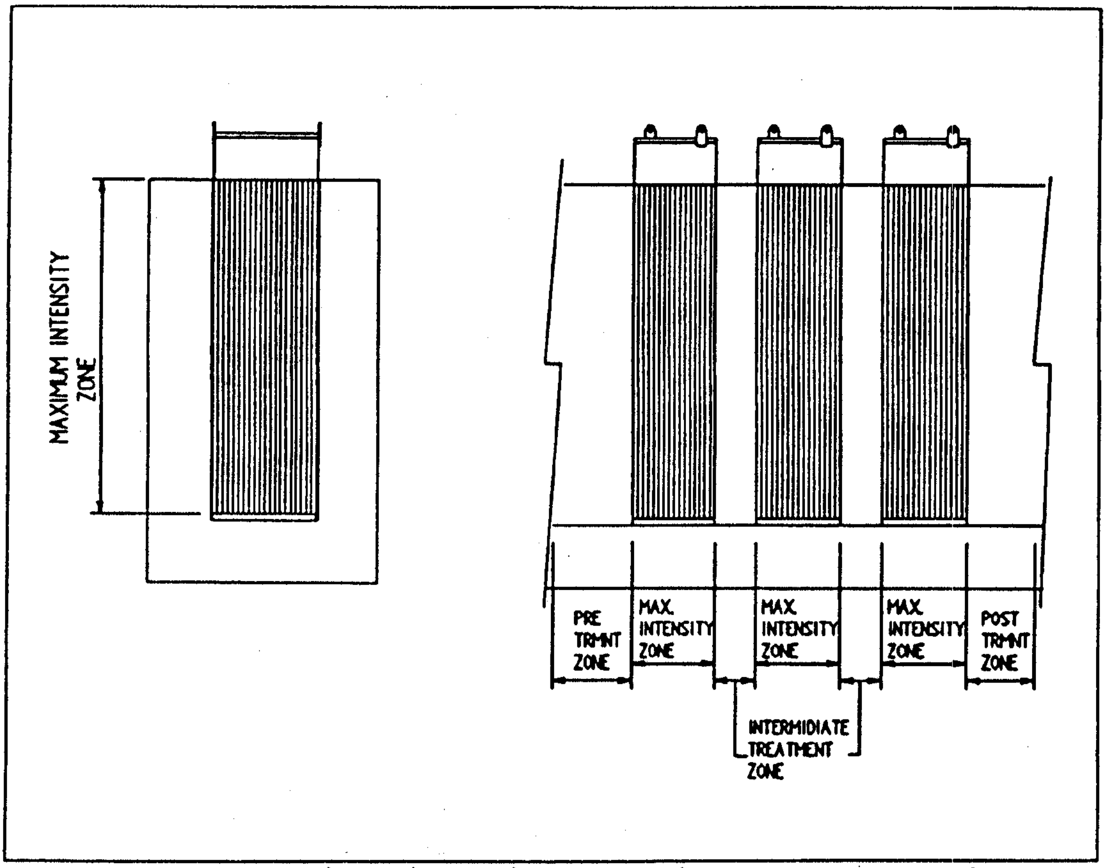


FIGURE 4-8 Maximum intensity zones in submerged vertical format reactor (Courtesy of Katydyn Systems, Inc. Bedford Hills, N. Y.)

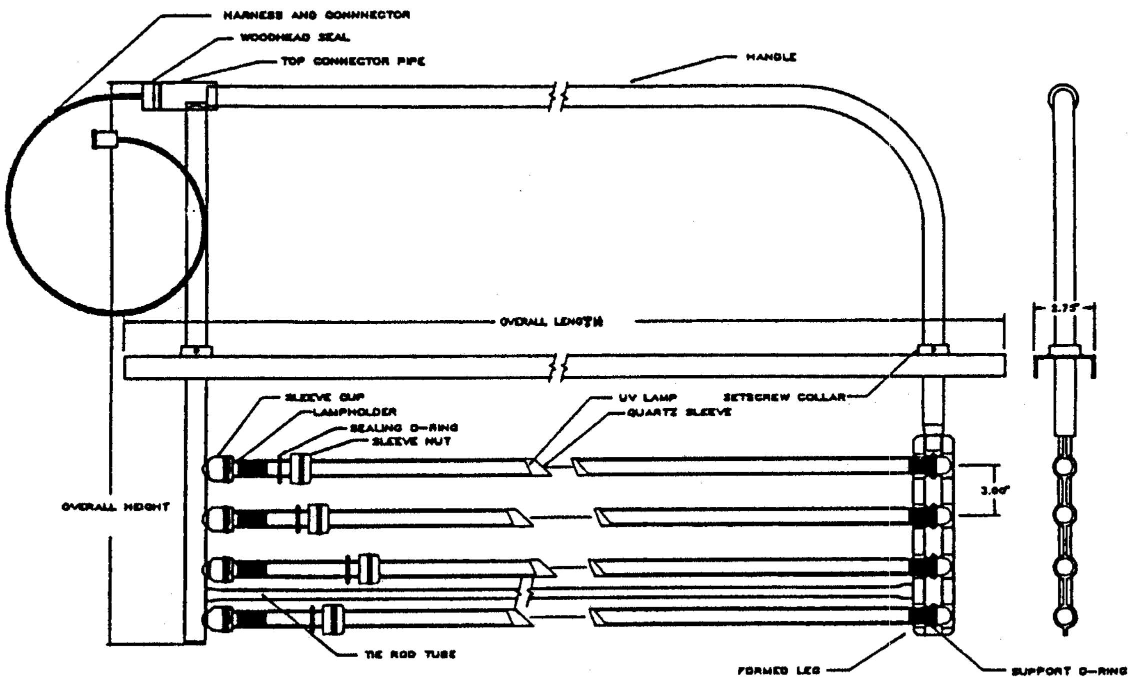


FIGURE 4-9 Typical 4-lamp module (Courtesy of Trojan Technologies, Inc., London, Ontario, Canada)

To provide optimum performance, any number of modules may be installed side-by-side, containing 2 to 8 lamps per module. The modular design also allows the system to be enlarged as flow volume increases simply by placing additional modules in the channel.

4.1.6 Individual Lamp Monitoring:

The UV system should be equipped with special electronic circuitry that reliably and continuously monitors the operation of all lamps in the system. The electronic circuit surveys each individual lamp, and visually indicates lamp operation on an illuminated display panel. Any lamp outage instantly activates both visual and audible alarm signals, and its location can be quickly pinpointed by checking the lamp status panel.

4.1.7 UV Intensity Monitoring:

The UV design should include a sub-system which utilizes a spectrally selective sensor that continuously monitors the UV intensity and which is strategically mounted at a point of minimum expected intensity in the channel. A continuous read-out should be provided on a direct-reading UV intensity meter and/or chart recorder. UV intensity monitoring gives the operator a good indication of lamp output, influent water quality and coating formation on quartz lamp jackets. Push-to-test circuitry allows the operator to check circuit integrity at any time.

4.1.8 Control Panel:

A control panel must be provided which enables operators to monitor the entire UV system. The configuration of lamps in the channel is reproduced on the panel so that the location of a failed lamp can be instantly seen. Changes in UV intensity are also recorded and displayed, and trigger one of two visual alarms on the control panel. For example, an amber warning light indicates a loss of lamp intensity that is still at a safe level, and a red light warning that lamp intensity is below the safe level. In addition, each lamp module should be equipped with a lamp life indicator showing elapsed operating time. A typical control panel is shown in Figure 4-10.

4.1.9 Level Control Systems:

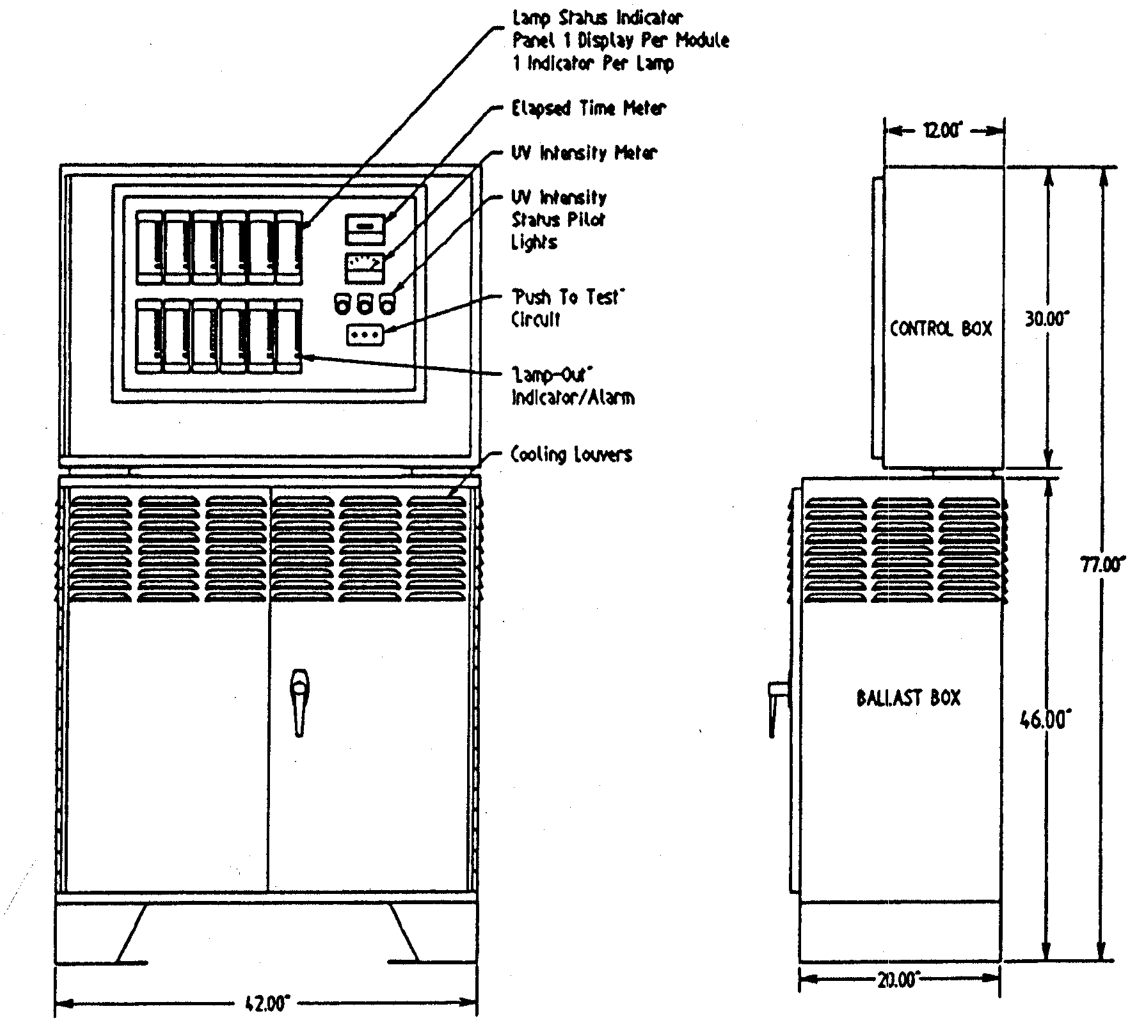


FIGURE 4-10 Typical modular control center (Courtesy of Katydyn Systems, Inc. Bedford Hills, N. Y.)

An accurate means of controlling the water level in the flow channel must be provided. The water level in the channel can be controlled by a simple weir if sufficient length is available (Figure 4-11) or by using a counter-balanced flap gate. Small gates are provided with weights for adjustment. Larger gates employ stainless steel counter-balance tanks (Figure 4-12).

4.1.10 Cleaning Options

A simple, reliable means for cleaning lamp jackets must be provided. After a time, all open channel lamp jackets will become coated, reducing their radiation transmitting effectiveness. Manufacturers offer three different ways of removing the coating: 1. in-place chemical cleaning within the channel; 2. cleaning in a portable station (Figure 4-13); or 3. manual cleaning, in which lamp modules are individually removed, wiped clean and repositioned.

4.2 Design Criteria

As with any process design, obtaining or assuming the correct information is a necessary first step. There are a number of considerations which need to be taken into account during design of a UV system and which impact on the extent, performance, and cost of the equipment required.

4.2.1 Water Quality Considerations

The effectiveness of UV disinfection of wastewater is strongly related to the quality of the waste stream. The presence of contaminants which can absorb radiant energy will reduce the ability of UV to destroy microorganisms. The UV coefficient of absorption, α, measured at 254 nm, is a useful parameter for the design, control, and monitoring of UV disinfection processes because it correlates very well with the routinely measured wastewater parameters such as total suspended solids, turbidity, and total and fecal coliform density[25]. Since it serves as the primary measure of UV attenuation, it is appropriate to use the UV coefficient of absorption as the major water quality parameter in UV system design and dosage application.[30]

4.2.2 UV Transmission Efficiency of Wastewater[34]

UV transmission is the single most important value which will directly influence the reactor design. It is a measure

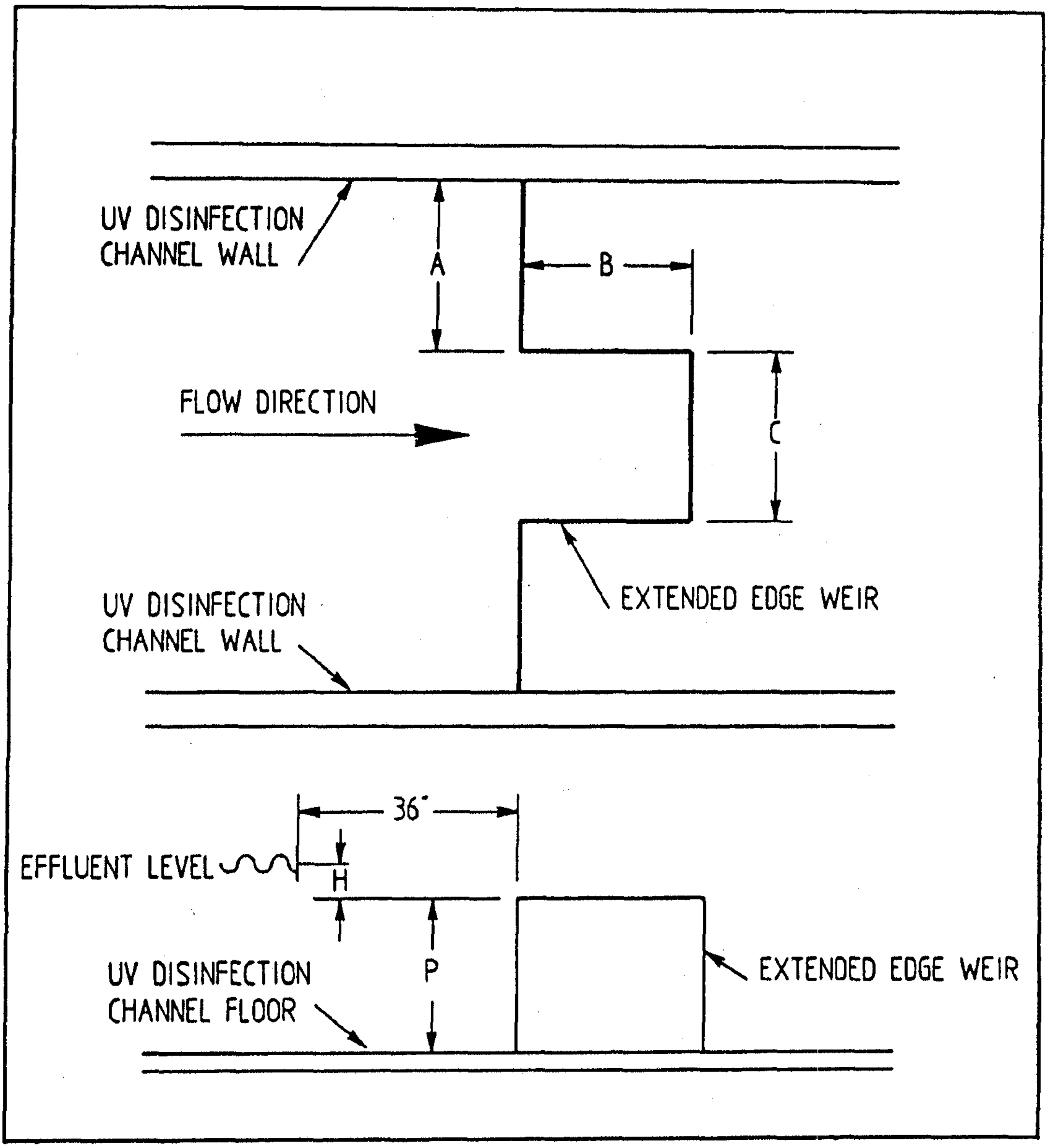


FIGURE 4-11 Typical extended weir design (Courtesy of Katydyn Systems, Inc. Bedford Hills, N. Y.)

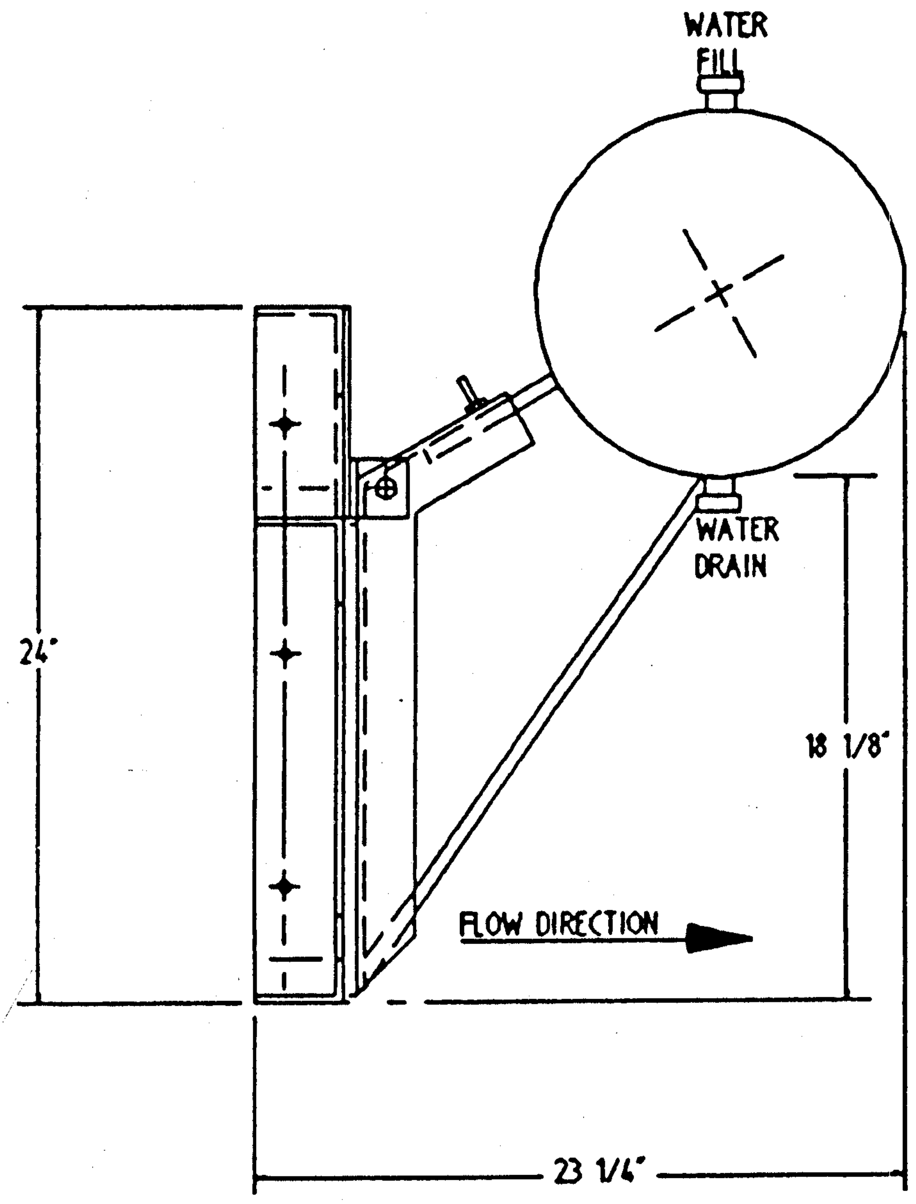
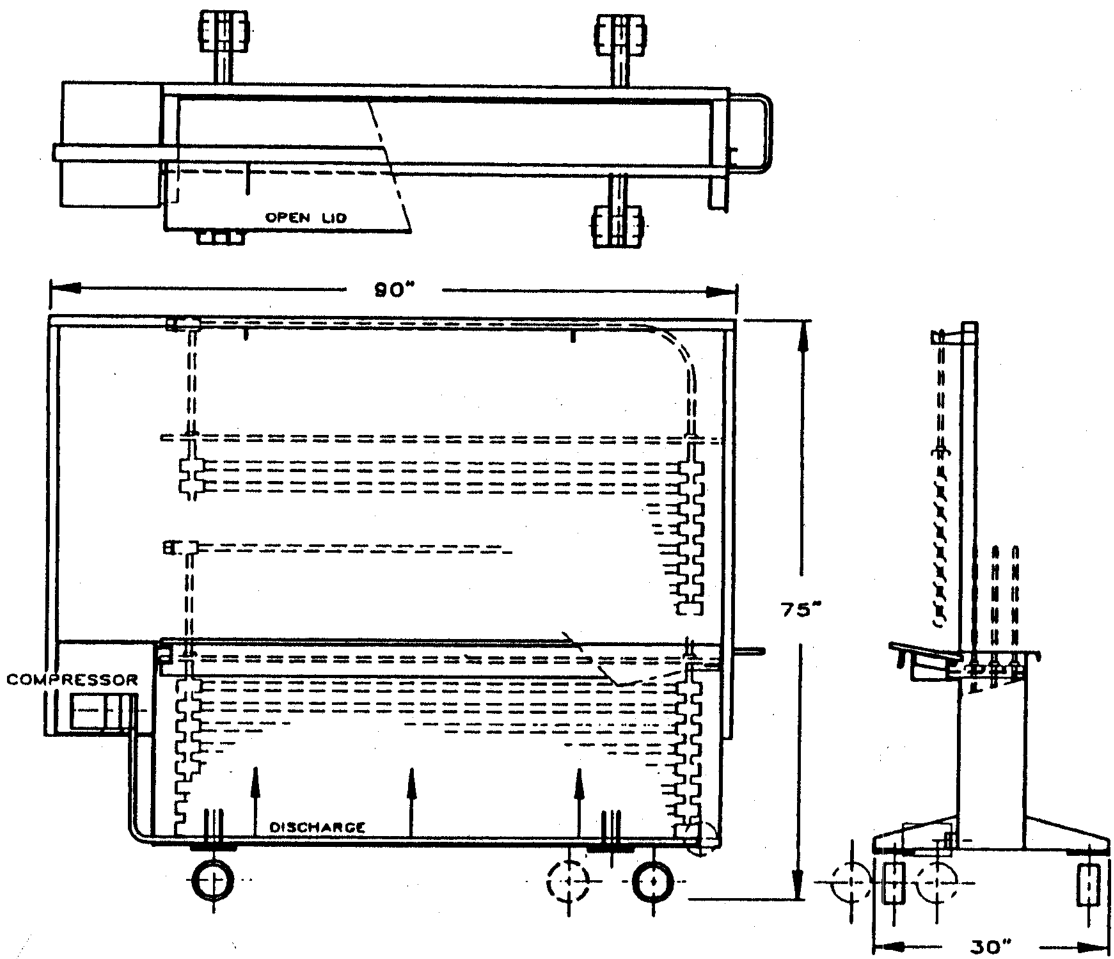


FIGURE 4-12 Typical automatic level control device (Courtesy of Katydyn Systems, Inc. Bedford Hills, N. Y.)



TANK IS CONSTRUCTED OF STAINLESS STEEL AND SIZED TO ACCOMODATE THREE UV MODULES AT ONE TIME COMPLETELY SUBMERGED IN THE CLEANING LIQUID. TANK IS EQUIPPED WITH A RACK ABOVE THE TANK TO HOLD THE MODULE ABOVE THE CLEANING LIQUID FOR HAND WIPING. TANK IS MOBILE WITH HANDLE BAR AND HAS SEALED COVER TO PREVENT SPILLING WHILE MOVING. A COMPRESSOR AND NECESSARY PIPING AND DIFFUSERS ARE MOUNTED ON THE UNIT TO AGITATE THE CLEANING LIQUID.

FIGURE 4-13 Typical horizontal module portable cleaning equipment (Courtesy of Trojan Technologies, Inc., London, Ontario, Canada) of the ease with which UV light passes through the wastewater so that the microorganisms may be directly inactivated. A measure of the UV transmittance is obtained by placing a sample of the wastewater to be treated into a spectrophotometer adjusted to the 253.7 nm wavelength. As mentioned in paragraph 3.6, there are several factors known to inhibit ultraviolet transmission: dissolved organics, iron in solution, color (textile dyes, etc. absorbing in the UV range) and turbidity. Unfortunately, it is not possible to be totally specific, either with regard to all the constituents factors or the concentration, hence, the importance of the actual measured test on a sample. If a sample cannot be measured locally, most equipment manufacturers can receive an effluent sample and perform the necessary test in their own laboratory at no charge. In the event that an actual wastewater reading is unobtainable, 65% transmission would be a reasonable assumption. This is the minimum transmission on which all of the empirical data used in equipment selection and sizing is predicated. Sizing of systems with lower transmissions will be totally dependent on pilot study data as discussed in paragraph 4.2.13.

4.2.3 Hydraulic Capacity

An ultraviolet light reactor must be sized to accommodate a range of flows including the peak hydraulic capacity[34]. The most important flow parameter is the peak condition since this is the basis of design of the reactor. However since most UV equipment designs permit control of the number of lamps in service (flow pacing) the range of flows is also desirable. Actual or estimated plant flow data, important and useful for design and evaluation of the system, are those typically considered for wastewater treatment systems, namely:

Annual average daily flow
Maximum 7-day average flow
Maximum 30-day average flow
Peak daily flow
Peak hourly flow

Although not critical to design sizing, average daily flows are important to estimating average utilization of the system for operation and maintenance needs.

4.2.4 Hydraulics of the UV Reactor[17]

The ideal flow conditions in a UV reactor is plug flow with minimal or no axial dispersion. Research has shown that the closer the reactor flow approaches ideal plug flow characteristics (zero dispersion), the higher the UV disinfection efficiency. Unfortunately, ideal plug flow does not exist under actual conditions and axial dispersion and velocity gradients will cause a distribution of residence times in the reactor.

The UV reactor should be designed hydraulically for plug flow and weirs used to route flows in multiple reactors to maintain these hydraulic conditions. Since the disinfection exposure time in UV reactors is considerably smaller (usually less than 1 minute) compared to chlorine disinfection (15 min), the volume of UV reactors is smaller. However, flow velocities greater than 1 fps are recommended to inhibit sleeve fouling in the reactor.

Several flow parameters can be specified in the contract documents to ensure that the UV reactor maintains near plug flow characteristics with minimum dispersion. The following mixing parameters to define plug flow were developed using a salt tracer conductivity residence time distribution (RTD) method introduced by Thampi and Sorber[18] for open channel reactors by steady-state injection of a tracer upstream of the UV unit. A number of the indices, derived from the RTD, can be used to qualitatively assess the adequacy of the physical reactor design.

4.2.4.1 Reynolds' Number[17]

Turbulent flow occurs with Reynolds' Number, R_e>2,000 in pipes or closed conduits. Ideal plug flow at Reynolds' numbers (R_e) greater than 2,000 ensures turbulent flow. Turbulent flow with minimum dispersion assures that all pathogenic organisms are exposed to the minimum effective germicidal dose. Higher dispersion causes greater short circuiting, which means greater numbers of organisms are not exposed to the minimum UV dose. This results in costly and inefficient reactor design since higher safety factors would have to be used. Open channel type reactors for UV disinfection should have R_e>4,000 at average flow and designers should ensure that excessive turbulence does not occur at open inlets as this creates dissolved air which will decrease UV disinfection efficiency by absorbing UV energy.

4.2.4.2 Aspect Ratio[17]

The reactor length (**x**) to hydraulic radius (**R_h**) aspect ratio (**x/R_h**) can be used to define turbulent plug flow with minimum dispersion for open channels and will occur when x/R_h is greater than 50. Plug flow characteristics are predominant in channels with narrow cross-sections with respect to length since cross-sectional velocities are more uniform, and less axial dispersion occurs.

4.2.4.3 Dispersion (**E**)[17]

This parameter accounts for hydraulic behavior deviation of the reactor from that of perfect plug flow. In effect it is a measure of the distribution of microorganism residence times in the reactor at continuous, steady-state flow. The units of dispersion, E, are cm^2/sec, and the dispersion number should be less than 100 cm^2/sec along the flow axis. Dispersion numbers higher than this value mean short circuiting, or greater probability of microorganisms exiting the UV reactor prior to the required minimum exposure time. For UV reactors, the longitudinal dispersion number along the flow axis by turbulent diffusion is of concern since the greater the longitudinal dispersion value the greater the non-uniform cross-sectional velocity and the greater the short circuiting.

The shape of the RTD curve for plug flow with dispersion less than 100 cm^2/sec will look similar to the simulated curve shown in Figure 4-14.

There are a number of uses for the RTD as a tool for diagnosing the hydraulic characteristics of a reactor since the shape of the curve and the distribution of the area under the curve will describe much of the hydraulic characteristics of a unit design and indicate whether or not it conforms with proper design practice.

4.2.4.4 Morrill Dispersion Index (MDI)

The MDI is the ratio of the time it takes for 90% of the tracer to pass, to the time it takes for 10% of the tracer to pass or t_{90}/t_{10}. The MDI should be less than 2.0 for UV reactors. MDI for ideal plug flow is 1.0.

4.2.4.5 Residence Time Coefficient (RTC)

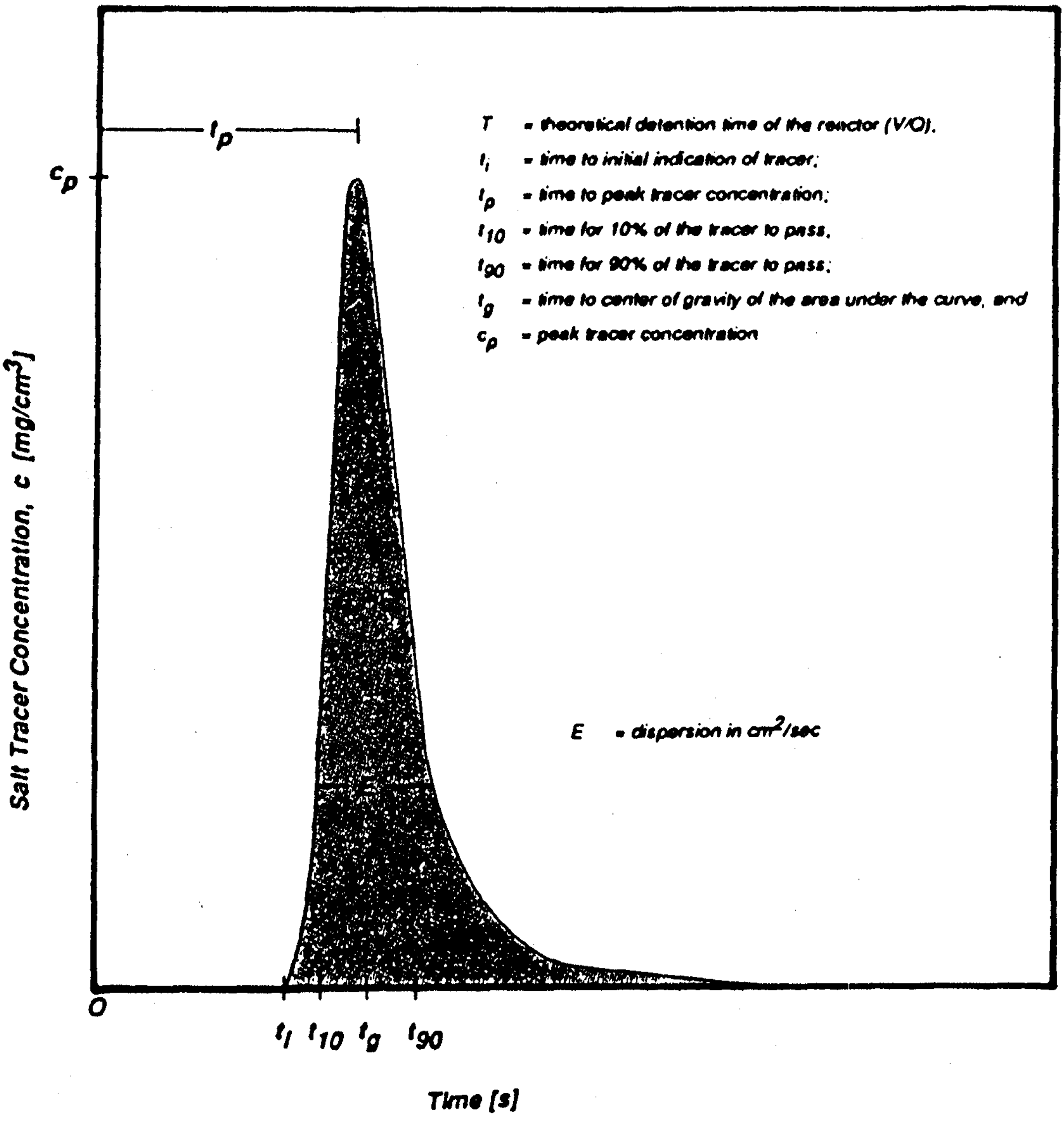


FIGURE 4-14 Typical concentration-residence time distribution curve with small amount of dispersion(E)[17]

The RTC is the ratio of the mean residence time to the theoretical residence time, or T_m/T, based on average flow. Theoretical residence time, T, is void volume, V_v, divided by average flowrate, Q_{avg}. The RTC should approach 1.0, the value for ideal plug flow, and be at least 0.9. Values significantly less than 1.0 would indicate that the effective volume is less than the actual volume being treated.

4.2.4.6 Average Velocity Short Circuiting Index (SCI)

The SCI is the ratio of the time for the peak concentration of tracer to appear to the theoretical residence time (t_p/T), should approach 1.0 and be at least 0.9 at average velocity.

4.2.4.7 t_i/T

The ratio of the time at which the tracer first appears to the theoretical residence time (t_i/T) is a measure of the most extreme short-circuiting. In a perfect plug flow reactor, the value is 1.0. For UV reactors t_i/T should be greater than 0.5.

4.2.4.8 Average Mass Short-Circuiting Index

The ratio of the time required for 50 percent of tracer to pass to the theoretical residence time, t_{50}/T should be between 1.0 and 1.1 and is indicative that the entire volume in the reactor is used effectively. The ideal plug flow short-circuiting index is 1.0.

4.2.4.9 Dispersion Coefficient (E)

The RTD curve can also be used to estimate the dispersion coefficient, **E**. Since the RTD closely approximates a normal distribution curve form, then $\delta_m^2 = \delta^2/T_m = 2E/ux$ where δ^2 is the statistical variance of the RTD; T_m is the mean residence time; δ_m^2 is the dimensionless variance; **u**, is the flow velocity and **x**, the length of the channel under direct exposure to UV light. The dispersion coefficient is estimated by inserting the determined value of δ_m^2, and known values of **u** and **x** into the formula. Good dispersion is achieved if **E** is less than 100 cm^2/sec.

4.2.4.10 Dispersion Number, d_n

The term **E/ux** is referred to as the dispersion number, d_n, and serves as a useful parameter in diagnosing a system or in the design of a new system. In plug flow reactors, the values of d_n can denote degrees of dispersion; for example, a value of 0 indicates zero dispersion, 0.01 low dispersion, 0.01 to 0.10 moderate dispersion and high dispersion greater than 0.1. For UV reactors, axial dispersion should be less than 0.05.

4.2.5 Secondary Treatment Process

Upstream processes can obviously influence the water being received into the UV reactor. Fixed film reactors, particularly trickling filters, can produce a secondary effluent which requires a more conservative approach.

4.2.6 Total Suspended Solids[34]

Suspended solids of themselves have little or no influence on the UV transmittance of the wastewater, however, the solid particles can encapsulate microorganisms (occlusion) and shield them from the effect of UV light. In the absence of measured data or a given value, assume that the maximum suspended solids concentration entering the reactor will be 30 mg for secondary treatment.

4.2.7 Absorbance

The constituents in water which increase UV absorbance depend on the degree of concentrations of dissolved organic matter and suspended solids[17]. Effluent prior to UV disinfection should be no greater than 20 mg/l total suspended solids (TSS) and 20 mg/l BOD_5. High suspended solids will shield microorganisms from UV rays. Absorbance (in cm^{-1}) is measured or calculated from the Beer-Bouger-Lambert Law shown in Figure 4-2 and the following equation:

$$I_1 = I_0\, 10^{-Ad} = I_0\, e^{-\alpha d} \quad [1]$$

where:

I_1 = measured intensity at distance d in cm,
I_0 = lamp surface intensity,
A = medium absorbance (cm^{-1}),
e = base of natural logarithms, and
α = coefficient of absorption

Effluent quality of 30:30 TSS:BOD_5 or greater may still be acceptable if absorbance does not exceed 0.2 cm^{-1}. A review of secondary effluent throughout the U.S. indicates that absorbance does not exceed 0.2 cm^{-1} [10,9]. An assumed absorbance value of 0.2 cm^{-1} can be used to size UV reactors based on the flow layer absorbing 90 percent of the germicidal energy.

4.2.8 Intensity and Dosing

Lamp intensity depends on the size and output power of the lamp and is expressed in watts. Manufacturers' literature should be consulted to find out how much germicidal UV at 253.7 nm is emitted[17]. One system inputs 36 watts, but average UV output intensity (I_0) emitted is 10.4 watts. UV energy emitted in microwatts/cm^2 ($\mu w/cm^2$) can be calculated at the surface of the lamp based on the lamp effective arc length. This lamp is 91 cm (36 in) long (effective arc length is about 81 cm (32 in) long) and has a diameter of 1.9 cm (0.75 in). So lamp surface output is 10.4 watts divided by the effective lamp surface area (81 cm x π x 1.9 cm) which gives I_0 = 21,380 $\mu w/cm^2$.

Most bacteria and viruses require relatively low dosages for inactivation (Table 4-1), usually in the range of 2,000 to 6,000 μw-sec/cm^2.

UV dosing in μw-sec/cm^2 is calculated as the product of exposure intensity (I) in $\mu w/cm^2$ (at 253.7 nm) and exposure time (t_n) in seconds as in Equation 2.

$$\textbf{Germicidal UV Dose} = I \times t_n \qquad [2]$$

The UV dose delivered by the UV system is defined as the product of the average intensity throughout the lamp array and the retention time within the bank of lamps. The average intensity dose is determined by a method called the "point source summation" method, in which each lamp is analyzed as a point source of light. The UV light reaching each point in a grid superimposed on the UV lamp array is determined as the sum of the light intensities from each point source, and the average is determined by averaging the intensities at all points in the grid. The retention time is determined by completing a hydraulic analysis for the lamp reactor and comparing the actual retention time to the theoretical retention time.

Table 4-1 Approximate dosages for 90% inactivation of selected microorganisms by UV (Source: 14)

Microorganism	Dosage (μw-sec)/cm²
Bacteria	
E. coli	3,000
Salmonella typhi	2,500
Pseudomonas aeruginosa	5,500
Salmonella enteritis	4,000
Shigella dysenteriae	2,200
Shigella flexneri	1,700
Shigella sonnei	3,000
Staphylococcus aureus	4,500
Legionella pneumophila	380
Vibrio cholerae	3,400
Viruses	
Poliovirus	15,000
Coliphage	3,600
Hepatitis A virus	3,700
Rotavirus SA	118,000
Protozoan cysts	
Giardia muris	82,000
Acanthamoeba castellanii	35,000

For organisms found in secondary wastewater effluent prior to disinfection, a UV dose of 16,000 μw-sec/cm² is sufficient to inactivate. Thus, from Figure 4-2, at least I_2 = 16,000 μw-sec/cm² should be maintained at the farthest point from the UV lamp. Intensity sensors, that warn when the lamp 253.7 nm emission drops below 10,000 μw-sec/cm², should be installed in each bank of UV lights.

4.2.9 Final Effluent Quality

Final effluent quality is the standard by which the UV system performance is measured, tested, and guaranteed[34]. It is, therefore, very important to establish this level of disinfection. Typically, the ultraviolet disinfection system will be required to produce a final effluent having less than 200 fecal coliform colonies per 100 milliliter for any 30 consecutive days (geometric mean) or a 30-day consecutive arithmetic mean (whichever gives worst case) of twice weekly samples. No excursion should exceed 400 total coliform colonies. Higher quality effluent can be achieved but may require additional upstream treatment such as filtration. For systems requiring better than 200 fecal coliform colonies per 100 ml without tertiary treatment, manufacturers of UV equipment should be contacted directly.

4.2.10 Feasibility Determination

It is important to determine whether an effluent is suitable for UV disinfection. The terms normally utilized to describe effluent quality such as BOD_5, suspended solids, color, and turbidity are not adequate to predict feasibility of UV[31]. This is because measurements of these parameters are based on visible light transmission whereas UV light follows an entirely different path. It is not unusual to find 10 mg/l BOD_5 and 10 mg/l suspended solids effluent with a lower UV transmission than a 30 mg/l suspended solids effluent. The correct feasibility determination for a UV system is to measure the transmittance at 253.7 nm (2537 Angstrom) with a spectrophotometer. The percent UV transmittance is the important factor in determining feasibility and also the ultimate design requirements. In the case of a new facility, the engineer should estimate the UV transmission percentage based upon the existing data for a treatment plant with similar flow, treatment, and influent characteristics just before disinfection.

4.2.11 Information Requirements

There are three stages in the selection and design of a disinfection system for a municipal wastewater treatment plant: (1) economic analysis, (2) system sizing, and (3) data collection. If necessary, a fourth stage, pilot testing, is also added.

4.2.11.1 Economic Analysis

Most UV manufacturers can prepare a budget quotation from data gathered by the designer. If UV disinfection is feasible economically, then the system can be more accurately sized and laid out. Appendix A provides a typical manufacturers data form and checklist which are helpful in requesting and performing the economic analysis and concept design.

4.2.11.2 System Sizing

If the system being evaluated is to be installed in an existing wastewater treatment plant then sampling of the effluent should be performed as described in paragraph

4.2.12.1 and information in Appendix A provided to the manufacturer. If a plant does not exist then a similar sewage treatment plant as that proposed for the Installation should be analyzed for UV transmission.

4.2.11.3 Data Collection

Samples for UV transmission should be analyzed as described in paragraph 4.2.12.2, UV Transmission Testing.

4.2.11.4 Pilot Testing

In some instances it may be necessary to pilot test a UV system at the existing wastewater treatment plant. The procedures to be followed are described in paragraph 4.2.13, Pilot Testing a UV System.

4.2.12 Sampling and Analysis

4.2.12.1 Initial Sampling

Grab or composite samples should be taken at a point after the final clarifier and before the chlorine contact basin. The best time to take the sample is at maximum and minimum diurnal flow since a comparison of both will help determine the performance of the final clarifier. Sample volume should be 500 ml. Sample collection preservation and storage should be in accordance with Standard Methods 906.

4.2.12.2 UV Transmission Testing

Transmission (or transmittance) is a measure of the amount of UV energy that will pass through 1 cm of water. It is measured using a UV spectrophotometer set at a wavelength of 253.7 nm. The spectrophotometer is calibrated using distilled water in a quartz cell with a path length of 1 cm since this liquid has zero absorbance or 100% transmission. A single beam from a deuterium lamp is then passed through a 1 cm layer of sample. The resulting light intensity is measured by a photomultiplier tube and registered as a percentage of the original beam intensity calibrated at 100% with distilled water. The absorbance of UV energy by chemicals or solids present in the wastewater (referred to as UV Demand) may be expressed as absorbance or transmittance. The procedure is summarized as follows:

(1) set spectrophotometer for wavelength 253.7 nm;

(2) filter the sample through 0.45 micron filter and analyze filtrate at 253.7 nm. (The UV absorption of the filtrate is likely an indicator of soluble and colloidal organics in the wastewater.);
(3) take the filtrate and add alum, $Al_2(SO_4)_3$, allow to settle and measure UV transmission of the filtrate after settling has occurred;
(4) measure the total suspended solids (TSS) of the sample;
(5) measure the hardness content of the sample;
(6) measure the iron content of the sample.

Direct readout from the spectrophotometer is in absorption units per centimeter, or A/cm. This is converted to a percent transmission by the expression,

$$\%T_r = (100)\ 10^{-(A/cm)} \qquad [3]$$

The coefficient of absorption, is related to **A** by the expression,

$$\alpha = 2.3\ (A) \qquad [4]$$

4.2.12.3 Comprehensive Sampling

Should the UV transmission of the entire sample be less than 55%, additional samples should be taken (1) after the primary settling tank(s), (2) after secondary treatment, (3) before the final clarifiers and, (4) after final clarifiers on each of seven consecutive days. Analyses (1) through (3) in paragraph 4.2.12.2 should be completed on each sample.

4.2.13 Pilot Testing a UV System[35]

Pilot studies at wastewater treatment facilities are conducted to determine several design objectives: (1) the effectiveness of ultraviolet light as a method of disinfecting effluent from the wastewater treatment plant. (In particular the pilot study will determine the UV dose in w-sec/cm² required to meet the fecal coliform limits required by the state and the effluent discharge permit); (2) the effectiveness of ultraviolet light versus chlorination in meeting the fecal coliform limits; (3) the frequency of quartz sleeve cleaning; and, (4) the most effective cleaning materials or products.

Equipment manufacturers can furnish a pilot system capable of disinfecting at the plant peak flow rate. The system would be equipped with a V-notch weir for flow measurement. It is also recommended that a properly calibrated flowmeter be installed upstream of the unit by others. Usually a factory-trained technician supervises the installation of the equipment at the site, completes start-up of the equipment and makes modifications to the equipment, if required during the test.

4.2.13.1 Sampling Procedures

Samples are taken immediately before and after the ultraviolet unit. Sampling and analysis are to be done in accordance with Standard Methods[32]. The frequency of sampling is to be determined by the UV equipment manufacturer and considering that the greater the number of samples generated, the greater the reliance that can be placed on the results. As a minimum, 60 samples should be taken over the duration of the testing.

4.2.13.2 Duration

The test duration must be as long as necessary to conclude that the objectives of the tests have been achieved. The test should last a minimum period of 30 days.

4.2.13.3 UV Dose

The ultraviolet dose delivered by the equipment is monitored by means of a sensor probe and meter. The system will deliver a UV dose for established values of Q (GPM), UV transmission (%), UV dose after 100 hr burn-in of lamps in $w\text{-}sec/cm^2$, and UV dose after 7500 hours of lamp operation in $w\text{-}sec/cm^2$. After the equipment is set up, the UV dose is calculated based on the transmission level of the effluent. The effluent should be sampled to ascertain the transmission level. The pilot system is designed so that the UV dose delivered can be varied. In this way the limits of the equipment can be ascertained and an adequate dose level for the coliform limit established. The dose level is varied by varying the flow through the unit.

4.2.13.4 Cleaning Frequency

The frequency of cleaning is determined by allowing the system to run continuously until three connective samples do not meet the coliform standard.

4.2.13.5 Cleaning Quartz Sleeves

From time to time the quartz sleeves will have to be cleaned. This is done by using a mild solution of citric of phosphoric acid. A commercially available cleaner is usually furnished with the pilot unit.

4.2.13.6 Sampling

Each time a sample is taken, a pilot study data sheet should be completed. The intensity (I) can be read from the meter on the front of the panel. If Q remains constant then the retention time will be constant.

4.2.14 Collection of Microbial Sample

The following is an outline of materials and methods required when collecting microbiological samples of ultraviolet treated water[32]. It is essential that all samples be placed in a cooler immediately and refrigerated to prevent bacterial growth between the time of sampling and culturing. High bacteria counts often result from improper storage and excessive transportation times.

4.2.14.1 Containers

Sample bottles must be sterile and should hold a volume no less than 100 ml. When sampling water with residual chlorine or bromine, a reducing agent such as sodium thiosulfate should be added before sterilization of the sample bottle. To a 120 ml bottle add 0.1 ml of 10% solution of sodium thiosulfate, $Na_2S_2O_3$. This will neutralize a sample containing 15 mg/l residual chlorine. When a UV transmission test is required, the sample bottle must not contain $Na_2S_2O_3$, since this chemical absorbs UV and thus gives a false reading for the transmission.

4.2.14.2 Sampling Procedure

Keep the sample bottle closed until it is to be filled. Do not contaminate the inside of the top or neck of the bottle. Fill the container, recap, and immediately store in an ice chest. When control samples are required, such samples would be taken before the water is exposed to UV. The performance test sample would be collected immediately after the UV unit.

4.2.14.3 Preservation and Storage

Ideally samples should be processed by the laboratory within one hour of collection. All microbiological samples should be transported on ice in a cooler and kept in a refrigerator until cultured.

4.2.14.4 Photoreactivation

When irradiated microorganisms are exposed to light, some are able to repair the genetic damage. In order to assess the degree of recovery due to photoreactivation, it is necessary, to take the following samples:

1. **Control Sample:** An influent sample taken before UV exposure to provide the original number of bacteria present before treatment.

2. **Dark Sample:** An effluent sample taken after UV exposure to determine the number of bacteria killed by UV. Painted or foil covered bottles are used to prevent light exposure.

3. **Photoreactivation Sample:** An effluent sample taken after UV exposure at the same time as #2. This sample will then be subjected to the same light and temperature conditions as the effluent for 3 hours.

4.2.14.5 Collection of Samples

Sterile glass bottles 100-250 ml size are normally used for sampling. Duplicate effluent samples (light, dark) are collected and stored immediately on ice in an ice chest and transported to the laboratory.

4.2.15 Simulation of Lamp Aging[35]

During the life of a lamp the intensity will decrease by 30-40% per year. This aging can be simulated by reducing the voltage from 120 volts down to 90 volts. Experience shows that further reductions in voltages cause the lamps to flicker or go out. Therefore, it is best to reduce the voltage as much as possible but carefully monitor the status of the LED's to ensure no lamps go out. A reduction of lamp output of approximately 25% can be simulated. The following steps should be followed:

1. clean lamps thoroughly;
2. take reading on UV sensor at 120 volts;
3. hook up variable metered transformer (10 amp);

4. disconnect sensor from circuit that the voltage is being varied and reconnect to 120 volt circuit. (The sensor cannot function on less than 120 volts);
5. vary voltage while at all times monitoring the LED's to ensure all lamps are energized. Measure voltage output using voltmeter;
6. do not decrease voltage below the level necessary to maintain the lamps energized;
7. monitor the intensity reading on the meter. (It is unlikely that a percentage decrease in voltage output will result in a similar decrease in intensity output. The decrease in intensity output will not be as great. This is due to the ballasts which tend to compensate for voltage drops;
8. any noticeable heat build-up in the variable meter transformer should be cooled by focusing the cooling fan on it and blowing air across it;
9. the LED's should be monitored at all times and especially during sampling just in case lamps are not burning;
10. suggest that this simulation be done for approximately one week and samples taken three times daily. The equipment should be monitored frequently during this simulation.

4.3 Design Considerations

4.3.1 Delivered UV Dose

The product of UV light intensity and exposure time, referred to as the UV dose is restated as follows:

$$\textbf{UV Dose } (\mu\text{w-sec/cm}^2) = I \times t_n \qquad [2]$$

where I = UV Intensity (μw/cm^2)

and t_n = exposure time (seconds)

4.3.2 Hydraulic Characteristics[34]

4.3.2.1 Flow

All UV reactors, regardless of the design selected, must possess hydraulic characteristics closely resembling turbulent yet plug flow. The turbulent flow will guarantee that all of the effluent at some time will pass through a region of highest ultraviolet intensity. The plug flow characteristic will guarantee uniform velocity through the reactor thereby assuring that the micro-organisms are within the effective treatment zone for the full retention time and not short-circuited with minimum treatment effect.

4.3.2.2 Flow Pacing

Depending on the size and complexity of the wastewater facility, the UV system can be made as simple or as sophisticated as necessary. The single biggest variation that the UV system may be asked to accommodate is the plant flow. On most small systems, sufficient lamp capacity is provided to meet the plant's maximum flow and all lamps are fully utilized throughout the entire flow range. Medium to large installations can be provided with "flow pacing" which is a system which allows lamps to switch on or off depending on the plant flow.

The benefits of flow pacing are twofold. First, energy is conserved since only the necessary quantity of lamps are in service, and second, useful lamp life is extended over a longer period of time. The flow variable also has to be considered with respect to water elevations in the disinfecting channel. Regardless of flow, a constant elevation has to be maintained. Wherever possible, a weir is recommended provided that sufficient weir length can be installed to ensure very small variations in crest depth. When a weir is impractical, a level control device has to be employed and this will usually be a flapper gate.

4.3.2.3 Level Control

This is a requirement of all open channel reactors. The performance of UV equipment in open channel is dependent on proper maintenance of the water surface elevation. Low water levels which will allow a horizontal lamp to operate dry can cause severe coating conditions due to the elevated surface temperatures of the quartz jackets. Fluctuating water levels will cause a constant wetting and drying of the quartz jackets also causing potential for severe coating problems. A high water surface will result in effluent passing above the effective treatment zone causing hydraulic short circuiting of the reactor.

There are currently two types of level control systems recommended for open channel applications. One is the fixed straight or serpentine weir, and the other is the gravity operated, bottom opening, flapper gate.

a. Weir. The primary level control preference should be the fixed straight or serpentine weir, either permanently installed, or installed as a removable slide gate. The fixed weir has no moving parts and allows for positive level control at zero flow. The fixed weir should be designed with a bottom cleanout to allow for biannual or annual flushing of the solids which will accumulate behind the weir. A flapper gate will provide a natural scouring of the channel floor caused by the bottom opening of the gate. The fixed weir should be installed in the channel such that the included angle between the fixed weir and the channel wall is between 45 and 90 degrees. If a serpentine pattern weir is used, the center section should be equal to or less than 1/3 of the channel width. The total length along each side and inside of the center section should be a minimum of three times the head over the weir at peak flow. The extension of the center section should be less than 2/3 of the channel width and greater than three times the head over the weir at peak flow.

b. Automatic Control Gate. The second level control choice should be the flapper gate. This gate does contain a minimum number of moving parts but does not provide positive level control at zero flow. It will provide accurate control over a ratio of approximately 3:1 for peak to minimum flow. The gravity operated flapper gate should be designed to provide safe operation at flow rates up to 125% of peak flow with the downstream effluent level at the one hundred year flood level. The design of the actual opening in the flapper is such that it forms a sharp edge rectangular orifice over a flapper gate angular travel range of 0 to 60 degrees.

c. Level Control Operation and Location. Level control using either type of device should be designed such that its overall height will not cause flooding in the flow channel. For horizontal modules, the level of the effluent should be maintained between just tangent to the top of the upper quartz protective jacket and 1-1/2 inches higher. For vertical modules the level of the effluent should be maintained between 1/2 inch above and 3 inches below the UV lamp top filament. Either level control device should be installed at a minimum of 60 inches downstream of the UV modules.

4.3.2.4 Profile and Headlosses

The head that is available will be a critical consideration when selecting a UV system. The hydraulic head which is required for each of the systems is highest for the vertical configuration system and the horizontal open channel system requiring the least amount of head.

For the facility which is going to be retrofitted with alternate disinfection resulting from the direct need to eliminate chlorine residuals or incorporated into a plant expansion, the open channel system is an ideal application.

The vertical lamp system will require a water depth of approximately 60 inches (152 cm), yet if installation is to be in a section of an existing chlorine contact tank, this depth is not usually a concern. Headlosses in this system are typically less than 6 inches (15 cm).

For the smaller facility, or where this depth is not possible, the horizontal lamp system is a better alternative. This system can be supplied with a water depth requirement of as little as 10 inches (25 cm). Headlosses due to friction are typically less than 3 inches (8 cm). Headlosses and water surface gradients in this system are critical to proper lamp submergence and therefore no more than two banks of horizontal lamps can be installed in series. Hence, only limited 50% incremental "flow pacing" is possible in a single channel installation.

4.3.3 Control and Monitoring

In any ultraviolet reactor the operator is protected from casual exposure to the UV light with screens, therefore, the control panel has to provide all the information needed to determine the status of the system. Every UV equipment design must incorporate the following status information:

a. Individual lamp condition

b. Ultraviolet intensity

c. Lamp life

The first two incorporate alarm warnings which can be used for remote indication to a variety of external monitors.

4.3.3.1 Individual Lamp Condition

The control panel incorporates an LED indicator lamp for every ultraviolet lamp in the system. These indicator lamps are illuminated all the while the UV lamps are in the "on" condition. Coupled with the indicator lamps is a lamp failure indicator, one per bank, module, or array of UV lamps. This lamp failure indicator is normally off and will only illuminate in the event that a UV lamp fails. The lamp failure indicator alerts the operator to a failed lamp condition and the lamp indicator identifies precisely which lamp has failed.

4.3.3.2 Ultraviolet Intensity

Ultraviolet intensity is a measure of the amount of UV light available for treatment. Since this intensity gradually diminishes, it is important to know the condition on a continual basis. A UV Intensity monitoring probe is mounted in a representative position in the channel and measures the light emitting from a UV lamp through a quartz jacket and through a set thickness of water. Since the UV intensity diminishes for lamp depreciation, quartz jacket fouling, or a change in water quality, this probe position is able to monitor any combination of these effects.

4.3.3.3 Lamp Life

Because ultraviolet lamps naturally depreciate over time, it is necessary to measure and record the period of time the lamps have been in the "on" condition. Each bank, or array of UV lamps in the system is equipped with a non-resetting elapsed time meter.

The output from this probe is displayed on a meter and is used in conjunction with three indicator lamps, for example, green registering a safe intensity level, amber registering function in the low end of the safe range, and red registering operation outside the safe range.

To check the operation and calibration of the system, "push-to-test" buttons are provided whereby the operator can substitute the output of the UV probe for signals corresponding to two scale deflections of the meter.

4.3.4 Cleaning Methods

Wastewater effluent often contain organic and inorganic material which may form a coating on the quartz lamp jackets in the UV reactor. This is common especially in plants having relatively high grease and oil content or a high hardness content. Fouling of the quartz surfaces will produce reduced efficiency and reductions in UV intensity as measured by in-line intensity probes. An acceptable cleaning system must be capable of cleaning these surfaces. Currently, four cleaning methods are available:

(1) disassembly, (2) in-place chemical cleaning, (3) ultrasonic cleaning, and (4) mechanical wipers.

4.3.4.1 Disassembly

This method can provide for the cleaning of surfaces, but may present problems with respect to down time and possible breakage of the quartz jackets and lamps. Mostly for use with horizontal lamp module systems, a mobile stainless steel cleaning tank is provided as an accessory by the UV equipment manufacturer. The tank is sized to accommodate a multiple of complete UV modules at one time completely submerged in a cleaning liquid which is usually a weak citric acid. The tank is usually equipped with a rack above the tank to hold a module above the cleaning liquid for manually wiping the jackets. The tank is also equipped with a compressor, piping, and diffusers mounted on the unit to agitate the cleaning fluid.

4.3.4.2 Chemical Cleaning In-Place

This technique apparently cleans effectively in a short period of time without removing the UV equipment from the reactor. A cleaning solution is introduced into the isolated disinfection channel and recirculated by a small pump. This method requires shutting down the UV system during the cleaning cycle for 20 to 30 minutes. There are numerous non-toxic, non-polluting cleaning solutions such as weak acids and detergents available which are suitable for discharge into sensitive receiving waters.

4.3.4.3 Ultrasonic Cleaning

This is a relatively new application which has been well established in other cleaning applications. Ultrasonics provides cleaning of quartz sleeve surfaces without the need to stop the disinfection process. The ultrasonics may be operated on a timed cycle to serve as a preventative to the formation of undesirable coatings; or as a cleaner after a coating or film has been formed. The effect of the ultrasonics can be enhanced by the use of a cleaning chemical in conjunction with the ultrasonic induced cavitation. Ultrasonics, apparently, has no adverse effect on the life of UV lamps or on the internal components of the UV system. Currently, there has been only limited, but favorable, field application and experience with this method.

4.3.4.4. Mechanical Cleaning

This method employs the concept of placing a wiper or scraper around the quartz jacket which may be mechanically actuated back and forth along the quartz surface continuously or on a timed cycle. Due to variations in the diameter of quartz jackets, and the lack of flexibility of the wipers; the cleaning quality varies from system to system and with the type of coating. As with ultrasonic cleaning, there is no long term history of performance for the mechanical wiper method and some of the designs tested have been found ineffective. Mechanical wipers are subject to wear and researchers have suggested an annual replacement schedule. Replacement of wipers involves shutting down the UV system, removing all lamps, removing all the quartz jackets and then replacing the wipers. This takes considerable time and should be considered when evaluating a cleaning method.

4.3.4.5 Teflon Tube Designs

There have been claims that UV units utilizing teflon tubes do not require cleaning but studies have established that teflon tubes become coated with film at the same rate as quartz jackets. Teflon tubes absorb between 40 - 50% of the UV intensity so that a significantly higher number of UV lamps are required in a teflon design to equal the dosage of a unit with quartz jackets.

4.3.5 Operation and Maintenance

Day-to-day operation of the facility will require a routine check of the control panel for lamp failure and changes in UV intensity, and a visual inspection of the channels of chamber to check for accumulation of solid material. Maintenance of the system is usually confined to routine component replacement, annual lamp replacement, and periodic cleaning of the quartz jackets. Each system should been designed to make this maintenance as simple as possible.

The design should incorporate means for the following routine maintenance:

<u>Daily:</u> Check UV monitoring device for UV intensity.
Check lamps for proper operation.

<u>Weekly:</u> Check for leakage around quartz tubes.

Calibrate UV intensity meter for proper sensitivity.

<u>2-6 Months:</u> Clean interior of UV channel.
Clean contacts on bulbs.
Check fail-safe devices for proper operation.

<u>Yearly</u> Replace bulbs.

4.3.6 Spares and Service

Included in most specified UV equipment packages is a minimum spares requirement. This would normally be 10 percent of the total installed number of lamps, quartz jackets, ballasts, and fittings. In the case of the open channel horizontal design, at least one spare frame assembly should be specified. Designers should insure that manufacturers maintain full inventory of all components and that any item can usually be supplied from stock.

The services of the UV manufacturer during the installation phase is usually specified for inspection of the general contractors installation, for equipment start up and for operator training. After-sales service should be available from the manufacturer using factory trained technicians.

The lamp tubes used in the system should be a specified generic type and not customized in any way that would prevent their replacement by lamps from another manufacturer.

Changing of lamps and sleeves should be capable of being performed by the operating personnel at the plant. Modules required to be returned to the factory for lamp replacement should not be permitted.

4.3.7 Contractor and Operator Safety

All UV systems should be designed to prevent casual exposure to the ultraviolet radiation and the equipment must bear legends advising that safety glasses should be worn in the area. It is also recommended that full face masks be employed when working on the equipment. Contractor and operator training and O&M manuals should alert operators that each lamp in the UV module is a powerful source of UV radiation. UV radiation can cause serious damage to unprotected skin and eyes, but is safe when the proper precautions are taken. The best protection is to prevent exposure to UV radiation. The UV modules pose no health threat when submerged and in their support racks but should be turned off when removed from the racks to prevent exposure to UV radiation. If it becomes necessary to work with an open source of UV radiation, gloves, protective long clothing, and UV face shield should be worn. Ordinary eyeglasses are not adequate protection. Neither are safety glasses with plastic lenses, or goggles that do not cover the entire face. No part of the body should be exposed to UV radiation and looking into a burning UV lamp and or exposing one self to a burning UV lamp can damage eyes and skin.

Individual UV modules, vertical or horizontal, should be protected with ground fault circuit interrupters (GFCI) to protect the equipment in the event of the entry of water. This is particularly important in the case of horizontal system because of the submergence of the ultraviolet lamps.

Other safety aspects to consider include safety railings, electrical interlocks, remote operating consoles, and adequate electrical wiring and waterproofing.[25]

4.4 Small Wastewater Treatment Plants[35]

The UV technology from large plant installations has been scaled down for use in plants up to 120,000 gpd. Small plants and packaged treatment plants can be retrofitted with the latest in UV equipment including (1) UV module, (2) control cabinet, and (3) effluent channel.

4.4.1 UV Module

The typical submersible module contains two UV lamps encapsulated in quartz jackets and suspended in a stainless steel frame. Weatherproof cable and connectors connect the module directly to the control cabinet. A single module usually can disinfect up to 25,000 gpd; two 60,000 gpd; three 90,000 gpd; and the four module system 120,000 gpd. Depending upon the effluent quality, these small systems are designed to maintain a fecal coliform count of less than 200/100 ml however, greater reductions can be attained by adding more modules.

4.4.2 Control Cabinet

An all weather control cabinet contains the power ballasts, electrical controls and electric current monitoring systems. Individual lamp and power status are monitored by observing the light emitting diodes through a view port. A continuous duty fan, with replaceable filter, provides constant cooling of the ballasts.

4.4.3 Effluent Channel

Usually an all stainless steel channel, containing the UV modules, is fitted into the new or existing packaged plant. A built-in weir of gate ensures that the water level is kept constant, thus ensuring that all the lamps are kept submerged, regardless of flow rate. The modules support racks usually come mounted in the channel, and therefore, only require the installer to simply lower the lamp modules into place.

A UV intensity monitoring system to measure the 254 nm wavelength is attached to the UV module and consists of a probe and a remote UV meter readout. The intensity probe measures the UV intensity through 1 cm of effluent and the signal at the readout indicates the UV intensity status at all times. If the UV intensity drops below a prescribed level, action is taken to replace the lamps, or correct pre-filtration.

4.5 UV Disinfection System Design Procedure

The design procedure recommended by Scheible and EPA[26, 27] for UV disinfection is based on a kinetic model developed by Scheible which relates the characteristics of wastewater to be disinfected to the intensity of radiation and the physical and hydraulic characteristics of the reactor. The relationship is written:

$$N = N_0 \exp \left[(ux/2E)\{1-(1+4KE/u^2)^{1/2}\} \right] + N_p \qquad [5]$$

where:

N = the bacterial density in organisms per 100 ml remaining after exposure to UV radiation;

N_0 = the initial bacterial density in organisms/100 ml measured immediately before entry into the UV reactor;

u = the velocity of wastewater in cm/sec traveling through the reactor calculated as $\mathbf{x}/(\mathbf{V_v}/\mathbf{Q})$ where $\mathbf{V_v}$ is the effective wastewater volume (void volume) in the reactor in liters and Q is the total flow in l/sec;

x = the characteristic length of the reactor in centimeters, defined as the average distance traveled by an element of wastewater while under direct exposure to UV radiation;

E = the dispersion coefficient in cm^2/sec, which quantifies the variation of residence time distribution of a particular reactor;

K = the rate of bacterial inactivation in sec^{-1}; and

$\mathbf{N_p}$ = the bacterial density in organisms per 100 ml associated with particulates which are unaffected by exposure to UV radiation.

The design procedures and calculations in this section encompass several situations which the designer can use for specific applications: (1) to design a new reactor; (2) to determine the adequacy of a proposed reactor design (e.g. backcheck design by equipment manufacturer); and/or (3) to evaluate the capacity and design adequacy of an existing UV system.

4.5.1 Design Steps

The following steps are involved in designing a UV disinfection system for wastewater treatment plants:

<u>STEP 1</u> Wastewater Data Collection

<u>STEP 2</u> Establish Mathematical Model Coefficients and Parameters

<u>STEP 3</u> Establish Reactor Parameters and Equipment Conditions

<u>STEP 4</u> Determine Reactor UV Density

<u>STEP 5</u> Establish UV Radiation Intensity

<u>STEP 6</u> Establish Inactivation Rate

STEP 7 Set Hydraulic Rates

STEP 8 Establish UV Loading/UV Performance Relationship

STEP 9 Establish Performance Goals

STEP 10 Size Reactor

Data is developed either by direct testing, by estimates or by assumptions. An explanation of each step is presented which explains the important model coefficients, parameters, and data requirements followed by a simplified design example which demonstrates how the mathematical model can be used to design a new UV system.

STEP 1 WASTEWATER DATA COLLECTION REQUIREMENTS

a. Flow, Q. The average and peak design flows are required to determine velocities and system loadings to be handled by the disinfection process. Flow rates should be for the ultimate design year of the plant. Peak flows are always used for sizing equipment and reactors. Average flows are important to estimating average utilization for operation and maintenance purposes.

b. UV Transmission and Coefficient of Absorption. Absorbance is a direct measure of the wastewater's UV "energy demand" that will attenuate the UV intensity. UV transmittance is measured spectrophotometrically and the coefficient of absorption is obtained by first calculating absorption units per centimeter (**A**/cm) from the measured percent transmittance in expression **[3]** ($100 \times 10^{-(A/cm)}$). The UV coefficient of absorption, α, is then computed as the product of **A**/cm and 2.3 (expression **[4]**). The UV coefficient of absorption is used later in the model expression and UV intensity calculation in cm^{-1}. Ranges of UV demand can be described for different levels of treatment as follows[31]:

Type Treatment	UV Coefficient of Absorption, α, cm^{-1}	Percent Transmission	Absorption (**A**/cm)
Primary	0.4 to 0.8	67 to 45	0.174 to 0.350
Secondary	0.3 to 0.5	74 to 60	0.130 to 0.220
Tertiary	0.2 to 0.4	82 to 67	0.870 to 0.174

c. Total Suspended Solids (TSS). The level of suspended solids in the effluent to be disinfected is primarily set by the type plant, and its operating conditions and the effluent permit limits the plant is designed to meet. The particulate bacterial density, N_p, in the mathematical model is directly related to the TSS concentration, by the expression $N_p = c(TSS)^m$ (see below). These are the particles which will not be inactivated and which have a significant effect on the design of the UV system.

d. Initial Coliform Density, N_o. This value is explicit in the mathematical model and should be determined under average and maximum flow conditions. The performance of the UV disinfection system is directly related to the initial density of indicator organisms. It is recommended that these data be generated before design by testing and analysis from a similar plant in the area, or at the existing facility if an upgrade or retrofit is being considered.

e. Disinfection Goal, **N**. This value is the bacterial density remaining after exposure to UV radiation in organisms per 100 mL and is set by the effluent limits for the wastewater being treated.

STEP 2 MODEL COEFFICIENTS AND PARAMETERS

Coefficients **c** and **m**; **a** and **b**. These coefficients are specific to a given wastewater application and reflect the site-specific sensitivity to UV radiation and the occlusion of coliforms in the effluent TSS. Preliminary design calculations can use the following values which are based on studies and regression analyses from existing plant data however, it is recommended that these be determined by direct testing where possible:

a. $c = 0.26$; $m = 1.96$
b. $a = 1.45 \times 10^{-5}$; $b = 1.30$

Coefficients **c** and **m** relate the particulate bacterial density, N_p, in the mathematical model to the total suspended solids using the expression

$$N_p = c(TSS)^m \quad [6]$$

Coefficients **a** and **b** describe the rate of inactivation, **K**, as a function of the average radiation intensity, $\mathbf{I_{avg}}$, in the expression

$$K = a(I_{avg})^b \qquad [7]$$

STEP 3 ESTABLISH REACTOR PARAMETERS AND EQUIPMENT CONDITIONS

a. Lamp Systems and Array. UV lamps are usually enclosed in quartz sleeves and are arranged in either (1) uniform array or (2) uniform staggered array as depicted in Figure 4-15 for open channel systems.

Uniform Array - The lamps with quartz sleeves (Figure 4-15(a) are arranged in even horizontal and vertical rows, with the centerline spacings the same in both directions. The flow path is typically perpendicular to or parallel to the lamps.

Staggered Uniform Array - Similar to the uniform array, except alternating rows are offset by one-half the vertical spacing, $\mathbf{S_v}$, as depicted in Figure 4-15(b). The flow path is typically perpendicular to or parallel to the lamps.

b. Centerline Spacing. The centerline spacing, **S**, $\mathbf{S_v}$, or $\mathbf{S_h}$, in cm and the average nominal intensity, $\mathbf{I_{avg}}$, as a function of the UV coefficient of absorption is presented in Figure 4-16 for uniform array and in Figure 4-17 for uniform staggered array. Centerline spacing is determined by entering the figures with known values of UV density for the lamp used and coefficient of absorption and selecting lamp spacing above the dashed line.

c. Lamps. Typical specifications for lamps are given in Table 4-2. Choose lamps from the various manufacturers with insignificant transmission at 185 nm wavelength in order to minimize the production of ozone. Ozone in the air gap between the lamp and quartz could result in alteration of the UV energy before it can reach the liquid. Data used in the design computations such as length, arc length, and nominal UV output are obtained from the table. The arc length, **Z**, defines the active, light emitting portion of the lamp. UV output, in watts per lamp at 100 hours and at 253.7 nm, is used in the computation for UV density, **D**.

d. Quartz Enclosure. The lamp enclosure is made of fused quartz or other highly transparent (to the 253.7 nm

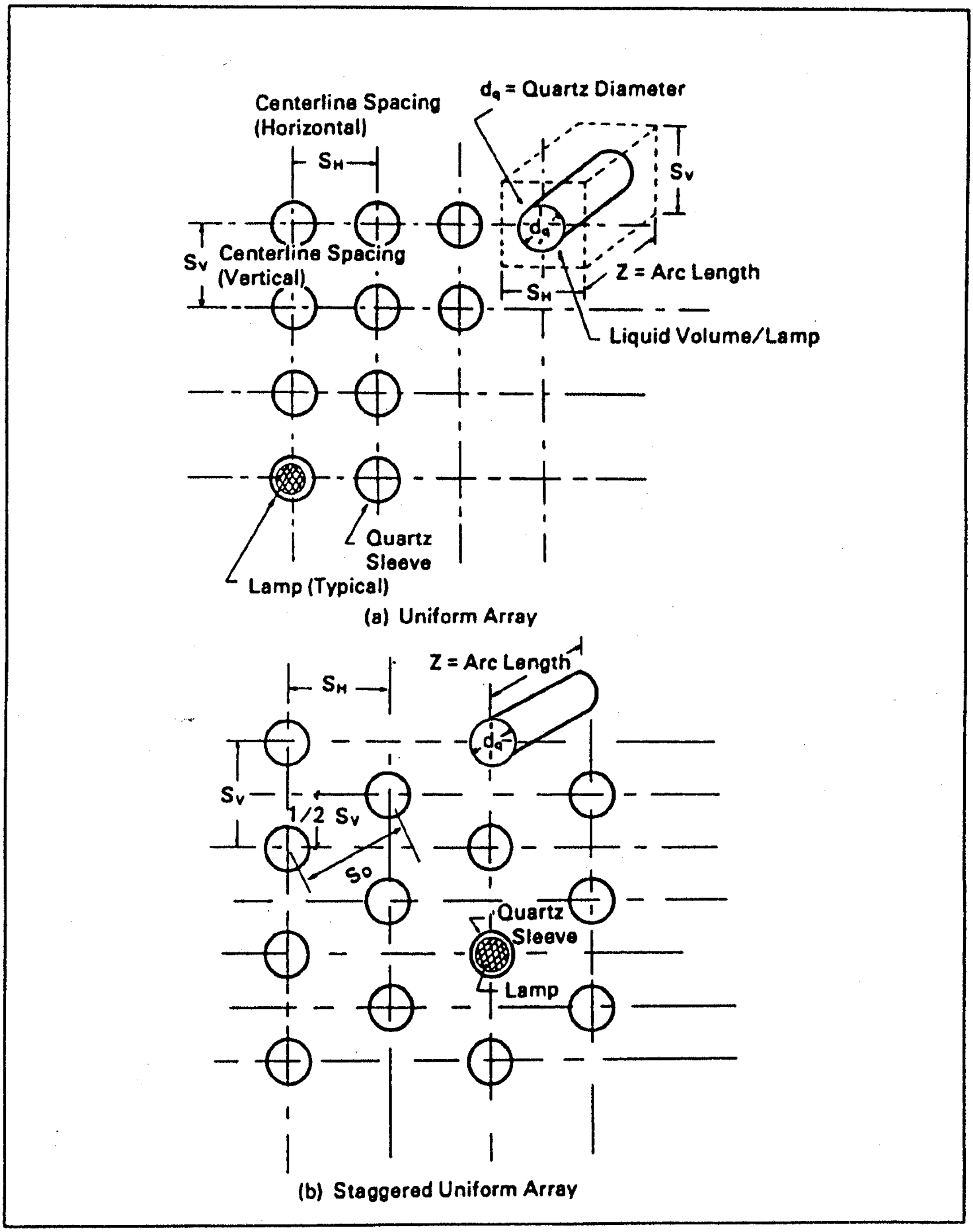


FIGURE 4-15 Schematic of uniform and staggered uniform lamp array[29]

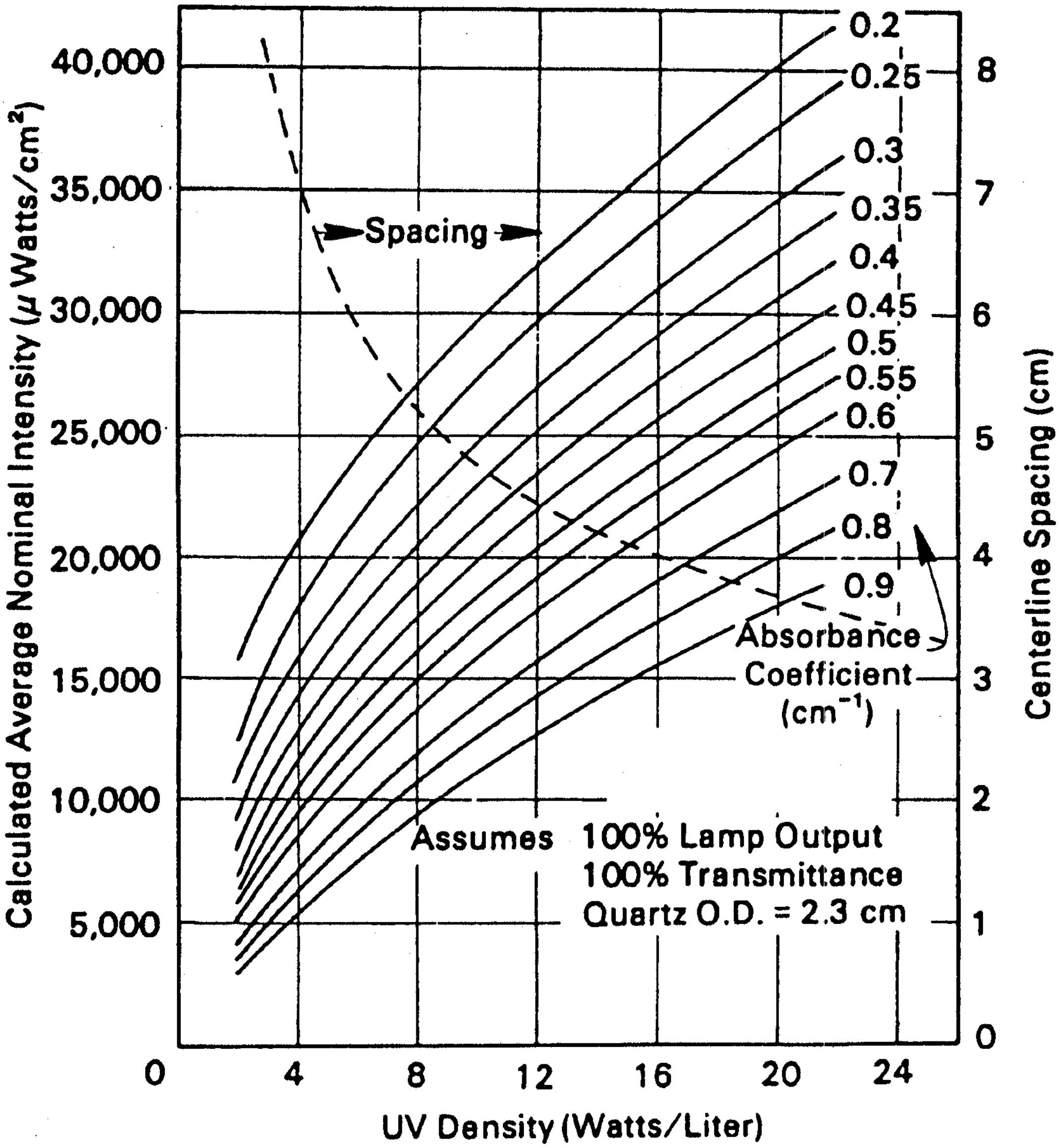


FIGURE 4-16 Uniform array intensity as a function of the reactor UV density and UV coefficient of absorption[29]

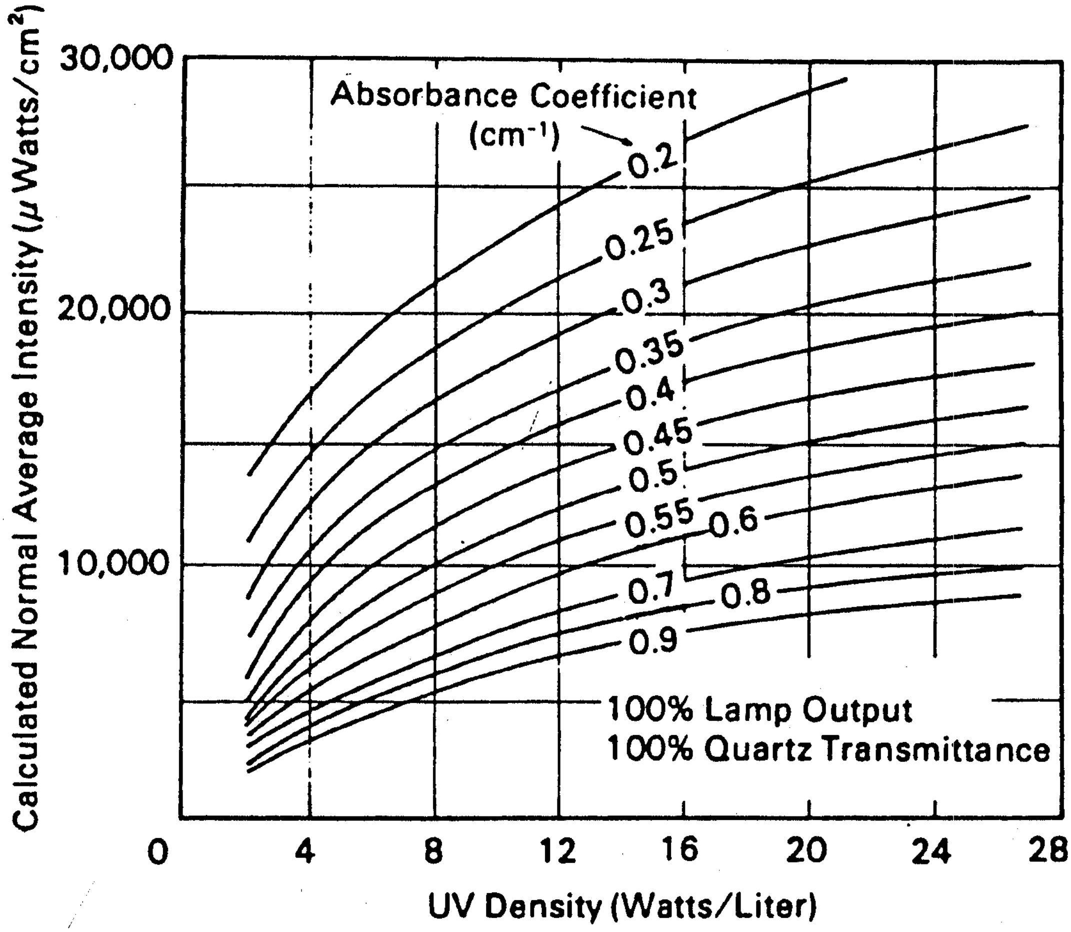


FIGURE 4-17 Staggered uniform array intensity as a function of the UV density and UV coefficient of absorption[29]

wavelength) glass. In quartz systems, the individual lamps are sheathed in quartz sleeves only slightly larger in diameter (d_q = 2.3 cm) than the lamp and the entire lamp/quartz bundle is submerged in the flowing waste stream. Quartz diameter is used to compute liquid volume flowing through the reactor and eventually determining the UV intensity requirements within the reactor.

Table 4-2 Examples of low pressure mercury arc lamp specifications (Courtesy Voltarc Tubes, Inc.)

Cat. No.	G36T6L G36T6H	G37T6VH	G36T6	G64T5L	G646L
Lamp Watts	39	40	36	65	62
Lamp Current, mA	425	425	425	425	425
Ultraviolet Output, watts (@ 100 hrs, 253.7 nm)	13.8	14.3	12.7	26.7	25.5
Microwatts/cm^2 @1 meter	120	124	110	190	180
Ozone generation (approx gm/hr)	H 0.5 L 0	15	0	0	0
Nominal Length, inches	36	37	36	64	64
cm	91.4	94.0	91.4	162.6	162.6
Arc Length inches	30	31	30	58	58
cm	76.2	78.7	76.2	147.3	147.3
Tube Diameter, mm	15	15	19	15	19
Tube Material	H: Vycor 7912 V: Vycor 7910	Quartz	Vycor 7910	Vycor 7910	Vycor 7910
Rated Life, hours (avg, at 8 hrs per start)	7500	7500	7500	7500	7500

e. <u>Lamp Configuration</u>. The lamp configuration may be axially parallel to one another; flow path parallel with or perpendicular to the lamps; vertical or horizontal to the flow axis.

f. Energy Loss Factors, F_p and F_t. Under actual operation, and for design purposes, the rated average intensity of lamps must be adjusted for aging of the lamps and the consequent reduction in UV output, and for the losses of energy as it passes through the quartz sleeves. F_p is the ratio of the actual output to the rated output of the lamps; and F_t is the ratio of the actual transmittance to the rated transmittance (100%) of the quartz sleeves. For new systems F_p should be 0.8; F_t should be 0.7 for plants with well attended maintenance and 0.5 to 0.6 for minimal operator attention or quartz especially prone to fouling because of wastewater conditions. The UV intensity, I_{avg}, is established as a function of UV density, D and adjusted with loss factors F_p and F_t using the expression

$$I_{avg} = (\text{Nominal } I_{avg}) \times F_p \times F_t \qquad [8]$$

STEP 4 DETERMINE REACTOR UV DENSITY

The UV density, D, in watts per liter, is defined as the total nominal UV power at 253.7 nm available within a reactor divided by the liquid volume flowing between the lamp/quartz bundle:

$$D = \text{total UV output/liquid volume} \qquad [9]$$

The UV density per lamp is expressed as

$$D_e = \text{Arc length} \times \text{UV output/liquid volume per lamp} \qquad [9a]$$

where, arc length, Z in cm and UV output in watts are obtained from Table 4-2 for the lamps selected and liquid volume, V_v, per lamp (see Figure 4-15) is computed from

$$V_v/\text{lamp} = (S^2Z) - [\pi d_q^2 Z/4] \qquad [10]$$

where:

S is the centerline spacing in cm,
Z is the lamp arc length in cm, and
d_q is the diameter of the quartz sleeve in cm.

The density will be directly related to the spacing of the lamps; the closer the spacing, the higher the UV density of the reactor.

STEP 5 ESTABLISH UV RADIATION INTENSITY

The average rated lamp intensity, I_{avg}, is estimated from Figure 4-16 or 4-17 for the lamp array chosen, the UV density computed in STEP 4, and the known UV coefficient of absorption, α. The nominal I_{avg} must then be adjusted to account for the average UV output degradation in the reactor and the minimum average transmission of the quartz sleeves as discussed in STEP 3g above using expression [8]:

$$\text{Adj } I_{avg} = (\text{Nom } I_{avg}) \times F_p \times F_t \qquad [8]$$

STEP 6 ESTABLISH INACTIVATION RATE

This is a direct measure of the sensitivity of microorganisms to UV radiation, and will be site specific to each design. The value is estimated as a function of the expected UV radiation intensity in the reactor. The inactivation rate constant, **K**, used in the mathematical model, Equation [7], is calculated from

$$K = a\ (I_{avg})^{b} \qquad [7]$$

Where coefficients a and b are obtained from STEP 2 b and I_{avg} (adjusted) is obtained from STEP 5.

STEP 7 SET HYDRAULIC RATES

Maximum performance is ideally accomplished in a perfect plug flow reactor. Since this condition can never be achieved, the hydraulic goal is to design the reactor for a low dispersion number, d_n. For UV reactors, axial dispersion should be less than 0.05 as explained in paragraph 4.2.4.10. This dispersion number must be reconciled with the headloss incurred by forcing the d_n to be low. The design objective is to optimize the hydraulic loading to the system while still meeting the performance goal (**N**). For the UV disinfection process, the hydraulic loading is defined as the ratio of the flowrate in lpm to the nominal UV wattage of the system, or:

$$\text{UV Loading Rate} = Q/W_n \qquad [11]$$

Once the loading is set, the nominal exposure time, t_n, is set using the expression:

$$t_n = (V_v/W_n)/(Q/W_n) \qquad [12]$$

Since the rate of inactivation becomes fixed at a given Q/W_n (because t_n is being set), there is a maximum attainable performance level (log N/N_0). This becomes a function of the dispersion characteristics of the reactor. If the ideal hydraulics is perfect plug flow, then the maximum performance will be at this condition. The way to approximate this is to design a near plug flow reactor that has a very low dispersion. Ignoring N_p in Equation [5] a series of solutions is developed to establish the relationship of maximum allowable Q/W_n with the log N'/No, where N' is equal to $(N-N_p)$.

a. <u>Estimate Dispersion Coefficient, E, in the Reactor</u>.

The dispersion coefficient (cm^2/sec), **E**, quantifies the distribution of residence times of the reactor and accounts for the deviation of hydraulic behavior from that of perfect flow. The distribution of residence times, after steady-state flow is achieved, is forced by the dispersion coefficient, **E**.

Little direct testing information in the literature is available to select a value for **E**. Procedures have been given to develop the RTD curve for an existing unit or pilot plant (see paragraph 4.2.4.3), and d_n and **E** can be estimated from these data. It is recommended that the RTD be developed directly, or that the equipment manufacturer supply direct, certified test data from hydraulically scaleable units. For new design, direct testing on quartz units has yielded estimated **E** values ranging between 10 and 500 cm^2/sec with values predominantly between 50 and 200 cm^2/sec. Note that both **E** and the reciprocal of d_n, ux/E, are included in the mathematical model [5]. Although **E** will vary with flowrate (ie velocity), the designer should consider only one value for **E** which is representative of the peak flow conditions. For purposes of design, check that the sizing based on a selected d_n, **u**, and **x**, implies an **E** less than 300 cm^2/sec. In addition, good dispersion is achieved if **E** is set less than 100 cm^2/sec.

b. <u>Set Dispersion Number and Dispersion Coefficient</u>.

Dispersion number, d_n, is defined as $d_n = E/ux$ **[13]**
and a key goal should be to set d_n between 0.02 and 0.05 to be representative of a plug flow reactor with low to moderate dispersion.

Dispersion Coefficient, **E**, is set to values similar to those determined by test results between 10 to 50 cm^2/sec.

c. Establish Velocity Relationship in the Reactor.

Velocity, **u**, is expressed in two ways:

$$u = E/d_n x \qquad [13a]$$

or

$$u = x/t_n \qquad [14]$$

d. Establish Expression for Effective Length of Reactor.

Combining equations **[13a]** and **[12b]** yields:

$$E/dx = x/t_n$$

from which $x = (E\ t_n/d_n)^{1/2}$ **[15]**

STEP 8 ESTABLISH UV LOADING/UV PERFORMANCE RELATIONSHIP

Prepare a table which shows a summary of calculations to determine Log (N'/N_0) for the configuration and spacing of lamps. The Log (N'/N_0) values are then plotted as a function of the Q/W_n (Figure 4-18). The individual column values are determined as follows:

Col 1 Loading, Q/W_n, in lpm/W_n, for raw values 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, and 6.0.

Col 2 Nominal time, t_n, in seconds. Compute from STEP 4 (V_v) and STEP 7 (t_n) for spacing, **S**; arc length, **Z**; and quartz diameter, d_q:

$$t_n \text{ (at S)} = [(V_v/W_n)/(Q/W_n)] \times 60 \text{ sec/min}$$

Col 3 Length, **x**, (cm): From STEP 7d, $x = (E\ t_n/d)^{1/2}$; $[(E/d)/\text{Col } 2]^{1/2}$

Col 4 Velocity, **u**, (cm/sec): From STEP 7c(2) expression, $u = x/t_n$; Col 3 / Col 2

Col 5 Log N'/N_0: At **K** from STEP 6, $N'/N_0 = \exp[(ux/2E)\{1-(1+4KE/u^2)^{1/2}\}]$ for the selected **E** and **K**; and $N' = N - N_p$

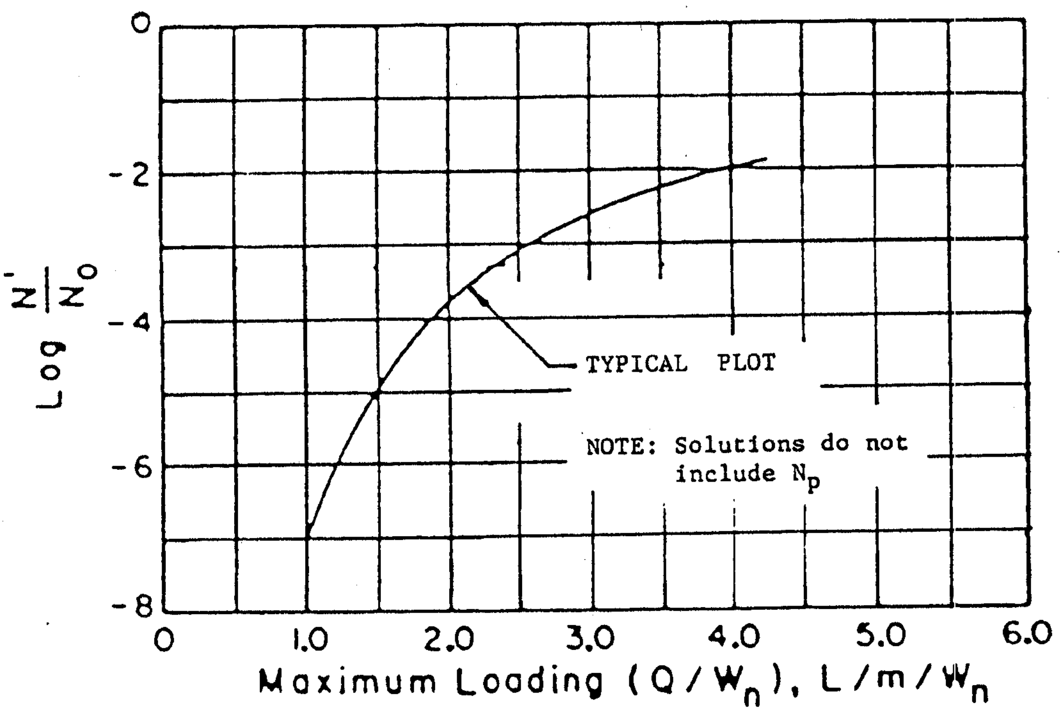


FIGURE 4-18 Typical UV Performance as a function of system loading[28]

where: N' = non-particulate exposed density
N = disinfection goal (STEP 1)
N_p= particulate coliform density (STEP 2)

STEP 9 ESTABLISH PERFORMANCE GOALS.

a. <u>Calculate Particulate Coliform Density (N_p)</u>.

Using TSS from STEP 1, and values for **c** and **m** from STEP 2a., calculate N_p from

$$N_p = c(TSS)^m \qquad [6]$$

b. <u>Calculate the Non-Particulate Exposed Density, N' from the expression:</u>

$$N' = N - N_p \qquad [16]$$

c. <u>Calculate Required Performance</u>.

Required performance = log (N'/N_o)

STEP 10 SIZE REACTOR AND UV EQUIPMENT COMPONENTS

a. Determine Maximum Q/W_n.

From Figure 4-18 prepared in STEP 8 read the value of Q/W_n for the allowed performance (STEP 9c) at the given intensity.

b. <u>Calculate Equipment Residence Time, t_n</u>.

From the expression in STEP 7, $t_n = (V_v/W_n)/(Q/W_n)$. and V_v/W_n (STEP 7) and Q/W_n (STEP 10a), compute t_n.

c. <u>Determine the Total Number of Lamps</u>.

The total number of lamps is calculated from the expression:

$$[Q/(Q/W_n)]/\text{nominal watts per lamp} \qquad [17]$$

for Q (STEP 1), Q/W_n (STEP 10a) and watts/lamp (STEP 3)

d. <u>Compute Effective Length of Reactor, **x**.</u>

Using expression **[15]**, $\mathbf{x} = (\mathbf{E}\ \mathbf{t_n}/\mathbf{d_n})^{1/2}$ from STEP 7 and $\mathbf{t_n}$ from (STEP 10), calculate **x**.

An example calculation is presented in Appendix B for a new UV system to demonstrate how the design procedure can be used.

4.6 Specification Preparation

It is important that the specification describing ultraviolet light for wastewater disinfection consider the specific requirements of the particular project. The UV transmission, and not BOD_5 and suspended solids, should be determined and a safety factor incorporated in the specifications. For example, if the UV transmission is measured as 80%, the specifications should require performance for 65% transmission. In addition, the flow rate must be determined from plant data and the specifications must require the UV system to function at the "peak" flow, not the average daily flow rate.

The required bacteriological standards for the discharge permit must be considered, and the UV dosage to meet that standard be determined. For example, if the coliform standard calls for 200/100 ml, a UV dosage of 12,000 μw-sec/cm^2 will be acceptable. If the coliform standard is less than 300/100 ml, the engineer may require a UV dosage of 16,000 μw-sec/cm^2.

The specification must require that the UV manufacturer submit a bioassay certification (conducted by a recognized independent laboratory) showing that a full size unit, or a scale model (first approved by the engineer) was tested and provided the minimum required dosage under the specified conditions of UV transmission, flow rate, and lamp output.

The specifications should also indicate the required features of intensity monitoring, lamp monitoring, and cleaning. Approval of designs will usually be based, in part, on the following requirements and specifications:

1. At least two units (banks of UV lights) being provided, each capable of disinfection of specified concentrations of BOD_5 and TSS domestic sewage effluent to obtain a residual coliform count of not greater than 200/100 ml fecal and 400/100 ml total (or the State standard)while treating the expected maximum (peak) flowrate. The residual

coliform count test to determine compliance with these limits should be performed on samples exposed to sunlight for three hours after passage through the disinfection unit.

2. The installed units should not be accepted by the Installation until coliform testing has established their capacity to meet the performance specified in #1 above. The testing should not commence until after start-up adjustments have been made by the UV manufacturer's representative and the units have been in operation, testing normal sewage effluent from the secondary treatment facility, for at least 30 days. The test period should include grab sampling for coliforms, 5 days a week for one week. The flowrate should be maintained at peak rate for at least one hour prior to sampling and the BOD_5 and TSS should be maintained as close to the specified concentration (mg/l) as possible. The testing must be performed under the direction of the Contracting Officer's representative and at the expense of the contractor. Should the testing indicate failure to meet the coliform limits in any of the samples, the contractor must be required to take the necessary action to correct the deficiency. The test program should then be repeated. The UV units would not be accepted by the Government until all tests in a one month test period fall within the allowable coliform limits.

3. The performance required in #1 should be warranted to the Government for a period of two years after acceptance of the facility. Should the unit not attain the required coliform limits at any time during this warranty period, while operating within the design conditions and manufacturer's recommendations, the manufacturer should be required to take all necessary actions to correct the deficiency.

4. Each unit should be capable of providing a dosage of at least 30,000 μw-sec/cm^2 of UV radiation at 254 nm to all portions of the flow stream for flows up to the expected peak flow and for sewage effluent quality up to the specified BOD_5 and TSS concentrations at the end of normal lamp life. The manufacturer must provide documentation of the dose capability satisfactory to the Government and State agency prior to acceptance of the units for initial installation. The manufacturer should supply for each unit, plots of the actual residence time distribution for the maximum and minimum flows expected.

5. Each unit should be supplied with a UV intensity meter and probe which is properly screened to accurately measure the UV radiation at the 254 nm level. The sensing unit (probe) should be located at the point of minimum expected intensity within the reactor. The manufacturer should provide the basis for location of the sensor.

6. Each unit should be provided with a means of adjustment of the UV dose. Power reduction to the lamps or deactivating lamps may be considered. The designer should evaluate the benefits and costs of automatic dose control paced with the flow.

7. Each unit should be provided with indicators which display the operating status of each lamp.

8. The UV lamps must be accessible and an automatic shut-off of power to the lamps must be provided when the disinfection unit is worked on.

9. Pre-screening at the disinfection unit may be required for protection of the UV lamp battery by preventing large pieces of debris entering the system and causing damage to the lamp sleeves.

10. Accessibility to the UV equipment and all parts for maintenance is required. A portable overhead crane system may also be provided to facilitate the occasional placement or removal of units, particularly in larger facilities.

4.7 Summary

The discussions, procedure and example presented, hopefully demonstrate the design and evaluation of UV disinfection systems that address the key UV process elements[30]. The procedure incorporates the geometry of the system, the UV radiation intensity, the dispersion and residence time distribution (RTD) characteristics of the reactor, and the significant water quality parameters.

Certain data are required prior to designing and evaluating for specific wastewater conditions, particularly those which affect the ability of UV radiation inactivate undesirable microorganisms. These include total suspended solids, transmission, initial coliform densities, anticipated flows, and the wastewater coefficient of absorbance.

Once the basic information has been obtained and incorporated into the calibrated model, any number of design configurations can be evaluated. In addition, the effect of varying specific parameters, such as the radiation intensity, dispersion, velocity, flow, initial density, etc. can be tested for the purposes of optimizing a design or controlling an existing UV system.

The ideal hydraulic design of a UV reactor is one with plug flow and minimal axial dispersion. The flow should also be turbulent to encourage thorough mixing and even distribution of flow across the entire lamp reactor. The dispersion number is a useful parameter in the assessment of the design of a reactor, and in the establishment of a design objective for a new system.

The average intensity of UV radiation required in a reactor can be estimated and can be described as a function of the measured or assumed coefficient of absorption of the wastewater.

An effective parameter in the description of sizing and system loading is the ratio of the flow rate to the UV output of the system. This ratio is used as an output parameter for the disinfection computational procedure. As with the UV intensity, the actual loading a system operates under would need to account for the reduction, with time, in lamp output.

APPENDIX A

MANUFACTURERS DATA FORM AND CHECKLIST

1. *What process units are included in your preliminary and primary treatment system?*

A [ ] *Screening*
B [ ] *Grit Removal*
C [ ] *Primary sedimentation*
D [ ] *Other, specify* ______________________________.

2. *What process units are included in your secondary treatment?*

A [ ] *Aeration basin*
B [ ] *Aerated lagoon*
C [ ] *Trickling filter*
D [ ] *Intermediate Clarifiers*
E [ ] *Rotating biological contactors*
F [ ] *Final clarifiers*
G [ ] *Other,specify* ___________________________.

3. *What process units are included in your tertiary treatment?*

A [ ] *Filtration*
B [ ] *Polishing pond*
C [ ] *Other,specify* __________________________.

4. *Are you using any chemicals at your WWTP? Check the appropriate chemicals and process units from this list.*

	Primary	*Secondary*	*Tertiary*	*Sludge*
Alum salts	[ ]	[ ]	[ ]	[ ]
Ferrous/ Ferric iron	[ ]	[ ]	[ ]	[ ]
Anionic polymer	[ ]	[ ]	[ ]	[ ]
Cationic polyer	[ ]	[ ]	[ ]	[ ]

*Other*____

5. *What process units are included in your sludge treatment?*

A [ ] *Gravity thickener* [ ] *batch* [ ] *continuous*
B [ ] *Thickener centrifuge* ____*hours operation daily*
C [ ] *Anaerobic digester*
D [ ] *Dissolved air flotation* ____*hours operation daily*
E [ ] *Aerobic digester*
F [ ] *Belt filter press* ____*hours operation daily*
G [ ] *Sludge drying beds*
H [ ] *Other,* ____

6. *Where do the underdrains and overflows of sludge treatment units discharge? If all return streams do not discharge to the same place, specify source and discharge point.*

A [ ] To primary influent
B [ ] To secondary influent
C [ ] Other part of process

7. *How do you remove sludge from primary and secondary treatment?*

A [ ] Sludge is removed continuously with a timer set pump
How long is the pump cycle?___
How many cycles in an hour?___
B [ ] Sludge is removed at certain time of the day.
The total time per day is____hours, starting at ______.
C [ ] Sludge is removed weekly, specify the days _________.
D. [ ] Other, ____.

8. *How do you remove the digester supernatant?(if you have a digester)*

A [ ] Continuous flow basis
B [ ] Daily at certain time of the day. What is the time_______.
C [ ] During certain days of the week. Specify the days______
D [ ] Other, ____.

9. *If you have an aeration basin,in your present process what is the average Solids Retention Time and solids concentration (MLSS) in the basin?*

____________________SRT, days
____________________MLSS, mg/l

10. *Please state your plant flows*

	[ ]mgd	*[ ]m^3/day*
	Present	*Design*
Avg daily	_______	_______
Max daily	_______	_______
Max hourly	_______	_______

11. At what time does the daily peak flow occur at your plant?

A [ ] Before 8 AM
B [ ] Between 8 AM and 9 AM
C [ ] Between 9 AM and 10 AM
D [ ] Between 10 AM and 11 AM
E [ ] Between 11 AM and 12 PM
F [ ] Other, ____.

12. Is your plant a Sequencing Batch Reactor (SBR)?

[ ] Yes
[ ] No

13. If yes, what is the decant rate?

________________________MGD

14. What is the pH of the influent/effluent wastewater?

	Normal	Max	Min
Influent	_____	_____	_____
Effluent	_____	_____	_____

15. What is the temperature (°C) of the influent and effluent wastewater?

	Normal	Max	Min
Influent	_____	_____	_____
Effluent	_____	_____	_____

16. Do you measure the turbidity of your effluent wastewater?

A [ ] No
B [ ] Yes, the average turbidity is _____NTU units.

17. What is the average hardness of the tap water in your service area?

__________________as $CaCO_3$ mg/l

18. What is the average monthly concentration of the following parameters in your plant influent?

SS ________mg/l[ ]Not measured
BOD_5________mg/l[ ]Not measured
COD ________mg/l[ ]Not measured
Grease______mg/l[ ]Not measured

19. What is the average monthly concentration of the following parameters in your plant effluent?

SS ______mg/l[ ]Not measured
BOD_5 _______mg/l[ ]Not measured
COD _______mg/l[ ]Not measured
Grease_____mg/l[ ]Not measured

20. Do you measure the UV transmission of your effluent?

A [ ] Yes
B [ ] No

21. Are there any major industrial wastewater sources that discharge to your sewer system?

A [ ] YES
B [ ] NO

22. If you answered yes to the previous questions, what are the main types of industry and what are their daily discharges?

1.______________[ ]MGD [ ]m^3/day
2.______________[ ]MGD [ ]m^3/day
3.______________[ ]MGD [ ]m^3/day
4.______________[ ]MGD [ ]m^3/day

23. Is there any water treatment plant backwash water or sludge discharged to your sewer system?

A [ ] No
B [ ] Yes, what kind of discharge?(what chemicals used)

24. What is the effluent coliform criteria in your wastewater treatment permit?

A [ ] 200 Fecal coliforms/100ml, 30-day geometric mean

B [ ] 1000 Fecal coliforms/100ml, 30-day geometric mean

C [ ] Other: ________________

25. How often do you analyze the fecal coliform bacteria of effluent wastewater?

A [ ] Daily
B [ ] Weekly, how many times a week? ____________________
C [ ] Other: ________________

26. How many Fecal Coliform analyses do you make per month?

____

27. At what time do you normally grab the bacteria sample?

A [ ] Before 8 AM
B [ ] Between 8 AM and 9 AM
C [ ] Between 9 AM and 10 AM
D [ ] Between 10 AM and 11 AM
E [ ] Other, ____.

Source: Trojan Technologies, Inc. London, Ontario, Canada

APPENDIX B

UV DISINFECTION SYSTEM DESIGN EXAMPLE

UV DISINFECTION SYSTEM DESIGN EXAMPLE

Scheible[30] has presented a simplified design example to demonstrate how the model expression [5] can be used to design a new system.

STEP 1: WASTEWATER DATA COLLECTION.

a. The treatment plant is a conventional activated sludge facility with the following design conditions:

Q_{avg} = 1.9 MGD (5000 l/min)
Q_{peak} = 3.8 MGD (10000 l/min)
UV Transmittance, T_r, measured of 67%
Total Suspended Solids (TSS) = 20 mg/l
Initial Fecal Coliform N_0 = 200,000/100 ml
Disinfection Goal **N**, 200/100 ml from effluent permit.

b. Calculate absorbance units per centimeter (**A**/cm)

$$\% \text{ Transmittance}, T_r, = 100 \times 10^{-(A/cm)}$$

$$67 = 100 \times 10^{-(A/cm)}$$

$$A/cm = 0.174$$

<u>Calculate UV Coefficient of Absorption, α</u>

$$\alpha = A \times 2.3 = 0.174 \times 2.3 = 0.4 \text{ cm}^{-1}$$

STEP 2: MODEL COEFFICIENT AND PARAMETERS.

From the literature **c** = 0.26, **m** = 1.96, **a** = 1.45 x 10^{-5} and **b** = 1.3

Therefore, for the example:

$$N_p = c(TSS)^m$$
$$N_p = 0.26(TSS)^{1.96} \quad [6]$$

and

$$K = a\ (I_{avg})^b$$
$$K = 1.45 \times 10^{-5}(I_{avg})^{1.3} \quad [7]$$

STEP 3: ESTABLISH REACTOR PARAMETERS AND EQUIPMENT CONDITIONS.

For illustrative purposes, the configuration chosen is a uniform array, with a centerline spacing, **S**, of 5.5 cm. The lamps will be G64T5 (Table 4-2), have an arc length, **Z**, of 1 x 47 cm, and a rated (nominal) UV output of 26.7 W at 253.7nm. Each lamp is sheathed in a quartz sleeve with diameter, d_q, of 2.3 cm. The dimensional layout of the array is depicted in Figure 4-15a, with the volume associated with each lamp/quartz included. In a uniform array, lamp spacing, $S=S_v=S_h$.

The average nominal intensity is presented on Figure 4-16 as a function of the UV coefficient of absorption. The lamps will be configured axially parallel to one another and the flow path perpendicular to the lamps. The values of the energy loss factors, F_p and F_t are set at 0.8 and 0.7, respectively as discussed in paragraph 3.3.1 step 3f. The maximum allowable headloss through the battery of lamps is set at 40 cm (16 in) and is exclusive of entrance and exit losses for the reactor.

STEP 4: DETERMINE REACTOR UV DENSITY

Compute Liquid Volume (Void Volume)

The liquid volume associated with each lamp/quartz is computed from:

V_v per lamp = $(S^2Z) - [\pi Z\, d_q^2/4]$ **[10]**
V_v per lamp = $[(5.5)^2(147)] - [\pi(147)(2.3^2/4)]$
V_v per lamp = 3840 cm^3 (3.84 lit)

Compute UV Density, D

D = Total UV output/liq vol **[9]**
D = arc length x UV output/liq vol
D = (26.7 w/3.84 liter)
D = 7 w/l

STEP 5: UV INTENSITY.

Determine Nominal Intensity

Enter Figure 4-16 (uniform array) with known values of D = 7 w/l and coefficient of absorption, α, = 0.40 cm^{-1} and read nominal I_{avg} of 17,500 $\mu w/cm^2$.

Adjust Intensity

$$I_{avg} = \text{Nom } I_{avg} \times F_p \times F_t \quad [8]$$
$$I_{avg} = 17{,}500 \times 0.8 \times 0.7$$
$$I_{avg} = 9{,}800 \ \mu w/cm^2 \ \text{(adjusted)}$$

STEP 6: INACTIVATION RATE

$$K = a\ (I_{avg})^b \quad [7]$$
$$K = 1.45 \times 10^{-5}\ (9{,}800)^{1.3}$$
$$K = 2.24/sec$$

STEPS 7 and 8: SET HYDRAULIC LOADING RATE AND UV LOADING/PERFORMANCE

UV Loading Rate = Q/W_n where Q = peak flow in lpm and W_n = nominal wattage. Once the loading is set, the nominal exposure time, t_n, is set using:

$$t_n = (V_v/W_n)/(Q/W_n) \quad [12]$$

For the example,

$$V_v/W_n = 1.144/W_n$$

and

$$t_n = (0.144/W_n)/(Q/W_n)$$

Calculate Dispersion in the Reactor

Set, dimensionless dispersion number, d_n, defined as $d_n = E/ux = 0.01$. Set E = 15 cm^2/sec which is similar to dispersion coefficients determined by test results. Thus **ux** must be greater than 15/0.01 cm^2/sec, and $u = 1500/x$.

Velocity **u** = UV exposure length/UV exposure time =

$$u = x/t_n$$

Expression for Effective Length of Reactor:

Substituting: $1500/x = x/t_n$

and $x = (1500\ t_n)^{1/2}$ **[15]**

Table B-1 shows a summary of the calculations used to determine log (N'/N_0) for the configuration spacing, **S** = 5.5 cm. The log (N'/N_0) values are plotted in Figure B-1 as a function of the Q/W_n ratios. Note that the UV performance is based on the non-particulate effluent fecal coliform density. The particulate fecal coliform , density, N_p, would be additive.

Table B-1 Calculation of performance based on loading (uniform array, S = 5.5 cm)

Loading Q/W_n lpm/W_n	Nominal[a] time, t_n (Sec)	Length[b] x (cm)	Velocity[c] u (cm/s)	log N'/N_o[d] at K of $2.24 s^{-1}$
0.5	17.2	160	9.3	-12.90
1.0	8.6	113	13.1	- 7.22
1.5	5.8	93	16.0	- 5.06
2.0	4.3	80	18.6	- 3.84
3.0	2.9	66	22.8	- 2.62
4.0	2.2	57	25.9	- 2.06
6.0	1.4	46	33.0	- 1.03

a $t_n = [0.144/W_n)/(Q/W_n)]$ x 60 sec/min

b $x = (1500\ t_n)^{1/2}$

c $u = x/t_n$

d $N'/N_o = \exp\ [(ux/2E)\{1-(1+4KE/u^2)^{1/2}\}]$ for $E = 15\ cm^2/sec$ and $K = 2.24/sec$

STEP 9: ESTABLISH PERFORMANCE GOALS

<u>Calculate Particulate Coliform Density</u> (N_p)

For TSS = 20 mg/l (Step 1'), **c** = 0.26, and **m** = 1.96:

$$N_p = c(TSS)^m \quad [6]$$
$$N_p = 0.26\ (20)^{1.96}$$
$$N_p = 92/100\ ml$$

<u>Calculate N'</u>:

$$N' = (N - N_p) \quad [16]$$

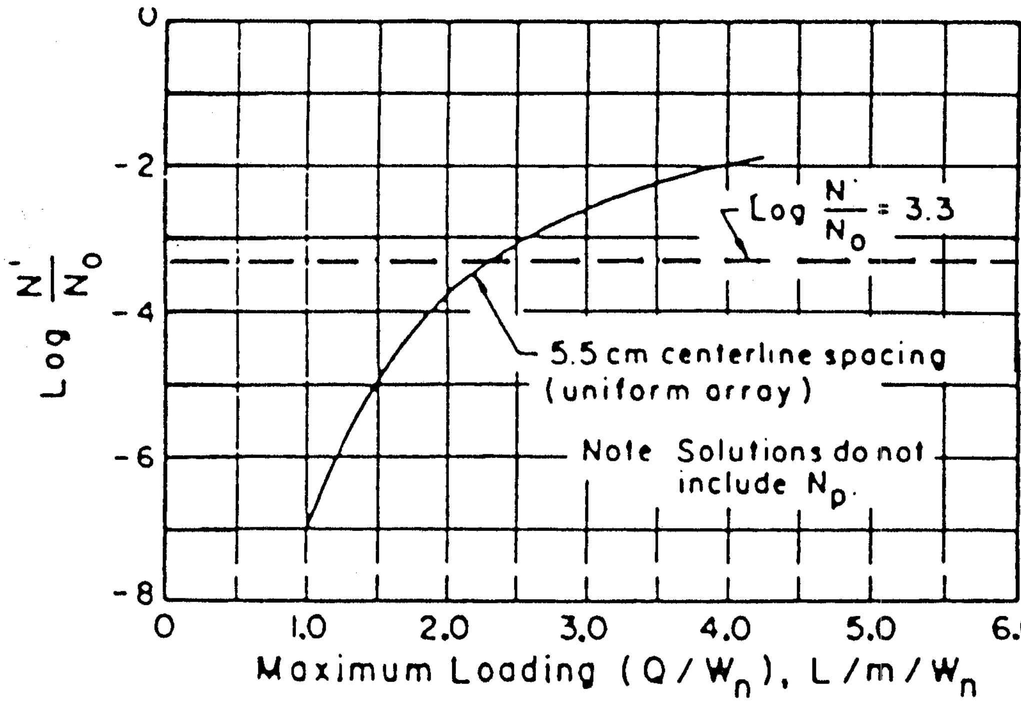


FIGURE B-1 Calculation of performance based on loading (uniform array, s = 5.5 cm)[28]

For the required effluent coliform limit, N = 200/100 ml and N_p = 92/100 ml:

$$N' = 200 - 92 = 108/100 \text{ ml}$$

Calculate Required Performance

Required performance = log (N'/N_o)

For N_o = 200,000/100 ml (STEP 1)
and N' = 108/100 ml

then, log (N'/N_o) = log (108/200,000) = -3.3

STEP 10: SIZE REACTOR AND UV EQUIPMENT COMPONENTS

From Figure B-1, maximum Q/W_n allowed for log (N'/N_o) of -3.3 is 2.35 lpm per W_n , at the given intensity, in order to meet the 200/100 ml effluent coliform goal.

Calculate Equivalent Residence Time, t_n

$$t_n = (V_v/W_n)/(Q/W_n) \qquad [12]$$

for V_v/W_n = 0.144 l/W_n (STEP 7)
and Q/W_n = 2.35 lpm/W_n (STEP 10),

then t_n = (0.144 l/W_n)/(2.35 lpm/W_n)
and t_n = 0.0613 min x 60 sec/min = 3.67 sec

Determine Number of Lamps

No. Lamps = [(Q)/(Q/W_n)]/nominal watts per lamp **[17]**

for Q = 10,000 lpm (STEP 1)
(Q/W_n) = 2.35 (STEP 10a)
watts/lamp = 26.7 (STEP 3)

then number of lamps = (10,000/2.35)/26.7 = 159

Compute Effective Length of Reactor

Effective length, $x = (1500\ t_n)^{1/2}$ (STEP 7) **[15]**

For t_n = 3.67 sec (STEP 10),

$x = [(1500)(3.67)]^{1/2}$ = 74 cm

Calculate No. of Lamps in x-direction

Lamps = x/S = 74 cm/5.5 cm = 13.5 since flow path is perpendicular to lamps

Summary

A total of 180 lamps is selected and placed in a 15 x 12 array. Recalculating, Q/W_n is now 10,000/(26.7 x 180) = 2.08 lpm, $t_n = V_v/Q$ = 0.144/2.08 = 4.15 sec, $u = x/t_n$ = (5.5 x 15)/4.15 = 19.8 cm/sec and $d_n = E/ux$ = 15/(19.8)(5.5)(15) = 0.0091. The example configuration is summarized in Table B-2.

Table B-2 Design sizing summary for 5.5 cm centerline spacing - uniform array

Length	15 lamps (66 cm)
Height	12 lamps (66 cm)
Total number of lamps	180
Q/W_n in lpm/W_n	2.08
Exposure time, t_n (seconds)	4.15
Velocity, (cm/sec)	19.8
Dispersion No., d_n, at E = 15 cm^2/sec	0.0092
Total power (KW)	14.4

The Q/W_n is now 2.08, which is below the maximum allowable of 2.35 (STEP 10). The dispersion number, **dn**, is slightly less than the objective of 0.01 (STEP 7).

Calculate Head Loss

$$h_L = c_f\ (x)\ (u^2) \qquad [18]$$

where c_f = 0.00025 sec^2/cm^2 (31)
x = 5.5 x 15 = 82.5 cm
u = 19.8 cm^2

h_L = (0.00025)(82.5)$(19.8)^2$ = 8.0 cm < 40 cm (o.k.)

The example is meant to illustrate the use of the mathematical modeling approach for a UV process design. The appropriate calibration data must first be obtained for the site specific wastewater application. The calculations are only an example and should not be used in the design of a system. Reference 27, Chapter 7 contains a more thorough computational analysis procedure and example problem.

APPENDIX C

IDENTIFICATION OF VARIABLES

IDENTIFICATION OF VARIABLES

a = Inactivation rate coefficient
α = Coefficient of absorption
A = Medium absorbance
b = Inactivation rate function
c = Particulate density coefficient
C = Concentration
d = Distance
d_n = Dimensionless dispersion number
d_q = Quartz sleeve diameter
D = UV density
D_e = UV density per lamp
e = Base of natural logarithms
e = Extinction coefficient
E = Dispersion coefficient
F_p = Energy loss factor, lamp output
F_t = Energy loss factor, transmission
h = Depth of water
I = Light intensity
I_o = Lamp surface intensity
I_1 = Measured intensity at distance d
I_t = Intensity of transmitted light
K = Rate of bacterial inactivation
L_p = Path length
m = Particulate density coefficient
μw = Microwatts
nm = Nanometer
N = Bacterial density remaining after UV exposure
N_o = Initial bacterial density
N_p = Bacterial density associated with particulates unaffected by exposure to UV radiation.
Q = Total flowrate
R_e = Reynolds number
R_h = Hydraulic radius
δ^2 = Statistical variance
$\delta_m{}^2$ = Dimensionless variance
S = Centerline spacing
S_v = Centerline spacing, vertical
S_h = Centerline spacing, horizontal
T = Theoretical residence time
T_m = Mean residence time
T_r = Transmission at a 253.7 nm wavelength
t_n = Exposure time
t_p = Time to peak
t_{10} = Time for 10% of tracer to pass

t_{50} = Time for 50% of tracer to pass
t_{90} = Time for 90% of tracer to pass
u = Velocity of wastewater traveling the reactor
V_v = Void volume of water in reactor
W_n = Energy output per lamp
x = Characteristic length of the reactor

APPENDIX D

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