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# **Design Manual**

## **Municipal Wastewater Disinfection**

**U.S. Environmental Protection Agency  
Office of Research and Development  
Water Engineering Research Laboratory  
Center for Environmental Research Information  
Cincinnati, OH 45268**

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***Notice***

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## **Chapter 7**

### **Ultraviolet Radiation**

#### **7.1 Introduction**

The use of ultraviolet (UV) radiation for the disinfection of wastewaters, relative to the established technologies of chlorination and ozonation, is an emerging process application which has been developed over the past 10 years. As a perspective, three major committee reports were issued in the mid to late seventies (1-3). All effectively described the use of ultraviolet radiation as "potentially" advantageous for the disinfection of relatively high quality treated wastewater. The U.S. Environmental Protection Agency (USEPA) Task Force Report on the Disinfection of Wastewater (1) concluded that: "although ultraviolet light has not been widely used to disinfect wastewater, there is limited information that indicates it may become a potentially desirable alternative. It is the only physical process whereas all the disinfectants are chemical processes. On-going research will provide answers as to its applicability to adequately disinfect wastewater." The Task Force went on to recommend that "the use of alternate disinfectants should be further pursued because of recent findings of the potentially hazardous halogenated organics in drinking water."

This chapter presents current state-of-the-art knowledge on the design of the UV disinfection process, much of which represents information developed over the past decade through research and demonstration of large scale applications of UV to the disinfection of wastewater. As a new application of the technology, the process design procedures are still formative, and in-field experience in the operation and maintenance of UV facilities is limited, but growing as new plants come on line. The underlying conclusion which should be stated at the beginning of this chapter is that the potential which had been foreseen earlier has been confirmed; the recommended investigations into UV and the demonstration of its application on a full scale basis have shown the process to be viable, feasible for application to a wide range of wastewater qualities, effective in the inactivation of pathogens, capable of complying with disinfection goals, and cost-effective. Its advantages lie in its relative simplicity and in the absence of both a residual and any chemical intermediates.

#### **7.1.1 Chapter Description**

It is reasonable to state that the UV disinfection process has reached a state of development where the mechanisms are understood and the critical design parameters have been identified and generally demonstrated. Field experience is limited, but gaining. There is not, however, a clear and concise compilation of this information, including the procedures by which a UV system can be designed or evaluated. This manual attempts to provide this, in addition to O&M considerations, which have been identified and demonstrated by direct field experience.

The objective, then, is to bring together the knowledge and experiences with UV as it is applied to the disinfection of municipal wastewaters. It is not the intent of these discussions to give an exhaustive teaching on the technical aspects of the components which make up the UV hardware, e.g., lamps, ballasts, etc.; rather the approach will be to discuss the basic concept and status of these components. References are provided if the reader wishes to pursue these aspects in more detail. The chapter will focus its attention on primary considerations for the design of a system such that it will meet both its performance requirements and will be amenable to efficient operations and maintenance (O&M).

*Introductory Section (7.1).* This gives an overview of the technology and its current status relative to wastewater disinfection application. Of particular interest are descriptions of UV reactors; these will give the reader a visual perspective of the system, which will be helpful in the subsequent sections on design. The chapter also provides listings of UV plants in Tables 7-2, 7-3, and 7-4, which will be helpful to the designer or operator who wishes to learn about UV disinfection experience at other installations.

*Background Discussions (7.2).* This section is not critical to the designer. It is useful, however, if one wishes to gain a perspective on the mechanisms of UV inactivation and the evolution of the process as it is applied to wastewater disinfection.

*Process Design Considerations (7.3).* This is the

section most important to the designer. It details the process design elements critical to effective design and offers guidance on defining specific design parameters. These particularly address:

- Hydraulics (7.3.2); of interest are discussions on dispersion, reactor layout, headloss, and residence time distribution.
- Intensity (7.3.3); a calculation technique is used, solutions are presented to give the intensity of any practical lamp reactor configuration, as a function of the UV density and the wastewater UV absorbance coefficient.
- Wastewater characteristics (7.3.4); this gives the designer guidance on the important wastewater parameters. These include the flow, initial density, suspended solids, UV absorbance coefficient, and the inactivation rates. Existing data are compiled for these parameters.

**Process Design Example (7.4).** A design example is given to demonstrate the design protocol, incorporating the considerations discussed in 7.3. The designer can use this as a stepwise outline for developing the design of a UV reactor.

**O&M and Facilities Design Considerations (7.5).** This last section should be used by both the designer and operator. It provides guidance related to effective O&M. Of particular interest are the cleaning aspects of the reactors. This is the single most important element for effective reactor performance.

### 7.1.2 General Description of the UV Process

Disinfection by ultraviolet radiation is a physical process relying on the transference of electromagnetic energy from a source (lamp) to an organism's cellular material (specifically, the cell's genetic material). The lethal effects of this energy result primarily from the cell's inability to replicate. The effectiveness of the radiation is a direct function of the quantity of energy, or dose, which was absorbed by the organism. This dose is described by the product of the rate at which the energy is delivered, or intensity, and the time to which the organism is exposed to this intensity.

The basic kinetics of disinfection have been discussed as part of Chapter 4. The ideal UV disinfection model follows first order kinetics, whereby:

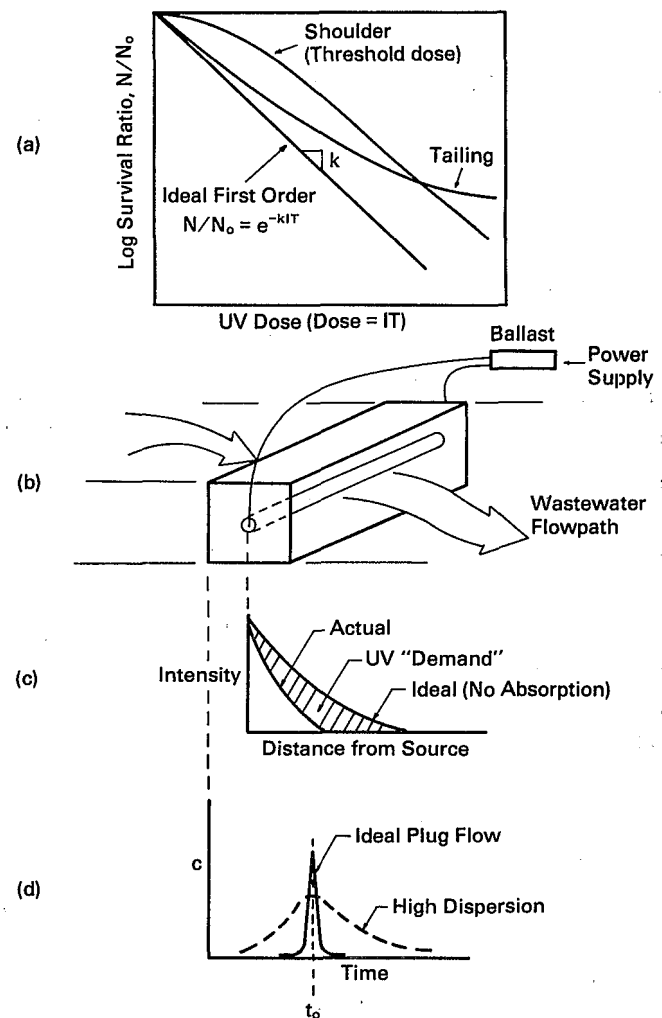
$$N = N_0 e^{-kIt}$$

where:

- N = bacterial density remaining after exposure to UV
- N<sub>0</sub> = initial bacterial density
- k = rate constant
- I = intensity of UV radiation
- t = time of exposure

The product  $It$  is the UV dose. Thus the response, noted by the log of the survival ratio,  $N/N_0$ , can be plotted against dose; the slope is the rate coefficient,  $k$ . This is shown on Figure 7-1(a). Deviation from this model is generally manifested by "shoulders," whereby minimal response is noted below a "threshold" dose; and by tailing effects, often attributed to occlusion (shadowing) of bacteria by particulate matter.

Figure 7-1. General description of UV design.



The primary artificial source of UV energy, at present, is the low pressure mercury arc lamp. It is almost universally accepted as the most efficient and effective source for disinfection systems application. The primary reason for its acceptance is that approximately 85 percent of its energy output is nearly monochromatic at the wavelength of 253.7 nanometers (nm), which is within the optimum wavelength range of 250 to 270 nm for germicidal effects. The lamps are long (standard lengths are typically

0.75 and 1.5 m (2.5 and 4.9 ft) arc lengths) thin tubes (typically 1.5 to 2 cm (0.6 to 0.8 in) in diameter). The radiation is generated by striking an electric arc through mercury vapor; discharge of the energy generated by excitation of the mercury results in the emission of the UV light.

These lamps can be suspended outside the liquid to be treated or submerged in the liquid; the intent is to get the energy into the liquid as efficiently as possible. Typically, if the lamp is to be submerged into the liquid, it is inserted into a quartz sleeve to minimize the cooling effects of the water. Figure 7-1(b) is presented to schematically represent the principal concerns when considering UV disinfection. In this example, the lamp is placed in the liquid, with the lamp perpendicular to the direction of flow. Other configurations may have the lamp parallel to flow, or the lamp may be suspended above the flowing liquid. Referring to Figure 7-1(c), as the lamp emits radiation, the intensity will attenuate as the distance from the lamp increases; this is due simply to the dissipation or dilution of the energy as the volume it occupies increases. A second attenuation mechanism involves the actual absorption of the energy by chemical constituents contained in the wastewater. This, analogous to the chlorine demand, is the "UV demand" of the wastewater.

The UV demand of a wastewater is quantified by a spectrophotometric measurement at the key wavelength of 253.7 nm; this expresses the absorption (or transmittance) of energy per unit depth. The output is absorbance units/cm, or a.u./cm. The percent transmittance can be determined from this unit by the expression:

$$\% \text{ Transmittance} = 100 \times 10^{-(\text{a.u./cm})}$$

The term most often used for design purposes is the UV absorbance coefficient,  $\alpha$ , expressed in base e:

$$\text{UV absorbance coefficient, } \alpha = 2.3 \text{ (a.u./cm)}$$

The unit for  $\alpha$  is  $\text{cm}^{-1}$ .

Although wastewater characteristics will be different site to site, ranges of the UV demand can be described for different levels of treatment:

	UV Absorbance Coefficient $\alpha$ ( $\text{cm}^{-1}$ )	Percent Transmittance	Absorbance (a.u./cm)
Primary Treatment	0.4 to 0.8	67 to 45	0.174 to 0.35
Secondary Treatment	0.3 to 0.5	74 to 60	0.13 to 0.22
Tertiary Treatment	0.2 to 0.4	82 to 67	0.087 to 0.174

A second major concern is the provision of adequate

exposure time to the microorganisms in order to meet the dose requirement at a given intensity. This was also generally discussed in Chapter 4; the key is to have plug flow through the system (see Figure 7-1(d)) such that each flow element resides in the reactor for the same amount of time. Perfect plug flow is not going to be achieved, of course; some dispersion will exist, such that there will be a distribution of exposure times about the ideal, theoretical exposure time. A design objective will be to minimize this distribution.

### 7.1.3 Current System Designs

In all, the design of a UV system must accommodate a few simple considerations: satisfy the UV demand of the wastewater; maximize the use of the UV energy being delivered by the lamps; and provide the conditions which encourage plug flow. Before proceeding with the detailed discussions of various technical aspects of the UV process, it is appropriate to first gain a perspective of UV system configurations. This is best done by reviewing design configurations which are currently being used at full-scale plants. This is done to enable the reader to better "visualize" the subsequent discussions. The use of these figures does not suggest that the configurations represent optimal designs; in fact, certain design configurations have been demonstrated to be inefficient.

Two basic generic reactors encompass current designs. The first is a contact reactor in which the lamps are submerged at all times in the wastewater; the submerged systems have the lamps encased in quartz sleeves which are only slightly larger in diameter than the lamp itself. The second reactor design does not allow contact of the water with the lamp (i.e., the quartz sleeve), but rather suspends the lamp above the liquid or surrounding conduits carrying the liquid. These conduits are transparent to the UV radiation.

Let us first consider the so-called submerged quartz systems. These can take on any number of configurations, generally described by the arrangement of the lamps relative to the direction of flow and to the hydraulic design of the lamp reactor. A common approach is the encasement of the lamp battery in a sealed reactor shell, as shown by the schematic on Figure 7-2. Flow enters the unit through an inlet pipe, typically perpendicular to the lamps, redirects and flows parallel to the lamps, finally exiting the reactor through the outlet pipe. A modification of this arrangement was provided at the Vinton Water Pollution Control Plant, Vinton, Iowa, as shown on Figure 7-3 (4). A steel plate was installed to split the cylinder in half lengthwise. Flow is directed down the unit on one side, then turns and flows down the second half before discharge. This encourages a plug flow condition by increasing the length of travel

Figure 7-2. Example of closed vessel UV reactor, with flow parallel to lamps (Courtesy of Ultraviolet Purification Systems, Inc., Bedford Hills, NY).

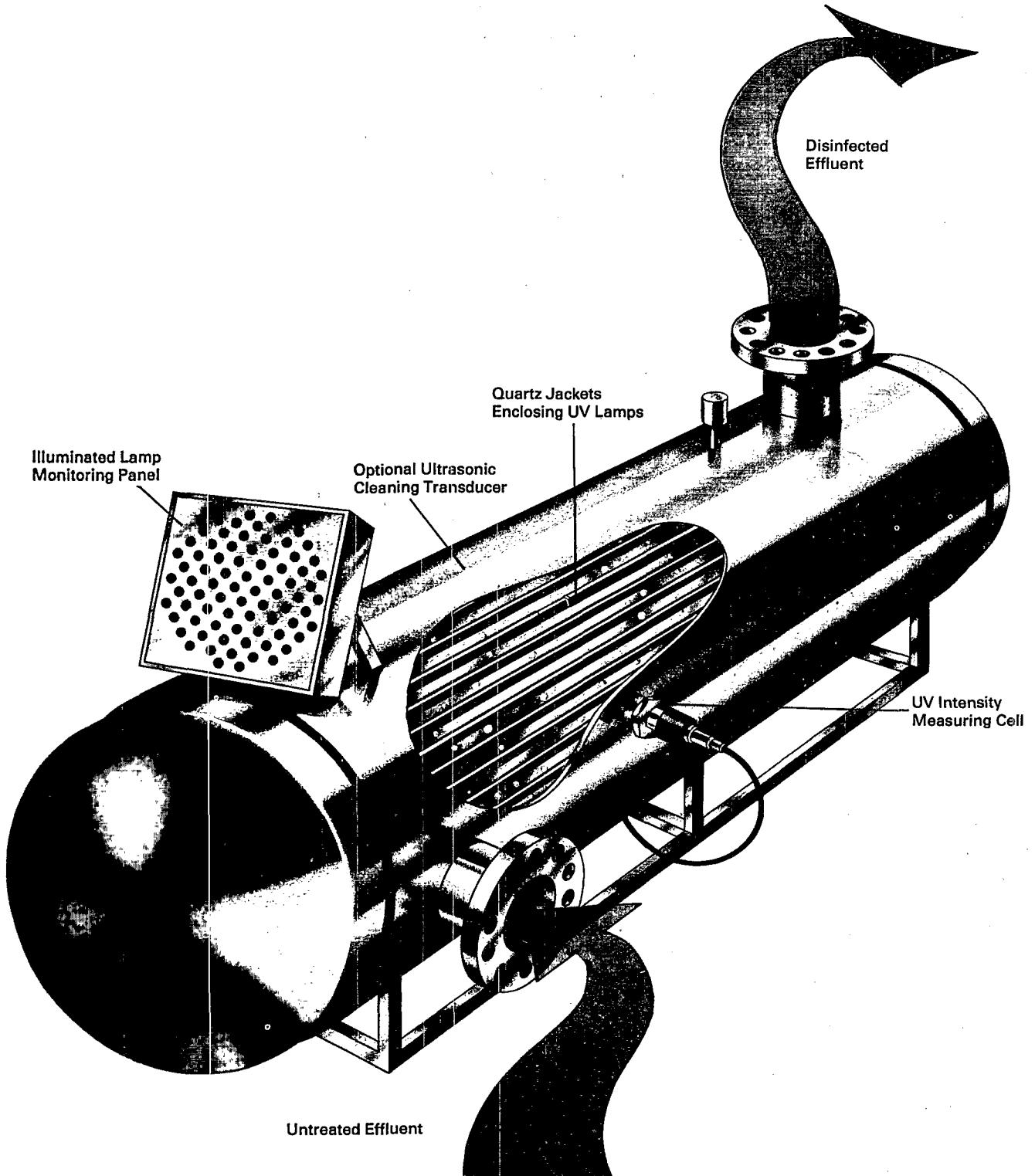
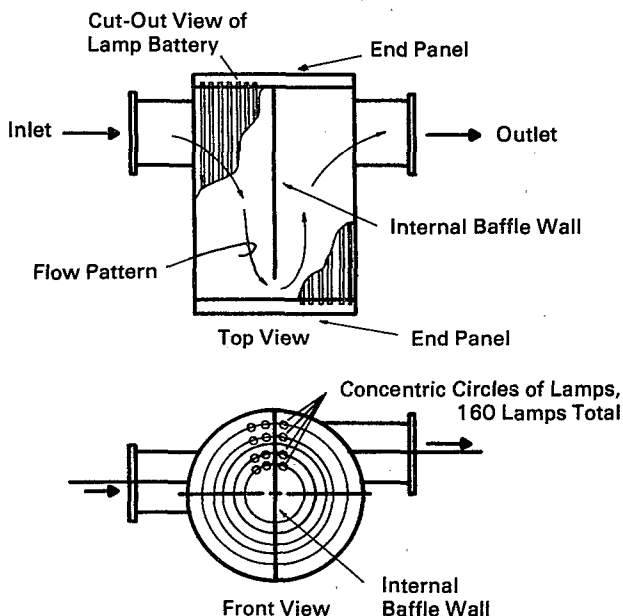


Figure 7-3. Schematic of quartz UV unit in Vinton, Iowa (4).

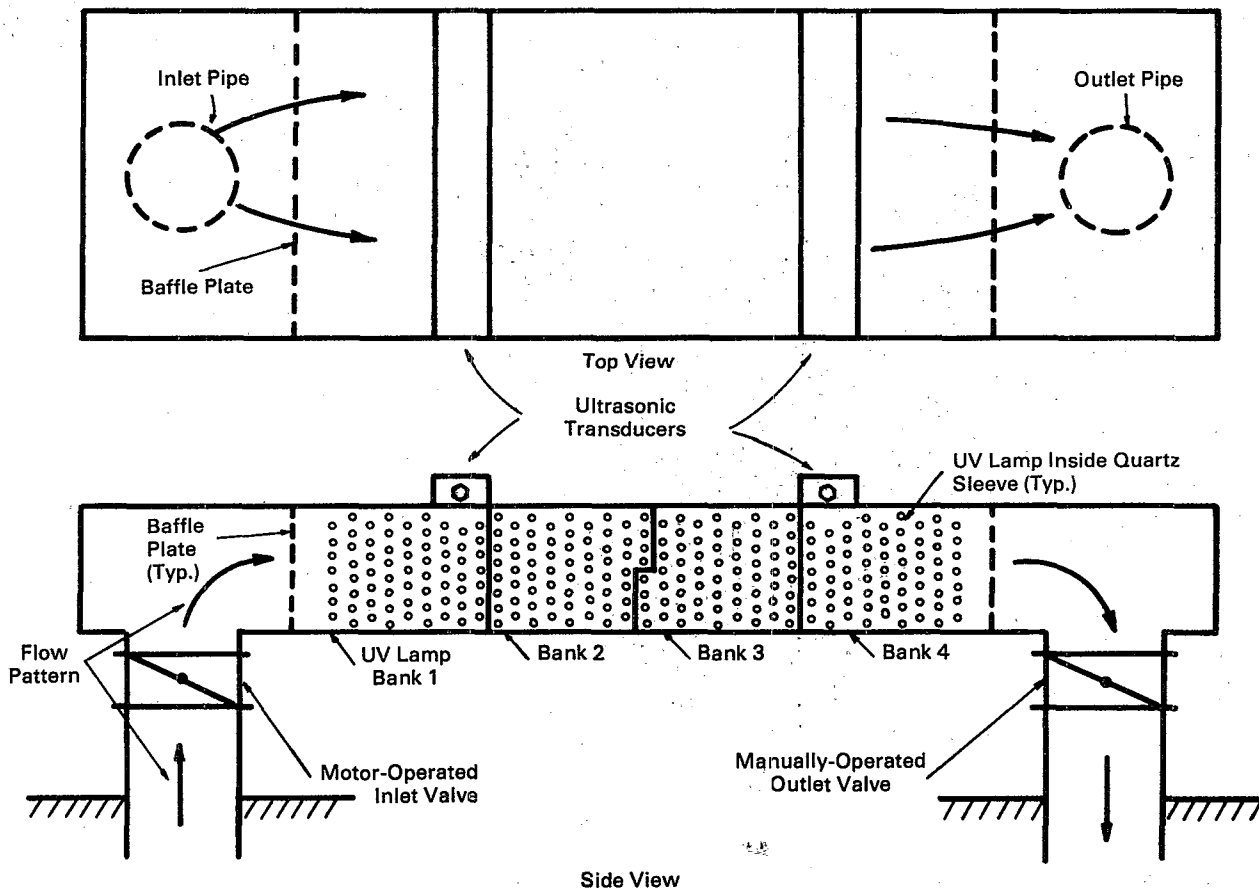


relative to the unit's hydraulic radius. Subsequent testing of this unit indicated that shortcircuiting occurred within the reactor and that its effective volume was significantly reduced. This is discussed further in Section 7.3.2.

The lamps can also be arranged perpendicular to the direction of flow in the same type of cylindrical reactor shell. Baffle plates distribute the wastewater along the length of the lamp battery; the flow is then directed upward through the lamp battery and over an internal overflow weir which runs the length of the reactor.

The sealed reactors can also be arranged to simulate channel flow. An example is provided on Figure 7-4, which is a schematic cross section of the UV units installed at the Suffern Water Pollution Control Plant, Suffern, New York. The lamps in this case are arranged in a symmetrical array, perpendicular to the direction of flow. The wastewater is pumped to the inlet chamber; a perforated baffle plate separates the chamber from the lamp battery to distribute the flow across the inlet plane of the lamp battery. A second plate is installed on the outlet side of the lamp section

Figure 7-4. Schematic of quartz UV unit in Suffern, NY.



before the liquid enters the outlet chamber for discharge through the effluent pipe. The lamps are staggered to encourage turbulence and the system is arranged with a long path length to influence a plug flow condition.

Figure 7-5. Example of open channel unit at Pella, Iowa, with flow directed perpendicular to lamps (5).

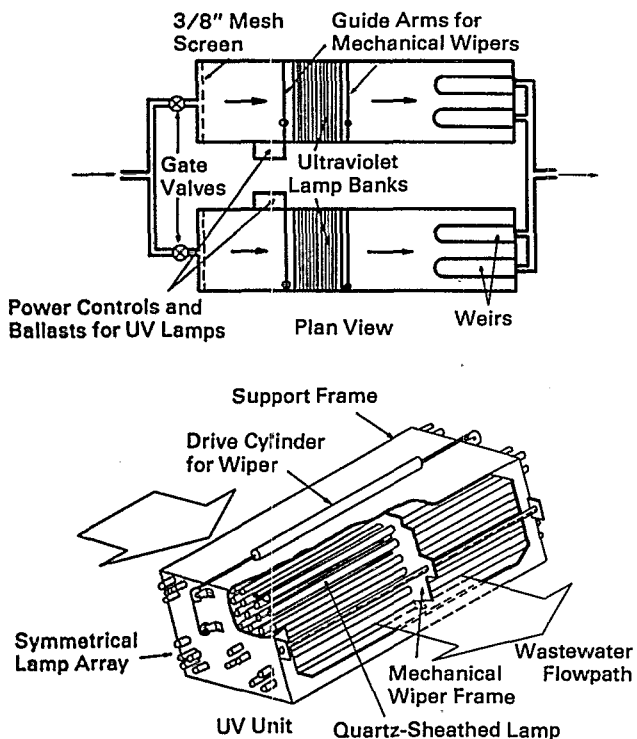
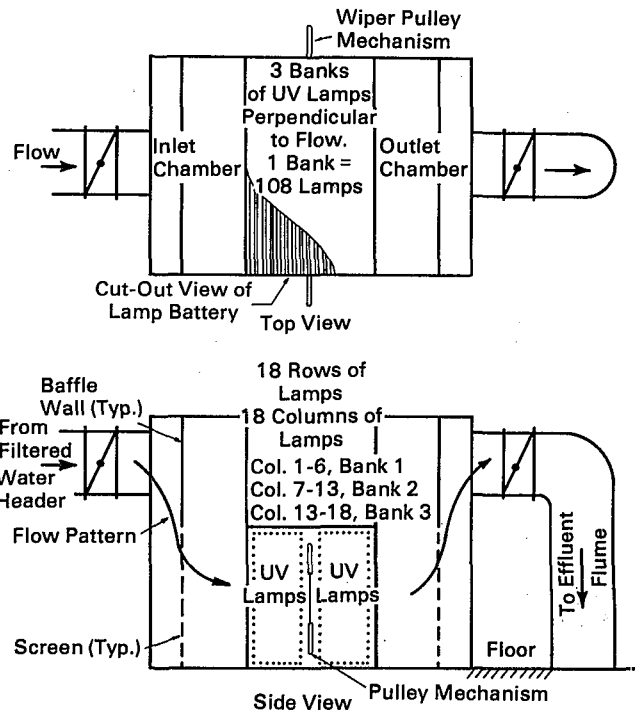


Figure 7-6. Schematic of quartz UV unit in Albert Lea, Minn.



lamps are arranged parallel to the direction of flow. The lamps were installed in the plant's existing secondary effluent channels. Each vertical module in these units is independent and can be removed by simply lifting them from the channel. A schematic of this modular, open channel design is shown on Figure 7-7.

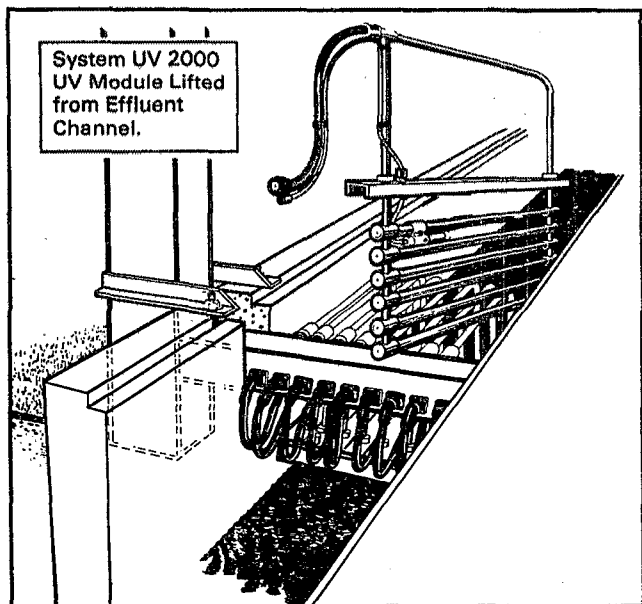
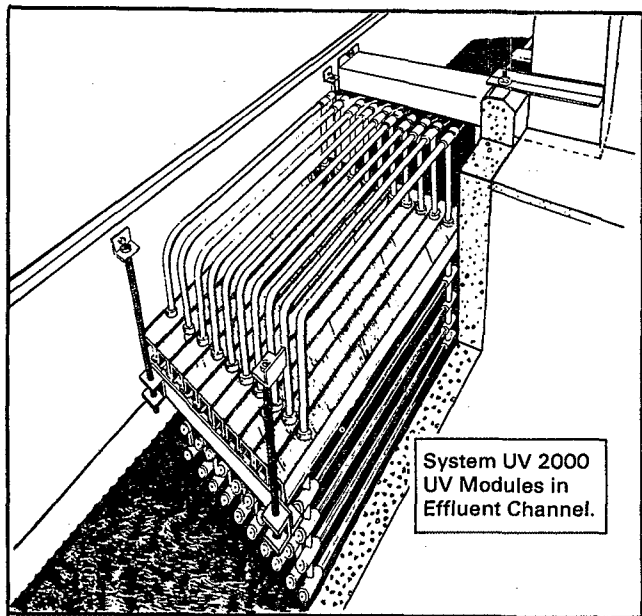
The submerged quartz systems are also arranged as open channel systems operating under gravity flow. An example is provided in Figure 7-5, which schematically presents the UV system installed at the Sents Creek Water Pollution Control Plant, Pella, Iowa (5). In this case the lamps are arranged in a symmetrical array, in the fashion of an open rectangular box as shown on the lower panel of Figure 7-5. The lamp battery is inserted into an open channel with the lamps perpendicular to the direction of flow (upper panel). Downstream of the lamp battery, the wastewater is collected in effluent launders for final discharge. This open-channel effect is also simulated by encasing the same type of lamp battery between open influent and effluent tanks. An example of this is the Albert Lea Water Pollution Control Plant, Albert Lea, Minnesota; a schematic of the units installed at this plant is presented on Figure 7-6.

The UV system for the Tillsonburg, Ontario (Canada) Water Pollution Control Plant is also installed as an open channel system. In this case, however, the

The non-contact UV systems are represented primarily by the system design in which the liquid is carried by thin-walled Teflon conduit transparent to the UV. The lamps are placed outside and parallel to the conduit. A schematic of this system arrangement is presented on Figure 7-8. The flow enters the influent chamber and is split to all or a portion of the Teflon tubes; the wastewater recollects in the effluent chamber and is discharged. The lamps, as shown on the figure, are typically inserted between the Teflon rows on removable racks (either vertically or horizontally). Pressure systems are also manufactured with the Teflon tubes; in this case the tubes are arranged in a serpentine pattern to reduce the overall size of the reactor.

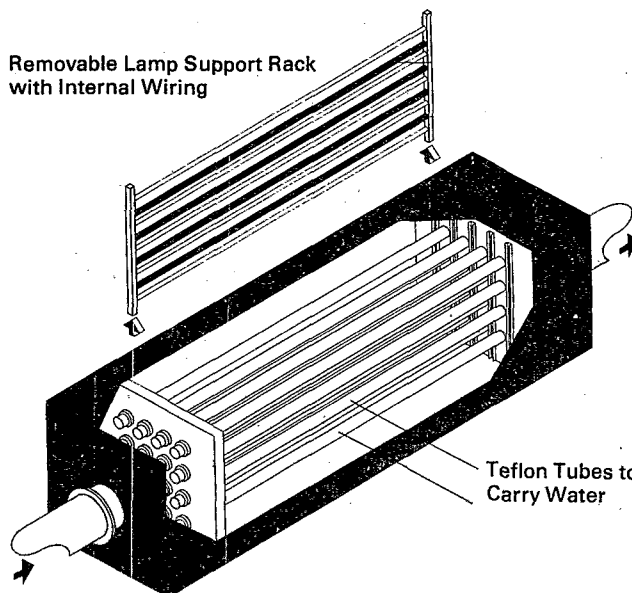
The systems presented in Figures 7-2 through 7-8 represent, reasonably well, the various configurations of germicidal lamps utilized in current UV disinfection systems. The total UV system must also accommodate the lamp ballasts. The ballast is placed in series with the lamp to provide a starting voltage and to maintain constant current. These are generally

**Figure 7-7.** Schematic of open-channel, modular UV system (Courtesy of Trojan Technologies, Inc., London, Ontario, Canada).



held in enclosures above the lamp battery (Figure 7-8), or are remote from the reactors in separate power panels (Figures 7-2 through 7-7). Instrumentation generally entails UV intensity monitors and individual lamp operations circuitry. Control of the system can be on a manual basis, often involving the selective operation of modules, or banks of lamps within a module, as a function of the hydraulic load to

**Figure 7-8.** Example of UV system utilizing Teflon tubes (Courtesy of Ultraviolet Technology, Inc., Rancho Cordova, California).



the system. Automatic controls generally slave the lamp bank (or in some cases the lamp voltage) operations to the flow rate and/or the water quality.

A major element in the operation of UV systems is the cleaning of the surfaces which must be kept transparent to the UV radiation for efficient performance. These include the quartz sheaths and the Teflon tubes. Most commercial systems include accessory equipment to assist in this cleaning task; these include the use of mechanical wipers, ultrasonic transducers, and the provision to chemically restore the surfaces.

#### **7.1.4 Current Technology Status**

As suggested by the foregoing discussions, the UV process is relatively simple. Not unlike chlorination, an agent is added to the wastewater in sufficient quantity to effect the inactivation of bacteria. Time in this case is not provided to allow for a specific reaction to take place, but rather to accomplish the necessary dose. The effect on the microorganism is not in itself lethal to the microorganism; the main effect is to impose sufficient damage such that the organism is unable to replicate. The process, like ozonation, requires on-site generation of the germicidal agent; the generator (the UV lamp), however, is far simpler in concept and operation than that required to produce ozone. Like both chemical processes, UV must also satisfy a "demand" of energy exerted by the wastewater itself.



Other than the simplicity of the process, UV also offers the advantages of system flexibility and a capability of responding quickly to changes in demand. There is relatively little complexity to the hardware, and maintenance generally requires low skill levels. The hazards of the process are low, principally related to the high electrical loads and the personal exposure to the UV radiation; these are conditions which are easily safeguarded. A major advantage of the process is the absence of a residual in the wastewater and any subsequent impact on the receiving water. A corollary to this is the ability to "overdose" with UV and still not affect the receiving water. This allows for a less rigorous control requirement than associated with the use of chlorine. The absence of a residual can also be viewed as a disadvantage when considering the operational control of the process. There is no immediate monitor of performance analogous to the chlorine residual. Since the energy levels are not high enough to affect chemical reactions, there are no significant intermediates formed by the process, even at overdose levels. This is clearly an advantage over the chemical addition processes.

Given its advantages, UV was still not seriously considered as an alternative to chlorination for wastewater disinfection until the mid-seventies. At that point the process was considered more in response to the negative aspects of chlorination; its potential was acknowledged if the perceived disadvantages with the process were overcome. These related to the lack of information on UV application to low grade waters and the impact of various water quality parameters (particularly suspended solids) on design, the lack of any clearly defined design procedures, and the previous history of system fouling. Subsequent investigations focused on these and other aspects of UV disinfection. A number of full scale plants were installed, encouraged by the support of the USEPA through its Innovative and Alternative Technologies funding, under the Construction Grants program. A total of 14 plants were funded under I/A by the USEPA (6). These and other facilities are providing much needed information on the operation and maintenance requirements of the systems and on refinements necessary for current and future installation designs. Plants funded under the I/A program are listed on Table 7-1.

**Table 7-1. Municipalities That Have Received I/A Funds for Designing and/or Constructing UV Disinfection Facilities (October 1978 to June 1981)**

Village of Suffern, New York	Northfield, Minnesota
Woodstock, New York	Albert Lea, Minnesota
Crawford, New York	Pella, Iowa
Rhineback, New York	Cassville, Missouri
Smithburg, Maryland	Dexter, Maine
Clear Spring, Maryland	Kennebunk, Maine
Evanston, Wyoming	Heston, Kansas

There are a significant number of plants now installed throughout the United States for the disinfection of treated municipal wastewaters. A list of UV installations which are operational, or in the design, bid, or construct stage is presented in Tables 7-2, 7-3, and 7-4 (5). This information is further reduced in Table 7-5 to reflect the distribution of plants with regard to size; as indicated, the existing plants in operation are predominantly small (less than 3800 m<sup>3</sup>/d or 1 mgd), while plants in the planning or construction stage tend to be larger.

## 7.2 Disinfection of Wastewaters by Ultraviolet Radiation

### 7.2.1 Ultraviolet Light

As presented in Figure 7-9, the ultraviolet region of the electromagnetic spectrum is generally defined as those radiations with wavelengths greater than the longest X-ray and less than the shortest wavelength visible to man; these wavelengths typically are set between 40 and 400 nanometers (nm). The ultraviolet region itself is divided. Near ultraviolet radiation is between 300 and 400 nanometers; far ultraviolet is between 200 to 300 nm. These two bands of ultraviolet are observed in solar radiation. Extreme ultraviolet radiation describes that energy between wavelengths 40 and 200 nm; energy at these wavelengths is strongly absorbed by air and its observation requires working in a vacuum or in a gas which does not absorb the energy.

Qualitatively, light is almost universally described by its wavelength. For the sake of convenience, a single unit of wavelength will be used throughout this chapter. This is the nanometer (nm), or 10<sup>-9</sup> m. There are 10 Angstroms per nanometer.

A more fundamental quantity describing electromagnetic radiation is its frequency of vibration. The frequency and wavelength of radiation are related by:

$$c = \nu \lambda \quad (7-1)$$

where:

$c$  = the velocity of light (3x10<sup>10</sup> cm per second in free space)

$\nu$  = frequency of vibration (vibrations per second)

$\lambda$  = wavelength (cm)

A number of terms are used to express the quantity of radiation. These physical units relate to work or energy. The ones most commonly used are the erg, calorie, and watt-second (joule); all are measures of total quantity of energy or work. The time rates at which this energy is delivered in the corresponding

**Table 7-2. Summary List of Facilities in the U.S.A. or Canada Utilizing Ultraviolet Light (UV) Disinfection Which are in Design**

Facility Name	Design Firm	Size, mgd Design	Start-up	Other Treatment Processes	Equipment and/or Comments
Bristol (CONNECTICUT)	Keys Associates Jim Geremis (401) 861-2900	10.75	7.0	Activated sludge	(Equipment not yet purchased)
Ridgefield (CONNECTICUT)	Albertson, Sharp & Ewing Mike Pastore (203) 846-4356	0.120	0.040	RBC System	N.C.
Salmon (IDAHO)	Ellsworth Engineering, Inc. Gary Marshall (208) 523-1662	Not estab- lished	Not estab- lished	Aerated lagoon/ Facultative lagoon (secondary cell)	N.C.
Ucon (IDAHO)	Forsgren-Perkins Engineering Dick Dyer (208) 356-9201	0.115 (80 gpm)	0.07-0.115 (50-80 gpm)	Facultative lagoon (secondary cell); UV is followed by 4- acre storage pond & land disposal	N.C.
Camp Point (ILLINOIS)	W.H. Klinger & Associates Dan Oliver (217) 223-3670	0.16	0.11	Two-cell stabiliza- tion pond (30-day Det. time) w/inter- mittent sand filter	N.C.
Iowa City (IOWA)	Keenstra & Kimm, Inc. Jim Kimm (515) 225-5000	13.0	9.0	Activated sludge	N.C.
Kennebunk (MAINE)	E.C. Jordan A. Peter Krauss (207) 775-5401	1.3	0.7	RBC system	(Equipment not purchased)
Limestone AFB (MAINE)	Dufresne & Henry Barry Bastian (207) 797-2010	2.5 (ADWF) (peak 5.2)	1.5	RBC system dry weather In wet weather, RBC (2.5 mgd) & up to 4.1 mgd primary ef- fluent	N.C.
Pittsville (MARYLAND)	Harrington & Associates William Harrington (301) 768-5400	0.125	0.06	Oxidation ditch, ter- tiary filtration	N.C.
Poolesville (MARYLAND)	Kamber Engineers Dennis Kamber (301) 840-1030	0.6	0.35	Sequencing Batch Reactor, pressure filter	Flow through UV unit will be under slight pressure
Morton (MINNESOTA)	Ayres Associates Dale Philstrom (612) 644-0604	0.132	0.067 (dry weather)	Aerated stabilization basin system	N.C.
Calhoun City (MISSISSIPPI)	Willis Engineering Co. Joe Sutherland (601) 226-1081	0.342	0.175	Hydrograph-control release facultative lagoon. Store wastewater during dry weather; discharge 1 to 10 times design flow during rainy season	UV selected due to periods of no flow, not because of ef- fluent require- ments.
Deer Lodge (MONTANA)	Christian, Spring, Sielbach & Associates John Connel (406) 656-6000	1.5 (peak 3.3)	1.3	Aerated lagoon sys- tem	N.C.
Dillon (MONTANA)	S & A Engineers Robert Scruton (406) 442-1532	0.8 (winter-0.65, summer-1.10)	0.8	Aerated lagoon sys- tem, storage basin (180 AF)	N.C.
Lewiston (MONTANA)	HKM & Associates Jim Kaercher (406) 245-6354	2.9	2.3 (current 9.0)	RBC system	N.C.

Table 7-2. (Continued)

Facility Name	Design Firm	Size, mgd Design	Start-up	Other Treatment Processes	Equipment and/or Comments
Stratford #1 (NEW HAMPSHIRE)	Hoyle, Tanner & Associates Gene Forbes (603) 669-5420	0.056	0.053	Slow rate (0.5 gpd/ ft <sup>2</sup> ) sand filters	N.C.
Stratford #2 (NEW HAMPSHIRE)	Hoyle, Tanner & Associates Gene Forbes (603) 669-5420	0.024	0.021	Slow rate sand fil- ters (0.5 gpd/ft <sup>2</sup> )	N.C.
Whitefield (NEW HAMPSHIRE)	Phillips & Emberly William Emberly (802) 434-2142	0.185	0.133	Aerated lagoon sys- tem	N.C.
Woodstock (NEW YORK)	Phillip J. Clarke David Wright (716) 454-4570	0.230	0.180	Oxidation ditch, sand filters in sum- mer months only	N.C.
Harrimon (NEW YORK)	Phillip J. Clarke John Tarolli (914) 294-8818	4.0	2.0 (existing)	Draft tube oxidation ditch, tertiary sand filters, parallel train: existing activated sludge, aerated pol- ishing lagoon	Lead design firm is: Erickson Schmitt, Al Schmitt (914) 294-8838
Loomis (NEW YORK)	Phillip J. Clarke David Wright (716) 454-4570	0.080	0.054	Overland flow, aer- ated polishing la- goon	N.C.
Ironton (OHIO)	Brundage, Baker & Stouffer, Ltd George Haggard (614) 888-3100	1.7	1.7	Trickling filter	N.C.
Northridge Subdivision Pladmont (SOUTH DAKOTA)	Hoskins, Western & Son- deregger Al Foster (605) 342-4105	0.023	0.011	Extended aeration	State wants a ter- tiary filter installed before they will ap- prove design
Beckley (WEST VIRGINIA)	Greenhorne & O'Mara Gary Beech (301) 982-2837	3.5	2.5-3.0	Activated sludge ex- tended aeration (post-aeration fol- lows UV)	N.C.
Buckhannon (WEST VIRGINIA)	Kelley, Gridley, Blair Wolfe Jim Downey (304) 345-0470	2.5	1.5	Oxidation ditch (post-aeration fol- lows UV)	Design around ENERCO
Green Valley- Glenwood PSD (WEST VIRGINIA)	Pentree Will Smith Bob Hazelwood (304) 425-9581	1.5	1.0	Oxidation ditch (post-aeration fol- lows UV)	N.C.
Marshall Co. PSD #1 (WEST VIRGINIA)	Green International Norman Katz (412) 471-5348	0.17	0.10	Extended aeration (package plant)	N.C.
Opequen Hedgesville (WEST VIRGINIA)	HNTB Dave Wright (414) 463-2310	0.80	0.55	Oxidation canal, post-aeration fol- lows UV	N.C.
PAX (WEST VIRGINIA)	G.A. Tice George Tice (304) 255-5400	0.06	0.045	Facultative lagoons	N.C.
Harper Eccles WWTP Raleigh Co. PSD (WEST VIRGINIA)	Greenhorne & O'Mara Turgay Ertugal (301) 982-2800	0.100	0.100	Oxidation ditch (package unit)	N.C.

Table 7-2. (Continued)

Facility Name	Design Firm	Size, mgd		Other Treatment Processes	Equipment and/or Comments
		Design	Start-up		
Salt Rock PSD (WEST VIRGINIA)	Dunn Engineers Dave Schultz (304) 342-3436	0.260	0.246	Oxidation ditch	N.C.
Riverton (WYOMING)	Airex Engineers Harry La Bonde (307) 856-6505	4.95	2.3	Oxidation ditch	U.V. Technologies
Athens (WISCONSIN)	Becker Hoppe Engineering Gerald Bizjak (715) 359-6147	0.225	0.070	Aerated lagoon (3 cells: primary, secondary, storage). Plant has controlled discharge of effluent by using the storage lagoon	Anticipating the use of ENERCO
Little Black (WISCONSIN)	Carl C. Crane, Inc. Victor Marz (608) 238-4761	0.012	0.008 to 0.010	Recirculating sand filters	N.C.
Collingwood (ONTARIO, CANADA)	Ainley & Associates, Ltd. (Owen Sound, Ont.) Colin Kent (705) 445-3451	1.2	0.5 low	Activated sludge, tertiary filtration	Anticipating Trojan Industries

N.C. - No comments.

units are ergs per second, calories per second, and the watt. These units and their cgs equivalents are as follows:

Watt-second (or joule)	w-sec	$10^7$ ergs
Calorie	cal	$4.2 \times 10^7$ ergs
Erg	—	—

The intensity or energy density of the radiation is expressed in terms of energy incident upon a unit area. The unit used in the context of this report is the micro-watt per square centimeter ( $\mu\text{watt}/\text{cm}^2$ ).

Quantum theory states that radiant energy occurs in discrete units, or quanta. The energy of these fundamental units is related to its frequency:

$$E = h\nu = hc/\lambda \quad (7-2)$$

where:

- E = energy of a single quantum (ergs)
- h = Planck's constant ( $6.62 \times 10^{-27}$  erg-sec)
- c = velocity of light ( $3 \times 10^{10}$  cm per sec)
- $\nu$  = frequency (vibrations per second)
- $\lambda$  = wavelength (cm)

The quantum is a very small energy unit, equivalent to  $(19.86 \times 10^{-17})/\text{wave length}$ , in cm-ergs. From this expression it is shown that the energy content of a quantum is identical for a given wavelength of light.

### 7.2.1.1 Source of UV Radiation

Practical application of UV for purposes of disinfection required a high intensity source at the desired

wavelengths. This can be traced by the evolution of the mercury vapor lamp. In 1835, Wheatstone described the intense light emitted when mercury is vaporized in an electric arc. The first true mercury vapor lamp was constructed by Downing and Keating in 1896 by passing an electric discharge through mercury in a partially evacuated tube. The problem was that the arcs would eventually go out because of the increase in the pressure of the vapor. Cooper-Hewitt resolved this problem in 1901 by devising a lamp in which the mercury was condensed at the same rate at which it was vaporized. This, along with the development of fused quartz and ultraviolet transmitting glass, initiated the successful commercial development of mercury vapor lamps (7).

The discharge type lamps were relatively inefficient, however, due to their low selectivity in the use of the energy, or electrical input. The generation of heat, excitation of several different spectral lines, and inefficient electrodes resulted in a distribution of energy to many outputs. The key development came in the 1920s, when it was determined that a discharge through a mixture of mercury vapor at a precisely optimum pressure and a rare gas (typically argon) at a somewhat higher pressure was extremely efficient in converting the electrical energy to ultraviolet light. Fully 60 percent of the energy input could be converted to monochromatic radiation at 253.7 nm (8).

The commercial development of the mercury-rare gas discharge lamps was directed to its use as a light source. The development of a suitable fluorescent

**Table 7-3. Summary List of Facilities in the U.S.A. or Canada Utilizing Ultraviolet (UV) Disinfection Which are Under Construction.**

Facility Name	Design Firm	Size, mgd Design	Start-up	Other Treatment Processes	Equipment and/or Comments
Galney Ranch (Arizona)	Greely & Hanson Elizabeth Zureick (602) 992-5000	1.7 (8 mo.) 1.0 (4 mo. winter)	1.7	Extended aeration, sand filters	ENERCO (formerly UV Technologies)
Payson (Arizona)	Moore, Knickerbocker & Assoc. Terry Moore (602) 265-3776	1.7	0.5	Bardenpho (& Clarifiers), backwash filters	UV Technologies (Now ENERCO)
Augusta (Arkansas)	Mehburger, Tanner, Robinson & Assoc. Daryl Laws (501) 375-5331	0.6 (current 0.4)	0.4-0.5	Orbal treatment system, Aeration disks	ENERCO #L1000
Heber Springs (Arizona)	Boulder Engineers Jim Little (501) 362-3118	1.8 (1250 gpm)	1.8 (intermittent pumped flow; ultimately; flow will be continuous)	Three-cell aerated lagoon (facultative) of 19 acres rapid sand filters	UV Purification Systems, Inc. (70 lamps; 9-sec. retention)
Presque Isle (Maine)	Wright, Pierce, Barnes & Wyman Dave Fuller (207) 725-8721	2.3 dry weather (5.4 wet weather)	0.7 (1.9 with I/I)	Oxidation ditch system	Pure Water Systems, Inc. (Two units-1 standby)
Clear Springs (Maryland)	Fellows, Reed & Assoc. Ed Renn (301) 739-5660	0.20	0.12	Oxidation ditch	Not yet purchased
Milford (Massachusetts)	Haley & Ward, Inc. Ben Bugbee (617) 890-3980	4.3	2.0	RBC & tertiary filters	Not yet purchased
Bemidji (Minnesota)	Rieke, Carroll, Muller & Assoc. Warren Kerstan (612) 935-6901	2.7	1.6 (current)	Activated sludge & tertiary filtration	UV Technologies
North Koochiching Area San. District (Minnesota)	Widseth, Smith, Nolting & Assoc. Don Anderson (218) 829-5117	2.3	1.1 (current)	Trickling Filter	UV Purification Systems, Inc.
Bonne Terre (Missouri)	Metropolitan Engineering Robert Vogler (314) 948-3860	0.6	0.4	Oxidation ditch	Not yet purchased
Emminence (Missouri)	Missouri Engineering Co. Corky Stack (314) 364-4003	2.9	0.5	Oxidation ditch, sand filter	UV Purification
Frederick Town (Missouri)	Crane & Fleming Greg Boettener (314) 221-4048	0.85	0.6	Oxidation ditch	UV Purification
Mineral Belt Area WWTP (Flat River, Mo.) (Missouri)	Metropolitan Engineering Robert Vogler (314) 467-3860	2.0	1.6	Oxidation ditch	Not yet purchased
Noel (Missouri)	Allgeier, Martin, & Assoc. Jan Tupper (417) 624-5703	0.2	0.15	Oxidation ditch	UV Technology

Table 7-3. (Continued)

Facility Name	Design Firm	Size, mgd Design	Start-up	Other Treatment Processes	Equipment and/or Comments
Summerset Plant Div., South Jefferson Co. (Missouri)	Horner & Shifrin (314) 531-4321	0.117	0.1	Lagoon facility (30- day detention time)	UV Purification Systems Inc.
Winona (Missouri)	C.B. Simmons C.B. Simmons (417) 732-2092	0.175	0.100	Oxidation ditch	ENERCO
Chinook (Montana)	Robert Peccia & Assoc. Alden Beard (406) 442-8160	0.50 (current 1.10)	0.35	Oxidation ditch	ENERCO
Bennington (Nebraska)	Johnson, Erickson, O'Brien & Assoc. Terry O'Brien (402) 443-4661	0.186	0.065-0.070	Extended-aeration activated sludge	Pure Water Systems, Inc. and U.V. Purification Systems, Inc.
Chatham Township (New Jersey)	Keller, Kirkpatrick Bob Kirkpatrick (201) 377-8500	0.120	very low	RBC, multi-media filter	UV Technologies, Inc.
Rhineback (New York)	Brinnier & Larios Dennis Larios (914) 338-7622	0.130	0.080	Oxidation ditch	ENERCO
Thompson (New York)	Phillip J. Clark & Assoc. David Wright (716) 454-4570	1.0	0.80	Draft tube oxidation ditch, aerated pol- ishing lagoon	ENERCO
Beech Mountain (ski resort) (N. Carolina)	Davis, Martin, Powell Ed Powell (919) 883-0032	0.400 (peak @ 2 1/2X)	0.04-0.20 seasonal	Contact stabilization	ENERCO
Waynesburg (Ohio)	Hammontree & Assoc. Richard Hunsinger (216) 499-8817.	4.0	0.23	Bio-drum	UV Purification Systems, Inc.
Mt. Pleasant (S. Carolina)	E.M. Seabrook, Inc. Louis Couthen or Brian Wright (803) 884-4496	3.2	1.0 (current)	Conventional acti- vated sludge	UV Purification Systems, Inc.
Coalville (Utah)	DMJM Reed Fisher (801) 262-2951	3.0	0.25	Oxidation ditch	Not yet purchased
Baker Heights Berkley Co. PSSD <sup>a</sup> (W. Virginia)	HNTB David Wright (414) 463-2310	0.34	0.34	Trickling filter	ENERCO
Moorefield (W. Virginia)	Kelley, Gidley, Blair, Wolfe Dick Kline (304) 345-0470	0.477	0.400	Aerated lagoon	ENERCO
Evanston (Wyoming)	Eckoff, Watson, Preater John McNeil (801) 486-5621	2.9 (current 2.5)	2.0	Oxidation ditch	UV Purification Systems, Inc.
Worland (Wyoming)	Airex Engineers Harry LaBonde (307) 856-6505	1.12	0.8 (current)	Aerated lagoons	UV Purification Systems, Inc.
Madison Met (Wisconsin)	Consour Townsend Ron Reising (312) 938-0300	50 (peak 115) largest UV fa- cility in world	35-40	Activated sludge w/nitrification	UV Purification Systems, Inc.

<sup>a</sup>PSSD = Public Service Sanitation District.

**Table 7-4. Summary List of Facilities in the U.S.A. or Canada Utilizing Ultraviolet Light (UV) Disinfection Which are in Operation**

Facility Name	Design Firm	Size, mgd		Other Treatment Processes	Equipment	Comments on Performance
		Design	Current			
Lake Creason, Cow Hilda Cove area (AR)	U.S. Army Corps of Engineers "Mac" Montgomery (601) 634-5301	0.015	0.015	Extended aeration-activated sludge, rapid sand filters	U.V. Technologies (Teflon Tubes)	In operation 1-1/2 years. Good performance.
Lake Ouachita, Little Fir area (AR)	U.S. Army Corps of Engineers "Mac" Montgomery (601) 634-5301	0.018	0.018	Extended aeration-activated sludge rapid sand filters	U.V. Technologies (Teflon tubes) Now ENERCO 1 unit, 8-lamps rated for 7500 hrs. use	In operation 1-1/2 years. Good performance. Operates March-Oct.
Lamar (AR)	Burrough, Uerling & Brasuell David Uerling (501) 646-5559	0.106	0.100	Overland flow	U.V. Technologies	Disinfection requirements met. Frequent bulb replacement. Failure to operate automatically. Weir causes UV tanks to be filled with silt. (Identical to Hatfield facility).
Tillonsburg (Ontario, Canada)	Anderson Assoc. Peter Laughon (416) 497-8650	2.4	1.3	Extended aeration	Trojan Industries	In operation for 2 years. Achieving 1/2 100 MPN coliform/100 ml.
Edon (Wisconsin)	Arthur Technology John Masters (414) 922-6973	0.16	0.10	1" clarifier, roughing filter extended activated sludge (for nitrification)	UV Technology	Good performance.
Conifer Center (Colorado)	ADG Engineering, Inc. Roger N. Venables (303) 761-5142	0.015	0.005	Package-activated sludge extended	Ultradynamics (Santa Monica, CA)	No performance problems to date, only 1 month of operation.
Erie (Colorado)	Keith Bell & Assoc. Keith Bell	0.30	0.18	Aerated lagoons (20-day det. time)	ENERCO	Tube fouling. Operational since Dec. 1983.
Cypress-Thompson Creek, Challis (Idaho)	Hamilton & Voelur (No longer in business) Contact: former employee of H & V Rance Bane Ellsworth Engrg. (208) 523-1662	0.720 (500 gpm)	0	3-stage lagoon	ENERCO	Operates 30 days/year in September. Too early to judge performance; flows too early to judge performance; flows too low. Fecal coliform die-off in ponds is 100%, prior to UV disinfection.
Newdale (Idaho)	Forsgren-Parkins Engrg. Dick Dyer (208) 356-9171 Earl Keemp (801) 364-4735 (Salt Lake City Ofc.)	0.045	0.022	Facultative lagoon (Land disposal)	ENERCO (Model G-30)	Start-up: Nov. 1983-99.9% bacterial die-off. Design engineer is Dick Dyer.
Red Top Meadows (Ketchum) (Idaho)	J.U.B. Engineers James Coleman (208) 733-2414	0.180 (dry 0.06)	0.180	Extended aeration oxidation ditch	U.V. Technologies (Now ENERCO)	Good performance. Fecal coliform count = 0 for 100% fecal coliform kill. Bulbs replaced annually. Operating since 10/82.
Pella (Iowa)	Veenstra, Kimm Engineers Jim Kimm, Mike Foreman (515) 225-8000	3.4	1.5	Activated sludge	Pure Water Systems, Inc. (Quartz jacketed UV lamps)	Mechanical wiper system not functioning. Using chemical cleaning with weak acid solution for lamp jackets (outside) approximated every 2 weeks vs. 6 mos to 1 year. New end seals were provided by the manuf. Operational since April 1982 (Oct. '81 for entire facility).
Heston (Kansas)	Wilson & Co. Engineers & Architects Jim Dowell (913) 827-0433 Contact: City of Heston, Maurice Bowersox or Bill Nitzsche (plant) @ (316) 327-4412 or 327-2635	1.3	0.25-0.30 (wet weather -0.40)	Orbal Activated Sludge (Effluent goes to golf course)	U.V. Purification Systems, Inc.	Ultrasonic cleaning not working up expectations. Consequently, light intensity is not as expected. Must chemical clean the lamps.
Sabbatus (Maine)	Woodward & Curran Frank Woodward (207) 839-6751	0.25	0.1	Imhoff tank & intermittent sand filter system	U.V. Technologies (G-500)	Meeting coliform count requirements. Operating 1 year. Still in shake-down. I/I problems; must bypass due to poor filtration.
Togus VA Hosp. (ME)	Hunter Balleau Barrie Patrie (296) 671-4721 or V.A. Center, Bob White (207) 623-8411 X338	0.2	0.15	Oxidation, ditch system	U.V. Technologies	Operating 1 year. Fecal coliform levels met. Initially, wiring and bulbs were faulty. Currently, ballast that runs UV bulbs weakens, diminishes intensity of bulbs. Must change ballast often; life is less than 2,000 hours.
Old Towne (Maryland)	Allegany County Sanitation Commission Kevin Beachy	0.04	0.03	Extended Aeration activated sludge	Pure Water Systems, Inc.	High maintenance. Initial ballast problem now corrected. (Auto wiper system shuts down UV unit when tubes get too dirty).
Smithsburgh (MD)	Fellows, Reed & Assoc. Ed Renn (301) 739-5660	0.20	0.12	Extended aeration	U.V. Purification Systems, Inc.	System in start-up.

**Table 7-4. (Continued)**

Facility Name	Design Firm	Size, mgd		Other Treatment Processes	Equipment	Comments on Performance
		Design	Current			
Thurmont (MD)	Harrington & Assoc. William Harrington (301) 768-5400	1.0 (4.0 weather)	0.3 (2.9 weather)	Oxidation ditch with tertiary filtration	ENERCO	Too soon to tell.
Albert Lea (Minnesota)	Tolz, King, Duvall & Anderson Dave Kirkwold (612) 292-4400	12.53	3.91	2-Stage activated sludge, tertiary filters	Pure Water Systems, Inc.	Good performance. Meeting coliform kill requirements. Coliform count is less than 1 MPN/100 ml. Some minor mechanical problems, which have been corrected. Operating since June 1983.
Northfield (MN)	Bonestroo, Rosene, Anderlick & Assoc. Dick Turner (612) 636-4600	2.5	2.1	2 Stage secondary system (trickling filters & RBC)	Pure Water Systems, Inc.	Poor operation. Have not achieved contract specification for operation. Still putting in corrective measures. Mechanical difficulties; electrical components burned.
Cossville (Missouri)	Allgeier, Martin & Associates Jan Tupper (417) 513-5703	0.5	0.7 (exceeding design capacity)	Oxidation ditch	Aquafine (No longer in market)	Excess heat in UV Bldg. - uncomfortably warm for operator. Fans alleviated this problem.  Plant is meeting discharge requirements. In operation 2-3 years.
Clinton (MO)	Bucher, Willis J. Ratliffe Jim Swanson (913) 827-3603	2.0	1.3	Oxidation ditch	U.V. Purification Systems, Inc.	Summer use only; in use for 1 yr. Some ballast problems. Some chemical cleaning problems.
Ozark (MO)	Anderson Engineering Steven Brady (417) 866-2741	0.72	0.20	Oxidation ditch	U.V. Purification Systems, Inc.	In operation 1 year. Initial problem with ultrasonic cleaning system achieving desired bacterial kill.
Briarwood (MO)	Sanders, Stewart, Gaston Paul Kinshella (406) 245-6366	0.180 (peak 0.72) (Health Dept. approved 0.123 to date)	0.0005 (500 gpm)	Oxidation ditch	ENERCO	Just starting up (as of 10 am 3/27/84) Using clear water.
Yellowtail Power Plant (Montana)	Bureau of Reclamation Craig Peterson (406) 657-6141 or Mr. Hergenreider (406) 666-2443	0.0006	0.001	Extended aeration package plant, tertiary filtration	U.V. Technologies, Inc.	Good performance.
Environmental Disposal Corp. (Pluckerman) (New Jersey)	Environmental Design Inc. (out of business) Contact: Ray Ferrara Princeton University (609) 452-4653 or Neil Callahan (Operator) (201) 234-0667	0.85 (590 gpm)	0.43-0.57 (300-400 gpm)	Bardenpho and multi-media filter	U.V. Technologies, Inc. (Now ENERCO)	Good performance. Fecal coliform @ 10-50 MPN/100 ml. (Permit 200 MPN per 100 ml) Feed to UV is "clean" 4-5 mg/l SS. 4-5 mg/l SS. Initially seals leaked - now replaced. Once clay got in stream, colored water, and reduce effectiveness of UV system. 2-750 gpm units run intermittently batch.
Educational Testing (N.J.)	CUHZA Manny Dios (609) 452-1212	0.080	0.030-0.038	Extended aeration, filtration (package, multi-media, high rate)	U.V. Purification Systems, Inc.	Operational since 9/81. Faulty photo cell, replaced in 1981.
Crawford (NY)	Phillip J. Clarke & Associates John Tarolli (914) 294-8818	0.15	0.08-0.085	Oxidation ditch (septic tank effluent)	U.V. Purification Systems, Inc.	Not yet in operation—summer requirements only (Plant on-line since 10/83).
Pennyann (NY)	Hershuy, Malone, & Associates Greg Barbour (716) 381-9250	1.8	0.6	RBC	U.V. Purification Systems, Inc.	In operation since 11/83. High flows blew out UV Tubes; cause uncertain: freezing or obstacles in flow.
Suffern (NY)	Thomas Riddick Norman Lindsay (914) 365-0446	1.9 (peak 4.0)	1.2	"Lighting Complete Mix" aeration (similar to activated sludge.)	U.V. Purification Systems, Inc.	Not yet in operation. Awaiting stabilization of activated sludge system.
McPherson (Kansas)	Wilson & Co., & Architects Jim Dowell (913) 827-0433 Contact: Plant operator, Walt Hundley (316) 241-3940	0.29 (200 gpm) (entire plant @ 2.0 mgd)	0-0.14 (0-100 gpm) (entire plant @ 1.7 mgd)	Trickling filter and Contact Stabilization basin in parallel. Combined discharge bypasses UV to creek or a portion (100 gpm) is discharged to lake, when lake level is low.	Aqua-fine	Poor performance. Coliform count is high. Difficult to keep quartz sleeve over lamps clean. Harness (mineral deposits won't wipe off. Sometimes operators use soap or chlorox. However, it's frequently necessary to chemically clean lamp sleeves.
Marietta (Oklahoma)	Bob McCoy (Now retired) Contact: Mark Daniels State Environmental Agency (405) 276-5493	0.231	0.19	Oxidation ditch	U.V. Purification Systems, Inc.	Maintenance problems i.e. burned out lamps.



**Table 7-4 (Continued)**

Facility Name	Design Firm	Size, mgd		Other Treatment Processes	Equipment	Comments on Performance
		Design	Current			
Berkeley County (South Carolina)	E.M. Seabrook, Inc. Ryan Wright (803) 884-4496	5.0 (peak 8.0)	3.0	Oxidation ditch	Pure Water Systems, Inc.	In operation for past 9 months. Good performance. Discharge requirements met. Some mechanical difficulties.
Civilian Conservation Center, Nemo	Case, Colter, Inc. (Denver) Ralph Olson (303) 288-1511 Other contacts: U.S.F.S: Carl Erikson (605) 348-3636 Terry Ambraster (303) 234-5223	0.024	0.017	Extended aeration, tertiary filtration.	U.V. Purification Systems, Inc.	Good performance.
Danville (Vermont)	Dufresne & Henry Bobbi Trudell (802) 886-2261	0.070	0.040	Aerated lagoon system (30-day det. time)	U.V. Purification Systems, Inc.	Good performance. Meeting discharge requirements.
Jacksonville (VT)	Dufresne & Henry Bobbi Trudell (802) 886-2261	0.050	0.025	RBC system, which treats septic tank effluent	Ultra Dynamics, Inc.	Good performance. Meeting discharge requirements.
Pawlet (VT)	Dufresne & Henry	0.040	0.023	RBC system; which treats septic tank effluent.	U.V. Purification Systems, Inc.	Good performance. Meeting discharge requirements. Operating since 12/83.
Whitingham (VT)	Dufresne & Henry	0.013	0.006	RBC system, which treats septic tank effluent.	Ultra Dynamics, Inc.	Good performance. Meeting discharge requirements. Operating since 12/83.
Cumberland Hospital	Gresham, Smith & Partners David Shood (803) 572-1300	0.030	0.002 to 0.003	Extended aeration	U.V. Purification Systems, Inc.	Discharge requirements not met in 6 of 9 months. In compliance for 2/84.
Tangier Island (VA)	Shore Engineering Emmett Ranson (804) 787-2773	0.1	0.032	RBC	Aquafine	Difficulty meeting discharge requirements.
Lander (Wyoming)	Western Design Consultants Mr. Chen (801) 486-5621	1.82	1.3	Aerated lagoon	ENERCO	Burning one end of the UV lamps due to float switch problem.
Rock Springs (WY)	Johnson, Fermelia, and Crank Dale Crank (307) 877-9093	2.0	2.0	Oxidation ditch	UV Technologies	Test runs of system resulted in overheating of bulbs. Fans were used to correct this.
Brooklyn (Wisconsin)	Carl C. Cranca, Inc. Dennis Truttman (600) 238-4761	0.160	0.025-0.030 (low)	Oxidation ditch	U.V. Purification Systems, Inc.	150-200 fecal coliform count. (Currently there is no state requirement.)
Cross Plains (WI)	Mead & Hunt, Inc. Bill Buth (608) 233-9706	0.450 (avg.)	0.180 to 0.200	Extended aeration oxidation ditch	U.V. Purification Systems, Inc.	Good performance. Requirements met.
Etrick (WI)	Davy Engineering Mike Davy or Arnie Finski (608) 782-3130	0.064	0.040	RBC	U.V. Purification Systems, Inc.	Problems-w/turbidity & coli killo.
Holomon (WI)	Davy Engineering Mike Davy (608) 782-3130	0.8	0.4	Extended aeration	U.V. Purification Systems, Inc.	Problems-start-up only Operational since 10/83.
Deerfield (WI)	Carl C. Crane, Inc. Dennis Truttman (608) 238-4761	0.195	0.100 flowmeter not working.	Extended aeration oxidation ditch	U.V. Purification Systems, Inc.	In start-up for 2 months. Still in shake-down.
Lodi (WI)	Mid State Assoc. Jim Owen (608) 356-8344	0.620	0.230 to 0.288	RBC	U.V. Purification Systems, Inc.	Operational since 7/83. Poor performance. Requirements not met.
Lyons (WI)	Robbers & Boyd Larry Boyd (414) 763-2652	0.100	0.020 (low)	Oxidation ditch	Aqua fine Corp.	Meeting discharge requirements. Operational since late 1981.
Poynette (WI)	Lakeland Engineers Mark Koletzke (608) 274-3898	0.190 (0.470 wet weather)	0.300	Oxidation ditch	U.V. Technologies (now ENERCO)	Operational since 8/83. Meeting coliform count requirements.
Spring Valley (WI)	Davy Engineering Arnie Finski or Mike Davy (608) 782-3130	0.189	0.100	RBC	U.V. Purification Systems, Inc.	UV is not to start-up until 4.1.84

**Table 7-4. (continued)**

Facility Name	Design Firm	Size, mgd		Other Treatment Processes	Equipment	Comments on Performance
		Design	Current			
Otay (California)	Lowry & Assoc. Matt Tebbetts (619) 283-7145	0.65	0.3	Activated sludge, filtration, pH reduction prior to UV, the R.O. unit.	UV Technology	
Jehovah Witness Church, Tujuas (Puerto Rico)	Radmes Torres (809) 725-5878 (in San Juan, P.R.)	0.22	0.006	Septic tank, sand filter, equalization tank.	Unknown	

**Table 7-5. Summary of UV Installations in U.S. in Operation, Construct, or Design Phase**

Size (Design)	In Operation	In Construction	In Design
<380 m <sup>3</sup> /d (<0.1 mgd)	15	—	7
380-1900 (0.1-0.5)	17	10	10
1900-3800 (0.5-1.0)	7	5	4
3800-19000 (1-5)	11	14	11
19000-38000 (5-10)	—	—	—
3800-190000 (10-50)	1	—	2
>190000 (>50)	—	1	—
	53	30	34

Note: List compiled Spring of 1984.

phosphor for application to the walls of the tube (to convert UV light to visible light) and efficient long-lived electrodes was accomplished in the 1930s. By the 1940s the fluorescent lamp was a commercial reality. Although there was no significant demand for the UV lamp ("germicidal lamps") per se, the successful commercial development of the fluorescent lamp technology resulted in the immediate availability of a relatively inexpensive, efficient, UV source.

### 7.2.2 Mechanism of UV Disinfection

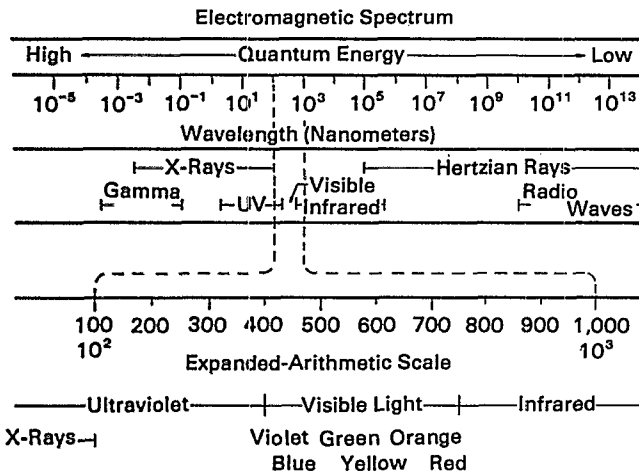
One of the earliest reports relating to the germicidal effects of UV was by Downes and Blount (9). They described the lethal effects of solar radiation on a mixed microbial population and assigned the cause of these effects to shortwave UV radiation.

The early interest in the application of UV for disinfection centered first on potable water. The equipment was not reliable, however, and the lamps were highly inefficient, as discussed earlier. Chlorine was becoming readily available by the early 1900s and was inexpensive. Chlorine also exhibited the very real benefit for potable water applications; this was the ability to maintain a residual. Interest in the application of UV subsequently faded, but not in the effects of UV or its mechanism. Research continued, at first centering on the effects of UV on different organisms and the optimum conditions for germicidal effectiveness. The more recent research, conducted primarily since the early fifties, was directed to the actual mechanisms by which radiant energy affects an organism.

These research efforts have been well documented in the literature and it is not the intent of this discussion to give a detailed accounting. Rather a brief description of the basic mechanisms is provided. The reader should refer elsewhere for greater detail (10-17). The basic premise to understand is that radiation must be absorbed before it can have an effect. Visible light is absorbed by molecules called pigments; color is observed by reflectance or transmittance. Radiation outside the visible spectrum can also be absorbed. Proteins and nucleic acids are basically colorless, but strongly absorb invisible shortwave UV light.

Recall from the earlier discussion of quantum energy that it is constant for a given wavelength, and will change as a function of the wavelength. The longer the wavelength the lower the energy (see Equation 7-2); conversely, the shorter the wavelength, the higher the energy. The effect of a quantum when it interacts with matter is a function of its energy content. Referring to the electromagnetic spectrum on Figure 7-9, infrared radiation at wavelengths greater than 1200 nm has relatively little energy and is unable to effect any chemical change. The energy is immediately converted to heat (hence the infrared heat lamps). At wavelengths from 1200 nm (near infrared) to about 200 nm (far UV) the energy content is sufficient to produce photochemical changes. Radiations with wavelengths less than 200 nm (extreme UV, X-rays, gamma rays, and cosmic rays) have energy contents so high that molecules in their path become ionized.

Figure 7-9. Electromagnetic spectrum.



Living organisms can use parts of solar radiation advantageously. The obvious examples are photosynthesis, phototaxis, and vision. The lethal effects are related primarily to the photochemical changes induced by molecular absorption of radiation. Cellular proteins and nucleic acids are strongly absorptive of far UV radiation; the photochemical changes caused by this absorption are very injurious to living cells, hence the bactericidal properties of UV. The most effective spectral region lies around 260 nm, which is the region of maximal absorption by nucleic acids. Cell death following UV radiation is almost entirely attributable to the photochemical damage of these compounds.

### 7.2.2.1 Photochemical Damage of the DNA Molecule

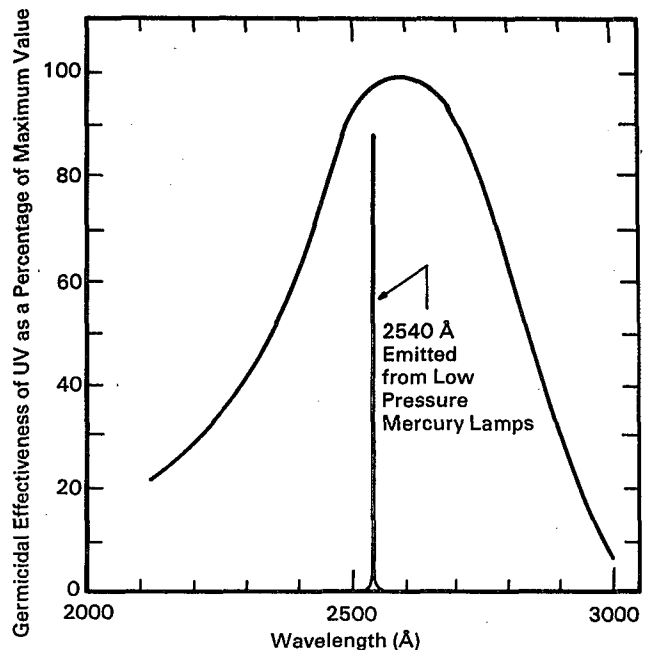
Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are chain-like macromolecules that function in the storage and transfer of a cell's genetic information. These compounds generally comprise 5 to 15 percent of a cell's dry weight, and effectively define the operations of a cell, particularly the type and quantity of enzyme production. The DNA molecule is considered to be the principal target of UV photons, and the primary component where significant biological effect, or damage, is incurred.

The monomeric units of the DNA (and RNA) are nucleotides. These all have three characteristic components: each has a nitrogenous heterocyclic base which can be either a purine or pyrimidine derivative; each contains a pentose sugar; and each has a molecule of phosphoric acid. There are four different deoxyribonucleotides which comprise the major components of DNA, differing only in their base components. Two are the purine derivatives adenine and guanine; the other two are pyrimidine derivatives

cytosine and thymine. Similarly, four different ribonucleotides comprise the major components of RNA. As with the DNA, they contain the purine bases guanine and adenine; the pyrimidine bases are cytosine and uracil. Thus, thymine is characteristically present only in DNA, while uracil is normally present only in RNA.

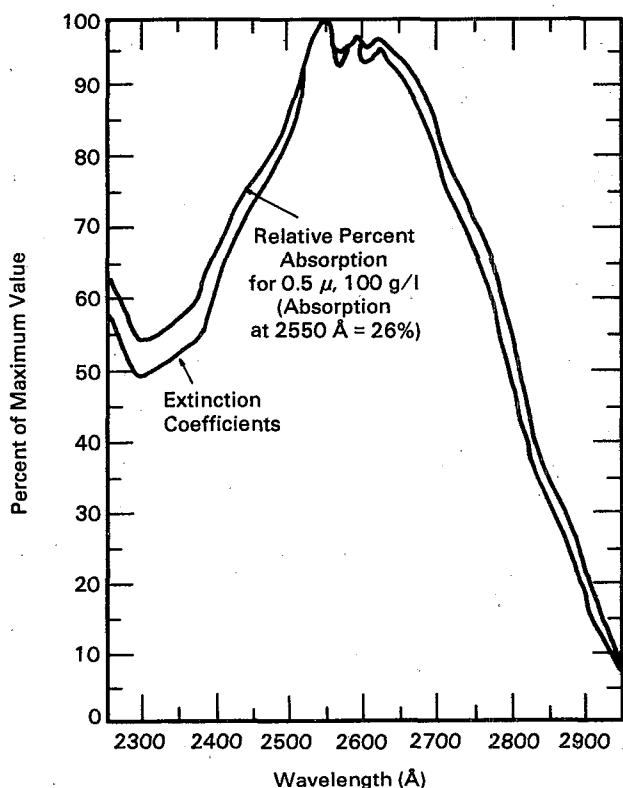
As has been mentioned earlier, the most effective spectral region for germicidal activity lies about the 260 nm wavelength. This is demonstrated on Figure 7-10 which presents relative germicidal effectiveness as a function of wavelength (17). The action spectrum of nucleic acids is very similar to this, as shown by Figure 7-11. On a relative scale, the extinction coefficients (a measure of the inhibiting effect on bacterial colony formation) are plotted as a function of wavelength. Maximal effect is shown to occur between the wavelengths of 250 nm and 265 nm. Overlaying this is the relative percent absorption for a solution of RNA. The similarities are striking, supporting the premise that the lethal effects of UV radiation are induced by the photochemical damage to the cell's nucleic acids.

Figure 7-10. Relative germicidal effectiveness as a function of wavelength (17).



The photochemical changes induced by UV radiation on the DNA of an organism have been thoroughly studied. Although several mechanisms exist, the most dominant is the dimerization of two pyrimidine molecules. To visualize this effect, consider the

Figure 7-11. Relative abiotic effect of UV on *E. coli* compared to relative absorption of Ribose nucleic acid (16).

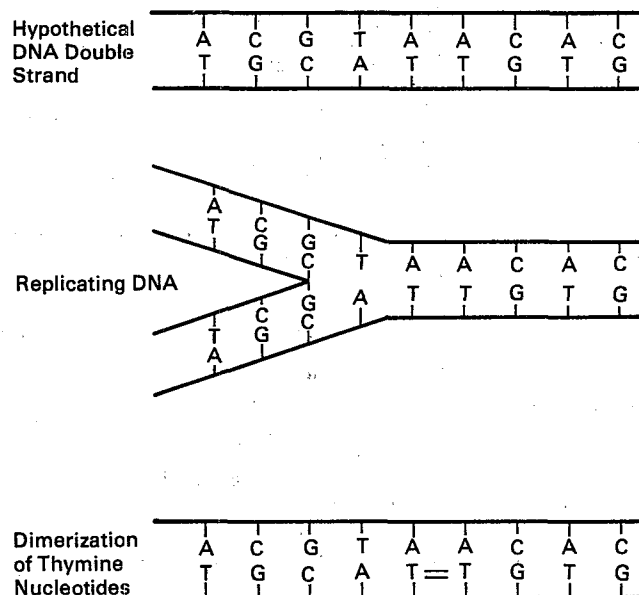


schematic representation of the DNA molecule on Figure 7-12. Recall that the DNA is a long polymer comprised of a double helix chain of simple monomeric units called nucleotides. The order of these nucleotides constitutes the genetic information of the cell. These are represented on the Figure by the letters A (adenine), G (guanine), C (cytosine) and T (thymine).

In the two strands, G is always opposite C and T is opposite A; if damage occurs in one strand the information still remains in the second strand. Thus, to repair the damage, a C is inserted opposite a G and a T opposite an A, and so on. As long as the information is retained on one strand, the second strand damage can be rebuilt. These are enzymatic processes. Before cell division occurs, a duplicate of the DNA is prepared by building a complementary strand to each of the parental strands.

The UV induced dimer between two adjacent pyrimidines in a polynucleotide strand has been demonstrated for all combinations of the pyrimidines (thymine, cytosine, and uracil). The thymine dimer is formed with the greatest efficiency, however. This is shown on Figure 7-12. There are two adjacent

Figure 7-12. Example of DNA and UV damage to DNA (18).



thymine monomers on one of the strands; during exposure to UV light new bonds are formed between the two such that a double thymine molecule, or dimer, is formed. Formation of many dimers along a DNA strand makes replication very difficult.

No comparable interactions of the purines have been demonstrated. The effect of the pyrimidine dimerization is a blocking of normal replication. Total and permanent inhibition of DNA replication would in itself be a lethal event.

Alternatively, replication may bypass such a distortion, producing an error in the copy and a subsequent mutant daughter cell which is unable to replicate.

#### 7.2.2.2 Recovery from Photochemical Damage

Just as a cell can be lethally affected by photochemical damage, there is a widespread prevalence in the world of living organisms to repair and reverse the lethal effects of UV. The mechanism is typically a photoenzymatic repair, requiring longer wavelength light in the near UV and visible spectrum. This phenomenon, unique to UV, has been broadly termed photoreactivation. Jagger and Stafford (19) suggested an explicit definition: "the reduction in response to far-ultraviolet irradiation of a biological system resulting from concomitant or post-treatment with non-ionizing radiation."

Although not explicitly characterized as such, photoreactivation effects were noted during the first half of this century. These observations related to the counteracting effects of visible and UV light. The discovery of the phenomenon is generally attributed

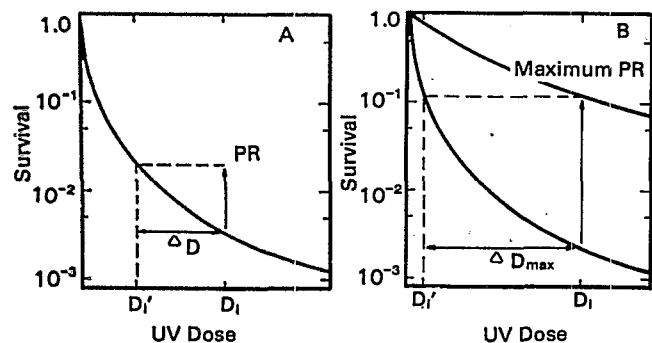
to K€lner (20) and Dulbecco (21), working independently in the late forties. The reader is referred to Harm et. al. (22) and Harm (23) for detailed discussions and reviews of research of this phenomenon.

The repair mechanism is not universal and there is no clearly defined delineation of characteristics which suggest which species would have the ability to repair and which would not. Organisms which have been shown not to have the repair mechanism include *Haemophilus influenzae*, *Diplococcus pneumoniae*, *Bacillus subtilis*, and *Micrococcus radiodurans*. Viruses generally do not have the repair ability except when in a host cell which can repair. Organisms shown to photorepair include *Streptomyces*, *Escherichia coli*, *Saccharomyces*, *Aerobacter*, *Micrococcus*, *Erwinia*, *Proteus*, *Penicillium*, and *Nuerospora*.

The catalyzing, non-ionizing radiation wavelength is not the same for all. It generally falls between 310 nm and 490 nm. In some cases photorepair has been induced by radiations between 230 nm and 240 nm (although these wavelengths are absorbed in the atmospheric ozone layer and would not naturally occur at the earth's surface). It is important to note that photoreactivating light is present in sunlight and, as such, is universally available. The effects are quick, occurring within minutes after exposure to the necessary reactivating light.

Observation of the effect has been accomplished by comparing, after UV radiation, the "dark survival" of cells with "photoreactivated survival." Quantitatively, this is described as the dose decrement. Referring to Figure 7-13, consider a dark survival curve as a function of UV dose. After a UV dose  $D_i$ , the culture is exposed to photoreactivating light and the survival increased to the level marked by PR; the resulting survival can be considered equivalent to the dark survival accomplished by dose  $D_i'$ . The difference,  $D_i - D_i'$ , called the dose decrement, can be used as a measure for the extent of photoreactivation. Since

Figure 7-13. Schematic representation of the effects of photoreactivation (23).



the number of lethal photoproducts (thymine dimers) is directly proportional to the UV dose, the dose decrement can be considered a measure of the number of repair events.

In the case of maximal photoreactivation, the dark and PR survival curves differ by a constant displacement factor. The two curves would coincide if the dose scale for one of the curves was changed by an appropriate factor. This was described as the "principle of constant dose reduction" and the displacement factor was called the dose reduction factor (24):

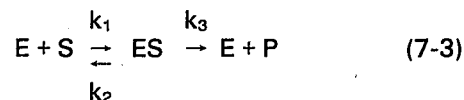
$$D_i'/D_i$$

this suggests the repair of a constant fraction of lesions. This fraction,

$$1 - (D_i'/D_i)$$

is called the photoreactivable sector, or  $PRS_{max}$ .

There are several mechanisms by which these repairs can be made. Rupert (67) established that the most dominant repair mechanism was by a photoreactivating enzyme (PRE). It is similar to other cellular enzymes, except that it requires light energy to initiate its activity. The reaction scheme suggested for this enzymatic repair can be expressed as:



This is a conventional Michaelis-Menton expression for enzymatic reactions, except that the rate  $k_3$  is absolutely dependent on light energy. E is the photoreactivating enzyme, S is the substrate (the photorepairable lesion), ES is the enzyme-substrate complex, and P is the repaired UV lesion. The enzyme binds the pyrimidine dimers, and upon exposure to the appropriate light energy monomerizes the dimers. The complex formation and dissociation can occur in the dark; the value of  $k_3$ , however, is zero in the dark.

A second mechanism has been demonstrated to occur without the light requirement, called dark repair. It is a multi-enzymatic mechanism (termed excision repair) in which the dimer is recognized by an enzyme; this enzyme nicks the dimer from the DNA strand on one side. An exonuclease then releases the dimer completely from the DNA strand and a replicating DNA enzyme then repairs the gap.

Environmental conditions which tend to inhibit active cell metabolism and cell division for a time after exposure will tend to decrease the effects of UV radiation. These inhibitory effects allow time for the cell to repair its DNA before it is erroneously (and lethally) replicated. Such conditions include low

temperature or low nutrient levels. Conversely, the repair mechanism will be attenuated by conditions which encourage high growth rates. A population in its lag or stationary growth stage will have a greater chance of recovery because, by definition, it is not replicating its DNA as quickly as an exponentially growing population. The recovery of irradiated phage is also dependent on the physiological condition of its host cell.

Photoreactivation is a phenomenon which can impact the performance and design of a UV system in certain situations. The conditions which exist in a treated effluent are conducive to the occurrence of photoreactivation; the nutrient levels are low and the population of organisms would likely be in the stationary growth stage at the point of the disinfection process. There are several variables involved in predicting the recovery effect in systems such as a wastewater treatment plant. Certainly sunlight, the source of the photoreactivating light, will differ in intensity and spectral distribution according to the season, time of day, and cloud cover. Effluent characteristics will affect the penetration of the photoreactivating wavelengths; this will in fact extend to the receiving water conditions. Shallow, clear receiving streams will be more conducive to repair than discharge to deeper, slow-moving, and turbid receiving waters.

Given the environmental factors which influence the degree and effect of photoreactivation, it is likely far more practicable to control (i.e., account for) the mechanism by increasing the applied UV dose. Manipulating the growth stage of the microorganisms would not be a practical operation in typical wastewater treatment operations. By designing for an increased UV dose, however, the effect of photoreactivation can be concurrently reduced (it cannot be eliminated). This was demonstrated by the discussion of Figure 7-13.

### **7.2.3 Recent Application of UV to Wastewater Disinfection**

The following discussions present a summary of the major studies which have been conducted to date with regard to the application of UV for wastewater disinfection. Several of these studies will be referenced again in subsequent sections. The intent at this point is to present an overview of the evolution of the technology and to identify those efforts which were and are important to the current state-of-the-art. The review is limited primarily to direct applications to wastewater disinfection and, as will be noted, to work reported after 1970. Before this, three studies are presented which, although not directed to wastewater treatment, were important in their evaluation of the applicability of UV on a large scale, its effectiveness, and the factors which would influence its design.

Kelly (25) reported on a study which evaluated the ability of UV to disinfect seawater used for the depuration of oysters. Tests had shown that the activity of the oysters was adversely affected when the water was treated by chlorination/dechlorination. Two different designs were set up to apply the UV; one was at Pensacola, Florida and the other was in Purdy, Washington. Both were tray designs in which the lamps were suspended over a shallow tray which received continuously flowing water. The Pensacola unit was the deeper of the two—6.4 cm (2.5 in); the slow moving system tended to accumulate particulates. The lamps and reflectors were cleaned on a daily basis and the troughs were flushed regularly.

The unit at Purdy was found to be a far more efficient system operationally, most likely because of the higher velocities, the thinner film thickness of the water, the greater agitation, and the improved flow distribution. The liquid level was kept at 1.9 cm (0.75 in) by the placement of a downstream weir. A perforated pipe provided for equal lateral distribution at the inlet to the unit. Six internal baffles were then installed to provide a rolling motion to the liquid as it traveled down the length of the unit. Forced draft ventilation of the unit was also provided in an attempt to optimize the operating temperature of the lamps.

The studies demonstrated the effectiveness of the systems in reducing the coliform levels by greater than three logs from an initial density between 1,000 and 10,000 MPN/100 ml and at turbidities up to 20 JTU. Kelly stated that a dose of 57,600  $\mu\text{Watt-sec}/\text{cm}^2$  was required to accomplish this. The intensity at the surface of the liquid was computed by the author by simply distributing the rated output of the lamps (unreflected) across the surface of the water. The pilot scale studies suggested that, with proper maintenance, the unit could operate with a high degree of dependability. The maintenance requirements were of a housekeeping nature; flushing the units on a periodic basis and cleaning the lamps and reflectors of accumulated debris.

Huff et al. (26) demonstrated that ultraviolet disinfection would be effective in treating ship-board potable water supplies. Doses varied between 4,000 and 11,000  $\mu\text{Watt-sec}/\text{cm}^2$ ; the intensity was measured by an intensity meter on the side of the UV unit. Effective kill of *E. coli*, *A. aerogenes*, and *S. faecalis* was accomplished. The study also studied the attenuating effects of turbidity, color, and iron on UV intensity and consequent effects on the performance of the UV unit. The apparatus was shown to effectively inactivate certain enteric viruses when operated at the recommended intensity and flow rates.

Hill et al. (27) followed up, in a sense, on the work of Kelly and others in investigating the application of UV for the disinfection of seawater. Their efforts were

directed to the virucidal efficiency of the process, which had become the treatment of choice for disinfecting seawater that is to be used for shellfish depuration systems. The Kelly-Purdy UV Seawater Treatment Unit was used for the study. Static tests first demonstrated the effectiveness and rate of inactivation for eight enteric viruses. The exposure required to obtain effective disinfection (99.9 percent reduction) at an applied intensity of  $1160 \mu\text{Watt}/\text{cm}^2$  was as follows:

Poliovirus 1	28 seconds
Poliovirus 2	31
Poliovirus 3	27
Echovirus 1	28
Echovirus 11	31
Coxsackievirus A-9	31
Coxsackievirus B-1	40
Reovirus 1	40

These static bioassays were conducted in shallow, unstirred petri dishes. The devitalization rate determined from dynamic tests with Poliovirus 1 were found to be significantly different than for the same virus under the conditions of the static test. The rate was, in fact, significantly increased in the flowing seawater system. This difference was attributed primarily to UV dose and the mixing effects provided by the unit. In all, the study concluded that the continuously flowing UV units would be highly effective for the inactivation of viruses in contaminated seawaters.

At approximately the same time, a federally sponsored study was investigating the application of UV to wastewaters which were being discharged to shell-fishing waters in St. Michaels, Maryland. Roeber and Hoot (28) used a system similar in design to the Kelly-Purdy shallow tray unit to disinfect the effluent from an activated sludge plant.

First order reductions were observed in total coliforms and bacteriophage densities, with a tailing effect after 99.99 percent kill of the total coliform. The average dose required to reduce coliform densities to 70 MPN/100 ml or less was estimated by the investigators to be  $25,000 \mu\text{Watt-sec}/\text{cm}^2$ . The intensity was calculated on the basis of measured estimates of the absorbance coefficient of the wastewater at 253.7 nm and direct measures of the intensity in the liquid. The average intensity was then estimated by integration of the Beer-Lambert equation over the fluid depth:

$$\text{Average Intensity} = I_0 [(1 - e^{-kd})/kd] \quad (7-4)$$

where:

- $I_0$  = initial intensity ( $\mu\text{W}/\text{cm}^2$ )
- $d$  = depth of the fluid (cm)
- $k$  = the absorption coefficient ( $\text{cm}^{-1}$ )

This average intensity would be multiplied by the average detention of the system in order to estimate the applied UV dose. The ultraviolet transmittance of the liquid averaged approximately 65 percent; its value was related more to the organic makeup of the water (as COD) than the turbidity. The study indicated a dependence on the initial coliform density and suggested that higher turbidity levels would affect the unit's performance.

Roeber and Hoot also presented the results of a series of photoreactivation tests. Coliforms and bacteriophage were shown to exhibit significant repair upon exposure to sunlight for one hour. In all, the report concluded that ultraviolet disinfection would be practicable for application to well-controlled activated sludge plant effluents. They suggested that at optimum conditions, an energy consumption of  $0.092 \text{ kWh}/\text{m}^3$  would be required to accomplish a coliform level less than 70 MPN/ 100 ml.

Singer and Nash (29) reported on a study which evaluated UV disinfection of a secondary step aeration plant effluent. The UV system was one normally used in potable water applications and consisted of a closed vessel containing nine germicidal lamps. The lamps were sheathed in quartz sleeves and were continually submerged. Flow would enter the rectangular reactor at one end perpendicular to the lamps, turn and flow down the length of the reactor and exit through a pipe located on the same side as the inlet pipe. This was one of the first reported applications of the submerged quartz configuration to wastewater disinfection. A water quality meter was attached which measured the intensity at a single point in the reactor. This was found to inversely correlate with the turbidity, suspended solids, and BOD of the wastewater.

Singer and Nash reported a tailing of the first order reduction with increasing dose, such that a base level of coliforms would be present in the waste. This was attributed to a degree of short-circuiting and the suspended solids in the wastewater. Effluent levels less than 200 MPN/100 ml could be consistently achieved as long as suspended solids levels were kept below approximately 22 mg/l. The report concluded that UV would adequately and cost-effectively disinfect a step aeration effluent and recommended further work to investigate closer spaced lamps to counteract the poor quality of the effluent and suggested that greater attention be paid to the hydraulic characteristics of the reactor. The quartz surfaces were found to require a periodic chemical cleaning, although the appropriate frequency was not determined.

Oliver and Carey (30,31) investigated methods to apply UV to conventional wastewater treatment systems. In a sense, the scheme was a modification of the Kelly-Purdy design; lamp units (double lamp units with reflector and ballast) would be suspended above secondary clarifiers, close to the clarifier overflow weirs. The effluent would be exposed to about the same dosage as it rises to the surface and passes over the weir in a thin film. Earlier laboratory studies indicated that relatively low dose levels were required to achieve a 2-log reduction ( $\text{Log survival} = -2$ ) in total and fecal coliforms and fecal streptococcus (32). They also determined that the bacterial inactivation was independent of light intensity; thus, a relatively low intensity arrangement could be implemented as long as sufficient exposure time were provided to achieve the desired dose. A significant result of these tests was the demonstration of the bacterial occlusion by particulates in the water. When sonication was applied as a pretreatment before UV exposure, greater inactivation efficiencies were accomplished. The ultrasonics appeared to disperse the particulate aggregates, making the bacteria contained in the particles more susceptible to the UV radiation.

Pilot studies of the overflow weir arrangement were conducted and provided excellent results. The investigators also noted that the lamps did not foul and maintained a constant output over a six-week period. The absorbance of the effluent ranged between 0.12 and 0.25 a.u./cm with little direct effect on the system efficiency. A dose of 130 Watt-sec/imperial gallon was reported to achieve a reduction of 2 logs. This is relatively inefficient, reflecting the ineffective use of the lamps' output by having them suspended above the surface of the wastewater. Greater energy efficiency would obviously be obtained by submersing the source in the liquid. Nevertheless, the report concluded that UV would be highly effective and would be competitive with the use of chlorine.

A limited study conducted in Syracuse, New York, evaluated the use of UV for the disinfection of waters from combined sewer overflows (CSO) (33). One liter samples were irradiated in a bell-jar vessel in which the walls were equidistant—5.7 cm (2.25 in)—from the UV lamp. The intensity at the lamp surface was computed to be  $5,800 \mu\text{Watts}/\text{cm}^2$ . The study suggested that a dose of  $500,000 \mu\text{Watt-sec}/\text{cm}^2$  would be required to achieve a residual coliform level of 2500 MPN/100 ml and concluded that UV disinfection of CSO waters was feasible and particularly attractive because of the absence of a residual. The scheme studied by Oliver and Carey (30), which was suggested for the CSO application (the UV lamps would be suspended over high rate swirl separators) would be impractical, however, because of the high dose requirements.

Petrasek, et al. (34), reported on a study conducted in Dallas, Texas, which investigated the feasibility of ultraviolet disinfection of treated municipal wastewater effluents to achieve fecal coliform levels less than 200 MPN/100 ml. Two system configurations were evaluated: the first system was the Kelly-Purdy shallow tray design; and the second system was a closed vessel design with the lamps (enclosed in quartz sleeves) submerged in a 53.6-liter (14.1-gal) chamber. The flow was parallel to the lamps.

The investigators concluded that the more appropriate system configuration for wastewater disinfection was the submerged quartz system. The Kelly-Purdy design, although effective in disinfection, was less efficient in the utilization of UV energy, would require greater space, and was susceptible to solids deposition in the unit. Hydraulic studies indicated that the unit operated poorly at low flows and at deeper liquid depths. Actual retention times approached theoretical when the unit was operated at shallow depths—2.5 cm (1 in)—and higher velocities. Relatively high dispersion was still observed under these conditions.

The hydraulic analyses of the submerged system also indicated relatively poor flow characteristics when compared to the ideal condition of plug flow. The time distribution curves constructed for a number of flows indicated a high degree of dispersion. The investigators also demonstrated the importance of the absorbance coefficient of the wastewater. This was spectrophotometrically measured at 253.7 nm and effectively quantified the UV "demand" of the liquid. The parameter was not found to be affected significantly by the suspended solids or turbidity of the water.

The authors recognized the lack of any direct measurement capability for estimating the UV intensity within a complex multi-lamp system, such as the submerged quartz unit. An approach suggested by the report was to mathematically calculate the intensity at any point in the reactor; they assumed that the radiation emits perpendicularly from the lamp and that the lamp is an infinite line source. The average intensity was then calculated on an areally-normalized basis. The technique accounted for the attenuation of intensity due to the absorptive characteristics of the liquid. No attempt was made to account for the deterioration of the lamp output or the quartz surfaces. The estimated intensity was found to correlate well with the total coliform reduction of the unit at a constant flow to the unit.

The authors found that UV was effective in the inactivation of Type 1 poliovirus and F2 coliphage. The coliphage was suggested as a good indicator for the inactivation of poliovirus. Photoreactivation was



also investigated; static tests indicated that subsequent exposure of UV irradiated coliforms to sunlight for 30 minutes induced a 1.1 log increase in total coliforms, and a 0.6 log increase in fecal coliforms.

Scheible and Bassell (35,36) reported the results of a full-scale prototype demonstration study conducted at the Northwest Bergen County Water Pollution Control Plant, Waldwick, New Jersey. The unit, similar to that shown on Figure 7-5, was a submerged quartz system comprised of 400 lamps. These were arranged in a symmetrical array, axially parallel to one another, and equidistant on horizontal and vertical centerlines. The flow path was perpendicular to the lamps. The spacing between quartz surfaces was only 1.25 cm (0.5 in), imposing a thin film of liquid as the wastewater passed through the lamp battery. The lamp battery was inserted into two bulkhead walls constructed in an existing chlorine contact chamber. The arrangement simulated an open channel, with the lamp battery inserted into the channel and the inlet and outlet planes of the lamp battery wholly exposed to the wastewater.

The time-distribution characteristics of the unit were not measured directly, although it was established that a relatively uniform velocity field existed across the exit plane of the lamp battery. The time of exposure was assumed to be the theoretical detention time of the unit, which ranged between one and four seconds under normal operating conditions. In order to estimate the dose under a given set of sampling conditions, the authors incorporated the use of the radial light model, as had been described by Petrasek, et al. (34), to calculate the intensity. In this case, however, the authors calculated the incident intensity at the surface of the lamp (dividing the rated UV output by the quartz surface area) and accounted for some deterioration in UV output with time. The lamps were presumed to be transparent to UV from a neighboring lamp, which is not the case, and likely resulted in an overestimate of the applied dose. The intensity calculations were demonstrated for any given symmetrical system and presented as a function of spacing, UV absorbance coefficient, and lamp rating. Dose was estimated by multiplying the intensity (which varied as a function of the UV absorbance coefficient and the output of the lamps) by the theoretical detention time.

Empirical regressions were developed to describe the performance of the system as a function of the applied dose. These reflected more an attempt to linearize the correlation of the coliform reduction with the dose; this was effective in determining the system performance and design requirements for the specific plant application. The UV absorbance coefficient was suggested to be the key wastewater

parameter for the design, control, and monitoring of the UV disinfection process. It correlated well in this case with the wastewater COD.

An extensive series of static and dynamic photo-activation tests were conducted during the study. The static-bottle technique, in which a light and dark bottle are held in sunlight for a period of one hour, was suggested as an effective and practical procedure for evaluating and/or monitoring the effects of photoreactivation. The results of the tests indicated a degree of temperature dependency, although this may have implicitly included the influences of reduced sunlight intensity during the winter months. At 10°C (50°F), a 0.3 log increase in coliform density was observed, while at 20°C (68°F) the increase was approximately 1.0 log. A detailed economic evaluation showed the cost of the process to be approximately \$0.008/m<sup>3</sup> (\$0.012/1,000 gal) for secondary treatment plants (1979\$). When compared to alternative processes, UV was found to be less costly than ozonation, more expensive than chlorination, and competitive with chlorination/dechlorination.

Severin (37) reported on the application of a commercially available UV system to the disinfection of a variety of treated municipal effluents. In determining dose, he estimated the average intensity by the integrated solution of Beer's law over a fluid depth, as presented by Roeber and Hoot (Equation 7-4) and by Petrasek et al. The UV unit was a closed flow-through vessel containing 10 lamps set longitudinally; flow was directed parallel to the lamps. A nominal average depth of liquid was computed for the reactor to use in the computation of the average intensity. Severin assumed a single source in the estimate of intensity and did not account for the additive affects of a multi-lamp system.

Experiments were conducted at a number of wastewater treatment plants which provided different levels of treatment. The quality of the wastewaters was very good in most cases, except where the effluents were artificially adjusted to yield higher absorbance values. Typically, the effluents had an absorbance coefficient between 0.2 and 0.3 cm<sup>-1</sup> (base e). The inactivation results of the overall experimental effort were described by a disinfection model which was linear with time to the one-third power. Time was assumed to be the theoretical detention time of the unit. The least squares regression yielded the expression:

$$\text{Log}_{10} (100 N/N_0) = -1.73 (P_{\text{avg}}/P_0) (t^{1/3}) + 2.598 \quad (7-5)$$

The expression was explicitly described as an empirical relationship applicable only to similar reactors under the same water quality conditions.  $P_{\text{avg}}/P_0$  is

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the ratio of the average intensity to the incident intensity.

Hydraulic tracer analyses of the system indicated that the unit did not behave in a plug flow fashion but exhibited a relatively high degree of dispersion. The author indicated that this deviation from ideal plug flow was not enough to account for the empirical observation that disinfection is a function of time to the one-third power. Overall, the conclusion was that UV was highly effective for wastewater disinfection. Further work was recommended in the areas of intensity estimates and the direct analysis of the impact of hydraulics and the effect of channelized flow in a non-uniform intensity field.

Johnson and Qualls (38) reported the results of a substantial pilot and laboratory scale effort which focused on a number of parameters which were key to the understanding and design of the UV process. In the early phases of the work they investigated the performance of two commercial units on contact stabilization effluent. The first unit was based on the close spaced, or thin film concept and contained fourteen 25 Watt submerged lamps at nominal spacings of 1.25 cm (0.5 in). The second unit utilized six 40-Watt, widely spaced lamps submerged in an 11 liter exposure chamber. Significant differences were noted, with the widely spaced unit providing far better performance. This was attributed to short-circuiting occurring in the first unit. The study also reported significant photoreactivation in UV irradiated samples which had been exposed to sunlight for 45 minutes at 25°C (77°F). Total coliforms were found to increase in density by 1.4 logs. The degree of photoreactivation was found to decrease with decreasing temperature.

A point source summation model was applied by the authors to estimate the intensity in a multi-lamp system. This calculation method treats a finite line source (the tubular germicidal lamp) as a series of point sources radiating in all directions. The attenuation of the radiation was inversely proportional to the square of the distance from the point source and was absorbed by the liquid medium according to the Beer-Lambert law. The intensity at any given point in a system was assumed to be the sum of the radiation received from all point sources in the system. The authors also demonstrated that direct beam, spectrophotometric measurement of the absorbance of the liquid overestimated the UV absorbance because scattered light would be measured as absorbed light, when in fact it is still available. The true absorbance of the liquid should be estimated by correcting for this scattering effect. The authors also demonstrated a spherical integration method for measuring the actual output of a lamp at any given time.

Qualls et al. (39), reported on the effect of suspended

solids on the performance capability of the disinfection process. Aside from the effect on the UV absorbance characteristics of the liquid, the major impact of the suspended solids normally found in a biologically treated domestic wastewater is the harboring or occlusion of the bacteria within the particle. These are protected from the UV radiation and will be measured as viable organisms subsequent to UV disinfection. The authors suggest that these protected coliforms are the major factor in limiting disinfection efficiency at -3 to -4 log survival units. Improved disinfection would be accomplished (if necessary) by prefiltration or improvements in solids-liquid separation steps at a typical plant.

A bioassay approach to estimate the actual dose in a system was proposed by Qualls and Johnson (40). A dose-response relationship would first be developed for a known, pure culture (spores of *Bacillus subtilis* were suggested as an appropriate test organism). This involved exposing the organism to a known, and measurable, intensity of collimated light (at 253.7 nm) over several exposure times. Dose would be the product of this measured intensity and the time of exposure. The calibrated spore would then be injected into a system. The response (log survival ratio) would then be compared to the calibration curve to determine the effective dose delivered by the UV unit. This technique was further applied to a dynamically flowing system concurrent with a conservative tracer to determine the time distribution characteristics of the unit. The spore survival ratio is measured, in this case, at several times after injection. By accounting for the hydraulic distribution in this fashion, the authors demonstrated that it was possible to implicitly solve for the average intensity within the unit. The estimates of intensity by the point source summation calculation method were found to compare favorably to the intensity estimates made by the bioassay technique. The authors proposed the use of this technique to evaluate, and/or compare UV systems, and as a method to separately evaluate the intensity and residence time distribution.

Bellen et al. (41), applied the bioassay technique to seven commercial UV units to determine the dose application performance of each unit and to compare their effectiveness. The application was to be shipboard potable water supplies. They coupled this with a separate analysis of the residence time distribution for each unit. The bioassay method was suggested as the only available technique to directly compare the performance of commercial units.

Haas and Sakellaropoulos (42) presented a series of rational analysis solutions for UV disinfection which incorporated first-order inactivation kinetics with the hydraulic characteristics of the UV reactor. These

were allowed to range from a completely mixed reactor to a perfect plug flow reactor. Their analysis supported the premise that the hydraulic characteristics of a reactor can strongly influence disinfection efficiency. The optimum hydraulic regime for disinfection involves turbulent flow with minimal axial mixing. Plug flow would be supported in systems with high aspect ratios (ratio of length to hydraulic radius). In similar fashion, Severin et al. (43) concluded that mixing in the radial direction (perpendicular to the direction of flow) was beneficial to disinfection efficiency. Mixing in the longitudinal direction (direction of flow) was not advantageous, although they suggested that some degree of axial (longitudinal) mixing may have to be accepted in order to ensure adequate radial mixing. Severin et al. (44), suggested the use of a series event inactivation kinetics model to describe the inactivation of coliforms in reactors of differing mixing characteristics. The model effectively predicted efficiency, and suggested the importance of discouraging stratified flow conditions (lack of radial turbulence) in a non-uniform intensity field.

Nehm (45) reported on pilot plant studies conducted at the Nine Springs Water Pollution Control Plant, Madison, Wisconsin, which evaluated commercial units from four different manufacturers. The objectives of these studies were to assess operational requirements; no attempts were made to measure dose or to scale-up to design. The results showed that consistent performance could be accomplished by all systems when they were kept clean. Scale formation occurred on both quartz and Teflon surfaces. This was found to be readily removed by the addition of a citric acid solution to the reactor. The report recommended the capability of chemically cleaning on any scale-up, in addition to a UV intensity sensor to monitor the status of the quartz surfaces. As a post-script to these studies, UV disinfection was recommended for the 2,200 L/s (50 mgd) plant, and the system is currently under construction. This was also one of the first major plants to require bioassays of equipment which could be scaled up so as to compare the performance capability of commercial units. This was imposed as a pre-bid qualification specification.

Ho and Bohm (46) and Bohm et al. (47) reported on the pilot scale application of UV to the disinfection of a number of tertiary and secondary effluents at Ontario (Canada) Water Pollution Control plants. The process was demonstrated to consistently meet effluent disinfection goals. Total coliform and fecal coliform densities were targeted at 2000 and 200 MPN/100 ml in the effluent, respectively. Corresponding reductions were demonstrated for *Pseudomonas aeruginosa*, fecal streptococci, and *E. coli*. *Salmonella spp.* were reduced to less than 4/100 ml in 80 percent of the samples. The investigators propose that UV transmission is a good surrogate parameter for

correlating effluent water quality to expected UV effectiveness. The authors estimated dose by calculating intensity from the Roeber and Hoot model and the measured mean contact time.

Bohm et al. (47), also assessed the effects of photoreactivation. Total coliforms increased by approximately two logs, fecal coliforms by one to two logs. Little or no photoreactivation was shown for *Pseudomonas aeruginosa* and fecal streptococci. Some increase was observed for the *Salmonella ssp.* Temperature did not affect repair, nor did dilutions with stream water by a factor of 1 to 10.

Whitby et al. (48) reported the results of a full-scale evaluation of a commercial UV disinfection process at the Tillsonburg Water Pollution Control Plant, Tillsonburg, Ontario (Canada). The system design, in this case, allowed the use of the plant's existing secondary effluent channels to retrofit a UV unit (see Figure 7-7). The units were comprised of a series of four-lamp (quartz-sheathed) modules. The modules had the lamps arranged in a vertical row; these were suspended on a support frame which had been inserted into the effluent channel. The number of modules was dependent upon the width of the channels. The wastewater flowed parallel to the lamps. The lamp battery was kept submerged at all times by a downstream control gate.

A direct comparison between UV and chlorination in disinfection efficiency was made in this study. UV was found to outperform the chlorination system; if photoreactivation were allowed to proceed in the UV exposed samples, the performance of the two processes was similar. This applied to the total and fecal coliform analyses. Fecal streptococci do not photoreactivate and substantial reductions were accomplished by the UV systems. A spore forming bacterium, *Clostridium perfringens*, which is known for its resistance to disinfection, was also tested. UV was found to be nearly twice as effective as chlorination in the inactivation of this organism. Similarly, the units accomplished greater than 99.97 percent inactivation of bacteriophages, as compared to the chlorination process, which averaged 95.1 percent.

The studies at Tillsonburg also included fish (rainbow trout yearlings) toxicity studies downstream of the plant's discharge which compared the effects of the chlorinated effluent and the UV irradiated effluent. Complete mortality was observed within 24 hours during the chlorination study; the UV disinfection test was non-lethal for a 48-hour exposure period. The report suggests very consistent operation of the system over an 18 month period. Maintenance was minimal; the lamps had been manually cleaned once and the lamp life had extended for greater than 12,000 hours for the reporting period.

Kirkwold (49) reported on the installation and performance of a UV disinfection system at the Albert Lea Water Pollution Control Plant, Albert Lea, Minnesota. The systems (see Figure 7-6) were reported to be operating well, after some startup problems, and performing very effectively. In fact, due to the high quality of the plant effluent, only a small fraction of the overall system is needed on a continuous basis. The author suggests that the cost of operating the UV system is \$5.3/1000 m<sup>3</sup> (\$0.02/1000 gal); this is less than half the operating costs estimated for a comparable chlorination/dechlorination process.

Scheible et al. (50) reported on the early studies conducted for an EPA project at a New York City treatment plant. They discussed the development of software to compute the average intensity of UV in a system of any lamp configuration. They presented the computed intensity as a function of UV absorbance and showed the effect of lamp spacing and lamp output. A procedure was also presented to measure and analyze the retention time distribution of a UV system. A subsequent article reported further results of the New York City project, particularly with regard to the maintenance of UV systems and the effect of quartz fouling and lamp aging (51). The development of a disinfection model was also suggested which incorporated the hydraulics of a system and the inactivation rate of coliforms as a function of the intensity.

#### 7.2.3.1 Current Evaluations of UV Disinfection

A significant amount of the information used to assemble this chapter on the UV process is from studies which were as yet unreported. Only drafts can be cited at this time, although these may be formally reported at the time this manual is printed and released. The following is a short review of these studies. Further reference will be made to them as appropriate in the subsequent discussions.

A major research and demonstration project was completed recently under joint sponsorship by the USEPA and the New York City Department of Environmental Protection (52). Conducted at the Port Richmond Water Pollution Control Plant, Staten Island, New York, it investigated the performance of three large scale UV systems in the disinfection of secondary effluent and high rate settled raw wastewater. The systems included two 100-lamp quartz systems which differed only in the spacing between quartz surfaces—1.25 cm and 5.0 cm (0.5 in and 2.0 in). The third unit used Teflon tubes to carry the wastewater, with the lamps suspended outside the tubes. The effluent characteristics were highly variable; the suspended solids ranged between 5 and 50 mg/l, with a UV absorbance coefficient (base e) between 0.25 cm<sup>-1</sup> and 0.5 cm<sup>-1</sup>. Primary effluent was also treated to determine the application of UV to

combined sewer overflow wastewaters. These were characterized by high suspended solids levels and UV absorbance coefficients between 0.5 cm<sup>-1</sup> and 1.0 cm<sup>-1</sup>.

The UV process was found to be very effective in the disinfection of secondary effluent. Log survival ratios between -3 and -4 could be achieved under practical loading conditions. Similarly, it was shown that a log survival ratio up to -3 could be accomplished with primary effluent. The studies also indicated that the quartz systems were more energy efficient than the Teflon system. An empirical system loading rate was suggested to monitor and compare systems; this was the ratio of the flow (Q) to the actual output of the UV system (W), in watts at 253.7 nm. This output would account for the age of the lamps and the degree of fouling on the surfaces through which the energy must be transmitted.

A major element of the Port Richmond study was the development of a protocol for the design of a UV disinfection process. The resulting model incorporates the retention time distribution of the system, and the inactivation rate of the bacteria described as a function of the calculated intensity in the reactor. This intensity was calculated by the point source summation technique and can be adjusted for the measured (or assumed for design purposes) average lamp output and the losses of energy due to absorption by the liquid and the fouling of the quartz (and Teflon) surfaces. The model was found to correctly respond to the variables associated with the UV process when applied to the Port Richmond experimental data. The study demonstrated the importance of suspended solids in the application of UV. Coliforms occluded by suspended particles will not be affected by UV and will, in effect, set the limiting density which can be achieved by UV radiation.

Photoreactivation effects were demonstrated in this study for both total and fecal coliforms. The results showed a constant fraction increase over densities measured immediately after UV exposure, regardless of the initial UV dose. The study also provided suggestions with regard to the maintenance and monitoring of the system which can enhance the efficiency and cost-effectiveness of the process. A cost analysis of the process shows it to be competitive with a comparable chlorination system.

As a follow-up to the funding of UV installations under the I/A program, the USEPA contracted for a number of post-construction evaluations (PCEs) to assess the status of these plants. These were summarized by White et al. (53). Six plants were visited: Pella, Iowa; Suffern, New York; Northfield, Minnesota; Togus, Maine; Eden, Wisconsin; and Lodi, Wisconsin. Overall, the report was favorable to the

application of the UV process. It cited the problems relating to equipment fabrication (ballasts, wiring), and O&M requirements which were more than originally anticipated. These will be discussed further in later sections. An earlier survey of a number of UV facilities in 1983 was limited due to the lack of operating experience at the plants.

A series of special studies were conducted at four operating UV plants to assess plant operations, plant performance, and to determine the applicability of the process evaluation techniques developed by the Port Richmond project (4,54). A one-month study was conducted at the Suffern, New York facility. The units (see Figure 7-4) were evaluated for their hydraulic characteristics, and performance in the disinfection of fecal coliforms and fecal strep. Tracer studies indicated some dispersion and a reduced effective volume. Analysis of data showed that the systems were adequately sized and would be able to meet performance requirements at design loads. The tests conducted at Suffern showed that sodium hydro-sulfite is a very effective chemical cleaning agent. Side by side testing of the system's ultrasonics cleaning device indicated that it was of limited benefit, and because of its energy costs, not cost-effective.

The Teflon system at Eden, Wisconsin was also evaluated. As expected, the Teflon tube arrangement was good hydraulically. Tracer analyses showed relatively low dispersion. Analyses indicated, however, that the system would not be able to meet requirements under design loading conditions. Although not directly tested at Eden, significantly reduced levels of transmissivity by the Teflon was suggested by the analysis as a major cause of the poor performance. Special studies were conducted to evaluate a method to directly measure the Teflon transmittance, utilizing chemical actinometry techniques. These showed that virgin Teflon transmitted 75 to 85 percent of the UV (the range being a function of thickness). Samples of Teflon from the Port Richmond facility, which were heavily fouled, were found to transmit only 5 to 30 percent of the UV. When the surfaces were thoroughly cleaned, the transmittance increased to 65 to 70 percent. Limited field studies were also conducted at the Vinton, Iowa facility (see Figure 7-3). The hydraulic tracer analyses indicated a large degree of dispersion and a significant reduction in effective volume.

A series of studies were recently completed which used the same pilot plant to test wastewaters at several wastewater treatment plants (55). The tests were directed to investigating the inactivation rate as a function of the intensity, and the level of bacterial occlusion by the suspended solids.

## 7.3 Process Design of the UV Wastewater Disinfection System

This section presents the design protocol for the UV process. The mathematical expressions which are presented are based on the analysis of the system as a chemical reactor, incorporating the retention time distribution of the system, and the inactivation rate as a function of the intensity of UV radiation within the reactor. The discussions in this section will be in the following format; first, the process design model is presented. This expression is the framework about which the process is designed and the system sized. The data requirements for the system design are then presented in general form. As will be shown, the design information falls into three major categories: hydraulics; UV radiation intensity; and wastewater characteristics (including bacterial sensitivity to UV).

Second, the hydraulic design considerations, as they relate to the UV reactor, will be discussed. These will encompass the flow and dispersive characteristic of the reactor, and the considerations of head loss, turbulence, and effective volume.

Third, the intensity of UV in the reactor will be discussed. The procedure for estimating the average intensity will be presented, including solutions for almost all practical UV lamp configurations.

Fourth, the relevant wastewater quality parameters are reviewed. Aside from the normal water quality parameters we will need to know, such as coliform densities, UV absorbance coefficients, etc., the discussions will also present procedures to determine the coefficients which describe the sensitivity of the coliforms to UV, and the densities associated with particulates normally found in treated municipal wastewaters.

Finally, the design protocol is presented in Section 7.4, incorporating the discussions of this section. The protocol will be demonstrated by using the design example which has been carried throughout this manual.

### 7.3.1 Process Model to Describe UV Reactor Performance

#### 7.3.1.1 First Order Kinetics for the UV Process

Recalling the discussions presented in Chapter 4, the inactivation of bacteria by UV radiation can be approximated by the first order expression:

$$N = N_0 e^{-kIt} \quad (7-6)$$

where :

$N$  = bacterial density after exposure to UV (organisms/L<sup>3</sup>)

$N_0$  = the initial bacterial density (organisms/L<sup>3</sup>)  
 $k$  = inactivation rate constant (L<sup>2</sup> Watts<sup>-1</sup>T<sup>-1</sup>)  
 $I$  = the intensity of the germicidal UV energy (Watts/L<sup>2</sup>)  
 $t$  = time of exposure (T)

The intensity is the rate at which the energy is being delivered to the liquid; in the context of this report, intensity has the unit microwatts per square centimeter ( $\mu$ Watts/cm<sup>2</sup>). When multiplied by the time to which an entity is exposed to this rate, the quantity of energy, or dose, is determined:

$$\text{Dose } (\mu\text{Watt-sec/cm}^2) = \text{Intensity } (\mu\text{Watt/cm}^2) \times \text{Time (seconds)} \quad (7-7)$$

The rate constant,  $k$ , is the slope of the relationship of  $\ln(N/N_0)$  as a function of the dose. It is generally held that the intensity and time are reciprocal in their effect on dose.

### 7.3.1.2 Incorporation of Particulate Coliform Densities

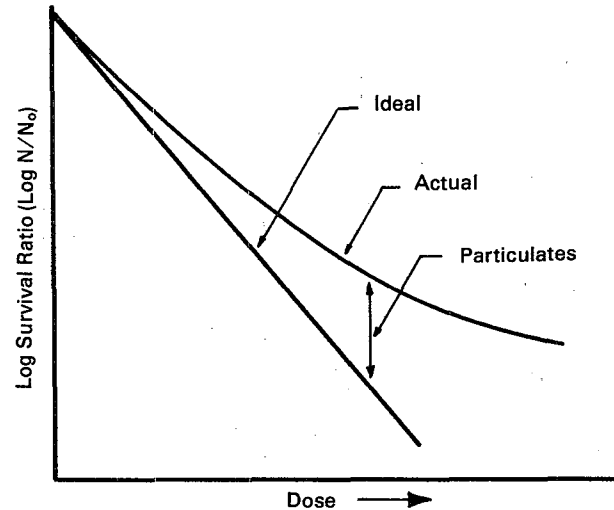
Although the first order expression is generally a good first approximation of the response to a given dose, direct testing on mixed cultures will often show a reduced efficiency with increasing dose. In the disinfection of treated wastewaters by ultraviolet radiation, in particular, this is attributed to the aggregation or the occlusion of bacteria in particulate matter (28,31,33,36). Ultraviolet light is unable to penetrate this material and effect inactivation of the bacteria. Qualls et al. (39) presented data which demonstrated that removal of particles (by filtration) large enough to harbor coliforms exerted dramatic effects on the dose-survival relationships. They concluded that these protected coliforms were the major factor limiting improved disinfection at -3 or -4 log survival units. Thus, as the dispersed or singlet bacterial organisms are inactivated, continued elevation of the dose will show a diminishing response as the residual active bacteria are protected in the particulates. This is schematically presented on Figure 7-14. In light of this, Equation (7-6) can be more accurately written as:

$$N = N'_0 \exp(-klt) + N_p \quad (7-8)$$

where  $N'_0$  is the initial, non-aggregated density, and  $N_p$  is the density associated with the particulates and unaffected by the UV radiation. When considering treated domestic wastewater,  $N'_0 \gg N_p$ , such that the total initial density,  $N_0$ , can be considered equal to  $N'_0 + N_p$ . The expression can then be written:

$$N = N_0 \exp(-klt) + N_p \quad (7-9)$$

Figure 7-14. Effect of particulates on UV disinfection efficiency.



### 7.3.1.3 UV Process Design Model

Considering Equation 7-9, the use of a single exposure time presumes the ideal case of perfect plug flow in the reactor, with no axial dispersion. Under actual conditions, this ideal plug flow does not exist. Axial dispersion and velocity gradients will cause a distribution of residence times; this will be a function of the dispersion characteristics of the reactor, which can be quantified by defining the spread (or variance) of the time distribution relationship for a specific reactor (see Chapter 4).

A disinfection model was developed and reported by Scheible et al. (56). Reference is made to that report for a detailed development of the model. It presumes the first order expression given as Equation 7-9, but also incorporates the dispersive properties of the reactor, in effect describing the residence time distribution of the reactor under steady-state conditions. This model forms the basis for the design protocol presented herein for the UV process. The general expression is written:

$$N = N_0 \exp \left[ \frac{ux}{2E} \left\{ 1 - \left( 1 + \frac{4KE}{u^2} \right)^{1/2} \right\} \right] + N_p \quad (7-10)$$

where:

$N$  = the bacterial density remaining after exposure to UV (organisms/100 ml).

$N_0$  = the initial bacterial density, measured immediately before entry into the UV reactor (organisms/100 ml)

$x$  = the characteristic length of the reactor, defined as the average distance traveled by an element of water while under direct exposure to UV (centimeters)

$u$  = the velocity of the wastewater as it travels through the reactor (cm/sec). This is calculated as:

$$u = x/(V_v/Q)$$

where  $V_v$  is the void, or liquid volume in the reactor (liters) and  $Q$  is the total flow (liters/second). In cases where significant "dead volume" is indicated within a reactor,  $V_v$  is adjusted to more closely approximate the "effective" liquid volume.

$E$  = the dispersion coefficient ( $\text{cm}^2/\text{second}$ ).  $E$  quantifies the spread of the residence time distribution of a particular reactor.

$K$  = the rate of bacterial inactivation ( $\text{seconds}^{-1}$ )

$N_p$  = the bacterial density associated with the particulates and unaffected by exposure to UV.

The rate of inactivation,  $K$ , is expressed as a function of the UV intensity. Thus, for a given time of exposure (or distribution of exposure times), the rate of inactivation will increase (or decrease) with an increase (or decrease) in the intensity. This is shown graphically on Figure 7-15. In this fashion, an expression can be developed in which  $K$  is estimated as a function of intensity:

$$K = f(\text{Intensity}) \quad (7-11)$$

As will be discussed in a later subsection, this correlation will be developed by relating the log  $K$  to the log Intensity, where the intensity is the average reactor intensity,  $I_{\text{avg}}$ . This yields the expression (when transformed),

$$K = a I_{\text{avg}}^b \quad (7-12)$$

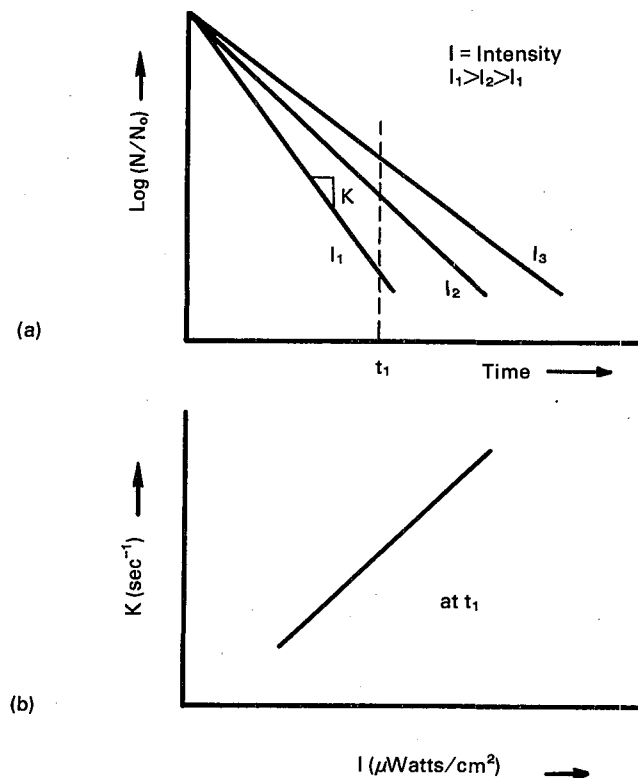
where  $a$  and  $b$  are the slope and intercept of the linear regression.

With regard to the particulate bacterial density,  $N_p$ , this is generally described as a function of some measurable index of particulate density in a wastewater, such as suspended solids or turbidity. Suspended solids is used in the context of this manual since it is the parameter most commonly measured and most relevant to wastewater treatment applications. The value of  $N_p$  is described as a function of the suspended solids by the correlation of the log effluent coliform density to the log SS. When transformed, the expression is in the form:

$$N_p = c SS^m \quad (7-13)$$

where SS is in mg/l. As will be discussed in a later section, the effluent densities for this analysis must

Figure 7-15. The rate  $K$  increases with increasing intensity for a given residence time.



be generated under very high dose conditions. In this fashion, it is appropriate to assume that the remaining bacteria are those which were occluded in the particulate matter and were unaffected by the UV radiation.

By incorporating Equations (7-12) and (7-13), into Equation (7-10), the UV design model can be expressed as follows:

$$N = N_o \exp \left[ \frac{ux}{2E} \left\{ 1 - \left( 1 + \frac{4E a I_{\text{avg}}^b}{u^2} \right)^{1/2} \right\} \right] + cSS^m \quad (7-14)$$

#### 7.3.1.4 Data Requirements to Use the UV Design Model

The information that would be required to effectively use the UV design model relate to the characteristics of the wastewater to be disinfected, and to the physical characteristics of the reactor itself. Consider first the wastewater application; the data which must be generated either by direct testing, or by estimates based on experience include:

**Initial bacterial density,  $N_o$ .** Explicit in the expression, this should be determined under the average and maximum conditions anticipated for the plant.

**Flow,  $Q$ .** The flows to be handled by the disinfection process. This is implicitly required to determine velocities and loadings to the system.

**UV absorbance coefficient,  $\alpha$ .** This will affect the intensity of radiation in the reactor, and is a direct measure of the energy "demand" of the wastewater.

**Suspended solids (SS).** This will be defined by the permit limitations the plant is designed to meet. As discussed later, the particulate bacterial density will be related to the suspended solids concentration.

**Particulate bacterial density,  $N_p$ .** This density associated with the particulate forms the minimum density level which can be achieved by the UV process. It is typically determined as a function of the suspended solids concentration.

**Coefficients,  $c$  and  $m$ .** These are determined from Equation (7-13) and describe the particulate coliform density associated with the suspended solids.

**Rate of inactivation,  $K$ .** This rate is a measure of the sensitivity of the bacteria to UV radiation, and will be site specific. As discussed, the value of  $K$  is estimated as a function of the intensity of UV radiation which a particular reactor can deliver. An estimation of this rate will, therefore, require knowledge of the actual intensity levels within the UV reactor.

**Coefficients,  $a$  and  $b$ .** From Equation (7-12), these describe the rate of inactivation as a function of the average intensity.

The remaining parameters which are to be addressed relate to the physical design of the reactor:

**Velocity.** The velocity of the liquid, as described above, is set by the rate of flow,  $Q$ , and by the physical dimensions of the reactor. Specifically, these are the characteristic length,  $x$ , and the liquid volume,  $V_v$ , of the reactor.

**Length.** The characteristic length of the reactor is the distance traveled by the liquid while under direct exposure to UV light.

**Dispersion coefficient,  $E$ .** This parameter accounts for the deviation of the reactor's hydraulic behavior from that of perfect plug flow; in effect, the distribution of residence times at steady-state is forced by the dispersion coefficient.

**Average intensity,  $I_{avg}$ .** The average intensity in a reactor is a function of the lamp (i.e., UV energy) density in the reactor and the UV absorbance characteristics of the liquid.

In the situation when one is evaluating an existing system, the physical dimensions are fixed. The task is to properly calibrate the model, which can then be used

to assess the system's capacity and to optimize its operations. When a new system is to be designed, the approach is to establish the wastewater parameters, ideally by direct bench or pilot scale testing, and then to determine the optimum hardware configuration and sizing.

### **7.3.2 Characterization of the Hydraulic Behavior of a UV Reactor**

Recall the objectives of an effective hydraulic design, as it would apply to the design of the UV disinfection reactor. (The reader should refer to the discussions in Chapter 4 regarding hydraulic considerations in disinfection reactor design.) First, the unit should be a plug flow reactor (PFR) in which each element of fluid passing through the reactor resides in the reactor for the same period of time. Second, the flow motion should be turbulent radially from the direction of flow. This is to allow for each element to receive the same overall average intensity of radiation in the non-uniform intensity field which exists in the reactor. The tradeoff in this requirement is that some axial dispersion will be introduced, yielding a dispersive or non-ideal flow reactor.

Third, maximum use must be made of the entire volume of the reactor; conversely, dead spaces must be minimized, such that the effective volume is very close to the actual volume available.

When evaluating an existing reactor, the hydraulic evaluation should entail direct testing of the unit to establish the residence time distribution (RTD). Subsequent analysis, as described in Chapter 4, can serve as an excellent diagnostic tool in examining non-performance or to determine system capacity.

New systems design requires the engineer to specify equipment configurations which will be hydraulically efficient. The indices and dispersion characteristics discussed in Chapter 4 can serve as design specifications. Evaluation of commercial reactors can rely on the development and evaluation of the necessary hydraulic information from scaleable pilot units or full scale modules.

The following discussions present the major elements of effective hydraulic design for UV systems:

- residence time distribution (RTD)
- dispersion
- turbulence
- effective volume

#### **7.3.2.1 Residence Time Distribution**

The evaluation of a specific reactor relies on the construction of the RTD appropriate for that reactor configuration. This can be accomplished by a number of experimental procedures; subsequent analysis of the residence time distribution curves determines the



hydraulic characteristics of the unit. Experimental procedures and analysis techniques were presented in Chapter 4. Particular attention should be paid to the discussions regarding reactors with short residence times.

Consider the analysis of a specific RTD to demonstrate the appropriate calculations and interpretation. The example is taken from the Port Richmond project described by Scheible et al. (55). Unit 2 in this study was a submerged quartz system configured in a fashion similar to that shown on Figure 7-6. It contained 100 lamps, parallel to one another, each held in quartz sleeves with an outer diameter of 2.3 cm. The method by which the RTD was developed was described in Chapter 4 and presented schematically on Figure 4-4(b). The relevant unit characteristics are:

$x$  = distance between tracer input and output, which is approximately equivalent to the lamp battery dimension in the direction of flow.  
= 47 cm

$V_v$  = liquid volume of reactor  
= 100 liters

$T$  = theoretical mean residence time,  $V_v/Q$   
= 7.0 seconds

At a flow of 890 Lpm, the velocity is computed to be 7 cm/sec. Figure 7-16 presents the tracer curve and resultant RTD developed for one run. The upper panel is the F-curve developed by the so-called step input tracer analysis described in Chapter 4 (see Figure 4-3(c)). A salt tracer is continuously injected upstream of the lamp battery until a steady-state concentration is read by the conductivity probe positioned immediately downstream of the battery (all at  $t < 0$ ).

At  $t = 0$ , the salt injection is discontinued. The trace on the upper panel is a record of the die-away at the downstream probe until a new steady-state condition is reached, which in this case, is the background level. Recalling that the derivative of the F-curve is the C-curve (see Figure 4-3), the C-curve can be constructed by plotting the slopes of tangents ( $dc/dt$ ) drawn at points along the curve against time. This is shown on the middle panel of Figure 7-16.

The analysis of the RTD curve can be accomplished graphically by breaking the curve into discrete areas at discrete time intervals. The calculations are demonstrated by the following, where  $c_i$  is  $dc/dt$  and  $t_i$  is the corresponding time:

$t_i$	$c_i$	$t_i c_i$	$t_i^2 c_i$	Cumulative (%)*
3.8	0	0	0	
4	0.003	0.012	0.048	0.47
4.6	0.011	0.0506	0.233	2.46
5.1	0.02	0.102	0.520	6.44
5.4	0.028	0.1512	0.816	12.3
6.3	0.039	0.246	1.548	21.9
7.0	0.049	0.343	2.401	35.3
7.2	0.061	0.439	3.162	53.5
8.3	0.044	0.409	3.806	68.4
10.0	0.029	0.29	2.9	79.8
11.2	0.017	0.190	2.13	87.0
13.0	0.01	0.13	1.69	92.2
13.9	0.008	0.111	1.55	96.5
14.1	0.005	0.071	0.994	99.2
16.2	0.001	0.016	0.259	100.0
$\Sigma$	0.325	2.561	24.39	

\*Cumulative percent tracer at observation  $j$  =

$$\frac{\sum_{i=1}^j t_i c_i}{\sum_{i=1}^n t_i c_i} \times 100$$

where  $j \leq n$   
 $n$  = total number of observations

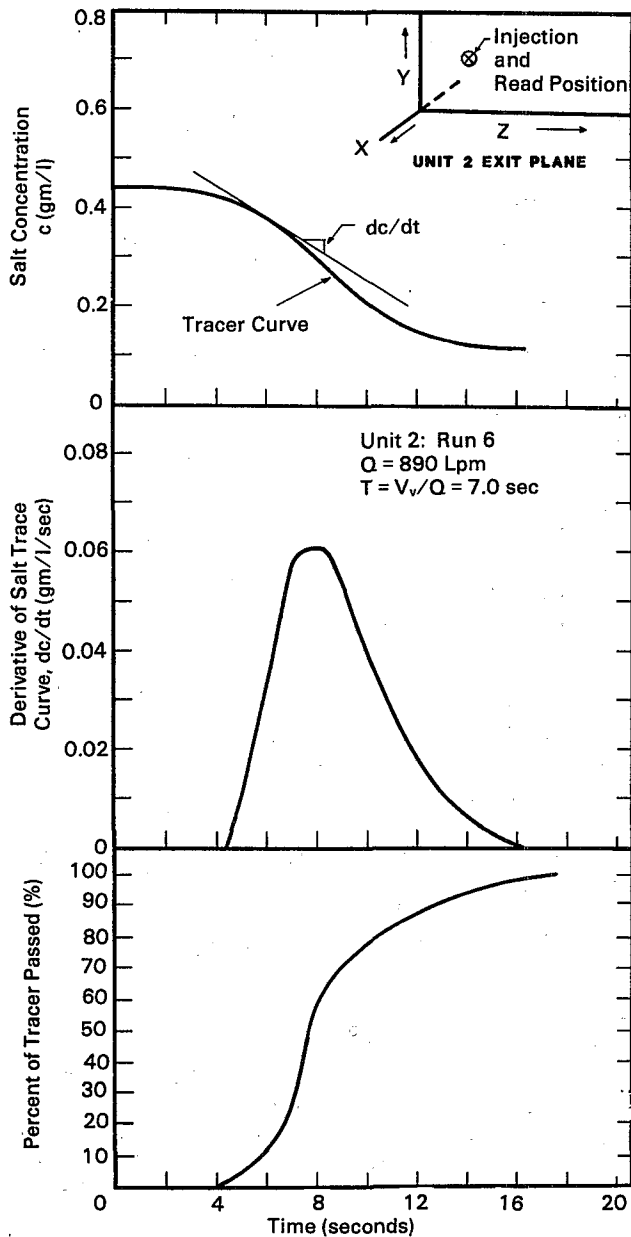
The mean residence time,  $\theta$ , is the centroid, or first moment of the distribution (from Equation 4-13):

$$\theta = \frac{\sum t_i c_i}{\sum c_i} = \frac{2.561}{0.325} = 7.9 \text{ seconds}$$

The last column in the above calculation is the cumulative area as a percent of the total. By plotting this against time, as shown on the lower panel of Figure 7-16, one can display the cumulative tracer with time. This then allows one to evaluate any number of the indices defined by Rebhun and Argaman (57) and discussed in Chapter 4. For this particular tracer analysis, the following parameters are determined:

ratio of initial to theoretical time	$t_i/T = 3.9/7 = 0.56$
ratio of peak to theoretical time	$t_p/T = 7.2/7 = 1.03$
Morrill Dispersion Index	$t_{90}/t_{10} = 12.4/5.3 = 2.3$
ratio of mean residence to theoretical time	$\theta/T = 7.9/7.0 = 1.13$
ratio of median to mean residence time	$t_{50}/\theta = 7.2/7.0 = 1.03$

Figure 7-16. Example of RTD curve developed for Unit 2 at Port Richmond by the step input method (55).



These analyses suggest that although the reactor is one which behaves in a relatively plug flow mode, there is a degree of dispersion. The ratio of  $t_{90}$  to  $t_{10}$  (Morrill Dispersion) has a value of 2.3; this is characteristic of plug flow, but is greater than 2.0, a suggested design goal ( $<2$ ) for disinfection reactors.

The ratio  $t_r/T$  is greater than 0.5, suggesting little significant evidence of short-circuiting. This is supported by the  $t_p/T$  being approximately equal to 1.0. The ratios of  $t_{50}/\theta$  and  $\theta/T$  are also very close to 1.0; this indicates that the entire reactor volume is used effectively.

Consider, as a way to gain a perspective for effective hydraulic design, the analysis of a Teflon tube reactor. The tubular reactor design most closely approximates the ideal hydraulic configuration for a disinfection system. Pipe flow with high length to diameter ratios (this is often referred to as the aspect ratio), are particularly conducive to plug flow, low dispersion conditions.

The step input tracer technique was used to test the Teflon system at Eden, Wisconsin (4). The unit is similar in design to that shown on Figure 7-8. The Teflon tube length is 1.8 m, with a diameter of 6 cm; this yields an aspect ratio of 30. A tracer analysis was conducted at a flow of 65 Lpm. The velocity was 38 cm/s, with a theoretical residence time of 4.7 seconds. The mean residence time was determined to be 4.9 seconds. As presented above, the following indices were computed from the RTD analysis:

$$\begin{aligned} t_r/t &= 0.68 \\ t_p/T &= 0.98 \\ t_{90}/t_{10} &= 1.4 \\ \theta/T &= 1.04 \\ t_{50}/\theta &= 1.02 \end{aligned}$$

The ratio of  $t_r/T$  is 0.68 in this case, which indicates no evidence of short-circuiting. The Morrill index ( $t_{90}/t_{10}$ ) is significantly less than 2 (1.4), and the values of  $\theta/T$  and  $t_{50}/\theta$  are both approximately 1, as is  $t_p/T$ . From this analysis, the tubular reactor is a good example of a plug flow design with little dispersion, and maximal use of the reactor volume.

### 7.3.2.2 Dispersion Characteristics

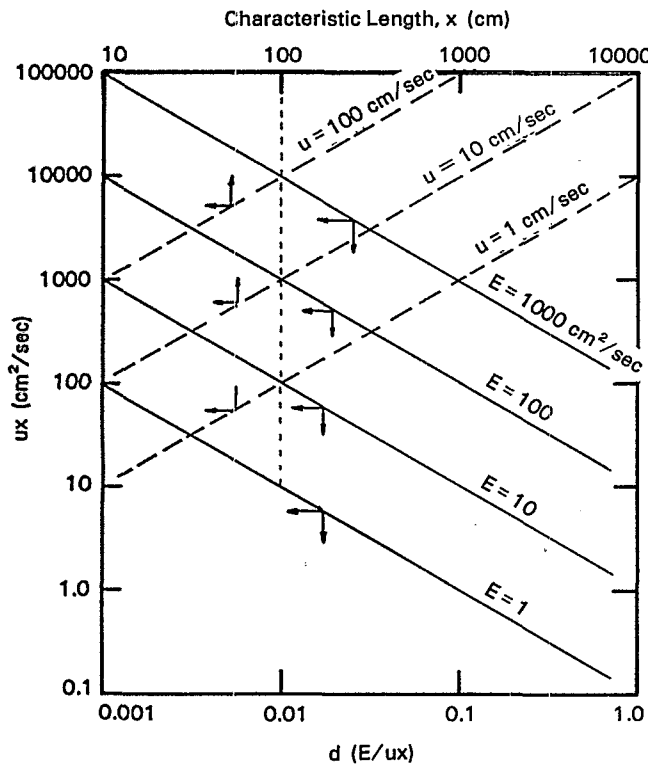
The design expression (Equation 7-10), incorporates the dispersion characteristics of a reactor. Recall from Chapter 4, the discussion of the dispersion coefficient,  $E$ , ( $\text{cm}^2/\text{sec}$ ), and the dimensionless dispersion number,  $d$ , which is equal to  $E/ux$ , ( $u$  is the velocity and  $x$  is the characteristic length).

The ideal reactor design for UV disinfection forces the dispersion number very low, preferably less than 0.01. From its definition, this will be forced by a low dispersion coefficient, a high velocity, and/or a long dimension,  $x$ . This is schematically presented on Figure 7-17.

Consider the two examples presented earlier. From Chapter 4, we know that the dispersion number can be estimated from the mean and variance. The mean residence time for the Port Richmond unit (Figure 7-16) was computed to be 7.9 seconds. The variance can be determined (Equation 4-14):

$$\begin{aligned} \sigma^2 &= \frac{\sum t_i^2 c_i}{\sum c_i} - \theta^2 = \frac{24.39}{0.325} - 7.9^2 \\ \sigma^2 &= 12.64 \text{ sec}^2 \end{aligned}$$

Figure 7-17. Relationships of velocity, length, and dispersion.



The dimensionless variance is computed (Equation 4-19):

$$\sigma_{\theta}^2 = \frac{\sigma^2}{\theta^2} = \frac{12.64}{7.9^2} = 0.203$$

The value of  $d$  can be estimated by (Equation 4-21):

$$\sigma_{\theta}^2 = \frac{2E}{ux} - 2 \left( \frac{E}{ux} \right)^2 \left( 1 - e^{-\frac{ux}{E}} \right)$$

or

$$\theta^2 = 2d - 2d^2(1 - e^{-1/d})$$

Ignoring the second term on the right, the first approximation of  $d$  is 0.102. Adjusting by trial and error for the second term, the value of  $d$  becomes 0.104. This suggests that the first Gaussian approximation was adequate, i.e.:

$$d \approx \frac{\sigma_{\theta}^2}{2}$$

Note also that  $d$  is  $\ll 0.5$ ; thus, it is reasonable to consider it as a closed vessel. The value of  $d$  (0.104)

also confirms the moderate to highly dispersive nature of the reactor.

The tubular reactor variance is  $0.624 \text{ sec}^2$ . The dimensionless variance is 0.026; from this, the dispersion number,  $d$ , is estimated to be 0.013, reflecting the low dispersion, plug flow nature of this particular reactor design.

The dispersion number and the dispersion coefficient are utilized in the design equation for the UV process (Equation 7-10). Correlations can be developed to estimate the dispersion number as a function of reactor characteristics relating to friction losses, hydraulic radius, velocity, etc. Such predictive models exist for pipe systems. Such models have not been developed for UV reactors. There is limited data available to attempt this; certainly further work is needed in this effort.

The dispersion coefficient should be expected to vary with velocity. In current practice, values of  $E$  are selected to represent conditions under high flow; a design goal is then set with the dispersion number (e.g.,  $d = 0.02$  to  $0.05$ ) which will force limits on  $ux$  for the given  $E$ . This is discussed further with the design example presented in Section 7.4, particularly as it relates to the impact on head loss.

### 7.3.2.3 Turbulence and Head Loss

An important consideration in the hydraulic design of a UV reactor is the turbulence of the fluid. By having turbulent flow, any particle has an equal probability of being at any point in the cross-section of the conduit, as it travels in the direction of flow. The importance of turbulence lies in the fact that the intensity field in the reactor, regardless of the way the lamps are configured, is non-uniform. Thus, if a particle is forced to move erratically by the turbulent conditions, it will likely see all intensity levels in the non-uniform field. In this case, then, it is acceptable to use the average intensity in the reactor to evaluate dose levels microorganisms receive as they move through the reactor. If true laminar conditions existed, streamlines may move through areas of low-intensity and receive little dose relative to the streamlines moving close to the lamps.

Flow through a reactor can be characterized by eddies, swirls, and irregular movements of large fractions of the fluid; these do not constitute turbulence. They may more correctly be described as "disturbed flow." Thus, a reactor flow may be laminar, but have disturbances; the lamps themselves can be the source of these disturbances. Turbulence is generally induced by high friction losses and high velocities.

*Turbulence indicated by head loss.* If the log of the head loss for a given length of uniform pipe is plotted against the log of the velocity, it will be found that effectively two regions exist. Where the velocity is low enough to

assure that laminar flow exists, the head loss,  $h_L$ , due to friction, will be directly proportional to the velocity,  $u$ :

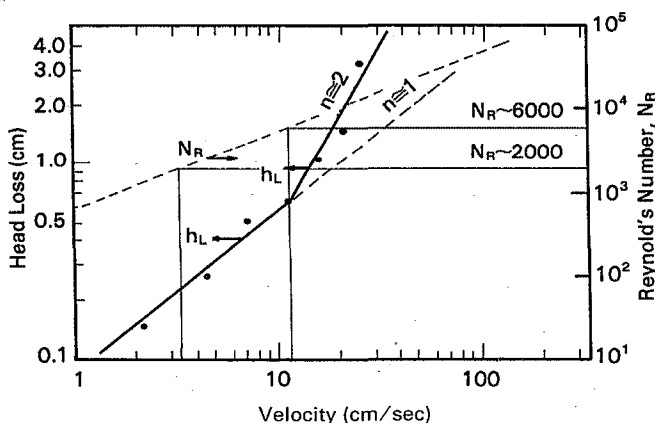
$$h_L \approx u^n, \text{ where } n = 1 \text{ (laminar)} \quad (7-15)$$

As the velocity increases, at some point turbulence is induced and the  $h_L$  is found to increase at a higher rate than the increase in velocity. In uniform pipe this value of  $n$  is greater than 1.0;

$$h_L = u^n, \text{ where } n = 1.75 \text{ to } 2.0 \text{ (turbulent)}$$

Such measurements were taken during the Port Richmond study for the quartz systems. The data for one of the quartz units are presented on Figure 7-18; these demonstrate the transition from the laminar to the turbulent flow condition. At velocities less than 10 cm/s ( $\log u = 1.0$ ), the value of  $n$  is approximately 1.0; at velocities greater than 10 cm/s, the  $n$  is estimated to be 2.0.

Figure 7-18. Log-log plot of head loss against velocity for Unit 2 at Port Richmond indicating transition from laminar to turbulent flow regime (55).



This type of information can be developed by direct measurement on full scale modules or hydraulically scaleable pilot units. Care should be taken that the head loss due only to the lamp reactor itself is being measured. Losses due to reactor entrance and exit conditions should be separated from the analysis.

**Turbulence indicated by Reynolds Number.** Velocity is not the only factor that determines if a flow is laminar or turbulent. The criterion is the Reynolds's number. This dimensionless number,  $N_R$ , is the ratio of inertia forces to friction forces in a completely filled conduit. Thus:

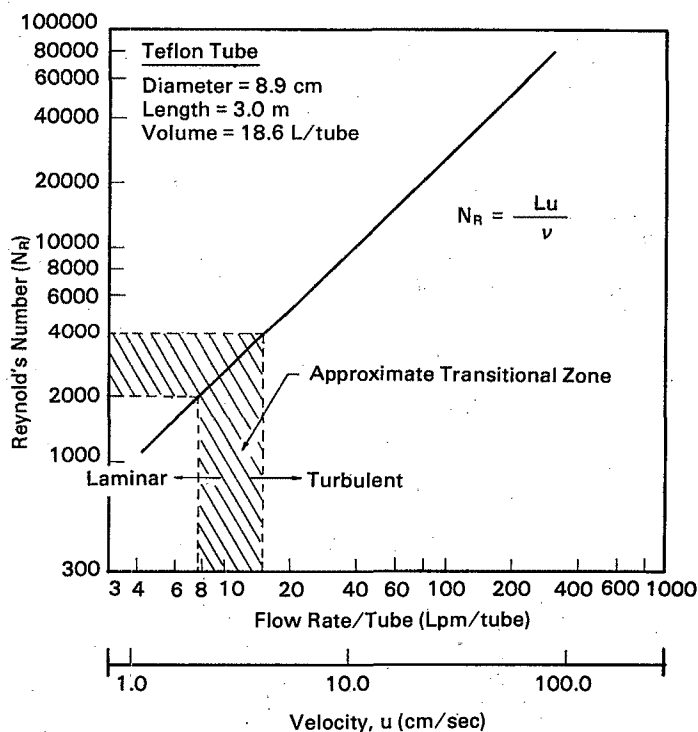
$$N_R = \frac{L^2 u^2 \rho}{Lu \mu} = \frac{Lu}{\nu} \quad (7-16)$$

where:

- $u$  = velocity
- $\rho$  = density of fluid
- $\mu$  = viscosity
- $L$  = linear dimension significant to pattern of flow
- $\nu$  = kinematic viscosity

The linear dimension,  $L$ , for pipes is generally taken as the pipe diameter. A straightforward example of the Reynolds number analysis is the tubular flow array. The linear dimension is taken as the tube diameter. The Reynolds Number is plotted on Figure 7-19 against the velocity and the flow rate per 3-meter long Teflon tube.

Figure 7-19. Estimates of Reynolds's Number for 8.9 cm diameter Teflon tubes.



Typically, the transition from laminar to turbulent flow will occur at a Reynolds number above 4,000; laminar conditions usually exist at values less than 2,000. Turbulent conditions exist in the Teflon tube at flow rates greater than 15 lpm or a velocity greater than 4 cm/sec. This is well below the normal operating range typically encountered for these systems.

The submerged quartz arrays do not allow as straightforward an analysis. The linear dimension is not as clearly defined. It is suggested that an approximation of the hydraulic radius be used in these analyses in order to estimate a Reynolds Number:

$$\text{Hydraulic Radius, } R_H = \frac{V_v}{A_w} \quad (7-17)$$

where:

$$\begin{aligned} V_v &= \text{liquid, or void volume (cm}^3\text{)} \\ A_w &= \text{total wetted surface area (cm}^2\text{)} \end{aligned}$$

The void volume is the total reactor volume minus the volume occupied by the lamps and quartz sheaths. The wetted surface area is the sum of the surface areas of the quartz sleeves and the internal wall area of the reactor.

For a circular conduit flowing full, the hydraulic radius is equal to one-fourth the diameter of the conduit. Thus, for Equation 7-16:

$$L = 4R_H \quad (7-18)$$

The Reynolds Number can then be estimated for the quartz, submerged reactors:

$$N_R = \frac{4R_H u}{\nu} \quad (7-19)$$

Consider Unit 2 from the Port Richmond study as an example of this calculation:

$$R_H = \frac{V_v}{A_w} = \frac{10.2 \times 10^4 \text{ cm}^3}{7.2 \times 10^4 \text{ cm}^2} = 1.4 \text{ cm}$$

At a kinematic viscosity of 0.0098 cm<sup>2</sup>/sec (water at 20°C), the Reynolds number is estimated:

$$N_R = \frac{4(1.4)u}{0.0098} = 580(u) \quad (7-20)$$

where the velocity,  $u$ , is in cm/s. This estimate of  $N_R$  is plotted on Figure 7-18 for Unit 2. From this analysis, the breakpoint appears at an  $N_R$  slightly less than 6,000. This is somewhat higher than the  $N_R$  of 4,000 normally considered as minimal for turbulent flow. The linear dimension estimate ( $4R_H$ ) may be a factor in this. The fact is, that as long as the method of estimating the Reynolds number is kept consistent, it is possible to qualitatively evaluate a unit design for turbulence.

Table 7-6 presents a summary of the Reynolds Numbers estimated for several lamp array configurations. These are based on the estimated hydraulic radius and the design flow range for each unit. As shown, all systems would typically operate at velocities high enough to yield turbulent flow. If a Reynolds Number of 6,000 were set as a minimum, the minimum velocity can also be shown. Such a criterion can be used in establishing specifications for new

systems designs. It should be understood that although the difference in performance has not been demonstrated, it is implicit in the physical mechanism of UV disinfection that the liquid be in turbulent motion. The Reynold's Number calculation offers a method to qualitatively evaluate this criterion.

*Estimating Head Loss.* There is little information on head losses caused by the UV lamp batteries. This will vary according to the size of the reactor, the velocity, and the placement of the lamps. The tubular reactor head loss can be estimated from pipe flow equations, assuming smooth wall friction coefficients. With regard to the quartz systems (submerged), one would expect higher losses in the unit with the lamps placed perpendicular to the flowpath, than those configured with the lamps parallel to the flowpath.

Scheible (56) reported an empirical relationship developed for the quartz units at Port Richmond. This would be representative of only that type of configuration: open channel structure, uniform lamp array, and the flowpath perpendicular to the lamps. Direct testing would have to be done on alternative configurations in order to determine head losses, although a similar approach can be taken in doing so.

The head loss expression is based on Darcy's equation for pipe flow:

$$h_L = \frac{fxu^2}{d_r 2g} \quad (7-21)$$

where  $x$  and  $u$  are the length (cm) and velocity (cm/s), respectively,  $d_r$  is the diameter (cm), and  $f$  is the coefficient of friction. In this case,  $d_r$  is set as the approximate hydraulic radius of the system from Equation 7-17. Finally, a new coefficient of friction is defined:

$$c_f (\text{cm}^2/\text{sec}^2) = \frac{f}{R_H 2g} \quad (7-22)$$

such that:

$$h_L = c_f(x)(u)^2 \quad (7-23)$$

At Port Richmond, direct  $h_L$  measurements of the lamp batteries in the two quartz systems yielded a  $c_f$  between 0.000173 and 0.00023 sec<sup>2</sup>/cm<sup>2</sup>.

The head loss can become a factor in the design of a reactor. Earlier discussions cited the dispersion number as a good design guideline; e.g., designing a reactor to yield a low  $d$  value. Recalling that:

$$d = \frac{E}{ux}$$

**Table 7-6. Summary of Reynolds Number Estimates for Different Lamp Configurations**

System	Configuration <sup>d</sup>	R <sub>H</sub> (cm)	Hydraulic <sup>b</sup> Flow Range (lpm)	Equivalent Velocity (cm/sec)	Reynolds Number N <sub>R</sub>	Velocity at N <sub>R</sub> = 6000 (cm/sec)
Port Richmond 1 <sup>o</sup>	uniform array	4.7	1,000 - 2,600	3.5 - 9.1	6,720 - 17,500	3.1
Port Richmond 2 <sup>o</sup>	uniform array	1.4	1,000 - 2,600	9.3 - 24.0	5,400 - 14,000	10.3
Vinton <sup>f</sup>	concentric array	4.74	2,000 - 4,500	6.8 - 15.4	13,000 - 30,000	3.1
Suffern <sup>f</sup>	staggered array	3.65	3,000 - 10,000	7.3 - 24.3	10,900 - 36,200	4.0
Port Richmond 3 <sup>o</sup>	tubular array	2.23 <sup>a</sup>	40 - 100 <sup>c</sup>	10.8 - 27.0	9,800 - 24,600	6.6

<sup>a</sup>Diameter/4.0.

<sup>b</sup>Design flows.

<sup>c</sup>Liters/min/tube.

<sup>d</sup>See section on UV intensity for definition of array configurations.

<sup>e</sup>Reference 56; also see Figures 7-6 and 7-8.

<sup>f</sup>Reference 4; also see Figures 7-3 and 7.4, respectively.

it can be seen that for a given E, the d is forced by ux. Thus, for an increasing E, the ux must be proportionately increased to maintain a fixed value of d. We see by Equation 7-23, however, that increasing velocity can have dramatic effects on the head loss, since it will increase by the square of the velocity. Increasing x can be done to some degree; this must stay within practical limits, however. One should understand that the head loss we are considering is that incurred through the lamp battery itself; additional head losses will be incurred at the inlet and outlet structures.

In all, d will need to be reconciled with the head loss. Increasing the acceptable d will allow one to reduce and keep the h<sub>L</sub> within design limits. Generally, for gravity flow systems, one should design about a d between 0.02 and 0.05. One should understand that these are still excellent dispersion numbers for a disinfection reactor.

### 7.3.2.4 Effective Volume

The lamp battery volume is that portion of the total system occupied by the UV lamps. By this fact, it is very important that the reactor is designed such that full use be made of the entire volume. Dead zones or short-circuited areas mean ineffective use of lamps and power, the two components which comprise a major portion of the capital and operating costs. This is primarily a design consideration for the submerged quartz systems. The tubular array configuration should inherently provide for maximal use of the Teflon tube volume.

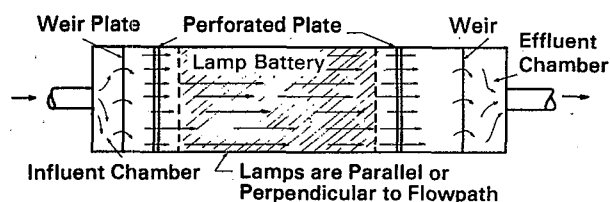
Maximum use of the reactor volume is directly related to the approach and exit conditions of the reactor. The design intent must be to first enter the front plane of the lamp battery with equal fluid velocity at all points. This same condition must exist at the exit plane. The approaches taken to encourage this include:

- open channel flow before and after the lamp battery,
- overflow weirs placed the full length of the reactor,

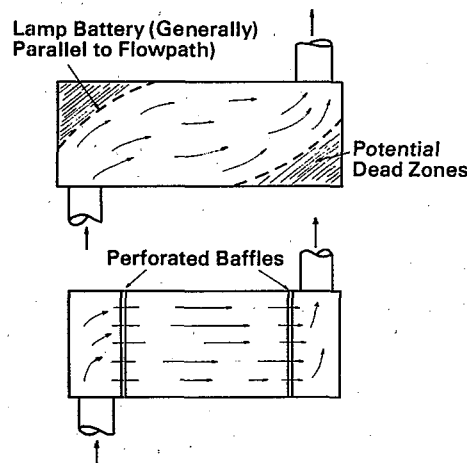
- perforated stilling walls before and after the lamp battery, and
- unidirectional flowpath throughout the approach, battery, and exit sectors.

Figure 7-20 schematically displays these considerations. The upper panel shows a plan-view of an open channel type configuration. The inlet and outlet chambers should be independent of the lamp battery. Weirs can be placed across the width of the reactor to distribute the flow evenly across the unit. The perforated baffle plates then serve to distribute the flow evenly both horizontally and vertically. The weir

**Figure 7-20. Inlet and outlet considerations for submerged quartz systems.**



(a) Open Channel-Type Configuration



(b) Sealed Cylindrical Reactor Configuration

plates may not be needed before the perforated baffle if there are no extreme velocity gradients coming into the unit. By having the same arrangement on the exit side, the flow paths are kept stable and unidirectional through the lamp battery.

In the middle panel of Figure 7-20, a sealed cylindrical shell type reactor is shown. The lamps are generally parallel to the flow path and the wastewater enters and exits the reactor perpendicular to the lamps. As shown, there is the tendency to induce flow channelling with this arrangement, causing dead zones in the reactor. A solution is shown on the lower panel, in which perforated baffle plates are installed at both ends of the unit. These serve to distribute the flow over the entire cross-sectional plane of the reactor.

To evaluate a system for effective volume, the indices derived from the RTD curve are useful. The ratio of the mean residence time to the theoretical residence time ( $\theta/T$ ) should be approximately 1.0. The actual fraction is reflective of the actual volume being effectively utilized.

It is suggested that the  $\theta/T$  ratios be used in specifying the hydraulic design of a UV reactor. A value greater than 0.9 is an appropriate requirement.

#### 7.3.2.5 Summary Considerations for Effective Hydraulic Design

In summary, the key points to address when evaluating or specifying the design of a UV reactor are as follows:

**Residence Time Distribution.** This should be constructed at a number of flow conditions for an existing system; it should also be required when specifying commercial systems. The RTD provides key information on the actual or anticipated hydraulic behavior of a reactor.

**Plug Flow.** This can be quantitatively described by indices derived from the RTD analysis. Appropriate guidelines for specifications can be:

$$\begin{aligned}t_f/T &> 0.5 \\t_{90}/t_{10} &< 1.0 \\t_p/T &> 0.9 \\t_{50}/\theta &= 0.9 \text{ to } 1.1\end{aligned}$$

Additionally, the dispersion coefficient,  $E$ , should be relatively low ( $<500 \text{ cm}^2/\text{s}$ ); the dispersion number should be less than 0.1 (preferably less than 0.05 if the head loss is acceptable).

Reactor designs which are conducive to plug flow have high aspect ratios,  $x/L$ . Thus, the length,  $x$  (i.e., the distance in the direction of flow), should be significantly higher than the appropriate cross-sectional dimension,  $L$ . In tubular reactors, such as the Teflon tube units, this is the diameter. In submerged

quartz units,  $L$  is  $4R_H$ , where  $R_H$  is the hydraulic radius. As a guideline, an aspect ratio greater than 15 should be incorporated into a reactor design.

Maintenance of plug flow within a reactor will be influenced by the approach and exit conditions. The design should have minimal disturbances at the inlet and exit planes of the lamp battery; directional changes in the flowpath would best be made outside of the lamp battery.

**Dispersion Number.** A key goal is to minimize the dispersion number,  $d$ . A design goal should be to have a  $d$  between 0.02 and 0.05. Levenspiel (58) suggests that this would be representative of a plug flow reactor with low to moderate dispersion. This can be accomplished by increasing the product of  $ux$ , even in a system with a relatively high dispersion coefficient. The designer should be aware, however, that extended lengths and higher velocities will cause higher head losses. In certain situations some adjustment of the dispersion number may be necessary in order to meet specific head loss requirements.

**Turbulence.** Radial turbulence is necessary due to the non-uniform intensity field. The reactor design should induce an estimated (by the procedure discussed earlier) Reynold's Number greater than 6,000 at minimum flow. If possible, it would be beneficial to confirm the laminar/turbulent flow transition velocity by direct head loss measurements on the lamp battery.

**Head Loss.** Direct measurements should be required for full-scale modules or scaleable pilot units as part of commercial equipment specifications. These should be determined over a wide velocity range and should exclude entrance and exit losses.

**Effective Volume.** Maximal use of the reactor lamp battery is essential to keep the process cost-effective. This will be related directly to the reactor's inlet and outlet design. The goal must be to have equivalent velocities at all points upon entering and upon exiting the lamp battery. Stilling walls (perforated baffles), and weirs should be incorporated into reactor designs to assure this. Guidelines for specifying commercial equipment should require the ratio  $\theta/T$  to be greater than 0.9 and/or the  $t_p/T$  to be greater than 0.9.

#### 7.3.3 Estimation of the Average Intensity in a UV Reactor

The second element of dose, after time, is the intensity of energy during the exposure time. Recall that the intensity is the rate, or flux, of delivery of photons to the target. In the UV process design model, Equation (7-10), the rate of bacterial inactivation is described as a function of the intensity. By this fact it becomes important to be able to quantify the intensity in a given system. The intensity in a reactor is a

function of the UV source (output), the physical arrangement of the source relative to the wastewater (the arrangement of the lamps and their placement in or out of the liquid), and the energy sinks present which will attenuate the source output before it can be utilized for disinfection purposes.

The UV source, as discussed earlier, is typically the low pressure mercury arc lamp. Table 7-7 presents lamp specifications for a series of germicidal lamp models. The lamps generally used in UV reactor systems are equivalent to the G64 and G36 units. The overall lamp length is approximately 0.9 m for the G36 and 1.6 m for the G64. The arc length defines the active, light emitting portion of the lamp (0.75 m and 1.5 m, respectively.) The diameter of the lamp is small, typically 1.5 to 1.9 cm. The lamp envelope is made of fused quartz or other highly transparent (to the 253.7 nm wavelength) glass, such as Vycor.

In the quartz systems, the individual lamps are sheathed in quartz sleeves only slightly larger in diameter (2.3 cm) than the lamp and the entire lamp/quartz bundle is submerged in the flowing liquid. In systems where the wastewater does not contact the quartz or lamp surface, separate conduits carry the wastewaters. The conduits are translucent to the UV light, with the lamps placed near the outside conduit wall.

Determining the intensity at any point in these complex lamp reactors is not straightforward. At present, there is no commercially available detector which can measure the true intensity in such a system. The problem lies in the fact that the detectors are planar receptors; only energy striking a flat surface will be measured. Such detectors will intercept fractions of light striking the surface at an angle. Only light which is normal to the surface, i.e., collimated light, however, will be wholly measured. "Cosine-corrected" detectors attempt to compensate for this by adjusting for the angular light. These still measure, however, only the planar intensity. Where light is not collimated, as is the case with a multi-lamp UV reactor, the flux of energy is three-dimensional. This same concept is enforced when the target of the radiation is considered. In turbulent motion, all particles can be expected to receive equal exposure.

Several approaches have been proposed to estimate light intensity, including chemical actinometry, biological assays, and direct calculation. The two procedures which have received the greater attention are the bioassay and direct calculation methods. The bioassay procedure has been applied in a limited fashion for a number of design specifications, primarily as a technique for quantifying the dose delivered by a specific piece of UV equipment. It can also be used to implicitly derive the intensity within a system.

The second method which is used and which is generally emphasized within the context of this manual, is the direct calculation of intensity. This is accomplished by the point source summation method. The discussions briefly describe the calculation framework which yields the average intensity as a function of the UV absorbance coefficient of the wastewater. A series of solutions are then presented which the designer can use to estimate intensity in a number of lamp configurations. Finally, discussions are presented regarding the factors of lamp deterioration and enclosure fouling which will absorb the UV energy, and thereby reduce the intensity.

#### **7.3.3.1 Bioassay Procedure to Estimate Intensity and UV Dose**

The assay procedure has been proposed as an effective method for estimating delivered dose and system intensity (40). This technique is shown schematically on Figure 7-21.

UV sensitive pure culture is calibrated to the UV dose using the collimated light device shown on Figure 7-21(a). The collimating device allows one to accurately measure the intensity directly with a commercial radiometer. Aliquots of the bacterial suspension are then exposed to this given intensity for a series of fixed time intervals, yielding known doses. The response is then plotted against the dose. This dose-response relationship serves as the calibration for the subsequent reactor assays (Figure 7-21(b)).

The unit to be tested is set to the desired flow and operating conditions and the culture is injected into the influent. The effluent is then sampled with time and assayed for the known bacterium. This same procedure is repeated without the lamps in operation. The resulting densities are as shown on Figure 7-21(c). For each time interval, the log survival rate is determined. The equivalent dose can then be estimated from the dose response calibration curve. When the dose is plotted against time (Figure 7-21(d)), the slope of the correlation is the dose-rate, or intensity.

This method for determining intensity in a system can require a fair sized laboratory effort. A quality analysis requires very frequent sampling and analysis and should be replicated to assure precision. This can be costly and is not cost-effective when compared to the alternative calculation method. It should be noted that Qualls and Johnson (40) used this assay procedure to independently verify the point source summation calculation method.

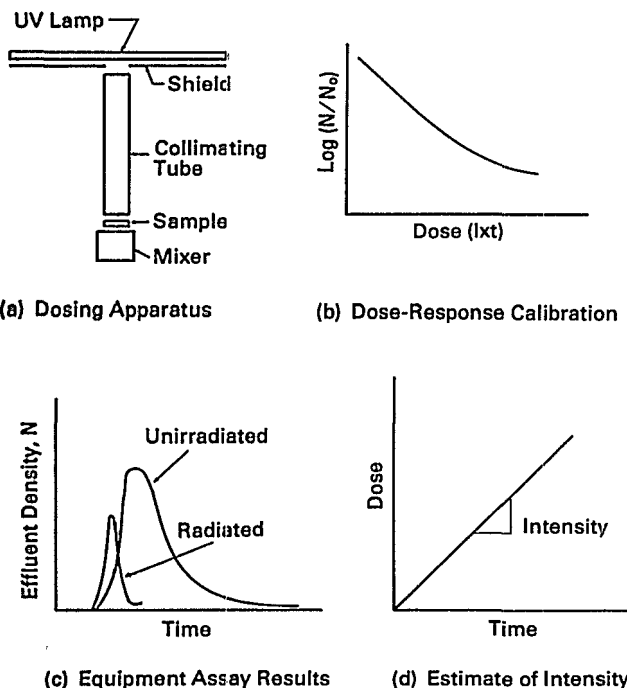
A possible simplification of the procedure for estimating the intensity involves injecting the bacterium stock at a steady rate. The effluent is assayed and the dose is determined from the log survival ratio. This is



Table 7-7. Examples of Low Pressure Mercury Arc Lamp Specifications (Courtesy Voltarc Tubes, Inc., Fairfield)

	G36T6L G36T6H	G37T6VH	G36T6	G64T5L	G64T6L
Lamp Watts	39	40	36	65	62
Lamp Current, mA	425	425	425	425	425
Ultraviolet Output, watts (at 100 hrs, 253.7 nm)	13.8	14.3	12.7	26.7	25.5
Microwatts/cm <sup>2</sup> @ 1 meter	120	124	110	190	180
Ozone Generation (approximate gm/hr)	H .5 L 0	15	0	0	0
Nominal Length, inches cm	36 91.4	37 94.0	36 91.4	64 162.6	64 162.6
Arc Length inches cm	30 76.2	31 78.7	30 76.2	58 147.3	58 147.3
Tube Diameter, mm	15	15	19	15	19
Tube Material	H: Vycor 7912 L: Vycor 7910	Quartz	Vycor 7910	Vycor 7910	Vycor 7910
Rated Life, hours (average, at 8 hrs/start)	7500	7500	7500	7500	7500

Figure 7-21. Schematic of bioassay procedure for estimating dose and intensity.



repeated over several flow rates. A separate RTD curve is developed for the reactor using a conservative tracer. The intensity can then be implicitly derived by trial and error calculations to match the RTD and the steady-state dose-response of the unit.

*Estimating the Dose by the Bioassay.* The steady-state bioassay method, generally using *Bacillus subtilis* spores, has been used as a specification in demonstrating the dose capacity of a given system. The dose is estimated as a function of flow rate through a scaleable pilot module. A minimum dose is then cited for the equipment specification.

The bioassay procedure, although a valid and unique experimental design, has several disadvantages which, at present, detract from its use as a routine testing and evaluation procedure. It is not standardized, and results will vary from lab to lab, both in the calibration and system assays. It can be costly and cumbersome to accomplish on a routine basis (particularly as a procedure to intermittently monitor a unit for intensity), although this should resolve itself with continuing direct experience. It is also wholly empirical and limited in its use for extrapolation to alternative system configurations.

On the positive side, however, the bioassay can offer several advantages. It is an independent verification of system design, and implicitly of design procedures.

As such, it can be used effectively as a post-construction performance test or to compare the performance of competing commercial units during design and/or bid phases of a facility installation.

The following is an outline of the procedure which can be used to develop the dose performance curve for a commercial unit. Example results are given from an actual test series conducted in response to specifications for the Bristol, Connecticut plant expansion; these demonstrate the data generated from the bioassay analysis.

## 1. Selection and Culturing of Bacterial Culture

The species selected for the assay should be one which is relatively easy to culture, identify, and harvest, and which has a dose-response which is reproducible and consistent. *Bacillus subtilis* spores, which are used in the example on Figure 7-22, have been used on several recent equipment assays. Originally used by Johnson and Qualls (38), the spores are relatively resistant to UV, and have been shown to be very consistent and reproducible within a specific harvest. *M. lutea* has also been used successfully and shows a response similar to that of the coliform group.

The culture should be harvested in sufficient quantity such that all necessary dose calibration and assay work can be accomplished with a single harvest. The *B. subtilis* are particularly suited to this since they can be stored for long periods and have been shown to retain their dose-response behavior through this period.

In situations where units are being compared (such as in a pre-qualification procedure for several manufacturers), a single organism should be specified. Additionally, the use of a single laboratory should be encouraged. It has not been established that reactors will yield the same effective dose for organisms with different dose-response relationships.

It has also been shown that different dose-response curves are developed lab to lab for the same organism. The better approach, then, in order to assure consistency and the ability to validly compare different units, is to use one organism generated from a single mixed batch and to have one laboratory conduct the calibration and equipment assays.

## 2. Dose-Response Calibration

A dose-response calibration curve can be developed using the laboratory collimated beam

apparatus shown schematically on Figure 7-21(a). As an example, the apparatus used for the example bioassay had a G8T5 lamp as the UV source. All but two inches of the lamp were shielded. The exposed portion of the lamp was suspended above a 25 cm long, 5 cm diameter non-reflective tube. The sample to be exposed was placed in a petri dish below the tube. The sample size (20 ml) was sufficient to give a liquid depth of 1 cm.

The purpose of the tube is to collimate the light, such that the light reaching the liquid is perpendicular to the surface. In this manner, the light can be accurately measured by a radiometer detector.

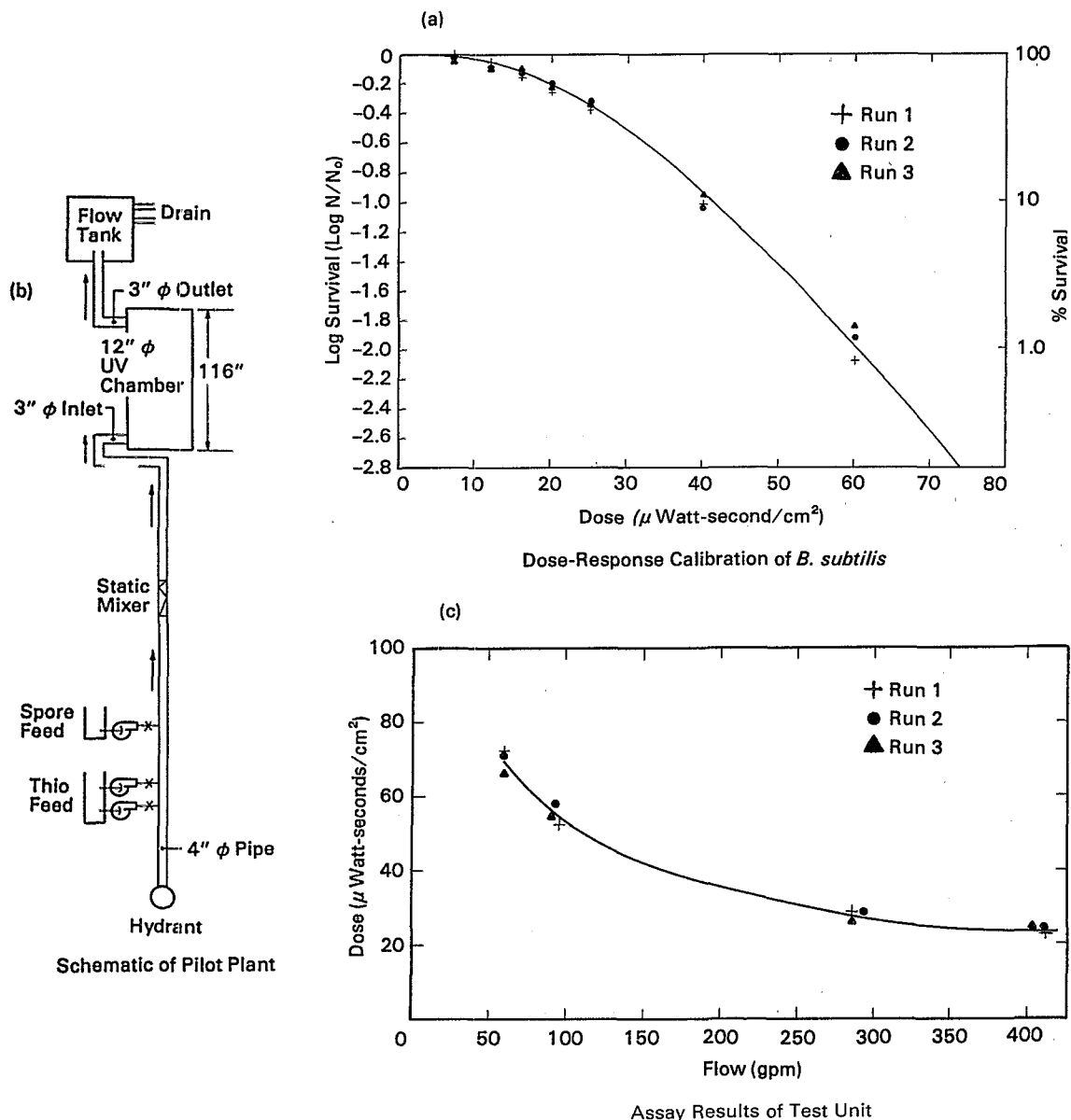
Prior to exposing the sample, the intensity of the ultraviolet radiation is adjusted (by movement of the lamp position) to  $100 \mu\text{W}/\text{cm}^2$  at the surface of the sample. A narrow band, calibrated detector should be used for these measurements.

During exposure, the sample should be gently stirred continuously, using an insulated magnetic mixer with a micro spinbar. The organism density should be adjusted to approximately  $10^5$ ; a buffered water should be used for dilution. After exposure, samples should be plated immediately, using a culturing medium appropriate to the organism being assayed. The same medium should be used for both the dose calibration and the equipment assay tasks. In situations where a clean, potable water can be used for the carrying liquid in the equipment assay, a non-selective nutrient medium can generally be used for microorganism enumeration. This was the case for the example bioassay; total plate count agar (pour plates) were used to grow the *B. subtilis* spores.

Five to seven exposure times should be run to develop the dose-response curve. Thus, at a set intensity of  $100 \mu\text{W}/\text{cm}^2$ , running exposure times between 50 and 400 seconds would yield a dose ( $I \times t$ ) range between 500 and 4000  $\mu\text{W}\text{-sec}/\text{cm}^2$ .

The dose runs (series of exposure times) should be conducted in triplicate, each from a separate dilution of the stock suspension. In all three dose runs the controls and exposed samples should be sampled in triplicate; three dilutions should then be plated in triplicate. A minimum of two controls (unexposed) should be run with each dose run, representing time zero and the longest exposure period.

Figure 7-22. Example of bioassay analysis of commercial UV system to determine dose (By permission of Ultraviolet Purification Systems, Bedford Hills, New York).



A dose-response calibration curve developed for the example assay is given on Figure 7-22(a). The log of the survival ratio (Log N/N<sub>0</sub>) for the *B. subtilis* is plotted against the delivered dose.

### 3. Test Unit and Experimental Setup

The test unit to be evaluated by the bioassay should closely simulate the design of the full-scale system proposed for the treatment facility. Since the UV equipment is generally comprised

of modules, the test unit need simulate only one module. In some cases, it may be practical to test the full scale module itself.

Particular attention should be paid to scaling the hydraulic design of the full-scale unit. The parameters of dispersion and the indices developed from the RTD of a unit can be considered in specifying the test unit. These were discussed in Section 7.3.2. Additionally, the test unit should have a similar aspect ratio (ratio of

length to diameter, or cross sectional dimension), and inlet and outlet designs. In particular, the inlet and outlet velocities should be equivalent. Although not always specified, it is recommended that residence time distribution curves be developed for the test module.

Generally, specifications should require that the test unit, once its similitude is established, be tested at the hydraulic loads to be encountered for the full scale system. This is determined on the basis of flow per unit lamp, e.g., lpm/lamp. The range of flows to be tested should encompass the peak design flow anticipated for the plant. The performance requirement generally specifies that the system sizing would meet a desired dose level under peak design conditions. Other requirements imposed on the test are that the lamp output be reduced to simulate end of life conditions; this is generally considered at 70 percent of the lamps' nominal output. The lamp output can be reduced by using a rheostat to adjust the voltage, or by using lamps which have reached 70 percent (this should be confirmed by direct measurement, see Section 7.5.1) of their original output.

The transmittance of the carrying water should also be adjusted to yield an absorbance coefficient, or percent transmittance, anticipated under design conditions. This is accomplished by adding a chemical which will absorb energy at the 253.7 nm wavelength, but will not interfere with the test. An appropriate compound is sodium thiosulfate.

Figure 7-22(b) presents, schematically, the experimental setup to test the UV module for the example bioassay. The water source was potable water from a hydrant at a wastewater treatment plant (with appropriate backflow protection devices). Sodium thiosulfate is injected at a rate needed to yield (by direct measurement) the desired transmittance.

The microorganism suspension is injected in similar fashion to yield a desired density level. Both the thiosulfate and spore suspension are injected upstream of an in-line static mixer to assure a homogenous solution before entering the UV chamber. Flow rates are set and measured by determining the rate of fill in a large (1000 L) tank. The tank drains to the primary clarifiers in this particular case.

#### 4. Experimental Field Test Procedure

Three to four flow rates should be tested in triplicate; these should, at minimum, bracket

the peak design flow. Once the appropriate water flow rate is set through the unit, a near saturated solution of sodium thiosulfate is metered directly into the water line. The feed rate is adjusted until the desired transmittance level is reached in the effluent.

Once the water is adjusted to the desired transmittance with sodium thiosulfate, the *B. subtilis* spore suspension (or other test organism) which is continuously mixed, is metered into the line with a second metering pump. The feed rate is adjusted, in this case, at each flow setting to yield an influent density of approximately  $10^4$  spores/ml.

The flow with thiosulfate and spore suspension is continued long enough to allow a minimum of seven volume changes in the unit before sampling. The influent and effluent are then sampled in triplicate using sterile sampling containers. The influent and effluent sampling lines should be kept flowing continuously to assure that the samples taken are representative of the run being done. An additional sample is taken of the influent for percent transmittance analysis.

Samples should undergo immediate (within four hours) analysis. A minimum of three dilutions should be plated in triplicate, using the appropriate medium. The percent ultraviolet transmittance at 253.7 nm should be measured by standard spectrophotometric procedures.

The results of the example bioassay are presented on Figure 7-22(c). The log of the survival ratio ( $\log N/N_0$ ) are first determined from the experimental data. These are then used to determine the effective dose delivered by the test unit by reference to the dose-response calibration curve (Figure 7-22(a)). This effective dose is then plotted against the corresponding flow rate. The example unit was operated at 70 percent lamp output (set by adjusting the voltage); the water transmittance was 70 percent (at 253.7 nm).

The relationship presented on Figure 7-22(c) allows one to then determine the flow (or flow per unit lamp) which corresponds to the minimum desired dose. As discussed earlier, this has often been used in equipment specification as a pre-bid or bid qualification requirement. The bioassay is also used to set specific performance requirements for equipment supplied to a facility.

### 7.3.3.2 Calculation of the Average Intensity by the Point Source Summation Method

The calculation approach is suggested as the method of choice because of its versatility and flexible application to varying configurations. The technique used to calculate intensity is the point source summation method. A brief description is presented herein; the reader is referred elsewhere for a detailed discussion of the calculation framework (52).

The point source summation technique was evaluated by Jacob and Dranoff (66) for light intensity profiles in a perfectly mixed photoreactor and was first applied to UV disinfection reactors by Johnson and Qualls (38). It presumes that the lamp is a finite series of point sources that emit energy radially in all directions. The intensity at a given point in a reactor would be the sum of intensities from each of these point sources.

**Intensity Attenuation.** UV intensity will attenuate as the distance from the source increases. This occurs by two basic mechanisms: dissipation and absorption. Dissipation is simply the dilution of the energy as it moves away from the source. The area upon which the energy is being projected is increasing; thus the energy per unit area is decreasing. This dissipation can be calculated by surrounding the point source by a sphere of radius R:

$$I = S/(4\pi R^2) \quad (7-24)$$

where I is the intensity at a distance R in  $\mu\text{Watts}/\text{cm}^2$ , R is the distance in centimeters, and S is power available from the UV source in  $\mu\text{Watts}$ . Thus, dissipation is seen to attenuate the intensity as the inverse of the radius squared.

The second attenuation mechanism relates to the absorptive properties of the medium through which the energy is transmitted. This is best described by Beer's Law:

$$I = I_0 \exp[-\alpha R] \quad (7-25)$$

where  $I_0$  is the intensity at a given surface on the source ( $\mu\text{Watts}/\text{cm}^2$ ),  $\alpha$  is the absorbance coefficient of the medium through which the energy is passing ( $\text{cm}^{-1}$ ), and R is the distance at which I is measured relative to the point represented by  $I_0$ . The absorbance coefficient reflects the absorbance at the specific wavelength being emitted; in the case of the low pressure mercury arc lamps, the wavelength is 253.7 nm.

Combining Equations 7-24 and 7-25 yields an expression which describes the intensity at a given distance from a single point source of energy:

$$I = [S/(4\pi R^2)] \exp(-\alpha R) \quad (7-26)$$

This equation serves as the basis for the point source summation calculation technique. A basic assumption is that a receiver (i.e., a microorganism) passing through the reactor is infinitely small and is spherical; by this it can then be presumed that the energy emitted from any point source element of the lamp will strike the receiver normal to its surface.

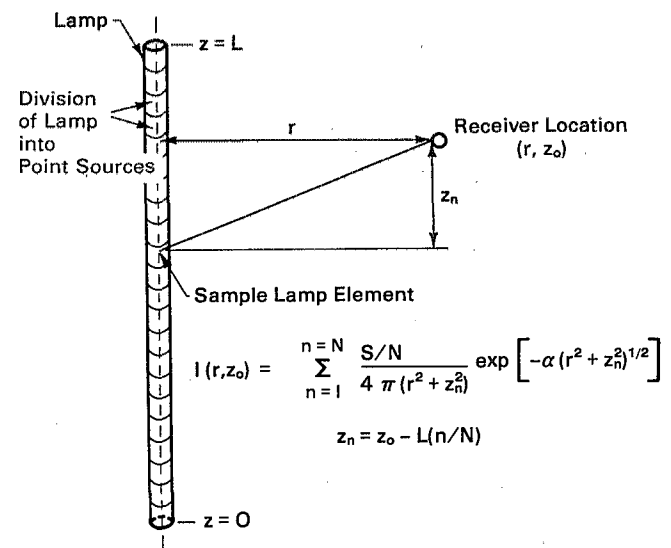
The model analysis also neglects the phenomena of reflection, refraction, diffusion, and diffraction of light and assumes that the absorptive properties of the liquid are independent of the light intensity. The intensity at a receiver is then the summation of the intensities from each of the point source elements of a lamp, (or lamps in a multilamp system). Figure 7-23 is a schematic representation of this calculation. As shown, the intensity at the receiver location ( $r, z_0$ ) is the summation of the intensities from each of the lamp elements:

$$I(r, z_0) = \sum_{n=1}^{n=N} \frac{S/N}{4\pi (r^2 + z_n^2)} \exp[-\alpha(r^2 + z_n^2)^{1/2}] \quad (7-27)$$

where N is the number of point source elements in the lamp. The value of  $z_n$  is:

$$z_n = z_0 - L(n/N) \quad (7-28)$$

Figure 7-23. Lamp geometry for point source summation approximation of intensity.



A practical analysis of intensity in a submerged or Teflon tube lamp battery system requires that the calculations be made at numerous receiver locations within the lamp battery. This is accomplished by dividing the cross-sectional space between lamps into an equal-area grid system. The average of the

receivers located in the center of equal area grid elements would then be equivalent to the average intensity within the total grid area. Within a system, this grid is expanded to encompass all or a section of the unit and can be moved about to evaluate boundary effects and other configurations which may affect the overall unit average intensity.

The model takes into account the geometry of a system, the characteristics of the lamps and enclosures (e.g., quartz or Teflon), and the given UV absorption properties of the fluid. Since the low pressure mercury arc lamps are excellent absorbers of light at the 253.7 nm wavelength, the model calculations presume that any energy at this wavelength entering a lamp from a neighboring lamp will be completely absorbed by that lamp.

Figure 7-24 is presented to illustrate the intensity field calculated by the point source summation method. This example shows four lamps, spaced 5 cm apart. The important note to this is the non-uniformity of the intensity field and thus, the need to have turbulent flow, as discussed earlier, such that a particle will have the opportunity to be exposed to all intensity levels. In this fashion, it is appropriate to use the average intensity computed for the reactor.

Computationally, the point source summation method is not convenient and is best handled by computer with the appropriate software. In lieu of this, a series of solutions have been developed, and are presented in this manual, which describe the average intensity for almost any practical lamp configuration which would be considered by the designer.

### 7.3.3.3 Nominal Average Intensity Estimates for Alternative Lamp Configurations

Different lamp configurations will yield different nominal intensities in the reactor. Calculations have been performed for a number of designs, and subsequently reduced to show the nominal intensity as a function of the UV density of the reactor, and the wastewater absorbance coefficient.

*UV Density.* The UV density,  $D$ , is defined as total nominal UV power (at 253.7 nm) available within a reactor divided by the liquid volume of the reactor:

$$D = \text{total UV output/liquid volume} \quad (7-29)$$
$$= \text{UV watts/liter}$$

As an example, Unit 1 in the Port Richmond study contained a total of 100 lamps. The liquid volume (internal reactor volume minus the volume occupied by the quartz sleeves) was approximately 375 liters. The lamps were the G37T6VH lamps described in Table 7-7. The nominal output is shown as 14.3 W/lamp; thus, the total UV output is  $100 \times 14.3 =$

1430 W. The UV density of the reactor is then 1430 W/375 liters, or 3.8 W/L.

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

*Lamp Array Configurations.* Four lamp "arrays" are considered; these are in common use today and, in effect, cover almost all practical configurations one would consider. The only assumptions which are made are that the lamps are always parallel to one another and that the single array pattern is continuous and symmetrical throughout the reactor. Both are appropriate and would be expected from a practical design. The four arrays are: (1) uniform array; (2) uniform staggered array; (3) concentric array; and (4) tubular array.

#### Uniform Array—

A cross-section of a uniform array is given on Figure 7-25(a). The lamps (with quartz sleeves) are arranged in even horizontal and vertical rows, with the centerline spacings equal in both directions.

#### Staggered Uniform Array—

This is similar to the uniform array, except that the alternating vertical rows are offset by one-half the vertical spacing,  $S_v$ , as shown on Figure 7-25(b). The flowpath is typically perpendicular to the lamps; the staggered effect is designed to influence turbulence.

#### Concentric Array—

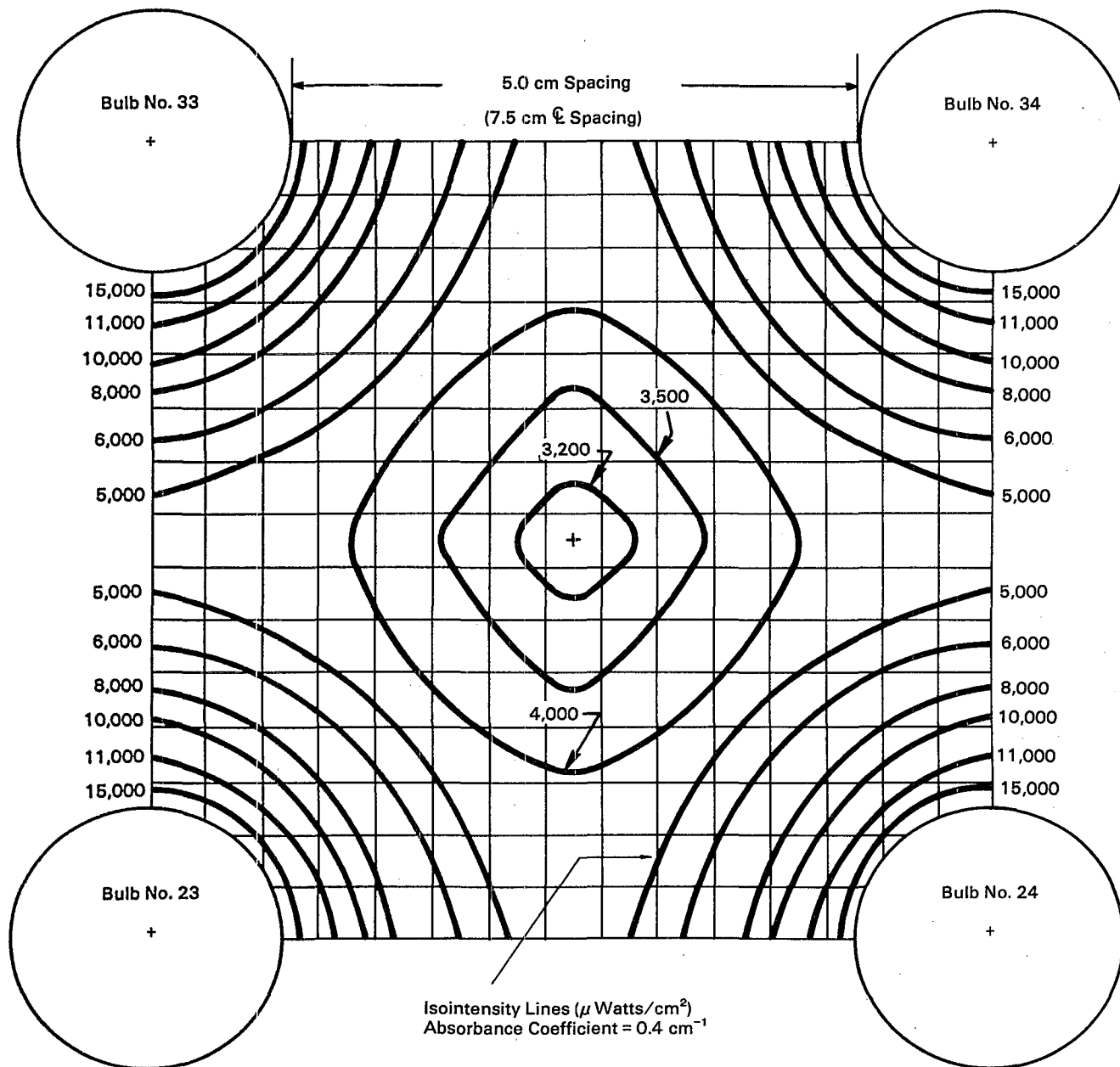
In this configuration, the lamps are arranged in concentric circles. This is illustrated on Figure 7-26(a), which is the cross-section of the unit at the Vinton, Iowa wastewater treatment plant. Typically, the array is designed to shut off banks of lamps. The banks are distributed throughout the reactor; this in effect, alters the UV density of the reactor as lamp banks are turned on or off. As more and more lamps are turned off, this can possibly cause very non-uniform intensity fields. This is not the case with the uniform arrays.

#### Tubular Array—

The tubular array describes the Teflon tube systems in which the lamps are suspended outside and parallel to a Teflon conduit. This is illustrated on Figure 7-26(b). The lamps and tubes are stacked vertically in alternating rows, with equivalent vertical and horizontal centerline spacing.

When considering the tubular array configuration, it is important to understand the effect which the number of vertical rows of tubes in a system have on the lamp requirement (and the consequent UV density). The meters of arc required for each meter of Teflon tube will vary with the number of vertical tube rows in the system. This is shown on Figure 7-27

Figure 7-24. Illustration of the intensity field calculated by the point source summation method.

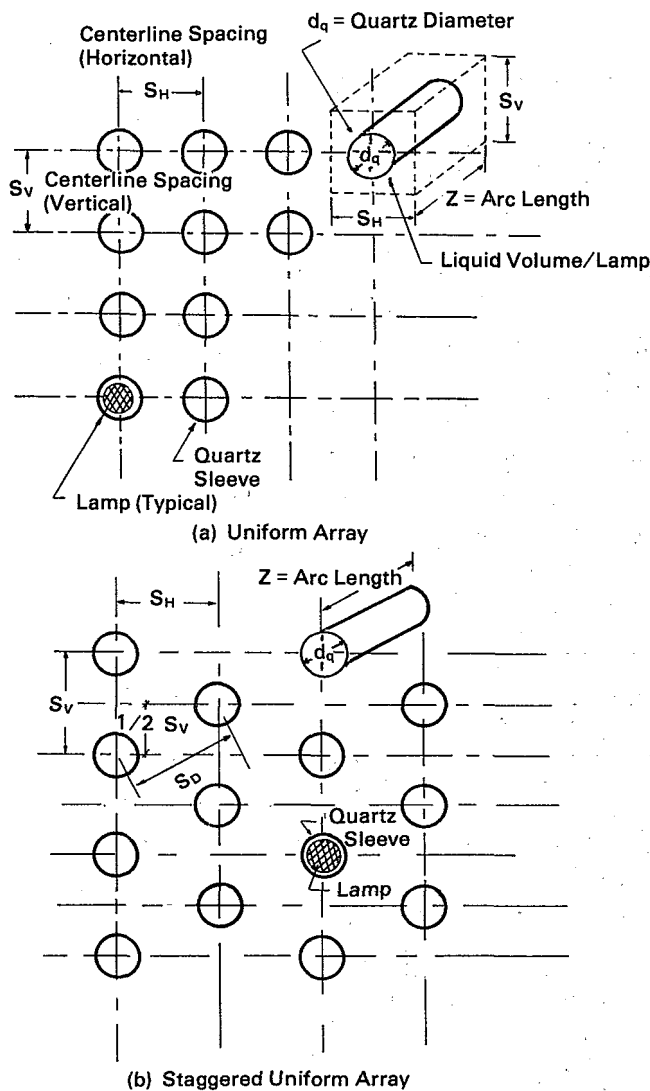


where  $n$  is the number of vertical rows of Teflon tubes in the unit. The number of lamp rows would be  $n+1$ . Thus, if the system has only one row of tubes, two rows of lamps would be required, yielding the ratio of 2 meters arc/meter tube. As  $n$  becomes greater, the ratio approaches 1.0. From Figure 7-27, the greater efficiency is achieved in systems with greater than 10 Teflon tube rows. In computing the UV density for the UV intensity solutions in this manual (Figures 7-31 and 7-32), the ratio of meters arc to meters tube is assumed to be 1.1.

**Nominal UV Intensity Estimates.** Figure 7-28 presents the estimated nominal UV intensity as a function of the UV density for the uniform lamp array configuration. These are shown for a range of UV absorbance coefficient values between 0.2 and 0.9 cm<sup>-1</sup>. In similar fashion, solutions are presented in Figure 7-29 and 7-30 for the staggered uniform array, and the concentric array, respectively.

Figure 7-31 presents the solutions for the tubular array, in which the lamp/tube/lamp centerlines are

**Figure 7-25. Schematic of uniform and staggered uniform lamp arrays.**



15 cm, as shown on Figure 7-26(b). The density for the system is adjusted by changing the diameter of the Teflon tube. Current designs use the 15 cm centerline configurations with a Teflon tube diameter of 8.9 cm.

An additional analysis is presented on Figure 7-32 for the tubular array configuration. This presents a comparison of the solutions for the 15 cm centerline spacing to the more compact (but equivalent density), 10 cm centerline spacing configuration. The tube diameter is 6 cm ( $D = 1.95 \text{ W/L}$ ); the nominal UV intensity is shown as a function of the UV absorbance coefficient. By drawing the lamps in closer to the Teflon tube, greater energy efficiency is achieved. The compactness of the tubular array, however, will be influenced and limited by practical fabrication considerations.

As shown on Figure 7-33, the greater efficiency is demonstrated by the quartz arrays. The tubular arrays are shown to be less efficient in accomplishing an intensity for a given UV density. This is an artifact of the physical constraints on the unit fabrication. In order to arrange the lamps and tubes and still maintain the system for easy assembly/disassembly and for access to these components, there will be limits as to how closely spaced the lamps and tubes can be.

#### 7.3.3.4 Energy Loss Factors to Adjust the Nominal Average Intensity Estimate

An important note applies to the solutions presented in Figures 7-28 through 7-33; the intensity is calculated at the nominal output of the lamp and assumes that the quartz sheath or the Teflon tube will transmit 100 percent of the energy emitted by the lamp. Thus, the term "nominal" average intensity. Under actual operation, and for design purposes, this nominal average intensity must be adjusted to account for the aging of the lamps, and the consequent reduction in UV output, and for the losses of energy as it passes through the quartz sleeve or Teflon tube wall. These losses are due to the quartz or Teflon wall itself and to fouling of the inside and outside surfaces. Thus, in order to estimate the actual intensity under a given set of conditions, it is necessary to adjust the nominal intensity:

$$I_{\text{avg}} = (\text{Nominal } I_{\text{avg}}) \times (F_p) \times (F_t) \quad (7-30)$$

where:

$F_p$  = the ratio of the actual output of the lamps to the nominal output of the lamps

$F_t$  = the ratio of the actual transmittance of the quartz sleeves or Teflon tubes to the nominal transmittance of the enclosures; the nominal transmittance is presumed to be 100 percent in the intensity calculation

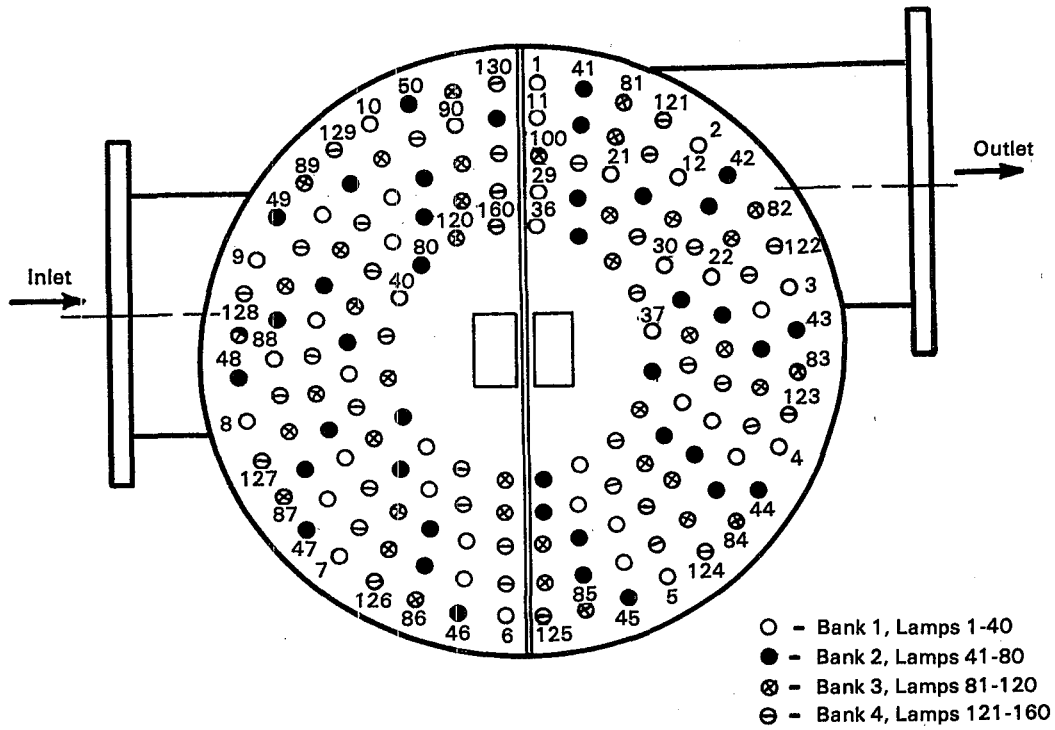
Procedures are described in a later section to directly monitor the average values of  $F_p$  and  $F_t$  for a given system, and are strongly recommended as control procedures in a plant's O&M program.

When designing a new unit, it is suggested that the system be designed at an average  $F_p$  of 0.7, which is representative of a lamp inventory output at approximately one half its operating life. In a sense, economics come into play here. The UV lamps are expensive. Their rated life of 7,500 hours can sometimes be greatly exceeded, but at a cost of reduced output. The inefficiency may be balanced by not having to buy new lamps.

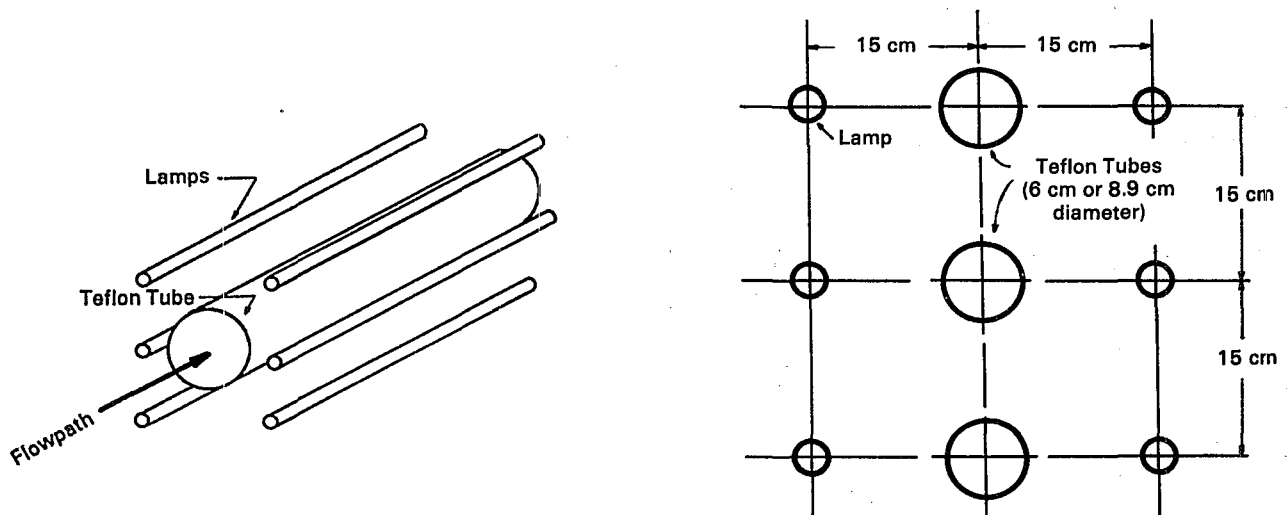
The  $F_t$  should reflect the anticipated maintenance input; if the system will be well attended, a reasonable



Figure 7-26. Schematic of concentric and tubular lamp arrays.

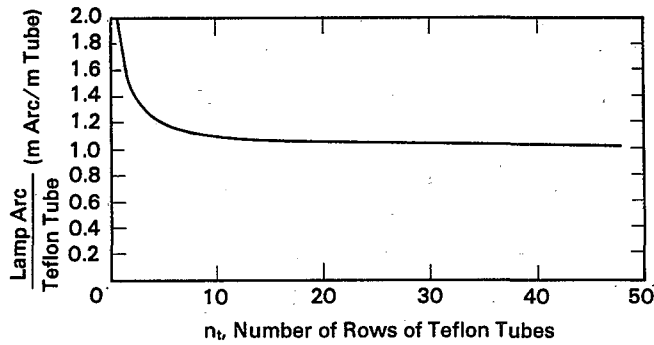


(a) Concentric Array

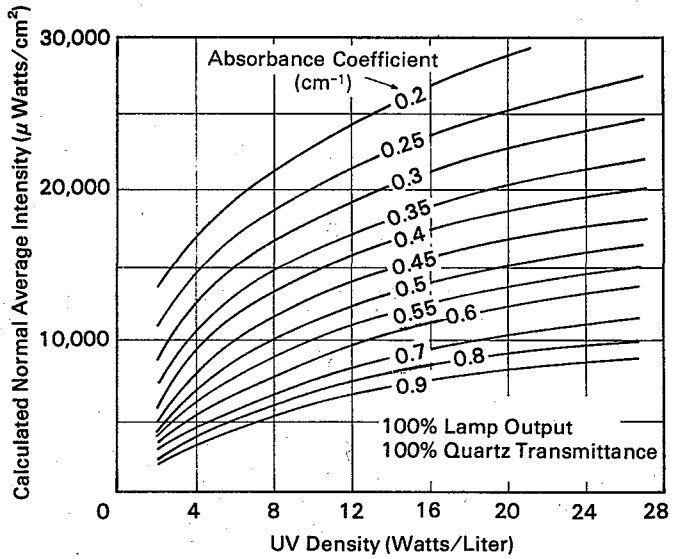


(b) Tubular Array

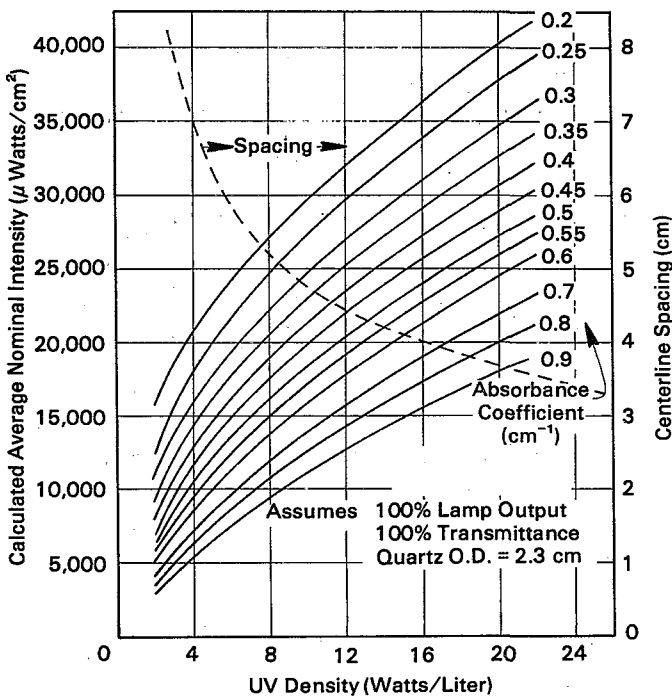
**Figure 7-27. Effect of Teflon system sizing on the power requirement efficiency.**



**Figure 7-29. Staggered uniform array intensity as a function of UV density and UV absorbance coefficient.**



**Figure 7-28. Uniform lamp array intensity as a function of the reactor UV density and UV absorbance coefficient.**



**Figure 7-30. Concentric lamp array intensity as a function of UV density and absorbance coefficient.**

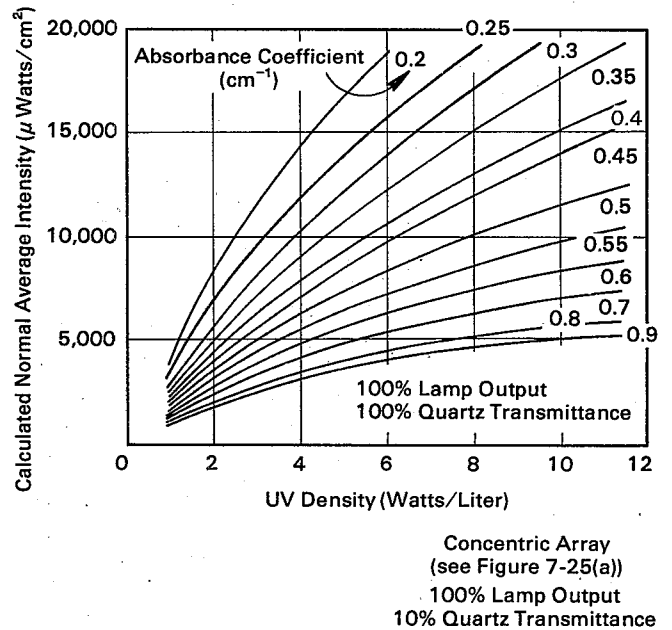


Figure 7-31. Tubular array (15 cm  $\phi$ ) intensity as a function of UV intensity and UV absorbance coefficient.

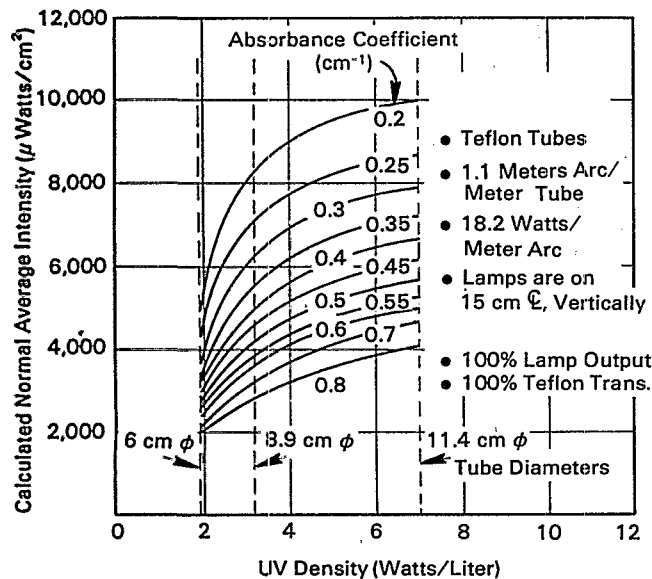
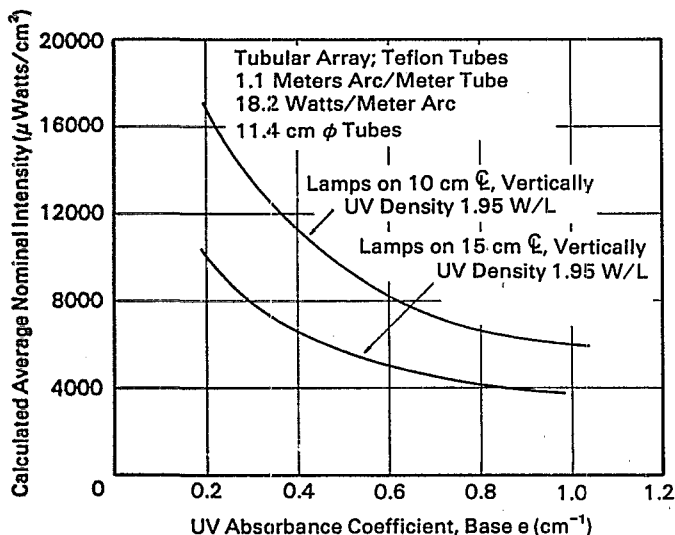
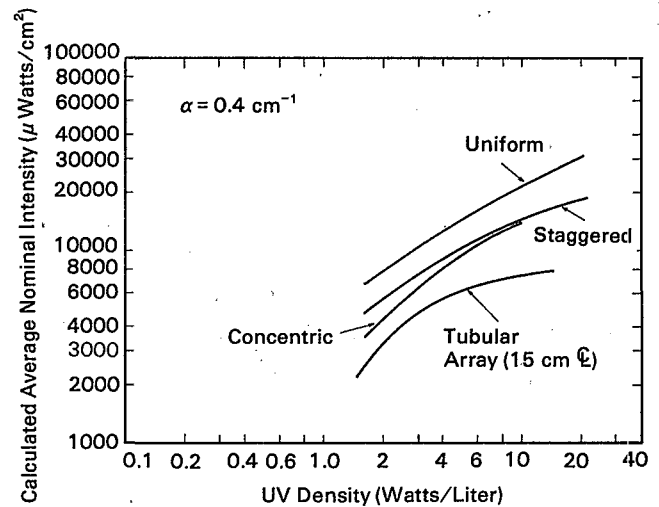


Figure 7-32. Effect of centerline spacing on intensity for tubular arrays of the same UV density.



minimum  $F_t$  would be 0.7 for a quartz system and 0.6 for a Teflon system. If minimal operator attention is anticipated, or if the enclosures are especially prone to fouling due to wastewater conditions, an  $F_t$  of 0.5 to 0.6 may be more appropriate for the quartz units and 0.4 to 0.5 for the Teflon unit.

Figure 7-33. Calculated intensity as a function of UV density for different lamp array configurations.



### 7.3.3.5 Summary—Estimation of the Average Reactor Intensity

The arrays which have been presented in these discussions encompass almost all configurations which are utilized in current systems, and which are practicable for future applications. Thus, the relationships on Figures 7-28 through 7-32 represent, in effect, solutions to the nominal average intensity calculations for any given practical lamp configuration. As long as the arrangement being considered can be represented closely by one of these solutions it is not necessary to independently apply the point source summation calculations. This would apply to units which will not be strongly affected by boundary conditions, which holds for systems with greater than 40 lamps.

Finally, the nominal intensity of the given configuration must be adjusted by the factors  $F_p$  and  $F_t$  to account for the actual (or planned) average lamp output and average transmittance of the quartz or Teflon enclosure.

### 7.3.4 Wastewater Quality Considerations in the Design of a UV System

Certainly, a major element in the effective design of a UV disinfection system is a clear and concise understanding of the characteristics of the wastewater to be treated. These are directly related to degree of pretreatment the material will receive before the disinfection step and certainly affect the sizing and performance of the disinfection system. Pretreatment ranges from very minimal, as in the case of combined sewer overflows and primary effluents, to very high quality, as in the case of advanced tertiary plants. Typically, with regard to UV disinfection application, the wastewater will result from secondary and advanced treatment facilities.

The following discussions will present the key elements of the wastewater application as they apply to the design, (and subsequent operation) of a UV disinfection system:

- wastewater quality parameters. These are the flow (Q), initial bacterial density ( $N_0$ ), suspended solids (SS), and UV absorbance coefficient ( $\alpha$ );
- estimated bacterial density associated with the suspended solids ( $N_p$ ). This includes a determination of the coefficients  $c$  and  $m$  in Equation (7-13);
- estimated inactivation rate (K). Recall that this is set as a function of the average intensity, requiring a determination of the coefficients  $a$  and  $b$  in Equation (7-12).

Relevant wastewater characterization data (including estimates of the coefficients,  $a$ ,  $b$ ,  $c$ , and  $m$ ) from existing wastewater treatment plants are summarized to demonstrate the range of values to be expected under typical wastewater applications.

Photoreactivation is then discussed, with a presentation of field data to demonstrate levels of repair one can expect to occur. Finally, some discussion is given to sampling considerations and to suggested monitoring programs.

#### 7.3.4.1 Key Wastewater Quality Parameters

The four wastewater parameters which most affect the design or performance of a UV system are the flow, initial bacterial density, suspended solids (or some measure of the particulates in the wastewater), and the UV absorbance of the wastewater.

**Flow Rate.** The flow rate is set by design of the main plant and projections of the hydraulic load to the plant. In evaluating the design requirements for the disinfection process, some consideration should be given to the equalization effects of the treatment processes before disinfection. This can have an effect on the sizing of the UV system.

Flow estimates should be for the design year of the plant. There should also be some knowledge of the progressive increase in the flows through the design life of the plant in order to determine if the system can be phased in by the addition of modules as the demand increases. Some consideration should also be given to the hydraulic load to the unit. The flow rates important to the design and evaluation of the system are those typically considered for wastewater treatment systems:

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

For disinfection, average flows are not critical to the design sizing; rather they are important to estimating average utilization of the system for operation and maintenance needs. Peak flows should be used for sizing, particularly reflecting diurnal variations.

**Initial Coliform Density.** The performance of a UV disinfection system is directly related to the initial density of the indicator organisms. This is not a parameter which is generally monitored at a treatment plant, particularly where the disinfection is accomplished by chlorination. In the case of disinfection by UV, however, it is critical. Performance is given by the log of the survival ratio,  $N/N_0$ , or by the number of "logs" the density is reduced.

Expected initial densities cannot be predicted solely from the type of treatment process preceding the disinfection process. Order of magnitude levels are given in Chapter 2 as guidelines. Examples drawn from several plants (presented in a later discussion) vary widely and do not correlate well with the types of systems or plant residence time. It is recommended that these data be generated before design; effluents can be analyzed from similar plants in the area, or at the existing facility if an upgrade or retrofit is being considered.

**Suspended Solids.** From the development of the disinfection model, it is clear that the occlusion of bacteria in the particulates will have a significant effect on the design of a UV system. It is recommended that the suspended solids measurement be used as the primary indicator to quantify these particulates.

The level of suspended solids in the effluent of a wastewater treatment facility is, in effect, set by the design of the plant. This then will limit the range of suspended solids concentrations to be considered in the design of the UV process. A further consideration is to understand the variability associated with the effluent suspended solids. As an example, if a plant is designed not to exceed 30 mg/l on average for any consecutive 30-day period, the suspended solids levels it must meet on an annualized basis will likely be between 10 and 20 mg/l. This can affect the sizing of a UV facility and determination of its average operational requirement.

**UV Absorbance.** The one parameter which is solely in the venue of UV disinfection is the UV "demand" of the wastewater. Specific organic and inorganic compounds in the wastewater will absorb energy at the 253.7 nm wavelength. This absorbance will affect the intensity of the radiation within the reactor; in specific design situations, the level of absorbance will affect the sizing of a system and possibly the configuration (spacing) of the lamps. Recall from the discussions of intensity, and its calculation in a

complex reactor, that the final product of these calculations is the average nominal intensity as a function of the UV absorbance coefficient.

There are a number of ways to express the absorbance of a wastewater. First, consider the manner in which it is measured. The wastewater sample is placed in a quartz cell (transparent to the 253.7 nm wavelength) of a given width. A spectrophotometric measurement of the absorbance is made of a direct beam of light (at 253.7 nm) which is passed through the quartz cell containing the liquid. A detector determines the amount of light which passes through, and by inference, the amount of light "absorbed" by the liquid sample can be determined. The output of this measurement is absorbance units per centimeter, or a.u./cm. The pathlength is set by the quartz cell; typically this is 1 centimeter.

The transmittance of the wastewater is a common parameter used to describe the "demand" of the wastewater. This can be determined from the absorbance measurement, and is most often expressed on a percent basis:

$$\% \text{ Transmittance} = 100 \times 10^{-(\text{a.u./cm})} \quad (7-31)$$

Conversely, the percent absorbed is simply 100 percent minus the percent transmittance. The parameter which is most often used for design purposes, and is the parameter used within the context of this manual, is the UV absorbance coefficient, expressed in base e:

$$\text{UV absorbance coefficient, } \alpha = 2.3(\text{a.u./cm}) \quad (7-32)$$

The unit of the UV absorbance coefficient is  $\text{cm}^{-1}$ . The reader is referred to Section 7.1.2 which presents typical absorbance levels for varying degrees of treatment.

The single beam, spectrophotometric method for measuring the UV absorbance of the liquid is the simplest procedure, requiring minimal effort and instrumentation. It is important to note however, that this "direct" UV absorbance measurement assumes that light which does not pass through the cell and is not seen by the detector has been absorbed by the liquid. This is not necessarily the case, especially in samples which have suspended or colloidal particles in the liquid. These will cause a portion of the light to be scattered; the light is still available, but it will not be seen by the detector since it has been deflected from its direct path through the quartz cell. Thus, the direct method tends to overestimate the "true" absorbance of the liquid.

Johnson and Qualls (38) and Scheible et al. (52), demonstrated that suspended or colloidal particles will not absorb any significant amount of light energy

and will in fact scatter the light back to the liquid. It becomes important, therefore, that the absorbance measurement must in some fashion account for the scattering effect and give a value representative of the true absorbance of the liquid. Note that the procedures to calculate the intensity in a reactor inherently presume that the UV absorbance coefficient reflects the true absorbance of the liquid.

The Port Richmond study incorporated the use of a standard accessory to the UV/Visible spectrophotometer which would correct the absorbance measurement for the effect of scattering. A sphere, in effect, surrounds the quartz cell; any scattered light is absorbed on the surface of the sphere, which integrates the quantity of light collected and corrects the absorbance measured by the direct beam detector. This absorbance, referred to by the Port Richmond report as the "spherical" absorbance coefficient, is felt to more closely represent the true absorbance of the liquid, and is more appropriate for use in estimating the intensity in a reactor.

In the case where the capability to measure the corrected UV absorbance coefficient is not available, the UV absorbance coefficient should, at minimum, be determined on filtered samples by the direct method. In most cases this will give an approximation of the true absorbance. The results would be further improved if this is accomplished by membrane filtration to remove particles greater than 1 micron in size. Care should be taken to prewash the filters; in some instances the filter material itself can contribute UV absorbing materials.

At Port Richmond, limited testing was conducted on an in-line continuous monitor of the UV absorbance. This was a prototype instrument which would continuously sample the influent of a UV system and determine the UV absorbance at 253.7 nm; the instrument would also correct, to some degree, for scattering. The monitor was found to respond well to the absorbance of the wastewater. Such a direct monitor would be useful, in conjunction with the flow rate meter, in controlling the operations of a UV system.

The daily average, maximum 7-day, and the maximum 30-day average UV absorbance coefficient would be important to design. Unlike the suspended solids, which is limited by permit and by the treatment process, the UV absorbance coefficient is not a parameter describing treatment goals. It is an artifact of the wastewater and the treatment of that wastewater. Thus, an estimate will have to be made of the UV absorbance coefficient, and its variability, either by direct measure of the treated wastewater (as in the case of an existing plant) or a similar wastewater undergoing the same degree of treatment.

In summary, the parameters of primary concern regarding the characteristics of the wastewater are the flow rate, UV absorbance coefficient, suspended solids, and initial coliform density. The peak design condition for a plant should not necessarily consider the concurrent occurrence of these parameters as the worst case condition. If sufficient data are available, running averages of combinations of these parameters should be constructed to determine the maximum 7-day and 30-day average of the combined parameter set.

The maximum 7-day coliform density may occur under average flow conditions, as an example. Analysis of the data in this fashion may allow a more realistic system sizing to achieve the desired performance under the anticipated worst case condition.

### 7.3.4.2 Estimating $N_p$ , the Bacterial Density Associated with the Suspended Solids

The estimate of  $N_p$  requires generating data under high dose levels. Recalling earlier discussions, the premise is that by determining the residual density after high doses, the residual can be attributed to those bacteria which were occluded from the radiation. These are then correlated to the suspended solids concentration which were present in the same sample.

In effect, one is generating information which is well out on the "tail" of a typical dose-response curve (see Figure 7-14). An example is given on Figure 7-34, which shows the log effluent fecal coliform (after exposure) plotted against the log effluent suspended solids. These data are from the Port Richmond study. A linear regression analysis yields the expression (when transformed):

$$N_p = 0.26 SS^{1.96} \quad (7-33)$$

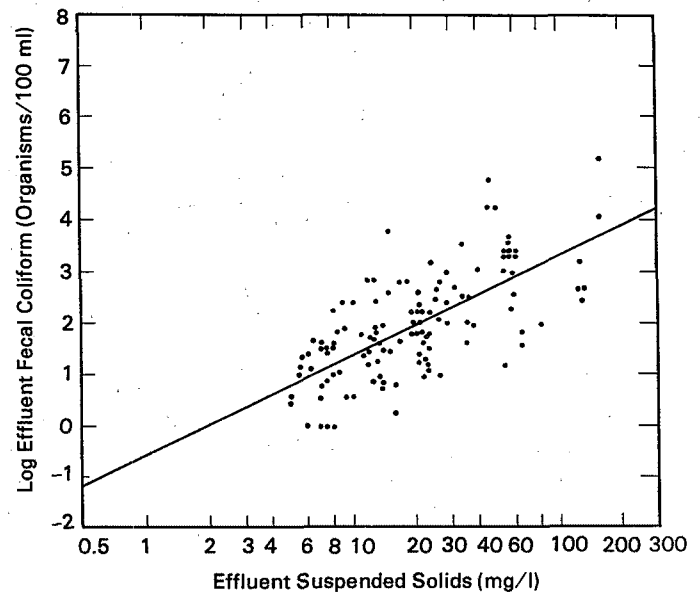
where  $N_p$  is in the units colonies/100 ml and SS is in mg/l. The coefficients 0.26 and 1.96 are the values of  $c$  and  $m$ , respectively, from Equation 7-13. The intercept of the regression on Figure 7-34 is  $c$ ;  $m$  is the slope.

It is best to determine  $c$  and  $m$  by direct testing. Values determined at several plants are presented in a later section. These had been developed from flow-through tests. Although batch tests have not been conducted, one should expect that these would provide acceptable data under the proper conditions.

### 7.3.4.3 Estimating the Inactivation Rate, $K$

It is necessary, again, to generate a specific set of data to estimate the inactivation rate as a function of the average intensity. The required samplings are those in which the operating conditions would not allow for maximum kill at some point in the reactor. In other

Figure 7-34. Example of deriving an estimate of the residual fecal coliform density associated with particulates as a function of suspended solids (55).



words, the apparent dose is low enough such that a significant coliform density would still be evident in the exposed effluent. This allows a valid estimate of the rate of inactivation in a specific sampling utilizing the initial and final coliform densities. One is, in effect, operating in the portion of the dose-response curve (see Figure 7-14), where the relationship is linear, with a constant slope.

The data are generated by piloting a system on the subject wastewater. For proper analysis of the data, the hydraulic characteristics of the unit need to be determined; these are the dispersion number and the dispersion coefficient. Once the data subset is developed, the rate coefficient can be estimated for each sampling by manipulation of the model equation (Equation 7-10) to solve for  $K$ . Estimates are first made of  $N_p$  from the suspended solids data and Equation 7-13, as described above. This is then subtracted from the densities measured after exposure:

$$N' = N - N_p \quad (7-34)$$

Solving Equation (7-10) for  $K$  yields:

$$K = [u^2 (P^2 - 1)]/4E \quad (7-35)$$

where:

$$P = 1 - [2E \ln (N'/N_0)]/ux \quad (7-36)$$

The rate  $K$  has the units  $\text{second}^{-1}$ . Equation (7-35) can be used to solve for  $K$  for each sampling; the inputs are the observed initial and final coliform densities,

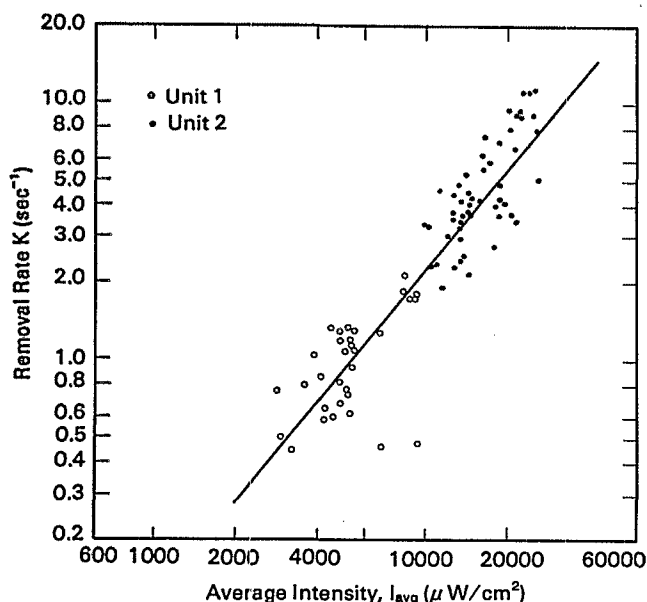
the velocity based on the observed flow rate, the  $x$  dimension based on the operating condition of the unit, and the dispersion coefficient determined for the reactor. These values of  $K$  are then correlated to the estimated  $I_{avg}$  in the reactor corresponding to the conditions for each sampling.

The correlation of  $\log K$  as a function of  $\log I_{avg}$  for fecal coliform data generated at Port Richmond are presented on Figure 7-35 as an example of the rate analysis. Linear regression analysis yielded the expression (when transformed):

$$K = 0.0000145 (I_{avg})^{1.3} \quad (7-37)$$

where  $I_{avg}$  is the average intensity in  $\mu\text{Watts}/\text{cm}^2$ . The coefficients 0.0000145 and 1.3 are the values of the intercept  $a$  and the slope  $b$ , respectively, of Equation 7-12. Values of  $a$  and  $b$  derived at a number of plants are presented in a later section.

Figure 7-35. An example for deriving an estimate of the inactivation rate for fecal coliforms as a function of the calculated average intensity (55).



Batch testing, although not applied or demonstrated at the time of this publication, can also be used to derive the coefficients  $a$  and  $b$ . A clear advantage to the batch technique would be its independence of hydraulic considerations.

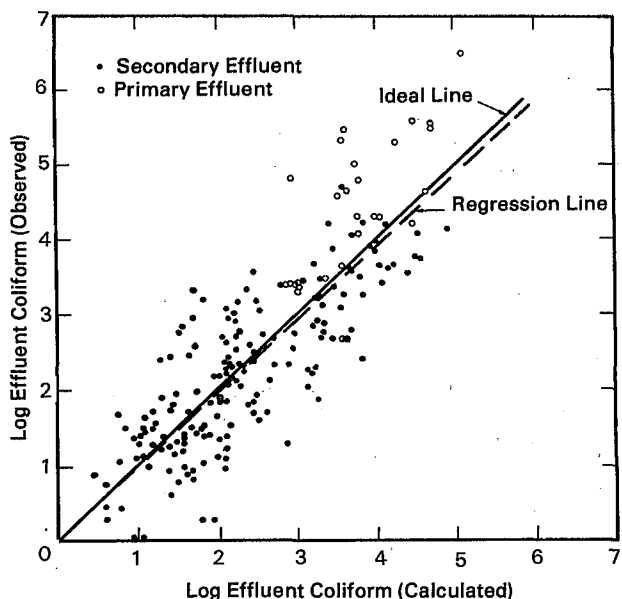
#### 7.3.4.4 Checking the Coefficients Determined for Use in the Model

The coefficients  $a$ ,  $b$ ,  $c$ , and  $m$  are specific to a given wastewater application and reflect the site-specific sensitivity of the microorganisms to UV ( $a$  and  $b$ ) and

the level to which microorganisms are occluded in the effluent suspended solids. When these are determined by direct piloting, it is appropriate to verify their values by checking against data generated independent of the data set used to derive the coefficients.

Influent and effluent data should be collected over a range of conditions. Using Equation 7-14, calibrated to the proper coefficients and operating conditions, the performance ( $\log N/N_0$ ) can be predicted for a given sample. This can then be compared to the observed performance. Again, an example of this type of analysis is presented on Figure 7-36, which shows the observed versus predicted fecal coliform densities from the Port Richmond study. An analysis of the data indicated that the regression line for the observed versus predicted correlation was not significantly different from the ideal line in which the slope is 1.0 and the intercept is 0.0. In all, the analysis suggests that the model correctly responds to the varying operating parameters of the UV system, and when properly calibrated, will successfully predict performance under any matrix of operating and hardware configurations.

Figure 7-36. An example of the comparison of disinfection model estimates to observed effluent fecal coliform densities (56).



#### 7.3.4.5 Summary of Wastewater Data from Existing Plants and Recent Field Studies

Wastewater quality data were compiled from several wastewater treatment plants. This was done to give the reader a perspective on water quality characteristics, particularly those parameters relevant to the

UV disinfection process. The list of plants is summarized on Table 7-8, including a brief description of the treatment process at the plant and the level of treatment the plant is designed to achieve. The plants were selected because full or pilot scale UV evaluations had been conducted at each yielding a consistent set of data relevant to UV.

The Port Richmond plant is listed first; data are given for both the primary and secondary treatment levels (52). The Suffern, Vinton, and Eden data are from special one-month studies (54). The Northfield plant (59) is an existing full scale facility and is one of the few facilities that routinely monitors on a frequent basis. Data from the 1984 disinfection season are presented. The Tillsonburg plant is a full-scale UV facility in Ontario; data are presented from a long-term demonstration study (48). The Northwest Bergen study entailed a one-year full-scale pilot evaluation (36).

Five plants are listed from Ontario, Canada: Toronto-Main, Georgetown, Milton (secondary and tertiary), Hamilton, and Toronto-Lakeview. They were all sites of UV pilot plant studies (47). Finally, the last four plant sites, New Windsor, Newburgh, Suffern, and Monticello (secondary and tertiary), are from special pilot studies conducted in 1985 (52). These studies also investigated the inactivation rate,  $K$ , and the particulate coliform density,  $N_p$ , as will be presented in the following discussions.

**Initial Bacterial Density.** Average bacterial densities are summarized on Table 7-9. These are all geometric means. The fecal coliforms are listed in all cases; this remains the indicator of choice in almost all permitting activities. Other indicators are listed when available.

As can be seen, there is little consistency in the density levels, nor is there any obvious correlation to the level of treatment. The fecal coliforms range from  $10^4$  to  $10^6$ ; for the purpose of preliminary sizing and/or system designs, a reasonably conservative initial fecal coliform density,  $N_o$ , would be  $2$  to  $5 \times 10^5$  for secondary treatment levels, and  $1$  to  $2 \times 10^5$  for tertiary levels.

**Treated Effluent Quality.** Table 7-10 presents average UV absorbance coefficient data and suspended solids information for each of the plant sites. Where available, turbidity, COD, and TKN data are also provided. Of particular interest is the UV absorbance coefficient; in all cases, the direct measurement (unfiltered) is provided. In several cases, both the direct and spherical measurements (unfiltered and filtered) are presented. Recalling the discussions in Section 7.3.4.1, the preferred method is the spherical (unfiltered) since it corrects for scattering and is the most representative of the actual UV absorbance

characteristics of the wastewater. An alternative is to use the direct method on a filtered sample; except for a few cases, this is shown to give a reasonable approximation of the spherical UV absorbance coefficient.

The direct analysis of an unfiltered sample is certainly the easier procedure, requiring no sample preparation or special accessory to the UV spectrophotometer. Figure 7-37 indicates an excellent correlation between the direct (unfiltered) and spherical (unfiltered) data from nine plants. Thus, for preliminary design purposes, it is reasonable to estimate the spherical absorbance coefficient from the direct (unfiltered) analysis:

$$\alpha_s = 0.6 (\alpha_D)^{0.64} \quad (7-38)$$

where  $\alpha_s$  and  $\alpha_D$  are the spherical and direct (unfiltered) absorbance coefficients (base e), respectively, with the unit ( $\text{cm}^{-1}$ ).

**Inactivation Rate,  $K$ .** Several plant sites were evaluated to directly determine the inactivation rate,  $K$ , as a function of the UV intensity (52). These used 2 pilot units; each had 12 lamps and differed only in spacing, and, therefore, in intensity. The results are presented on Figure 7-38, including the coefficients  $a$  and  $b$  (Equation 7-12). The Port Richmond regression (from Figure 7-34) is also presented (this also used two units, each differing significantly in intensity).

There is significant variability among the regression coefficients presented on Figure 7-38, although the actual values of  $K$  are not as varied. At the lower intensities ( $\sim 3000$ ) the average  $K$  ranges between  $0.2$  and  $0.6 \text{ sec}^{-1}$ , a factor of 3. The  $K$  ranges between  $1.6$  and  $3.8$  at an  $I_{\text{avg}}$  of  $10,000$ , a factor of 2.4.

The data from the four plants were combined; the resulting regression line is also given on Figure 7-38. The Port Richmond plant is shown to be nearly equivalent to this combined regression.

At this point, sufficient data are not available to clearly demonstrate a uniformity in the  $K$  rate as a function of the  $I_{\text{avg}}$ . For this reason, it is strongly suggested that these data be generated by direct testing for specific plant applications. Preliminary design calculations can use an  $a = 1.4 \times 10^{-5}$  and a  $b = 1.3$ , based on the results of the Port Richmond and combined plants regression analysis. The reader should understand that the  $I_{\text{avg}}$  is estimated on the basis of the spherical absorbance coefficient.

**Particulate Density,  $N_p$ .** The same plant studies which had evaluated the inactivation rate, also evaluated, on a limited basis, the coliform density associated with the suspended solids. These data are shown on Figure 7-39. As would be expected, there is



**Table 7-8. Wastewater Treatment Plants Which are Sources of Wastewater Characterization Data**

Treatment Plant Location	Treatment Level	Description
Port Richmond WPCP Staten Island, NY	Secondary	Step aeration activated sludge, secondary clarification
Port Richmond Staten Island, NY	Primary	High rate primary clarification
Suffern, NY	Advanced	Trickling filter; single stage (nitrification) activated sludge, clarification
Vinton, IA	Secondary	Extended aeration activated sludge, final clarification
Eden, WI	Secondary	Activated sludge, secondary clarification
Northfield, MN	Secondary	RBC and secondary clarification
Tillsonburg, Ontario	Secondary	Activated sludge; clarification
NW Bergen, NJ	Advanced	Single stage (nitrification) activated sludge; clarification
Toronto-Main, Ontario	Secondary	Conventional activated sludge
Hamilton, Ontario	Secondary	Conventional activated sludge
Georgetown, Ontario	Secondary	Conventional activated sludge
Milton, Ontario	Secondary	Conventional activated sludge
Milton, Ontario	Tertiary	Conventional activated sludge; rapid sand filtration
Toronto-Lakeview Ontario	Secondary	Conventional activated sludge
New Windsor, NY	Secondary	Trickling filters; clarification
Newburgh, NY	Secondary	Activated sludge; clarification
Suffern, NY	Advanced	Trickling filters; single stage (nitrification) activated sludge; clarification
Monticello, NY	Secondary	Oxidation ditch; secondary clarification
Monticello, NY	Tertiary	Oxidation ditch; secondary clarification; sand filtration

considerable scatter, not unlike the variability shown on Figure 7-34 for the Port Richmond study. The data tend to fall about the regression line developed for Port Richmond. This poor correlation can be due to several factors, including analytical precision at low levels; site differences; differing particle size distributions; etc. For preliminary design purposes, it is suggested that the coefficients  $c$  and  $m$  be set to 0.25 and 2.0, respectively.

#### 7.3.4.6 Photoreactivation

The phenomenon of photoreactivation had been described in Chapter 7.2.2.2. Unique to ultraviolet radiation, the mechanism involves the repair of

damage caused by exposure to UV, allowing for subsequent replication of the organism. The enzymatic mechanism generally involved requires subsequent (or concurrent) exposure to light at wavelengths between 300 and 500 nm; such light is available in sunlight and in most incandescent and fluorescent light sources.

The procedure to quantify the effects of photoreactivation is by the so-called static bottle technique. The method involves splitting an exposed sample to three aliquots: the first is set immediately for coliform enumeration; the second is placed in a bottle opaque to visible light; and the third is placed in a bottle

**Table 7-9. Initial Bacterial Density Before Disinfection<sup>a</sup> (organisms/100 ml)**

Plant	Treatment Level	Total Coliforms	Fecal Coliforms	Fecal Streptococci	<i>Escherichia coli</i>	<i>Pseudomonas aeruginosa</i>
Port Richmond	Secondary	1,020,000	361,000	-	-	-
Port Richmond	Primary	31,700,000	12,500,000	-	-	-
Suffern	Advanced	-	95,500	25,120	-	-
Vinton	Secondary	-	89,100	-	-	-
Eden	Secondary	-	44,700	21,400	-	-
Northfield	Secondary	-	75,500	-	-	-
Tillsonburg	Secondary	53,000	15,600	1,240	-	-
NW Bergen	Advanced	190,000	48,000	-	-	-
Toronto-Main	Secondary	1,300,000	120,000	33,000	110,000	2,500
Hamilton	Secondary	1,300,000	180,000	15,000	30,000	1,300
Georgetown	Secondary	77,000	9,200	3,500	8,300	29
Milton	Secondary	140,000	23,000	1,900	22,000	140
Milton	Tertiary	77,000	13,000	820	6,600	40
Toronto-Lakeview	Secondary	160,000	14,000	2,500	12,000	80
New Windsor	Secondary	-	1,900,000	-	-	-
Newburgh	Secondary	-	77,000	-	-	-
Suffern	Advanced	-	60,800	-	-	-
Monticello	Secondary	-	1,124,000	-	-	-
Monticello	Tertiary	-	736,000	-	-	-

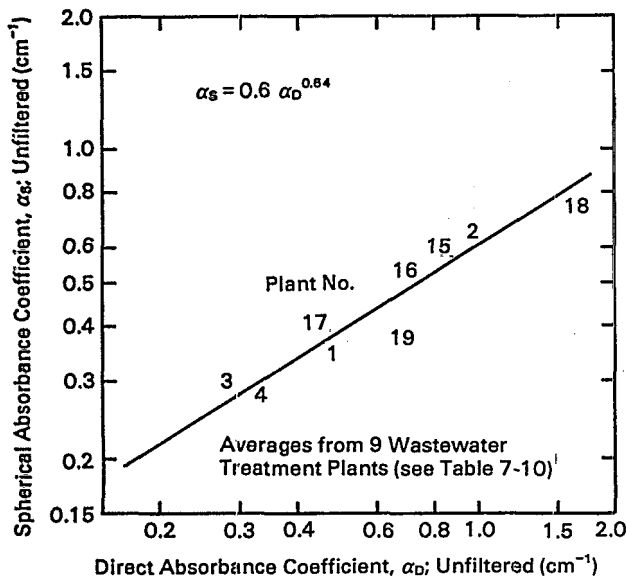
<sup>a</sup>Geometric Means; data from analysis of grab samples.

**Table 7-10. Treated Effluent Characteristics From Several Wastewater Treatment Plants<sup>a</sup>**

Plant	Treatment Level	Average UV Absorbance Coefficient (base e) (cm <sup>-1</sup> at 253.7 nm)				Suspended Solids (mg/l)	Turbidity (NTU)	COD (mg/l)	TKN (mg/l)
		Direct		Spherical					
		(Total)	(Filtered)	(Total)	(Filtered)				
Port Richmond	Secondary	0.466	0.404	0.372	0.358	14.3	4.0	44.5	6.9
Port Richmond	Primary	0.865	0.747	0.593	0.533	80.9	25.7	134.0	-
Suffern	Advanced	0.290	0.273	0.282	0.271	8.3	4.4	34.4	-
Vinton	Secondary	0.331	0.275	0.296	0.260	8.3	-	28.9	-
Eden	Secondary	0.391	0.354	-	-	33.2	8.6	39.0	-
Northfield	Secondary	0.378	-	-	-	12.2	-	-	-
Tillsonburg	Secondary	0.250	-	-	-	6.1	1.9	14.6	1.2
NW Bergen	Advanced	0.390	-	-	-	6.4	3.7	28.0	14.0
Toronto-Main	Secondary	1.07	-	-	-	26.8	6.3	92.0	28.6
Hamilton	Secondary	0.565	-	-	-	12.2	3.2	39.1	26.5
Georgetown	Secondary	0.348	-	-	-	5.8	2.0	34.8	14.5
Milton	Secondary	0.366	-	-	-	9.1	2.0	38.8	9.2
Milton	Tertiary	0.271	-	-	-	2.6	1.2	23.2	4.3
Toronto-Lakeview	Secondary	0.657	-	-	-	6.4	3.2	49.1	3.9
New Windsor	Secondary	0.894	0.705	0.578	0.500	31.6	-	-	-
Newburgh	Secondary	0.739	0.495	0.518	0.444	26.7	-	-	-
Suffern	Advanced	0.454	0.379	0.374	0.362	7.3	-	-	-
Monticello	Secondary	1.627	0.589	0.766	0.352	72.4	-	-	-
Monticello	Tertiary	0.687	0.440	0.416	0.328	13.3	-	-	-

<sup>a</sup>Arithmetic means; data from analysis of grab samples.

Figure 7-37. Correlation to estimate the spherical absorbance coefficient from direct unfiltered absorbance coefficient.



transparent to visible light. The two bottles are then held for sixty minutes (this time is not standard, it can vary from one half hour to three hours), at 20°C, exposed to sunlight. The samples would then be set for coliform enumeration; the opaque bottle is the "dark" sample, and the transparent bottle the "light" sample. Holding the visible light exposure at constant temperature (20°C) is not critical. In situations where it is desired to monitor photoreactivation seasonally, it is more appropriate to suspend the two bottles just below the surface of the plant effluent or the receiving water. In this fashion, the degree of photoreactivation is being monitored under current temperature conditions.

The repair mechanism has a dependency on temperature (36). The analysis suggests that at 10°C, a two-fold increase in fecal coliform density will be caused by photoreactivation. If the temperature is approximately 20°C, a ten-fold (one log) increase in the effluent density is observed.

A series of tests were also conducted as part of the Port Richmond study to evaluate the impact of photoreactivation. Again, the tests centered on the indicators total and fecal coliforms, and utilized the static bottle technique. The resultant data are presented on Figure 7-40, which is taken from the Port Richmond report. Total and fecal coliforms at time 0 and 60 minutes (light) are plotted as a function of the loading parameter,  $Q/W$ , which is the ratio of flow (Lpm) to the UV output of the system (Watts at 253.7 nm). The suspended solids averaged 11.8 mg/l during

Figure 7-38. Comparison of inactivation rate estimates from several wastewater treatment plants.

	$a ( \times 10^{-5} )$	$b$
— Newburgh	1.08	1.29
- - - New Windsor	0.00061	2.2
- - - Suffern	0.004	1.92
- - - Monticello (Unfiltered)	0.69	1.4
- - - Monticello (Filtered)	10.0	1.09
— Combined	1.387	1.28
- - - Port Richmond	1.45	1.3

$I_{avg}$  Based on Spherical Absorbance Coefficient

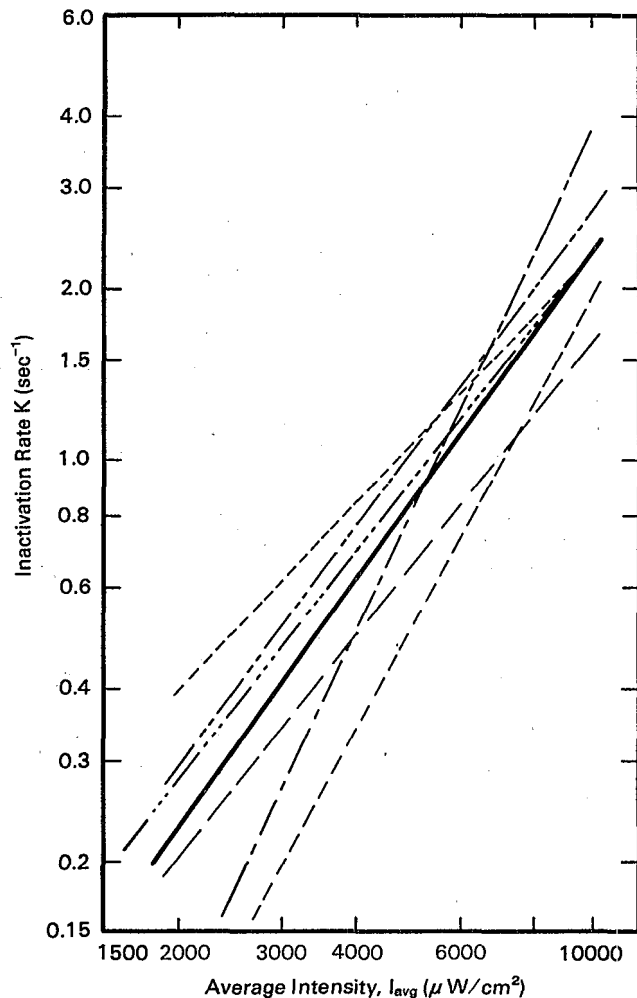
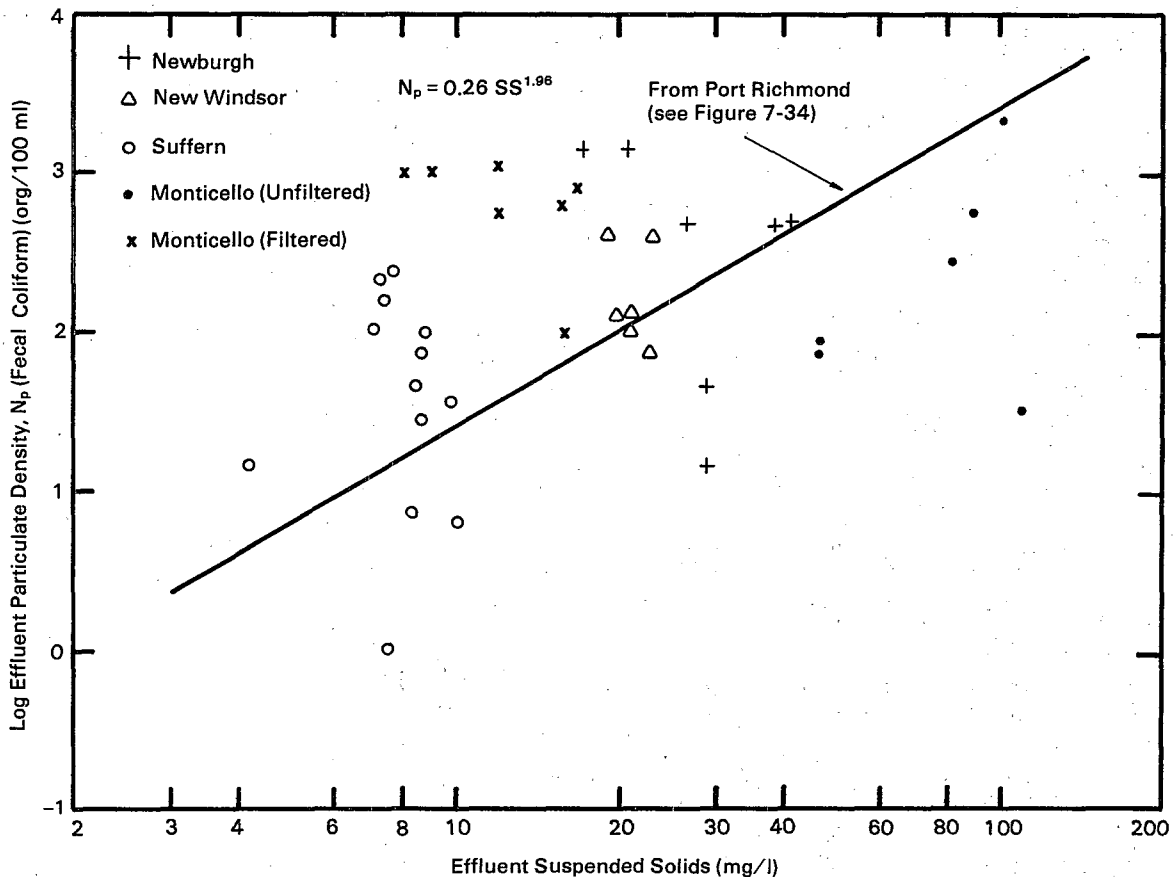


Figure 7-39. Estimation of  $N_p$  from several plants.



this period and the average spherical absorbance coefficient was  $0.448 \text{ cm}^{-1}$ . The temperature was approximately  $23^\circ\text{C}$  during the test period. As shown on the figure, the photoreactivation mechanism causes an increase of approximately 1.3 logs in either the total or fecal coliform: The increase is relatively constant, regardless of the applied dose. This is expected, since the degree of photoreactivation is independent of dose.

At present, the effects of photoreactivation are not directly addressed in most state permitted activities. Thus, it is appropriate to minimize the effect in the sampling and analysis of the exposed effluent. The degree to which this phenomenon exists among the pathogenic organisms is not fully understood; as an example streptococci do not photorepair, while *Shigella* do exhibit the ability. Viruses generally cannot photorepair, except in cases where the host cell can photoreactivate.

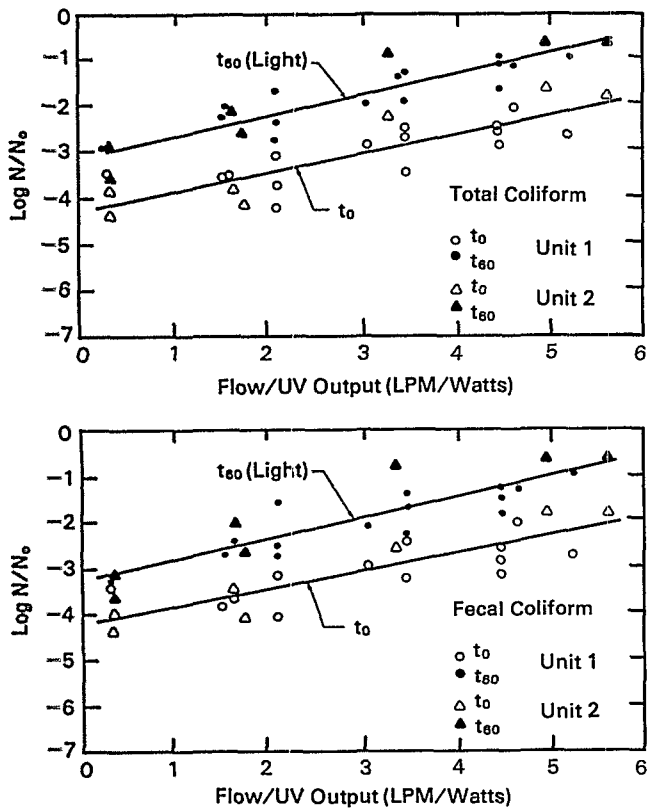
If the permitting agencies require that the photorepair phenomenon must be addressed in assessing the performance of a UV disinfection process, the design of the process can accommodate such a requirement.

Based on the results of previous studies, it is also appropriate to assume that total and/or fecal coliforms would still serve as adequate indicators of pathogen activity. The design of the system must now address the inactivation of an additional fraction of the initial coliforms in order to meet guidelines after photorepair takes place. The critical design period is during the warmer temperature, higher sunlight intensity summer months. The system should generally be designed to accomplish approximately one additional log reduction. Thus, if it is determined that a 3-log reduction will be required to meet the permit levels, the system should be designed to accomplish a 4-log reduction to account for the effect of photoreactivation.

#### 7.3.4.7 Wastewater Sampling Considerations for Design

The design and performance monitoring of a disinfection process is based on the measure of bacterial density. These are typically coliforms or fecal strep. Sampling for these can be accomplished only on a grab basis. Furthermore, the sampling for coliforms must typically be accomplished during daylight hours, often set between 10 a.m. and 3 p.m. This time period

Figure 7-40. Photoreactivation effects for total and fecal coliform at Port Richmond (55).



is considered the maximum loading period for a treatment plant, and reflects the maximum density levels with regard to the disinfection process. With this in mind, it is appropriate that the data that are generated to characterize the effluent for suspended solids, UV absorbance, initial coliform density, and flow should also be collected as grab (or short-term) analyses, and should correspond to the time of day in which the system is to be monitored for disinfection performance.

Twenty-four hour composites, which are typically collected at a plant, will not directly reflect conditions under which the system should be designed. At minimum, sufficient data should be generated to understand the variability of these parameters during a diurnal period. There is an additional benefit which can be gained from this information. The data will likely indicate significant improvement in absorbance and lower initial densities and suspended solids during the off-peak, early morning hours. The system can be adjusted to account for this, potentially resulting in energy savings.

The data base developed for design should reflect analyses of grab samples taken during the peak load

hours. The parameters which must be monitored include suspended solids, coliform density, and the UV absorbance coefficient. Secondary parameters useful to characterizing a wastewater for design purposes are grease/oil, iron, and hardness. These will be important in considering the cleaning requirements of a system.

## 7.4 UV Disinfection System Design Example

The preceding sections presented the various elements important to the design of the UV process. These considered the hydraulic design of a reactor, the intensity of radiation, and the wastewater quality for the specific application. All were related to a design protocol based on a disinfection model (Equation 7-10).

This section presents a design example to demonstrate the use of the design protocol. It does not attempt to provide comprehensive solutions, but rather the procedures and calculations which the designer can use for specific applications. This can encompass several situations: to design a new reactor; to determine the adequacy of a proposed reactor design (e.g., by equipment manufacturer); and/or to evaluate the capacity and design adequacy of an existing system.

### 7.4.1 UV Disinfection Design Example

The example presented in this section of the manual is intended to illustrate the design considerations involved with development of a UV disinfection system. The wastewater treatment design information for the example design problem is shown in Table 7-11. The plant is an air-activated sludge plant located at an elevation of 1,070 m (3,500 ft) above sea level. The influent to the UV disinfection system is the effluent from the secondary clarifiers.

For this example, we are assuming that the wastewater data (fecal coliform and UV absorbance) represent grabs taken during the peak diurnal period (see discussion in Section 7.5.4). The disinfection portion of the plant will operate under gravity flow. There are no area constraints and the plant treats domestic wastewaters only. The plant's permit calls for year-round disinfection.

### 7.4.2 Setting Design Conditions and Parameters for Equipment Sizing

From the disinfection model (Equation 7-10), the information needs, aside from wastewater characteristics described earlier, are an estimate of the dispersion properties of the proposed reactor configuration (i.e., dispersion coefficient and the dispersion number), the inactivation rate,  $K$ , and the coliform density associated with the particulates,  $N_p$ .

**Table 7-11. Example UV Disinfection System Design**

Average Daily Wastewater Flow .....	28.4 mL/d (7.5 mgd)
Peak Daily Wastewater Flow .....	56.8 mL/d (15.0 mgd)

NOTE: The daily peak flow rate will not exceed 15.0 mgd because of storm flow equalization facilities.

Start-up Daily Average Wastewater Flow ..	13.2 mL/d (3.5 mgd)
Start-up Peak Daily Wastewater Flow .....	28.4 mL/d (7.5 mgd)
Average Effluent BOD/TSS .....	15/15 mg/l
Maximum Daily Effluent BOD/TSS .....	30/30 mg/l
Design Required Effluent Fecal Coliform	
Weekly Maximum Limitation	
(Geometric Mean) .....	400 per 100 ml
Average Monthly Limitation	
(Geometric Mean) .....	200 per 100 ml
Disinfection System Influent Fecal Coliform	
Geometric Mean Concentration (Daily) .....	500,000/100 ml
Maximum Concentration (7-day Mean) ....	2,000,000/100 ml
Maximum Concentration (30-day Mean) ...	1,000,000/100 ml
UV Transmittance (% at 253.7 nm)	
Daily Average .....	70%
Minimum 30-day Average .....	65%
Minimum 7-day Average .....	60%

**7.4.2.1 Model Coefficients**

The hydraulic characteristics are a direct function of the reactor configuration, particularly the lamp placement and spacing, and the reactor's inlet and outlet design. This can best be characterized by direct testing of full-scale modules, or hydraulically scaleable pilot modules. Alternatively, these data can be required from the equipment manufacturer as a bid and/or warranty specification. The procedures for these analyses have been described earlier. Specifically, the information should encompass the following:

- a. Residence time distribution curves developed at several flow rates. These should encompass, at least, the minimum, average, and maximum design flows for the system.
- b. Head loss measurements, again over a range of velocities (i.e., flow rates).

Calibration of the model requires direct determination of the inactivation rate as a function of the intensity and an estimate of the residual coliform density associated with the suspended solids. These are the coefficients a, b, c, and m in Equation 7-14. They will be site specific and will need to be determined experimentally. As more field experience is gained with the application of UV, these coefficients may be found to cluster about certain levels relative to the type of wastewater and the degree of treatment. Estimates of these coefficients for several plants were summarized in Section 7.3.4.5. These may be used as approximations for first-cut design estimates; it is recommended at this point, however, that direct testing be conducted to verify and/or refine these estimates.

**7.4.2.2 Testing Requirements**

Testing need be directed only at the data which are necessary for the model calibration. Demonstration of long term performance at a given loading or an evaluation of O&M needs over time are not issues which can be effectively resolved by limited piloting or lab tests. These elements of a system evaluation are best answered by observation of existing full scale facilities and the experiences of engineers and operators directly involved in their design and operation.

The tests should incorporate the ability to obtain data at two significantly different intensity levels. If direct piloting is conducted, this may best be accomplished by using two units which differ significantly in lamp spacing, such that the UV density, and consequently the intensity, differ significantly. The sizing of the systems does not need to be large, although it is recommended that the units should have 10 lamps (0.75 arc lamps would be sufficient) at a minimum. There are no restrictions on the configuration of the lamps relative to flow (e.g., parallel or perpendicular), or in the arrangement of the lamp array (the lamps should be parallel to one another, however).

The wastewater effluent should be piped to the unit and there should be the capability to vary the flow rate. Flow rates must be accurately measured. The sampling and analyses will center on measurement of the influent and effluent bacterial density (typically, this will be total and/or fecal coliforms), the UV absorbance coefficient, and the suspended solids.

The pilot unit lamp configuration would first require evaluation by the point source summation method to calculate the intensity in the unit as a function of the UV absorbance coefficient. This would be similar to the relationships presented in Figures 7-28 through 7-32, depending on the array configuration. During the term of the pilot study, direct measurements should be made to determine the output of the units' lamps and the transmittancy of the quartz and/or Teflon enclosures. These tasks can be accomplished by methods which are described in Section 7.5.1. The information on lamp output and quartz transmittance would be used to adjust the calculated intensities. The adjusted intensity would also be affected by the UV absorbance coefficient measured at the time of sampling.

The hydraulic characteristics of the pilot units would then have to be defined directly by running tracer analyses. The procedures were described in Section 7.3.2, including the analysis of the resulting data. The required information would be an estimate of the dispersion coefficient, E, and an estimate of the actual detention time (mean) versus the theoretical detention time. If the mean detention time is significantly different from the theoretical detention time,

then this measured value should be accounted for in the analysis of the system by adjusting the effective volume.

The procedure for determining  $N_p$  was discussed earlier. Samplings should be conducted under very high dose levels in the pilot units (high exposure times); the premise is that the residual density measured after such a high apparent dose is attributable to the bacteria being protected by occlusion in the suspended solids. Linear regression analyses of the log effluent residual coliform density as a function of the log of the effluent suspended solids will yield the coefficients  $c$  (intercept) and  $m$  (slope). It is important to evaluate the units in this fashion over a significant range of suspended solids concentrations. It may be necessary to artificially adjust the wastewater to accommodate this requirement.

Influent and effluent data should be collected at flow rates which are high, yielding low "apparent" doses in order to determine the rate of inactivation; this requires that the exposure time be sufficiently low to allow significant bacterial density levels in the effluent. The rate,  $K$ , is then determined by solution of the model expression. A linear regression analysis of the log  $K$  as a function of the log intensity will then yield the intercept and slope, which are the coefficients  $a$  and  $b$ , respectively.

Testing can also be conducted on a bench-scale basis to determine the UV coefficients. Although procedures have not been reported in the literature, simple batch test methods can be used. This, in turn, would greatly simplify the testing requirements described above. Care should still be taken, however, in devising the experimental apparatus. In order to simulate the high intensity levels experienced in the multi-lamps full-scale units, the bench-scale batch units should use several lamps to attain higher intensities. The collimated beam apparatus in Figure 7-21 would not be adequate as shown; intensities generally do not exceed  $1,000 \mu\text{W}/\text{cm}^2$ , even with modifications of the arrangement.

#### **7.4.3 Assumptions for the Design Example**

Given the protocol presented in the earlier discussions, the disinfection model can be used to determine the optimum design for a given application. The model approach allows the testing of several design scenarios and any number of unit configurations. At minimum, it allows the designer to evaluate directly the systems proposed by manufacturers.

The primary design objective (and operating goal) is to maximize the loading to the system while still meeting performance goals. For the UV disinfection process, this UV loading is defined as the ratio of the flow,  $Q$ , to

the nominal UV wattage (at 253.7 nm) of the reactor,  $W_n$ :

$$\text{UV Loading} = Q/W_n = \text{Lpm}/\text{UV Watt, nominal}$$

Additionally, we will define the performance of a reactor as the log of the survival ratio,  $\text{Log } N/N_0$ . Thus, our goal is to design a system which can handle the maximum loading,  $Q/W_n$ , and meet the desired  $\text{Log } N/N_0$ .

At the start, let us make the following assumptions. The model coefficients, based on direct testing, are:

$$\begin{aligned} a &= 1.45 \times 10^{-5} \\ b &= 1.3 \\ c &= 0.25 \\ m &= 2.0 \end{aligned}$$

Further, the assumptions we will make regarding the reactor are:

- a. Quartz system with a uniform lamp array. This was described in section 7.3.5.3 and schematically presented on Figure 7-25(a).
- b. The centerline spacing will be 6.0 cm. The average nominal intensity is presented on Figure 7-28 as a function of the UV absorbance coefficient.
- c. The lamps will be G64T5, or equivalent (see Table 7-7). The lamps will have insignificant transmission at 185 nm, in order to minimize the production of ozone. This ozone is generated in the air gap between the lamp and the quartz sleeve; the ozone absorbs energy at the 253.7 nm wavelength, resulting in attenuation of the UV energy before it can reach the liquid.
- d. The lamps will be 1.6-m long with an effective arc length of 1.47 m; the nominal UV output is approximately 18.2 W/m arc.
- e. Each lamp is sheathed in a quartz enclosure with an outer diameter of 2.3 cm.
- f. The lamps will be configured axially parallel to one another; the flow path will be perpendicular to the lamps.
- g. The values of the energy loss factors,  $F_p$  and  $F_t$  (see Sections 7.3.3.4 and 7.5.1) are set at 0.8 and 0.7, respectively.
- h. The maximum allowable headloss through the lamp battery is set at 40 cm. This is exclusive of the entrance and exit losses for the reactor.

Regarding the wastewater characteristics, several adjustments are made to the Table 7-11 parameters

to reflect diurnal and maximum average design conditions.

For convenience, the problem is restated. The treatment plant is a conventional activated sludge facility with the following effluent:

- Maximum 30-day average BOD<sub>5</sub> = 15 mg/l
- Maximum 30-day average SS = 15 mg/l
- Maximum 7-day average BOD<sub>5</sub> = 30 mg/l
- Maximum 7-day average SS = 30 mg/l
- Maximum 30-day average fecal coliform = 200 org/100 ml (GM)
- Maximum 7-day average fecal coliform = 400 org/100 ml (GM)

The anticipated design hydraulic capacity of the plant, will be:

- Average daily flow (dry weather) = 7.5 mgd (28,000 Lpm)
- Peak daily flow = 15.0 mgd (56,000 Lpm)

These flows are anticipated at 5 years; the average daily flow is expected to be 3.5 mgd at startup. The relevant wastewater characteristics are:

- Average daily fecal coliform =  $5 \times 10^5$  org/100 ml
- UV transmittance (% at 253.7 nm)
  - Daily average = 70 percent
  - Minimum 30-day average = 65 percent
  - Minimum 7-day average = 60 percent

Other wastewater quality characteristics relate to the variability of the parameters; these can be established by the analysis of data collected over an extended period of time:

- Ratio of maximum 7-day average flow/average daily flow = 1.25
- Ratio of maximum 30-day average flow/average daily flow = 1.1
- Ratio of maximum hourly flow/average 24-hour flow = 1.3

#### 7.4.4 Design Sequence

The following steps will comprise the sequence of calculations for the design example:

1. determine UV density, D,
2. establish intensity as function of D; adjusted for loss factors,
3. establish inactivation rate, K,
4. set hydraulic parameters to accommodate dispersion and headloss limitations,
5. establish UV loading-performance relationship,
6. establish performance goals, and
7. reactor sizing.

#### 7.4.5 Design Example

The following calculations demonstrate the procedure for sizing the UV system. The wastewater characteristics have been given on Table 7-11; the design criteria and assumptions are discussed in Section 7.4.3 and 7.4.4.

##### Step 1—Reactor UV Density

The liquid volume per lamp (see Figure 7.25(a)) is computed:

$$V_v/\text{Lamp} = (S^2z) - [(\pi d_q^2/4)z] \quad (7-38)$$

where S is the centerline spacing (cm), z is the lamp arc length (cm), and d<sub>q</sub> is the diameter of the quartz sleeve (cm). For the uniform array, with

- S = 6.0 cm
- z = 147 cm
- d<sub>q</sub> = 2.3 cm

$$V_v/\text{lamp} = [(6.0)^2 (147)] - [\pi(2.3)^2 147/4]$$

$$V_v/\text{lamp} = 4700 \text{ cm}^3 \text{ (4.7 liters)}$$

The UV density, D, is calculated from Equation (7-29):

$$D = (1.47 \text{ m arc} \times 18.2 \text{ W/m arc})/4.7 \text{ liters}$$

$$D = 5.7 \text{ W/liter}$$

##### Step 2—Intensity

The nominal average intensity can then be estimated from Figure 7-28 (uniform array) for this density and the anticipated wastewater conditions, i.e., absorbance coefficients. These are summarized on Table 7-12. The percent transmittance is first converted to the UV absorbance coefficient, α (base e). The nominal average intensity is then determined from Figure 7-28. Note that the absorbance coefficient information has been assumed to be derived from measurements corrected for scattering (α<sub>s</sub>-Total).

This nominal average intensity must then be adjusted to account for the anticipated average lamp output in the reactor and the minimum average transmittance of the quartz sleeves. Recalling F<sub>p</sub> = 0.8 and F<sub>t</sub> = 0.7:

$$I_{\text{avg}} = \text{Nominal } I_{\text{avg}} \times 0.8 \times 0.7$$

The adjusted I<sub>avg</sub> values are given in Table 7-12 to reflect these conditions.

##### Step 3—Inactivation Rates

Once the adjusted intensity values are determined, the inactivation rates can be estimated from Equation 7-12, with the coefficients a and b determined earlier. The rates are given on Table 7-12 for each of the design conditions.



**Table 7-12. Estimate of Intensity and Rate, K for Design Example**

Design Condition	UV Transmittance at 253.7 nm (%)	UV Absorbance Coefficient (cm <sup>-1</sup> )	Nominal <sup>a</sup> Average Intensity (μW/cm <sup>2</sup> )	Adjusted <sup>b</sup> Average Intensity (μW/cm <sup>2</sup> )	Inactivation <sup>c</sup> Rate (sec <sup>-1</sup> ) K
Average Daily	70	0.35	17300	9700	2.21
Maximum 30-Day Average	65	0.43	15100	8450	1.85
Maximum 7-day Average	60	0.51	13000	7300	1.53

<sup>a</sup>From Figure 7-28 for a density of 5.7 W/L

<sup>b</sup>Assumes an F<sub>p</sub> = 0.8 and an F<sub>t</sub> = 0.7

<sup>c</sup>a = 0.0000145; b = 1.3, Equation 7-12.

**Step 4—Set Hydraulic Rates**

Recalling the discussions on hydraulics (Section 7.3.2), the maximum performance would ideally be accomplished in a perfect plug flow reactor. Since there will always be the non-ideal case, the goal is to design a plug flow reactor with a low dispersion number, d. As was also discussed, this dispersion number must be reconciled with the headloss incurred by forcing the d to be low.

Scheible et al. (54) had estimated the c<sub>f</sub> in Equation 7-23 for headloss to be between 0.00017 and 0.00023 sec<sup>2</sup>/cm<sup>2</sup>, based on direct head loss measurements for quartz units with a flowpath perpendicular to the lamps. This estimate would apply only to this type of configuration. There is little direct data available to determine c<sub>f</sub> for a variety of configurations. It is very important that these data be generated; the designer should at least specify this in the equipment specs.

It is suggested that a conservative value of c<sub>f</sub> = 0.00025 sec<sup>2</sup>/cm<sup>2</sup> can be used in estimating headloss in most quartz reactors where the flow path is perpendicular to the lamps. One should understand that this applies only to the lamp battery itself and does not take into account losses from pipe inlets, stilling walls, etc.

The example plant is to operate by gravity with the maximum allowable headloss due to the lamp battery set at 40 cm. We can use this to set a practical design goal with regard to the dispersion number. From Equation 7-23:

$$h_L = c_f(x)(u)^2$$

$$40 \text{ cm} = 0.00025(x)(u)^2$$

this implies that:

$$x \cong 160,000(u)^{-2} \tag{7-42}$$

We have defined d as:

$$d = \frac{E}{ux}$$

Consider the product, ux. We can estimate u and x over a range of ux values which will keep the h<sub>L</sub> below 40 cm. As an example, at:

$$ux = 10,000 \text{ cm}^2/\text{sec}$$

substitute Equation 7-42:

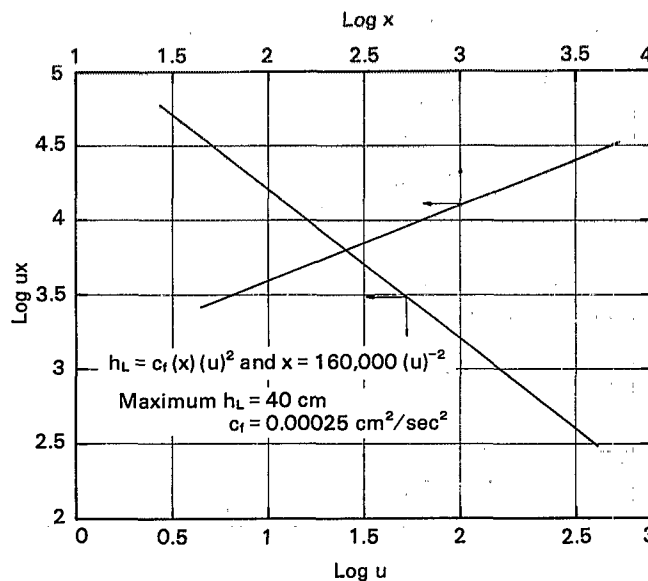
$$(u)^{-1} = \frac{10000}{160000} = 0.0625$$

$$\text{or } u \cong 16 \text{ cm/sec}$$

$$\text{and } x \cong 10,000/16 = 625 \text{ cm}$$

Figure 7-41 presents similar solutions; these are all to yield an h<sub>L</sub> < 40 cm for the example system.

**Figure 7-41. Example of calculating the limiting U and X on the basis of head loss (flowpath perpendicular to the lamps).**



A dispersion number should then be approximated for design purposes. From earlier discussions, a practical range of d is 0.03 to 0.05. If we consider d = 0.03, this implies a plug flow reactor with low to moderate

dispersion. The components of  $d$  are the dispersion coefficient  $E$ , the velocity  $u$ , and the characteristic length,  $x$ .

Little direct testing information is available to select a dispersion coefficient as a function of the selected reactor configuration. Procedures have been given to develop the RTD curve for a given unit; the  $d$  and  $E$  can be estimated from these data. For this reason, it is strongly recommended that it be developed directly, or that the equipment manufacturer supply direct, certified, test data from hydraulically scaleable units.

In the long term, as more information is developed, it may be possible to develop empirical relationships which will give reasonable approximations of  $E$ . To date, direct testing on quartz units has yielded an estimated  $E$  between 10 and 500, with values typically between 50 and 200  $\text{cm}^2/\text{sec}$ . Little data is available on the Teflon tube configuration; these indicate a value between 10 and 50  $\text{cm}^2/\text{sec}$ . Although  $E$  will likely vary with flow rate (i.e., velocity), it is sufficient to consider one  $E$ ; this should be representative of the maximum flow conditions. For purposes of design, one should check that the sizing, based on a selected,  $d$ ,  $u$  and  $x$ , implies an  $E$  less than 300  $\text{cm}^2/\text{sec}$ .

Let us select a characteristic length,  $x$ , of 200 cm for the UV unit (this can be varied in evaluating alternative design configurations). From Figure 7-41, this implies a  $ux$  of 5,600  $\text{cm}^2/\text{sec}$  and a  $u$  of 5,600/200 = 28  $\text{cm}/\text{sec}$ . Maintaining  $u$  below 28  $\text{cm}/\text{sec}$  will assure an  $h_L$  below 40 cm at peak flow.

Recall that we set a  $d$  of 0.03 as a design guideline:

$$d = 0.03 = \frac{E}{ux} = \frac{E}{5600}$$

This implies an  $E$  of approximately 170  $\text{cm}^2/\text{sec}$ , which falls within acceptable limits.

In summary, as the first approximation of the system design, we are setting:

$$\begin{aligned} d &= 0.03 \\ x &= 200 \text{ cm} \\ u &= 28 \text{ cm}/\text{sec} \\ E &= 170 \text{ cm}^2/\text{sec} \end{aligned}$$

#### Step 5—UV Loading

Recall the disinfection model (Equation 7-10):

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

The next step in the design procedure is to develop the relationship of the reactor performance ( $\text{Log } N/N_0$ ) as a function of the maximum UV loading ( $Q/W_n$ ), based

on the above relationship, and the assumptions discussed earlier.

Before this, one should understand that for a given loading, there is an equivalent nominal exposure time,  $t_n$ :

$$t_n = \left( \frac{V_v}{W_n} \right) / \left( \frac{Q}{W_n} \right)$$

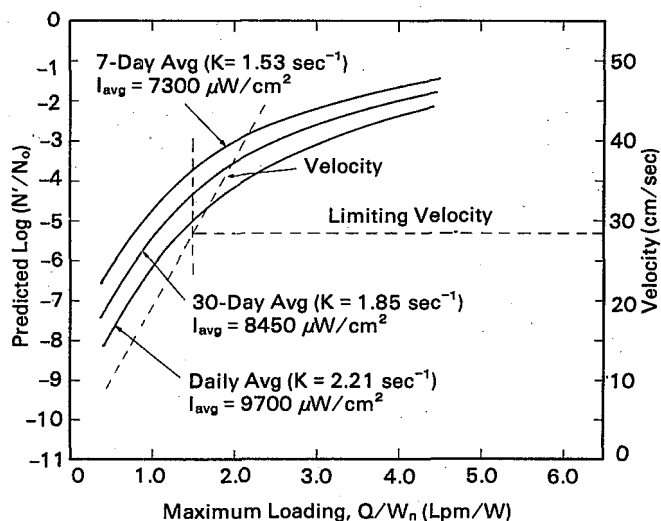
At the 6-cm spacing for the uniform array the liquid volume,  $V_v$ , associated with the lamp and quartz sleeve is 4.7 liters. Thus, for the reactor configuration we are considering for this example:

$$\frac{V_v}{W_n} = \frac{4.7 \text{ L}}{1.47 \text{ m arc} \times 18.2 \text{ W}_n/\text{m arc}} = 0.176$$

$$\text{and } t_n = \frac{(0.176)}{(Q/W_n)}$$

Calculations are summarized on Table 7-13 for the design conditions. The  $\text{log } (N'/N_0)$  values are plotted on Figure 7-42 as a function of the  $Q/W_n$ . Understand that the performance is based on the non-particulate effluent fecal coliform density,  $N'$ . The particulate fecal coliform density,  $N_p$ , is additive. The velocity is also plotted as a function of the loading; the limiting velocity is based on the maximum headloss.

Figure 7-42. Predicted performance as a function of loading for design example.



Uniform Array, 6.0 cm  $\varnothing$  Spacing

Solutions at:

$$\begin{aligned} d &= 0.03 \\ x &= 200 \text{ cm} \\ E &= 170 \text{ cm}^2/\text{sec} \\ D &= 5.7 \text{ W}/\text{L} \\ F_p &= 0.8 \\ F_t &= 0.7 \end{aligned}$$

**Table 7-13. Calculations of Performance on the Basis of Loading for the Design Example**

UV Loading, Q/W <sub>n</sub> (1 pm/W <sub>n</sub> )	Nominal <sup>a</sup> Exposure Time, t <sub>n</sub> (seconds)	Characteristic Length, x (cm)	Velocity <sup>b</sup> u (cm/sec)	Log N'/N <sub>0</sub> <sup>c</sup>		
				Daily Average k = 2.21 sec <sup>-1</sup>	Maximum 30-Day Average K = 1.85 sec <sup>-1</sup>	Maximum 7-Day Average K = 1.53 sec <sup>-1</sup>
0.5	21.1	200	9.5	-7.8	-7.0	-6.2
1.0	10.6	200	18.9	-6.2	-5.4	-4.8
1.5	7.04	200	28.4	-5.0	-4.4	-3.7
2.0	5.38	200	37.2	-4.2	-3.6	-3.1
3.0	3.52	200	56.8	-3.1	-2.6	-2.2
4.0	2.64	200	75.8	-2.4	-2.0	-1.7

<sup>a</sup>t<sub>n</sub> = [(0.176)/(Q/W<sub>n</sub>)] x 60 sec/min

<sup>b</sup>u = x/t<sub>n</sub>

<sup>c</sup> $\frac{N'}{N_0} = \exp \left[ \frac{ux}{2E} \left\{ 1 - \left( 1 + \frac{4EK}{u^2} \right)^{1/2} \right\} \right]$  where E = 170 cm<sup>2</sup>/sec, x = 200 cm, and N' = N-N<sub>p</sub> (see Equation 7-34)

**Step 6—Establish Performance Goals**

Returning to the plant design, it is necessary to determine the performance goal for the system design conditions. These calculations are summarized on Table 7-14. The design values for N<sub>0</sub> are set to reflect the variability of the data base, as given on Table 7-11. Regarding the suspended solids, in order to meet the maximum 30-day permit level, it is necessary to achieve an overall average no more than 50 to 70 percent of the maximum 30-day average. For this example, then, the daily average SS is set at 10 mg/l.

**Table 7-14. Estimation of Reactor Performance Requirements for the Design Examples**

	Daily	Maximum 7-Day	Maximum 30-Day
Initial Fecal Coliforms Density, N <sub>0</sub> (org/100 ml)	500,000	2,000,000	1,000,000
Suspended Solids (mg/l)	10 <sup>a</sup>	30	15
Particulate Coliforms Density, N <sub>p</sub> (org/100 ml)	25	225	56
Permit Requirement, N (org/100 ml)	200	400	200
Performance Goal, N' (org/100 ml)	175	175	144
Log (N'/N <sub>0</sub> )	-3.45	-4.05	-3.84

<sup>a</sup>Assumed value; acknowledges that the verage daily is generally 50 to 70 percent of the maximum 30-day average

The values of N<sub>p</sub> are calculated on the basis of Equation 7-13, with the coefficients c and m equal to 0.25 and 2.0, respectively. These are then subtracted from the permitted effluent fecal coliform densities to yield the design performance goal. This can then be used to compute the design Log (N'/N<sub>0</sub>).

**Step 7—Reactor Sizing**

Table 7-15 presents a summary of the reactor sizing calculations for the design examples. The I<sub>avg</sub> and performance goals are restated. The maximum allowable loadings are then determined from the performance curves on Figure 7-42.

The lamp requirement is estimated on the basis of using 1.47 m arc lamps with a UV output of 26.7 W/Lamp:

Number of Lamps = [(Q)/(Q/W<sub>n</sub>)]/26.7 W<sub>n</sub>/Lamp

**Table 7-15. Sizing Calculations for the Design Example**

	Daily Average	Maximum 7-Day	Maximum 30-Day
Adjusted I <sub>avg</sub> (μW/cm <sup>2</sup> )	9700	7300	8450
Performance, Log (N'/N <sub>0</sub> )	-3.45	4.05	-3.84
Maximum Q/W <sub>n</sub> (lpm/W) <sup>a</sup>	2.63	1.35	1.90
Flow, (lpm)	28000	35000	30800
Adjusted Design Flow (lpm) <sup>b</sup>	36400	45500	40000
Peak Dry Weather Flow (lpm)	57000		
Peak Wet Weather Flow (lpm)	76000		
Nominal Exposure Time, t <sub>n</sub> (seconds) <sup>c</sup>	4.0	7.8	5.6
Characteristic Length, x <sup>d</sup> (cm)	200	200	200
Nominal Velocity, u (cm/sec) <sup>d</sup>	50.0	25.6	35.7
Lamp Requirement at peak dry weather	518	1262	788
	811		

<sup>a</sup>From Figure 7-42

<sup>b</sup>Set flows to peak diurnal conditions; adjusted daily = 1.3 x daily; adjusted 7-day = 1.25 x adjusted daily; adjusted 30-day = 1.1 x adjusted daily.

<sup>c</sup>t<sub>n</sub> = (0.176)/(Q/W<sub>n</sub>) x 60 sec/min

<sup>d</sup>u = x/t<sub>n</sub>

From Table 7-15, the maximum design requirements are the 7-day maximum and the peak wet weather conditions. The minimum number of lamps required is approximately 1,300.

**Table 7-16. Reactor Sizing Requirement for the Design Example**

	Daily Average	7-Day Maximum	30-Day Maximum
Required Number of Lamps (see Table 7-15)	518	1262	788
<i>Reactor Sizing Requirement—Perpendicular Flow Path</i>			
Length (x) cm	200 (34 lamps)	200 (34 lamps)	200 (34 lamps)
Height (y) cm	96 (16 lamps)	222 (37 lamps)	138 (23 lamps)
Width (z) cm	150 (1 lamp)	150 (1 lamp)	150 (1 lamp)
Total Lamps	544	1258	782

Once the number of lamps is determined, the actual modular configuration of the UV system can be considered. Table 7-16 summarizes the combined reactor dimensions which will satisfy the critical design elements of the  $Q/W_n$  (i.e., number of lamps) and the characteristic length,  $x$ . This is to form a uniform array reactor in which the flowpath is perpendicular to the lamps.

Recall that, the  $x$  dimension is set by dividing the required  $x$  by the centerline spacing  $S$ , to determine the number of lamps in the  $x$  direction. Thus, for the design example, we can determine the number of lamps in  $x$ :

$$200 \text{ cm} / 6 \text{ cm} = 33$$

As shown on Table 7-16, this is set at 34 for a total  $x$  dimension of 204 cm. The width of the reactor is set by the length (i.e., effective arc length) of the lamp. This is approximately 1.5 m. The height then, is set to satisfy the total lamp requirement: For the average daily condition:

$$\text{No. of Lamps in } y = 518 / 34 = 15.2 \text{ or } 16 \text{ lamps}$$

This yields a total  $y$  dimension of 96 cm.

The maximum requirement is set by the 7-day condition. A possible arrangement of UV modules would be as follows:

- 4 modules; 408 lamps/module (Total 1500 lamps)
- Each 34 lamps long (2.0 m)
- 12 lamps high (0.72 m)
- 1 lamp length wide (1.5 m)

The average condition can be met by 2 units; three modules would be required under the peak condition. The fourth unit would be solely for standby.

The reactor modules can be installed in any number of configurations. The critical consideration is the design of the approach and exit portions of the system. This was discussed in Section 7.3.2.4. In both parallel and perpendicular flow path cases, the key is to simulate open channel flow with a constant velocity profile across the cross-sectional plane on both the inlet and outlet sector of the lamp battery (see Figure 7-20).

Weirs and stilling walls should be used on both ends of the reactor to effect this even flow distribution. Other design considerations regarding system layout and facilities requirements are discussed in Section 7.5.

#### 7.4.4 Summary

The preceding calculations are given to demonstrate the design protocol. The numbers used should not be used for an actual design application. The procedure, once the model is calibrated, can be very effective. Several alternative configurations can be evaluated and, most importantly, the sensitivity to the key design parameters can be assessed. This applies particularly to the hydraulic parameters of velocity, dispersion, and head loss.

The calculations also demonstrate the importance of having direct test information on several aspects of the design:

Wastewater:	flow and flow variability UV absorbance initial coliforms suspended solids coefficients $a$ , $b$ , $c$ , and $m$
Reactor Characteristics:	RTD curve (range of flows) head loss (lamp battery only) dispersion coefficient

The reader is referred to Section 7.5 for discussions of other design aspects relating to O&M and to facilities requirements.

## 7.5 System Design and Operational and Maintenance Considerations for the UV Process

Sections 7.3 and 7.4 present the protocols by which a UV disinfection system can be designed and evaluated. The discussions centered on the design basis and the process elements which are key to the design. These were the hydraulic behavior of the unit, the

calculation of the intensity in the reactor, and the generation of the appropriate wastewater characterization data. Finally, an example was presented to illustrate the design procedure.

This section presents other peripheral topics which the designer (and operator) must consider. These address system design elements which will affect the operation and maintenance of the system, and the overall economics. Specifically, the following items are presented:

First, the factors that affect the reactor intensity will be addressed. These relate primarily to the lamp output and lamp aging, and the attenuation of intensity due to fouling of surfaces in the reactor.

Second, methods are presented to monitor a system directly for lamp aging and unit fouling.

Third, design considerations are presented which will encourage effective maintenance, and assure the disinfection performance of the unit.

Fourth, a brief discussion will be given in regard to the major reactor components and system controls.

Fifth, the safety aspects of the system will be discussed.

Sixth, and finally, design considerations will be presented as they relate to ancillary facilities, materials, labor requirements, and system layout.

#### **7.5.1 Factors Affecting UV Intensity in a Reactor**

A critical element in the evaluation of a system's performance or in the design of a system is the actual energy available in the germicidal range. The key is to understand how efficiently the 253.7 nm energy is being utilized and, conversely, how it is being lost. This information is necessary to make the required adjustments to the calculated nominal average intensity solutions presented in Figures 7-28 through 7-32, and quantified in Equation 7-30 as the factors  $F_p$  and  $F_t$ .

The reduction in available energy can be divided into two major areas: the loss of lamp output ( $F_p$ ) and the change in transmittance of the enclosures separating the lamp from the liquid ( $F_t$ ). These enclosures are typically the quartz sleeves or the Teflon tubes.

##### **7.5.1.1 UV Lamp Output**

Electrical discharge lamps generate light by transforming electrical energy into the kinetic energy of moving electrons, which is then converted to radiation by some kind of collision process. Mercury vapor kept at an optimum pressure in the presence of a rare-gas (generally this is argon—which is the reason for the blue-green glow seen with germicidal lamps),

is a remarkably efficient emitter of light at 253.7 nm, when an electrical potential difference is applied across the device. The basic process as it takes place in the discharge lamp can be described in three steps:

1. Free electrons are accelerated by a potential difference applied across the lamp. This voltage drop is maintained by an external source of power, the current being the motion of the electrons.
2. The kinetic energy of the accelerated electrons is released as they collide with atoms in the plasma.
3. The energy of the atoms is dissipated as radiation as the atoms relax back to their lowest energy levels.

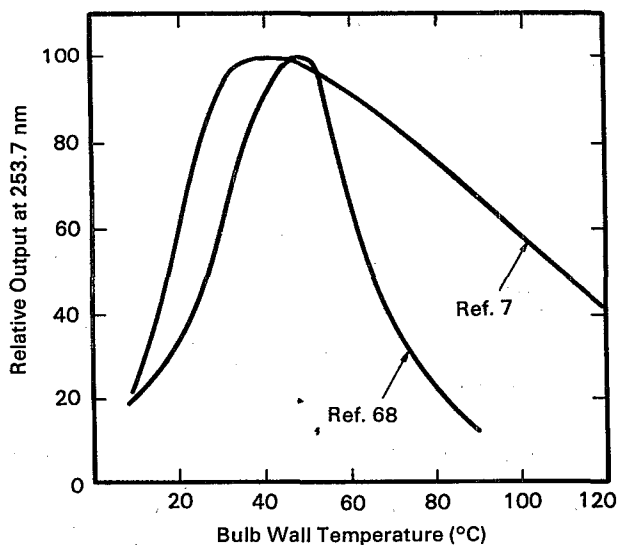
The lower the vapor pressure of mercury in an electric discharge, the greater the intensity of the mercury resonance line at 253.7 nm. Exploiting this fact, construction of the low-pressure mercury arc lamp yields a lamp which is nearly monochromatic in its radiation. The greatest output occurs under conditions which favor having the highest numbers of "excited" atoms close to the wall of the lamp. In this way, the radiation they emit as they relax will have a higher probability of passing through the wall, and not being re-absorbed by atoms in the low energy state. This is a reason for the thin tubular design of the lamps, the smaller the pathlength (diameter of the tube) the less likely the radiant energy will be re-absorbed. In the same fashion, the lower the pressure, the greater the chance of the radiation reaching the wall before making a collision. Under higher pressures the concentration of the atoms in the excited resonance state is high, but because of this higher density, the chances of the radiation reaching the bulb wall is small. Conversely, at extremely low pressures the number of available atoms becomes too small.

The resonance output of the lamp depends to a large extent on maintaining the optimum conditions of the discharge requirements in the vapor, and on the operating conditions during the life of the lamp. In large part, many of the factors which establish the output are independent of the designer or operator and will simply be set by the environmental conditions the unit must operate under. Still it is important to understand the major factors which come in to play.

Output at any given time will be influenced by lamp temperature and by the voltage potential applied across the lamp. Additionally, output at the resonant frequency will always degrade with time of operation due to any number of "aging" factors.

**Temperature.** As was discussed, there is a maximum resonance output which is dependent on the vapor pressure in the lamp. For a given lamp, this pressure will be influenced by the temperature of the lamp wall. The optimum wall temperature for maximum efficiency is generally between 35 and 50°C (95 and 122°F). Figure 7-43 presents data relating the relative UV output (at 253.7 nm) to the bulb wall temperature. In the quartz systems which are submerged in the flowing liquid, the lamps are insulated by inserting them in the quartz sheaths. The air layer between the quartz and the lamp wall serves as a buffer and prevents the lamps from being cooled by the wastewater. There is little information available regarding actual lamp skin temperatures during normal wastewater disinfection operations. Scheible and Bassell (36) reported that cold water temperatures had little effect on the measured bulb wall temperature. In the study at Northwest Bergen, the lamp temperature averaged 43°C (110°F) at an average water temperature of 21.3°C (70.3°F). At water temperatures averaging 10.5°C (50.9°F), the lamp wall temperature decreased to an average of 40°C.

Figure 7-43. Effect of bulb wall temperature on the UV output of a low pressure mercury arc lamp (7,68).



In the submerged systems it is not practical under most design conditions to control the lamp temperature. In the non-contact systems, such as the tubular arrays, it is possible to maintain the lamps at their optimum wall temperature by controlling the temperature of the ambient air surrounding the lamps. This is currently being practiced in commercial applications. Heat given off by the lamp ballasts is circulated into the lamp reactor in cases where heat is required;

otherwise fans vent the reactor with cooler outside air. These operations are thermostatically controlled.

**Voltage.** A characteristic of electric discharge arcs is that they have a negative volt-ampere relationship. This means that the voltage decreases with an increase in the current. Such devices are inherently unstable. This instability is counteracted by putting the arc in series with a resistance. This resistance (or reactance in the case of a-c circuits), is called the ballast. This ohmic resistance has a positive volt-ampere characteristic.

Radiance will be a function of the arc current. This fact can be exploited by adjusting the voltage, in order to vary the output of the lamp. Decreasing the voltage will result in a decrease in the current. Such a control mechanism has been installed at full scale facilities as an energy conservation measure. During periods of low UV demand, the lamps are "dimmed" by turning the lamp supply voltage down. This results in a reduction in the power draw of the lamp. Generally, the lamp intensity can be reduced to levels no less than 50 percent before the lamp current becomes too low and the lamp will begin to flicker and eventually turn off.

**Lamp Aging.** A number of factors combine to effectively age a lamp and limit its useful life. These include failure of the electrodes, plating of the mercury to the interior lamp wall (blackening), and solarization of the lamp enclosure material (reducing its transmissibility). These all cause a steady deterioration in the lamp's output at the 253.7 nm wavelength, such that its output at the end of the lamp's life can be 40 to 60 percent of its nominal output.

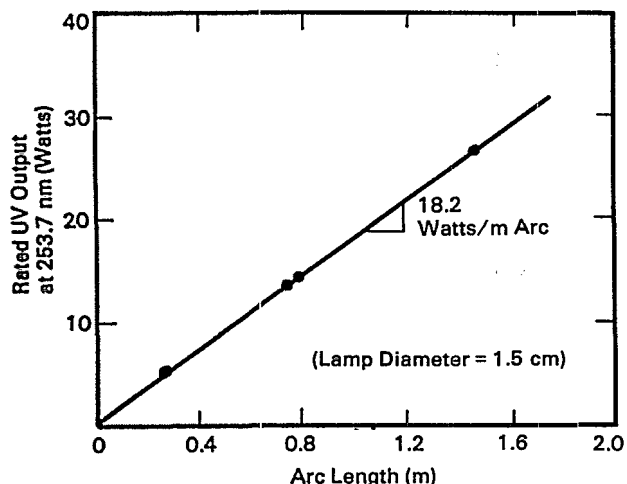
The output of the lamp through its life is affected primarily by the extent of blackening and solarization of the glass tube; the actual life of the lamp is governed by the condition of the electrodes. The germicidal lamps are typically of the hot cathode type. These will progressively deteriorate with increasing number of starts. Thus, the lamp life expectancy is generally rated according to the number of times the lamp is started, or the burning cycle. The lamp life normally cited by most manufacturers is 7,500 hours, based on a burning cycle of eight hours. The average UV output at this point is estimated to be 70 percent of the lamps output at 100 hours (note that the nominal output of the low-pressure mercury arc lamps represents its output after a 100 hour "burn-in" period).

An unusually long lamp life has been demonstrated by the units at Tillsonburg, Ontario. Lamps have been in operation for a documented period of greater than 13,000 hours. This may be due to the fact that the entire lamp, including the electrode connections, are

submerged and thus cooled by the flowing water (see Figure 7-7). The cooling of the electrodes may be a factor in extending the life of the electrode. Conversely, excessive blackening and deterioration of the end of the lamps has been noted for systems in which the lamps are inserted through a metallic bulkhead. There is no cooling in this case and, in fact, this may cause a buildup of heat.

**Measurement of the UV Output of the Lamp.** Table 7-7 presented the specifications for a number of slimline type germicidal lamps. Each is specified with a rated UV output at 253.7 nm, expressed in Watts, and the arc length, which is the length of the radiating portion of the lamp column. Figure 7-44 presents the output of the 1.5-cm diameter lamps as a function of the arc length. The slope of this is 18.2 UV W/m of arc. This will be slightly lower for lamps with a diameter of 1.9 cm. One should understand that this is the nominal output of the lamp; as discussed, this will decrease with time.

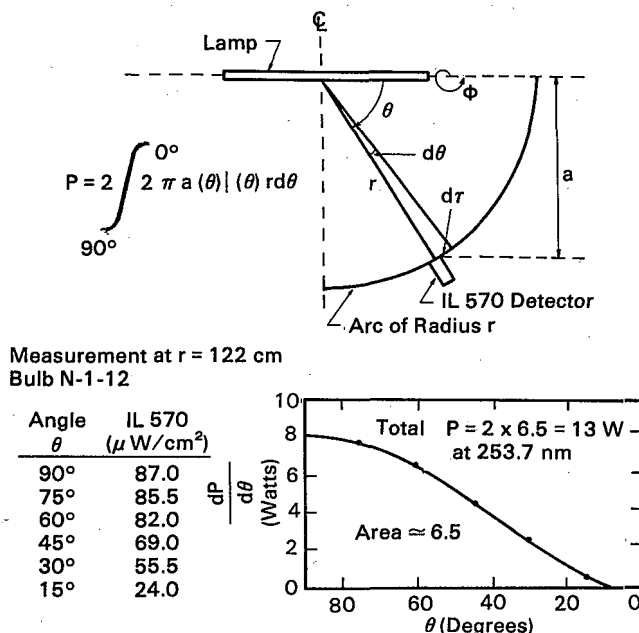
Figure 7-44. Nominal lamp output as a function of arc length.



A test procedure for determining a lamp's UV output was described by Johnson and Qualls (38). The procedure, in effect, treats the lamp as a single point source of light. A UV detector measures the intensity along an arc scribed at a fixed radius from the center of the lamp. These intensity readings are integrated over the surface of a sphere with the same radius, resulting in an estimate of the total output from the lamp.

Figure 7-45 is a schematic representation of the experimental set-up to measure the total output and a sample analysis of a set of data. The expression to

Figure 7-45. Measurement and analysis technique for estimating the total UV output of a lamp.



compute the power, P, at any point at distance r from the center of the lamp, at angle  $\theta$ , is written:

$$P = 2 \int_{90^\circ}^{0^\circ} 2\pi a(\theta) I(\theta) r d\theta \quad (7-46)$$

where:

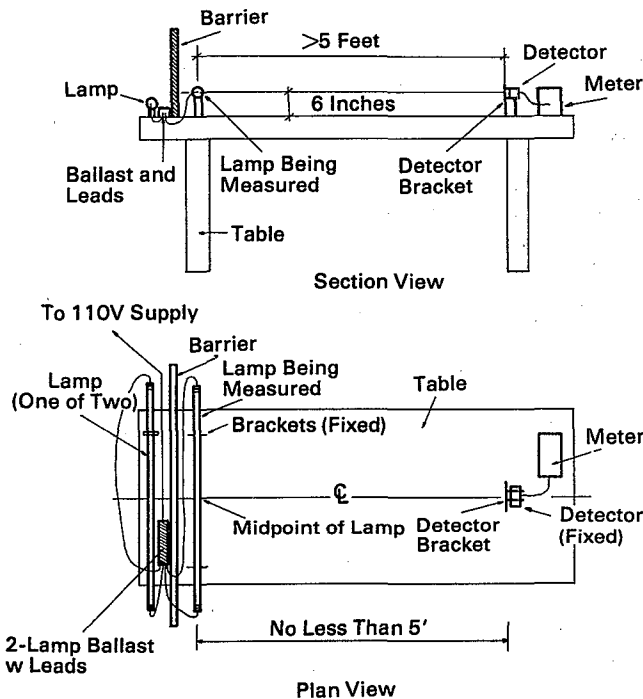
- P = the total power at 253.7 nm (Watts)
- $\theta$  = angle of the detector from the longitudinal centerline of the lamp (0 to 90 degrees)
- I = intensity reading at radius r at a point (T) along the arc
- r = radius of arc (distance from center of lamp to detectors) (cm)
- a = distance from detector to axial line of lamp (cm)

This can be solved graphically by plotting  $dP/d\theta$  against  $\theta$ , as shown by the example on Figure 7-45. The area under the curve is power output at the wavelength 253.7 nm, and represents one-half of the sphere about the lamp. Doubling this power estimate yields the total output of the lamp.

In the Port Richmond study, a total of 9 lamps were measured by this method after 100 to 300 hours operation. The measured output ranged from 12.2 to 15.9 W, with an average output of 13.6 W; this is close to the rated output of 14.3 W given by the manufacturer.

A far simpler technique can be used to implicitly monitor the average lamp output with time. The setup with the lamp and the detector is the same as shown on Figure 7-44. In this case, however, a single intensity reading can be taken at  $\theta$  equal to 90 degrees and compared to the same intensity reading for a new lamp. Figure 7-46 is a sketch of a simple table-mounted unit which can be used at a full-scale facility.

Figure 7-46. Sketch of lamp monitoring set-up.



Two lamps are operated off a single ballast. The lamp to be measured would be placed on brackets which are in a fixed position from the detector. The other lamp should be operating but placed behind a barrier to prevent it from interfering with the lamp being measured. Between three and five minutes warm-up time should be allowed before a measurement is taken. The leads from the ballast should be wired to end caps which can then be quick fitted onto the lamps. The lamps should not be repositioned by disconnecting them; they should be moved with their leads in-place.

As shown, the setup can be placed on a table-top; the lamp brackets should be thin and should not shield light. The lamp which is not being measured can be shielded by fitting a length of cardboard tubing (or thin opaque plastic tubing) over it. The tube can be slit lengthwise and should fit loosely (to prevent overheating the lamp). Alternatively, as shown on the sketch, a barrier can be set up between the lamps.

The detector is set up at the other end of the table. The mounting bracket should be rigid and fixed. The bracket should allow for removing and inserting the probe without changing the position of the detector in any direction. The objective is to always have the lamp and detector in a fixed position; these positions must also be reproducible from day to day. The detector should be on the same horizontal plane of the lamp centerline and perpendicular to the midpoint of the lamp. The distance between the lamp and the detector should be no less than five feet.

The procedure for monitoring the lamp intensity, once the setup is in place, is rather simple. The idea is to measure a lamp's intensity relative to that of a new lamp. The first step is to measure the intensity, at the fixed distance, of 3 to 5 new lamps which had been burned for approximately 100 hours. The average of the five then becomes the benchmark to determine the relative output of the lamps in use with the system (percent of new lamp average). Each lamp should be tagged and given an I.D. number; this allows direct monitoring of individual lamps and allows the operator to keep an appropriate mix of lamps in a system and to know when to discard a lamp.

The same procedure is used to monitor the transmittance of a quartz sleeve. In this case a single lamp is used; first the intensity is measured with and without a new, clean quartz sleeve in place over the lamp. Similar measurements are then taken with the unit's quartz sleeves and compared to the transmittance of the new quartz. This can be done before and after the quartz is cleaned.

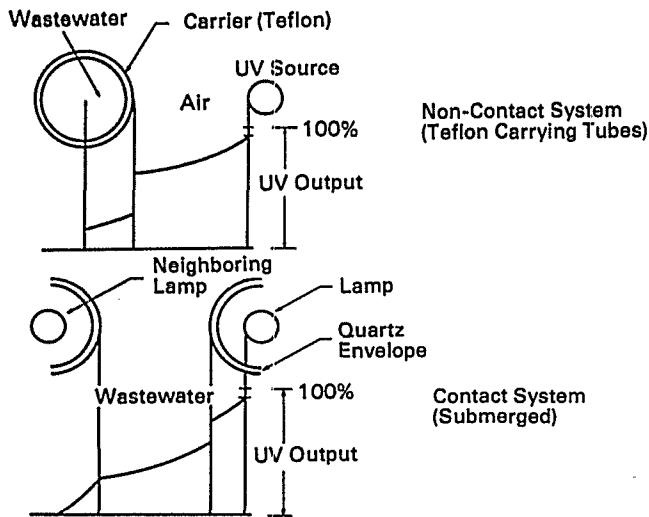
### 7.5.1.2 Losses of UV Energy through the Quartz and Teflon Enclosures

The UV output of the lamps themselves can be monitored with time, as discussed above. This is generally a non-controllable parameter, although optimum conditions can be maintained (such as voltage and temperature) to keep the output at its maximum. The lamps will age, however, and lose output. A key consideration regarding the UV source in both system design and subsequent operation and maintenance relate to maximizing the utilization of the source output and understanding the known energy sinks within a given system.

Figure 7-47 schematically presents two typical UV lamp configurations and the known energy sinks. The first is the tubular array; the second is the submerged quartz array. In either system there are several ways the UV energy is lost before it reaches the liquid and can be utilized for its primary germicidal role. First, the lamp wall itself can become dirty. In the non-contact tubular array systems the lamps are in an open air environment within the reactor. The air is often circulated to keep the ballast cool and/or to control the lamp temperature. This can introduce dust



Figure 7-47. Energy sinks in UV reactor.



which settles on the lamp surface and becomes an energy absorber. This same problem will also cause the outer surface of the Teflon tubes to become dusty and reduce the Teflon's transmittance. Filters are now installed in such units to minimize these problems.

In the quartz systems, some units are installed which either seal the quartz ends or leave them open. In the open arrangement, convective air currents can carry air (often humid) through the quartz sleeve, causing some deposition on the lamp surface. Additionally, the same air convection will cause the inner surface of the quartz sleeve to become dirty. This may also occur to some degree in sealed systems due to condensation effects, although there is no current information regarding these effects.

Passage through the quartz sleeve or the Teflon tube wall will itself cause a loss of energy. The fused quartz sleeves are highly transmissible of UV at 253.7 nm. The transmittance of the Teflon will vary with the thickness of the tube wall and is typically less than that of the quartz. Lastly, the surfaces of the quartz sleeves or the Teflon tubes which contact the wastewater will foul and cause the transmissibility of either to be reduced. The O&M tasks will naturally be directed to keeping these surfaces clean and maintaining the maximum transmittance of the quartz or Teflon.

**Quartz Systems.** The quartz sleeves are typically high quality fused quartz, with a transmittance greater than 90 percent when in a new, clean condition. In the Port Richmond study, relative output readings of a lamp were taken with and without the

quartz sleeve in place by the procedure discussed earlier. The average (of 12 measurements) reduction in intensity measured when the quartz was placed over the lamp was approximately 25 percent, with a range of 15 to 35 percent. Obviously, this is significantly different from the 90 percent for a new and clean quartz; the reasons relate to the dirtiness of the surfaces and the loss due to ozone absorption.

The lamps used at Port Richmond were made of quartz, which is transparent to energy at the 185 nm wavelength, a spectral line characteristic of the low pressure mercury arc. Energy at this wavelength will ionize free oxygen to ozone which, in turn, is an excellent absorber of energy at the 253.7 nm wavelength. Thus, with any production of ozone in the gap between the lamp and the quartz sleeve, it is likely that there would be a consequent absorption of UV energy. Direct testing in the Port Richmond project confirmed this effect.

Not all lamps will transmit this energy. In fact, the majority of lamp designs utilize a lamp envelope which has a low transmittance at the 185 nm wavelength. This is shown on Table 7-7. It is recommended that these types of lamps be used for UV disinfection systems.

Table 7-17 is excerpted from the Port Richmond report (54), and shows the effects of fouling on the quartz transmittance. Intensity readings taken immediately after the quartz were removed from the unit averaged  $61.8 \mu\text{W}/\text{cm}^2$ , which was 81.6 percent of the reading obtained with the new quartz sheath. Cleaning the inside surface of the quartz improved the output to an average  $70.1 \mu\text{W}/\text{cm}^2$ , or 92.8 percent of the new quartz reading. Finally, the output increased to  $75.3 \mu\text{W}/\text{cm}^2$  when the outer surfaces were cleaned, which is essentially equivalent to the new quartz reading.

The inside of the quartz had last been cleaned five months before these tests; the report then ascribed a 15 percent output decrease per five months due to the inside surface fouling. The outside surfaces were cleaned with an acid/detergent solution on a frequent basis, and immediately before these readings were taken. The results indicated that although this procedure was effective, there is apparently a film layer which stays on the surface; this was presumed to cause a loss of approximately eight percent of the UV output at any time.

The Port Richmond report presented a summary analysis of the lamp output and quartz transmittance monitoring conducted during the term of the project. This is repeated herein as Figure 7-48, and provides an excellent example of the importance of both monitoring these conditions and accounting for them

in the design of a system. The procedures are relatively straightforward and require little expense in terms of monitoring equipment. The primary commitment is the labor requirement for taking the necessary readings.

The manufacturer's rating for these lamps was confirmed by direct measurement of their UV output; this was shown to degrade to approximately 60 percent of this output after 8300 hours. A 25 percent reduction is taken to account for the quartz sheath absorbance, and losses attributable to ozone absorbance within the air gap between the lamp and the quartz sheath. If low or zero ozone producing lamps are used, this reduction will be approximately 10 percent. A constant eight percent loss is taken to account for the film layer on the outer surface of the quartz sheaths. This was considered the base line loss as discussed earlier; with increasing time between chemical cleaning cycles, this loss will increase. If not attended to (cleaned) this surface fouling can cause significant deterioration in the system performance. The internal fouling, although not as significant as the outside surface, will still have an effect. It should be a requirement, particularly in systems where the quartz ends are open, to clean these surfaces at least once to twice per year.

The lower line on Figure 7-48, therefore, is an estimate of the actual average UV output for the lamps at any time during the operating period for the Port Richmond study. It is significant to note that although a system may start with a nominal output from a lamp source, this is immediately reduced to approximately 70 percent of nominal simply by its placement in the quartz sheath and by the development of a film layer with time. Over the operating age of the lamp, this output, even with good maintenance, will deteriorate to approximately 35 to 45 percent of this nominal output after one year. Thus, it is important to maintain the system and keep this output at its maximum.

**Teflon Tubular Systems.** A number of tests were also conducted during the Port Richmond study on a sample of the Teflon tubes used in Unit 3 of the project. Lamp intensity readings were taken with and without clean Teflon in place; these readings also evaluated the transmittance with the lamp on both the convex and concave side of the Teflon. The results are presented on Figure 7-49, excerpted from the Port Richmond report. They are not wholly conclusive; there appears to be some apparent effect due to the curvature of the Teflon, with the higher transmittance measured when the lamp is on the inside of the Teflon arc.

All of the used samples were vigorously cleaned in the lab with hot soapy water and a soft brush after the

transmittance measurements were made. The UV transmittances after this cleaning are also shown in Table 7-17. As can be seen, considerable improvement was obtained. However, none of the cleaned samples demonstrated UV transmittances at the level one would expect for a virgin Teflon sample of the same wall thickness, suggesting that Teflon may undergo a transformation and lose some of its ability to transmit UV light over time. This may be caused by continued exposure to the UV lamps.

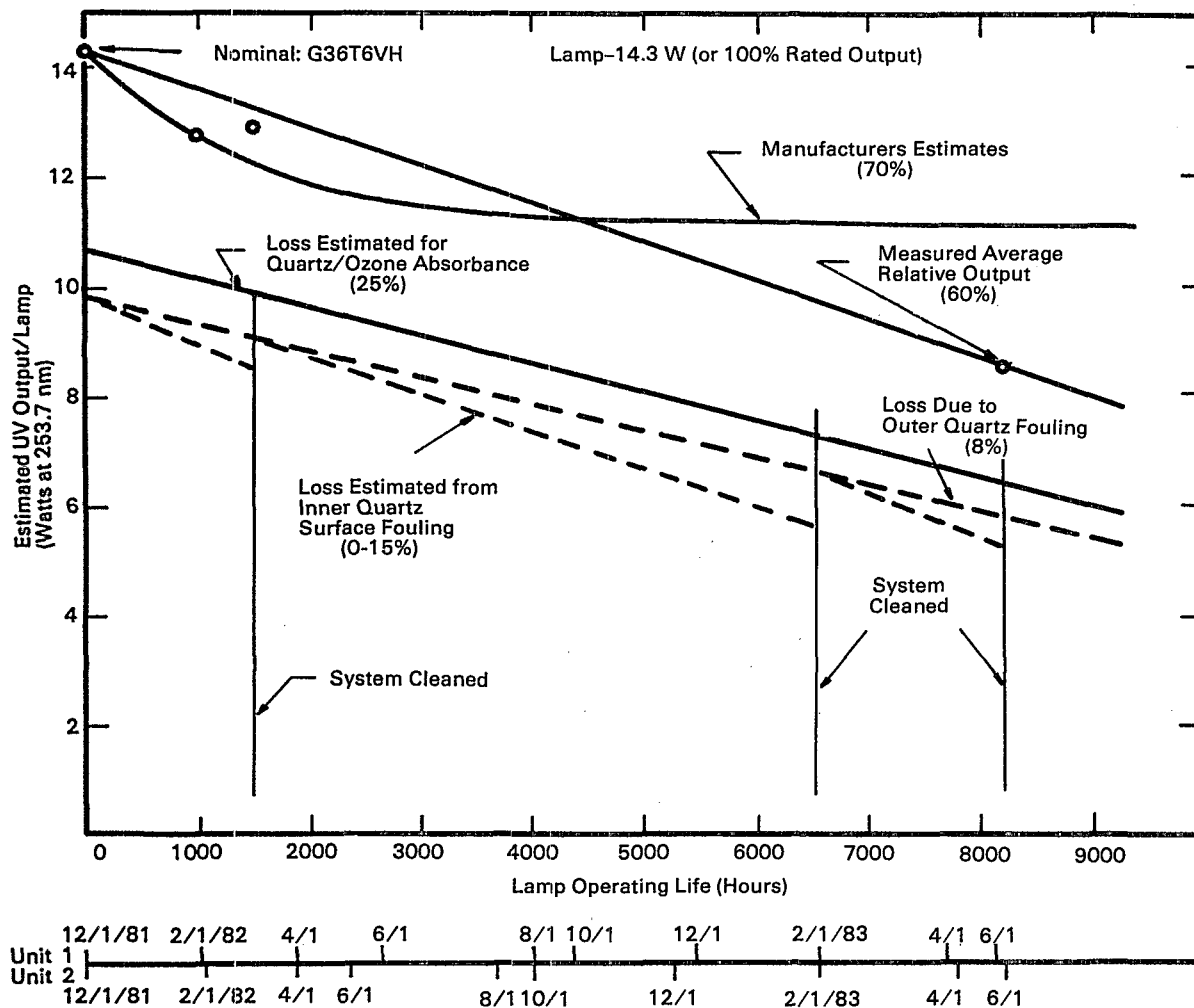
The Teflon used in the Port Richmond tests had been in use for a period of time. The inside surface was observed to be dirty, but was cleaned before the readings were taken. These results compare poorly with the 75 percent transmittance cited by the manufacturer as characteristic of Teflon. In their report, the authors suggested a transmittance level for the Teflon to range between a maximum of 75 percent when new to as low as 30 percent under significant fouling conditions.

A special series of tests were conducted using an alternative and possibly more accurate method to determine the transmittance of the Teflon. These tests (4) involve the exposure of a chemical actinometer to UV light. The compound was 0.006 M potassium ferrioxalate; upon exposure, the ferric ions will be reduced to ferrous ions in proportion to the amount of UV light received by the actinometer. The ferrous concentration is measured spectrophotometrically at 510 nm, using phenanthroline as the color reagent. The chemistry procedures follow those by Baxendale and Bridges (60) and Parker (61).

A sketch of the bench-scale setup is given in Figure 7-50. Note that, although these tests addressed Teflon, the same procedures are applicable also to quartz. Work should be conducted in a darkened room. The ferrioxalate is placed in a 1.3-cm diameter by 8-cm long fused quartz test tube (volume = 6 ml) capped with a non-reactive stopper, and covered with an aluminum foil sheath. The UV lamp is allowed to stabilize for a minimum of five minutes before any test. The test tube containing the actinometer would be clamped in a fixed position from the lamp; exposure would be accomplished by slipping the aluminum foil off the test tube for a preset period of time. The ferrous concentration would then be measured. Exposures are conducted with and without the Teflon tube in place.

The tests are conducted to encompass a range of reaction times. The reaction rate is determined by plotting the ferrous concentration against exposure time. The transmittance of the Teflon is estimated by determining the reduction in the reaction rate of the actinometer. Examples of these results are given in Figure 7-51. Results are given without the Teflon and

Figure 7-48. Approximation of average lamp UV output at 253.7 nm with time for quartz systems, accounting for lamp aging and surface fouling (54).



with different Teflon wall thicknesses. As an example of the calculation, the slope of the line in Figure 7-51 without Teflon is  $3.86 \times 10^{-6}$  M/sec; the slope of the line for Teflon with a wall thickness of 0.81 mm is  $3.29 \times 10^{-6}$  M/sec. The ratio is 0.85, suggesting a transmittance of 85 percent.

Kreft et al. (4) reported results of tests on both new and used Teflon by the actinometry method. Representative virgin Teflon samples of varying diameters and wall thicknesses were obtained from a manufacturer of the ultraviolet equipment. Used Teflon samples were obtained from secondary wastewater treatment plants in Port Richmond, New York; Chinook, Montana; and Beech Mountain, North Carolina. Table 7-18 shows the results of virgin and used Teflon UV transmittance analyses by chemical actinometry. It can be seen that the virgin Teflon

transmittance varied with the wall thickness, but not significantly with the diameter of the tube. Figure 7-52 shows the relationship developed from these analyses. Current designs typically have thin walls with a thickness less than 0.9 mm; thus, the virgin Teflon transmissivity for these units can be estimated to be in the range of 80 to 90 percent.

The Teflon samples showed varied degrees of internal fouling. The Port Richmond samples were obtained after a fairly continuous operating period of five months while treating secondary effluent. The Chinook samples were obtained after an operational period of approximately two months. Table 7-18 presents results of the UV transmittance measurements from these used Teflon samples. The Port Richmond samples were heavily fouled with a rust-colored material. UV transmittance for these samples

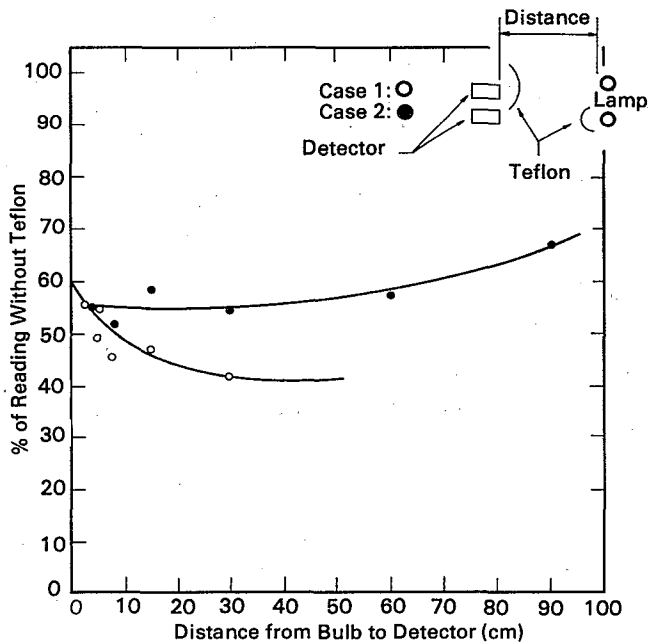
**Table 7-17. Effects of Fouling on the UV Transmittance of Quartz (54)**

Tube Number	After Removal from Unit <sup>b</sup> ( $\mu\text{Watts}/\text{cm}^2$ )	Relative to New Quartz	Intensity Readings		Cleansed Outside of Quartz ( $\mu\text{Watts}/\text{cm}^2$ )	Relative to New Quartz
			Cleansed Inside of Quartz ( $\mu\text{Watts}/\text{cm}^2$ )	Relative to New Quartz		
4	50.5	66.9%	66.5	88.1%	77.5	102.6%
34	60.5	80.1%	67.5	89.4%	73.5	97.3%
64	63.5	84.1%	70.5	93.4%	74.0	98.1%
74	68.5	90.7%	73.5	97.3%	73.5	97.3%
84	66.5	88.1%	73.5	97.3%	72.5	96.0%
94	60.0	79.5%	69.0	91.4%	81.0	107.3%
Average	61.5	81.6%	70.1	92.8%	75.3	99.8%

<sup>a</sup>Intensity of bulb without quartz is  $90.5 \mu\text{W}/\text{cm}^2$  at 1.2 m. The intensity with a new quartz in place is  $75.5 \mu\text{W}/\text{cm}^2$ . This is used as the reference intensity.

<sup>b</sup>Cleansed by acid/detergent solution while in the unit.

**Figure 7-49. Estimate of Teflon transmittance by use of a UV detector (54).**



**Figure 7-50. Test set-up to conduct actinometry experiments (4).**

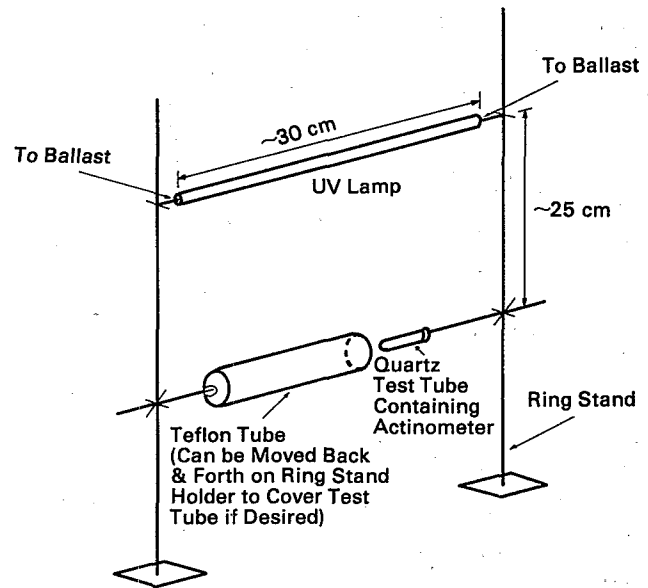


Figure 7-51. Example of chemical actinometry tests to determine Teflon UV transmission (4).

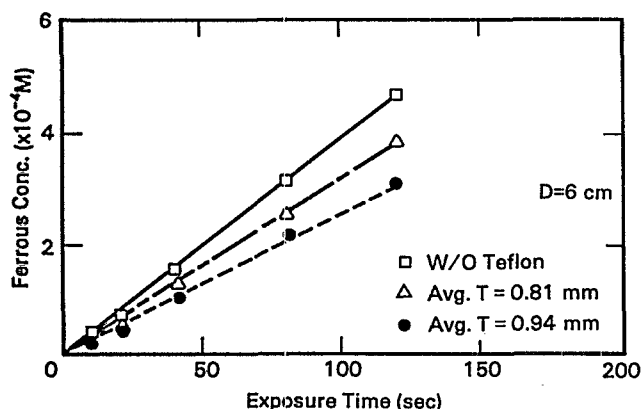


Figure 7-52. Effect of wall thickness on Teflon transmittance, as determined by chemical actinometry (4).

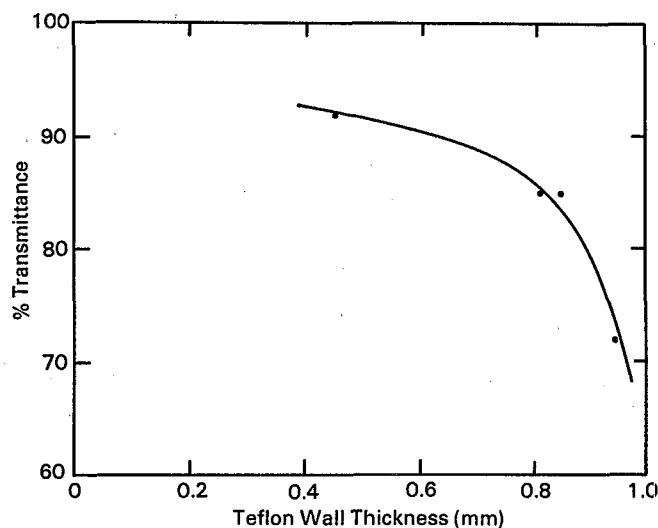


Table 7-18. UV Transmittances of New and Used Teflon as Determined by Chemical Actionmetry

Teflon Tube I.D.	% UV Transmittance As Received	% UV Transmittance After Lab Cleaning
New, D=6 cm, T=0.81 mm	85%	--
New, D=6 cm, T=0.94 mm	72%	--
New, D=8.9 cm, T=0.46 mm	92%	--
New, D=8.9 cm, T=0.84 mm	85%	--
Port Richmond #1 <sup>a</sup>	7	68
Port Richmond #2	9	71
Port Richmond #3	5	72
Port Richmond #4	18	64
Port Richmond #5	30	76
Chinook—3800 hours <sup>b</sup>	30	75
Chinook—3800 hours (Cleaned in field with water and vinegar)	66	78
Chinook—100 hours	55	80
Chinook—100 hours (cleaned in field with water and vinegar)	70	85
Beech Mountain #1 <sup>c</sup>	33	74
Beech Mountain #2	47	78

<sup>a</sup>Port Richmond tubes had D=3.5" and T=0.030".

<sup>b</sup>Chinook tubes had D=3.5" and T=0.032". One half of the tube had been exposed to UV light for 3800 hours, the other half for 100 hours. Each of those halves was cut into sections; one section was cleaned with a high pressure nozzle washer with water and vinegar, the other not.

<sup>c</sup>Beech Mountain tubes had D=2.375" and T=0.033".

Note: D = inside diameters, T = wall thickness

ranged from 5 to 30 percent. The Chinook samples were not as obviously fouled, but they did have noticeable whitish precipitate deposits and some scum and grease attached to the Teflon. Their UV transmittance were in the range of 50 to 60 percent. Beech Mountain samples also demonstrated UV transmittances in the 50 to 60 percent range.

### 7.5.1.3 Summary—Adjustments to the Estimated UV Intensity

The lamp output will decrease with operating time. It is recommended that the system be designed (and subsequently operated) on the basis that the average output is approximately 80 percent of the nominal output. This is equivalent to an  $F_p$  of 0.8 in Equation 7-30. With time, it will be necessary to mix newer lamps ( $F_p > 0.85$ ) with older lamps ( $F_p < 0.75$ ) in order to maintain the desired output level. This will require monitoring by the procedures suggested earlier.

The quartz sleeves and Teflon tubes will require effective maintenance to keep their transmittances at reasonable levels. For design purposes, one needs to consider the minimum transmittance to be expected. With the quartz systems this is suggested to be 60 to 70 percent of nominal. This is equivalent to an  $F_t$  of 0.6 to 0.7 in Equation 7-30. For the Teflon systems, an  $F_t$  between 0.5 and 0.6 is recommended. In situations where the disinfection units are not to be frequently attended (remote, smaller plants), the values of  $F_p$  and  $F_t$  should be reduced further. Values of 0.7 and 0.4 are suggested, respectively.

### **7.5.2 System Design Considerations for Effective Maintenance**

An overriding concern in the proper maintenance of the UV reactor for effective performance is to keep all surfaces through which the radiation must pass as clean as possible. The effects of surface fouling on energy utilization efficiency were discussed in detail earlier in this section. It is critical, and can very often be pointed to as the primary reason for the non-performance of a particular system. Other concerns relate primarily to the accessibility to UV reactors and to keeping adequate records to control replacement cycles and maintenance schedules.

#### **7.5.2.1 Reactor Maintenance**

The most reliable method to determine if a reactor is becoming dirty and requires cleaning is by visual inspection. The unit should be drained and the surfaces observed for fouling. In open systems this can be done rather conveniently and quickly. Reactors which are sealed vessels can be difficult; these designs should accommodate such visual inspections by incorporating large portholes or manways in the reactor shell.

Generally the surfaces of submerged quartz systems contacted by the wastewater will become coated by inorganic scale, very much like boiler scale. This will especially be the case in areas where there is hard water. Additionally, the inside surface of the quartz and the outer surfaces of the Teflon tubes will eventually develop a grimy dust layer, primarily from airborne dirt and water vapor.

Fouling of the reactor's internal surfaces will be signaled by reduced performance efficiency, or by reductions in the intensity measured by in-line probes. While these may provide some signal of fouling, it is still necessary to be able to physically inspect the surfaces.

Subsequent discussions will present procedures and equipment for routine cleaning of the reactor surfaces which contact the wastewater. First, however, it is appropriate to discuss a maintenance task which should be conducted at least once per year, or once per disinfection season. This is to completely overhaul the reactor, cleaning all interior surfaces, and determining the lamp outputs and quartz (or Teflon) transmittances.

These procedures were demonstrated for quartz systems at Port Richmond (54). Each lamp is removed from the reactor and washed with a mild soap solution, rinsed, and swabbed with an alcohol (isopropyl) soaked rag (cheesecloth). Then the interior surfaces of the quartz sleeves are cleaned by the same procedure by using a gun-barrel type cleaning rod to swab the interior surfaces. At the same time, each lamp, which is tagged with an ID number, is

measured for relative output. Those which are below a specified level are discarded and replaced with new lamps. These new lamps are also tagged with a number. In this manner each lamp can be traced on the basis of operating time and output. A reactor lamp inventory can then be mixed and controlled to maintain a minimum average output level.

In similar fashion, the quartz should be monitored for transmittance. It may be cumbersome, however, to remove all the quartz from a system. It is recommended, instead, that a representative fraction of the quartz sleeves be monitored. Ten to fifteen percent of the quartz inventory would be sufficient. The same quartz should always be monitored; these would be considered as representative of all quartz in the system. If the tagged quartz begin to show marked deterioration due to aging and wear, it may then be appropriate to broaden the monitoring and to begin replacing the quartz sleeves. This replacement can be accomplished gradually. As with the lamps, there will eventually be a mix of old and new quartz in the system. There is little experience in determining the effective life cycle of the quartz sleeves; certainly it will vary by site, but generally should be between four and seven years.

In Teflon systems, the lamps are removeable on racks; they should be cleaned and monitored in the same manner as the quartz systems. The Teflon tubes should be cleaned on occasion; this can be done by swabbing the tubes with soapy water/alcohol. A non-abrasive material should be used. Each tube should also be monitored for transmittance, just as with the quartz sleeves. This may not be as straightforward, however, because of their limited accessibility and problems in getting direct measurements with a UV radiometer/detector. The actinometry procedure described earlier may be the more appropriate method for this application.

This system overhaul, as mentioned, should be accomplished at least once per year. In the case of plants with seasonal disinfection requirements, the most appropriate time would be before the start of the disinfection season.

#### **7.5.2.2 Routine In-Place Cleaning**

Regardless of a particular system's accessory cleaning equipment, it is likely that periodic chemical and/or detergent cleaning will be required to maintain the outer quartz, or inner Teflon surfaces. This is particularly the case where the wastewater is relatively dirty (secondary or primary effluents), has a relatively high grease and oil content, or has a high hardness content. A major cause in fouling the quartz surfaces (and to a lesser extent, the Teflon surfaces) has been found to be inorganic magnesium and calcium carbonates. The inorganic deposition is also

easiest to control; simple acidification of the reactor water will generally dissolve the material and restore the surface. In the case of organic fouling (usually from a high grease content) it is necessary to use a detergent or some combination of cleaning agents. This is typically determined by trial and error for a particular situation. The frequency with which this cleaning task has to be accomplished will also be site specific, and will be determined with experience.

A number of systems commercially available offer accessory equipment which are purported to maintain the surfaces of the Teflon or quartz. Currently, these are the mechanical wiper, ultrasonic transducer, and a high pressure spray nozzle. The mechanical wiper and ultrasonic devices are applicable to the quartz systems, while the high pressure spray wash is applicable to both the Teflon and quartz systems. Although these components may be effective in cleaning the appropriate surfaces, intermittent cleaning with chemicals is generally required, and it is strongly recommended that provision be made in the overall system design to allow for chemically cleaning the system. In certain cases, the accessory cleaning devices can be used to assist and increase the efficiency of the chemical cleaning task.

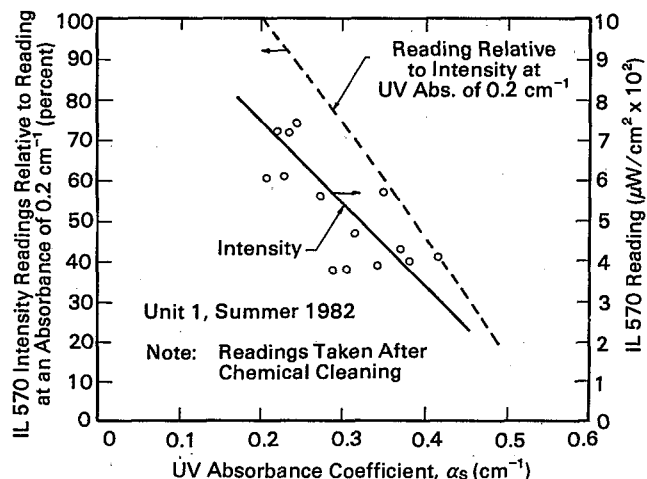
**Chemical Cleaning.** The task of cleaning the UV reactor on a routine basis is generally a very straightforward and simple task. The procedures and equipment requirements will generally be a function of the type of reactor and the system size. There is no standard procedure or equipment design, nor should there be. A system and procedure should be developed which best suits the application. This will be influenced by the size of the plant, the level of operator attention, the type and characteristics of the wastewater, and the UV system configuration.

The simplest procedure is applicable to the exposed open channel units. Examples are the systems at Pella, Iowa; Northfield, Minnesota; and Tillsonburg, Ontario. These are all open channel systems where the lamp batter can be drained, is accessible, and can be easily inspected visually. The unit at Port Richmond were also similar to these types of systems.

At Port Richmond, a combination of acid and an industrial detergent was used. The unit to be cleaned was isolated by diverting flow to the second unit; acid was then added to adjust the reactor water pH to approximately three. The acid was sulfuric in this case; a pH meter would be used as the entire reactor liquid volume was acidified by direct addition. Once acidified, the detergent would be added in similar fashion. The wiper stroke would usually be increased to assist the cleaning operation. This procedure was found to be very effective and typically required no more than one hour of a single operator's time.

An operational concern regarding this aspect of system maintenance is determining the frequency and/or need to chemically clean. Visual inspection has already been mentioned as the most effective procedure. An in-place intensity monitor would be effective, although there are concerns for this type of fixed place detector. The window for the probe must itself be kept clean in some fashion; additionally, the probe sees only the surfaces in the near vicinity, and the probe cannot directly account for the absorbance characteristics of the wastewater itself. At Port Richmond, a portable radiometer was found to be more effective, when used in conjunction with the UV absorbance measurements taken on each sampling. Intensity measurements were taken by placing the detector at selected (and reproducible) positions along the influent and effluent plane of the lamp battery. Figure 7-53, taken from the Port Richmond report, shows detector intensity readings versus the absorbance readings of the wastewater. These were taken after the unit was chemically cleaned. The relationship is important, not from the absolute intensity readings as a function of absorbance, since these will change with lamp age, but from the relative change as a function of absorbance. In this particular example, the intensity is shown relative to the intensity at an absorbance coefficient of  $0.2 \text{ cm}^{-1}$ . Thus, by knowing the relative effects of the wastewater absorbance, the operator can make reasonable judgements from the radiometer readings as to the condition of the quartz surfaces. This same procedure can be accomplished with the Teflon system by inserting the detector (always to the same fixed position) into the Teflon tubes.

Figure 7-53. Example of radiometer intensity readings as a function of UV absorbance at Port Richmond (54).



At Pella, Iowa, direct provision was not made for chemical cleaning (62). The system has mechanical wipers which are generally effective, but the units do foul. The operators isolate one of the two units, drain the channel and inspect the lamp battery. If dirty, the unit is rinsed, then sprayed with an acidic detergent. The wiper is stroked across the unit several times and the lamp battery is rinsed once again. The surfaces are inspected and the procedure is repeated, if necessary. The unit is then put back into service. This entire procedure is efficient, requiring one-half to one hour, and is typically done once every one to two weeks.

At Northfield, Minnesota, the quartz units are constructed very much like the units at Port Richmond, with inlet and outlet tanks. The lamp battery is open on both the inlet and outlet planes. Again, this plant had been designed with mechanical wipers and no provision to chemically clean the quartz. The area is marked by very hard water and the quartz were found to foul fairly quickly with an inorganic scale. The operators had cleaned the unit by adding citric acid to the reactor water (having first isolated it from the system) and allowing it to soak for several hours. The wipers would also be kept in operation during this period. This was generally effective, but relatively expensive. Each application involved adding 50 to 100 lb of citric acid, costing over \$100 per sequence.

This procedure has subsequently been modified. The citric was replaced by a cheaper mineral acid, (sulfuric acid). Less than a nine pound bottle is needed to reduce the pH to approximately three. It is recommended that the acid input be controlled by a portable pH meter to prevent addition of excess acid. A small metering pump with a small bulk acid drum (stored outside the building), is also recommended to further reduce the cost of the acid (low grade or waste mineral acid is sufficient). A recirculation pump is also added to rapidly mix the tanks and provide agitation. The water level is typically lowered to the top of the lamp battery to further reduce acid requirements. Once acidified, the unit is allowed to stand for a period of time, with the recirculation pump in operation and the wiper moving. The tank is then fully drained (drainage to the head of the plant) and the quartz is inspected. It is rinsed, sprayed with an acidic detergent, and then rinsed again with a high pressure hose. A wand sprayer is used to be sure the internal quartz are reached. The unit is then brought back into service. This procedure is effective and requires only one to two hours to accomplish. The frequency is generally once every week.

The Tillsonburg, Ontario unit is set in the plant secondary effluent channel and does not have any accessory cleaning equipment (63). This too can be easily cleaned because of its accessibility. The unit is

isolated, the channel drained, and the quartz cleaned by the procedures described above. Alternatively, this particular design allows for individual lamp modules (each containing four lamps) to be pulled from the unit. The unit does not have to be shut down, and, if necessary, a spare lamp rack can be inserted temporarily. The lamp racks are then inspected and thoroughly washed and rinsed. The unit design also incorporates the application of a proprietary polymeric coating to the quartz surface which is designed to retard fouling.

In sealed quartz systems, it is not possible to easily inspect the quartz or to access the internal quartz with sprayers or high pressure wash lines. At Vinton, Iowa the units are designed with ultrasonic devices, and a supplemental ability to chemically clean the reactor (64). The reactor is first drained, then it is filled with clean water and a chemical cleaning agent. These are added through piped inlets to the reactor. The system is also designed with inlet ports to inject either high pressure air or water to agitate the solution inside the unit. The unit is then drained (back to the head end of the plant), and returned to service.

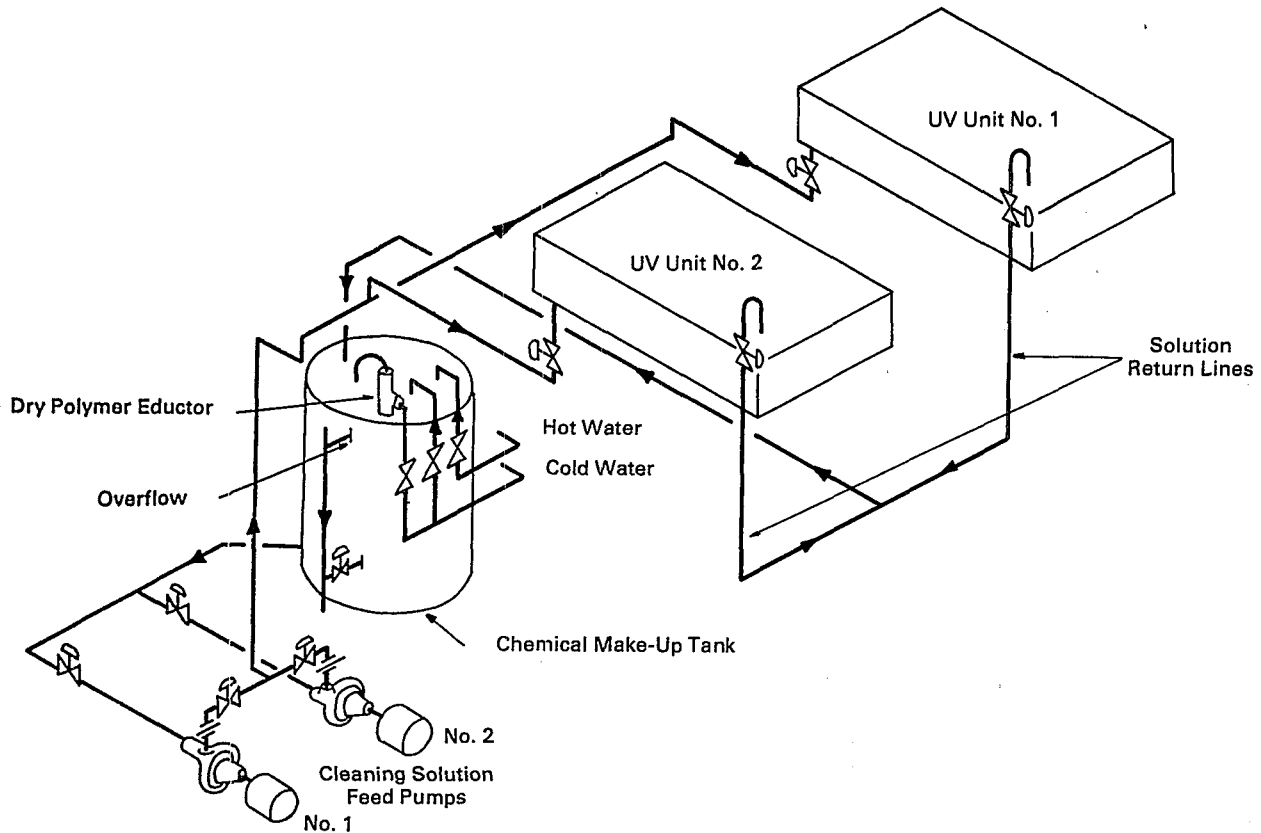
At Suffern, New York, the system is also sealed. Ultrasonics are incorporated as the primary cleaning device, with a supplementary chemical cleaning system (4). The chemical cleaning system includes a solution mix tank, and recirculation pumps. A schematic is provided on Figure 7-54. A solution of the cleaning agent is prepared in the tank with warm water, and then recirculated for a period of time. Food grade citric acid or sodium hydrosulfite is used.

During startup at Suffern, the quartz became heavily fouled (the units had been allowed to sit for a long time filled with wastewater); the citric acid was not effective in this case. The sodium hydrosulfite was very effective; however, it is highly reactive and a strong oxidant. This material would likely be the most effective in sealed systems where the cleaning relies solely on contacting the surface under agitated conditions. It must be handled with great care, however, and special precautions would be required to properly store and handle the material. The chemical manufacturer should be consulted on these aspects.

A special note is also made under this topic of routine chemical cleaning. In several cases, it has been observed that a luxuriant growth (believed to be a fungus) will develop on the wetted metallic surfaces of the UV reactor. Additionally, particularly in reactors which have quiescent zones, sludge accumulations can develop. When the systems are drained and/or cleaned, an effort should be made to remove these accumulations.



Figure 7-54. Schematic of in-place chemical cleaning system at Suffern, New York (4).



**Mechanical Wipers.** A number of full-scale systems incorporate the use of a mechanical wiper. Recall from Figure 7-5 the schematic of the wiper blade on a submerged quartz system. These entail a machined frame in which the wipers are fixed; these then fit over the quartz sleeves. A single frame usually services the entire lamp battery. The wiper is driven by cable (pneumatically pulled) or by a piston. This can then be stroked across the reactor at a preset frequency. Examples of systems which have wipers are Pella, Iowa; Northfield, Minnesota; and Albert Lea, Minnesota.

Generally, the wipers are looked upon favorably by plant operators. At Pella, the wiperblades are a rubber-base ring. These tend to wear and will typically require replacement every one to two years. The wiper does not accomplish its original intent, which was to keep the surfaces clean, precluding the need for chemical cleaning. The wiper is felt to serve a useful purpose, however, by continually removing small debris particles, including grit, plastic fibres, and strings of algae (from the secondary clarifiers and channels). When the unit is taken down for chemical

cleaning, the wipers are used to provide a degree of scrubbing.

Similar observations are made at the Northfield plant. The rings, in this case, are made of Teflon. Although they should not wear as quickly, it is found that the Teflon ring becomes distorted. It has no memory; thus, if there is a variation in the surface of the quartz, the Teflon will respond but will not recover its original shape. The wiper is still considered a benefit, however, because of its ability to keep the surface free of debris, and the ability to use it during the chemical cleaning task.

At Albert Lea, the wiper also uses Teflon rings but of a different design (and at present the most current design). These rings are split by cutting the ring on a bias at one point on its circumference. A spring then surrounds the ring, its compression causing the ring to always try to close. In this fashion, if the wiper passes over a section of the quartz which is larger in diameter, the ring will expand. As the quartz diameter decreases, the Teflon will also close down on the surface because of the spring action.

A limited series of tests were performed at the Albert Lea plant to assess the effectiveness of the wipers. These tests involved monitoring quartz clarity from modules which were operated with and without the wiper. The results were not wholly conclusive. Kreft et al. (4), reported that the wipers were effective in reducing the buildup of scale and biological growth on the surfaces of the quartz, when compared to the unit with no wiper in operation. The report also noted problems which must be addressed in the design and operation of system with the wiper devices. The cable drive is sheathed in Teflon; this was found to crack and cause water leaks onto the outside electrical connections (this same problem was reported in the Port Richmond study). This resulted in electrical hazards which on one occasion caused a small electrical fire. The second problem arose due to the misalignment of the wiper frame. This will cause, at minimum, incomplete wiping of the quartz; at worst, the misalignment will cause breakage of the quartz sleeves.

Other considerations which should be taken into account are the time requirements for the disassembly and repair of these wiper mechanisms. Experience up to now has involved the equipment manufacturer accomplishing this task; this may be appropriate since it requires extensive handling of the quartz sleeves and precise alignment of the frame when reassembled. The design of the UV system should address these tasks, particularly their costs, including the costs of replacing the individual wipers (e.g., the spring loaded split Teflon rings).

*Ultrasonics.* Ultrasonic devices rely on the surface cavitation caused by high frequency sound waves. When properly applied, debris which coats a surface will simply fall off. This concept has been applied at a number of full-scale plants, including the Suffern, New York and Vinton, Iowa installations. The ultrasound transducers are typically inserted across the length or width of the reactor, parallel to the quartz sleeves. They are operated on an on/off cycle, the on-time determined by the specific site requirements.

The units at Vinton each have two transducers which have 1.8 kW ultrasound input; thus, each unit is equipped with a total of 3.6 kW input. The units are rated to have an effective radius of activity of approximately 0.75 m over a 180° arc.

The total lamp power in each of the units at Vinton is approximately 12.8 kW; this yields a ratio of ultrasonic power to lamp power of 0.28. With the ultrasonics operated 25 percent of the time, the energy utilization by the ultrasonics comprises approximately seven percent of the total when all lamps are being operated and 28 percent when one bank of lamps (out of four banks) is in operation. These would

increase if the ultrasonics are required for greater periods of time.

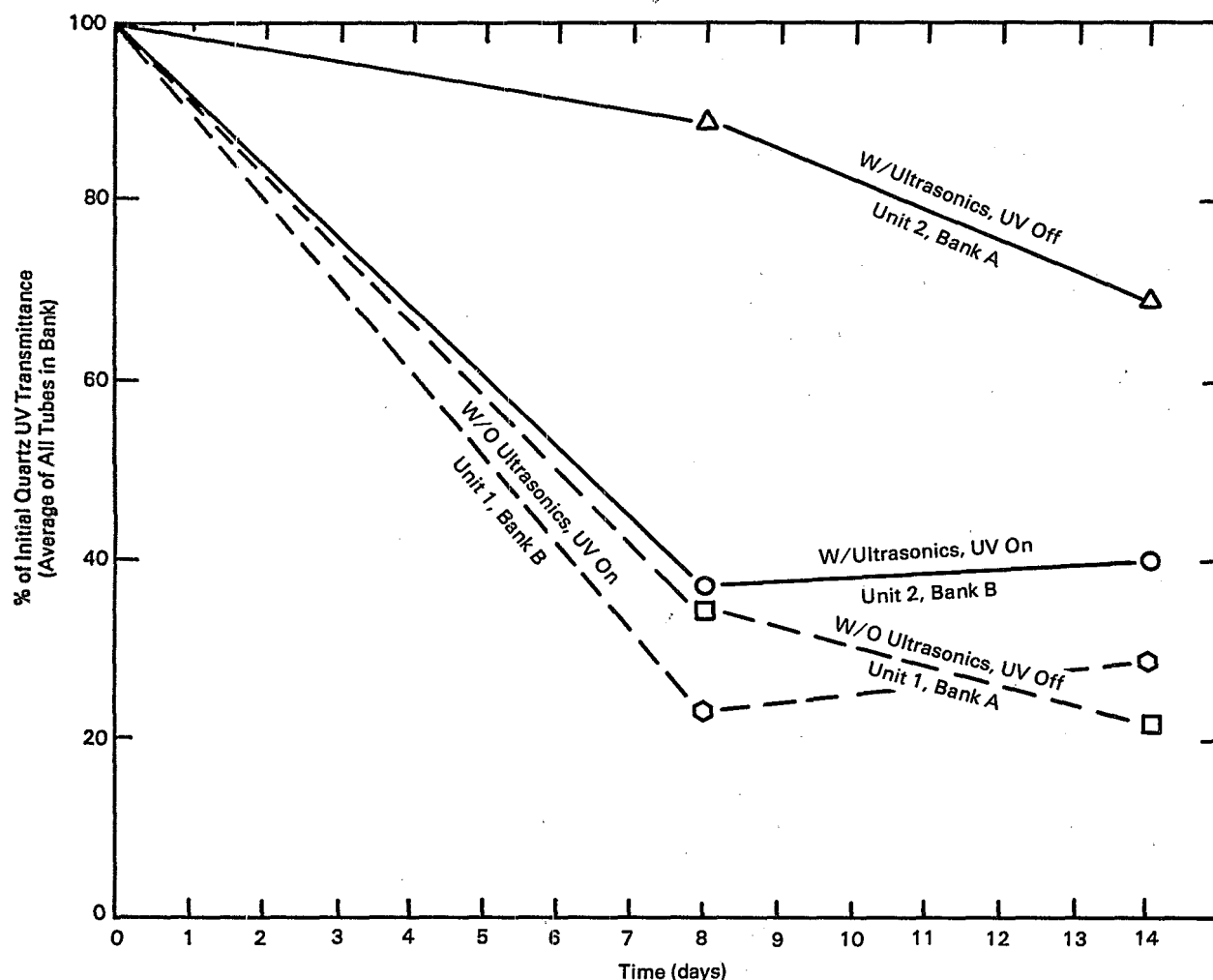
The system at Vinton has been in operation for approximately two years. At first the ultrasonics were operated with approximately 25 percent on-time. This was not felt to be effective and was gradually increased to nearly full time. This is excessive; its cost of operation negates its utility. Hypochlorite had been used to chemically clean the Vinton reactors. This is not effective, and may have contributed to the poor performance of the ultrasonics.

The Suffern units each have one 1.5 kW transducer per two banks of lamps, or two per unit. The ratio of ultrasonic to lamp power is approximately 0.14, or half that at Vinton. A limited series of tests were recently performed at this plant to evaluate the effectiveness of the ultrasonics (4). The tests were conducted over a two week period, using unit 1 without ultrasonics and unit 2 with ultrasonics. The ultrasonics were operated on a cycle of 30 minutes on and 30 minutes off (50 percent on-time). Flow was generally split evenly between the two units. As discussed earlier, the quartz will accumulate buildup differently, depending on whether the lamps remain on or off for extended periods of time. With the lamps on, an inorganic scale tends to develop; with the lamps off, the quartz simply provide a surface for a biological film to develop. The ultrasonics were evaluated as to the ability to retard the buildup of either type of material. In either unit a select number of quartz sleeves were monitored in a bank where the lamps were kept off and in a bank where the lamps were continuously operated.

The results of the evaluation, taken from the study report, are presented on Figure 7-55. The dashed lines are from Unit 1, which operated without the ultrasonics; there appears to be no significant difference between the banks with the lights on or off. It may be said that the bank with the lights on tended to degrade at a faster rate than the bank with no lamps on. By the fourteenth day, however, the transmittance of the quartz sleeves in either bank was between 20 and 30 percent of the initial transmittance.

The results of the test in Unit 2, which operated with the ultrasonics, show a significant difference between the banks with or without the lamps on. With the lamps off, the ultrasonics appear to have been very effective; after 14 days, the quartz transmittance was still approximately 70 percent of the initial transmittance. In the bank which had the lamps on, however, the ultrasonics was ineffective; by day eight, the transmittance was between 35 and 40 percent of the initial transmittance. It appears that the ultrasonics are unable to retard the softening effect in which the inorganic carbonates plate out on the

Figure 7-55. Comparison of ultrasonic cleaning performance at Suffern, New York (4).



quartz surface. This phenomenon will occur only when the lamps are on.

In all, current experience has not confirmed the utility of ultrasonics as a cleaning device. This would especially be the case in areas with hard waters. Additionally, consideration should be given to the cost of the accessory device on the basis of both additional capital cost and added operating cost due to its energy requirements.

**High Pressure Wash.** This is closely related to the earlier discussions of routine chemical cleaning. Commercially available industrial cleaning units are available which use pressurized water to clean surfaces. The type of hose nozzle or spray wand used to discharge the water will vary and will depend on the application. In the Teflon units, a nozzle is fitted to the end of a flexible hose; spray is directed radially from the nozzle as the hose is snaked down the Teflon

tubes. The systems have the capability of educting a detergent or acid solution into the wash stream. The same type of system would be applicable to quartz systems. In this case, however, a wand type sprayer would be more appropriate to reach the insides of the lamp battery. The system is inexpensive, easy to use, and recommended for most UV reactor applications.

Equipment manufacturers for the Teflon tube systems have been supplying a high-pressure nozzle spray cleaning system with several recent installations. Kreft et al. (4) reported on visits to wastewater treatment plants at Chinook, Montana and Rock Springs, Wyoming to observe performance of the cleaning systems. The Rock Springs UV disinfection unit had moderate to heavily-fouled Teflon tubes (black and brown coatings) caused by heavy solids and foam and grease carry-over into the tubes. During cleaning, it was noted that the high-pressure nozzle system was able to remove, in some cases,

significant portions of the fouled material from the inside surfaces of the Teflon, but was not consistent for all tubes. In some tubes, very little material was removed and, therefore, the UV transmittance would be assumed to still be minimal. A series of repeated cleanings may be necessary to remove the material from all tubes. This is a critical point; if a few tubes remain dirty, their consequent poor performance can have a dramatic effect on the overall performance of the system.

At Chinook, the amount of fouling on the tubes was not as heavy as at Rock Springs and the high pressure cleaning system appeared to remove most of the material attached to the inside of the Teflon tubes. A sample of a cleaned tube was measured by the chemical actinometry method along with the used samples that were taken from the Chinook plant. It was verified, as shown in Table 7-17, that the in-place cleaning did return the Teflon tube to a UV transmittance in the range of 65 to 70 percent from an uncleaned transmittance of 30 to 55 percent.

The authors concluded that the high-pressure nozzle washing systems have some benefit in helping to clean the interior surfaces of Teflon tubes. Since the Teflon tubes are themselves usually difficult to access, the nozzle cleaning system offers some advantages and provides the operator with a simpler cleaning task. They did indicate, however, that internal swabbing of the Teflon tubes with a soft rag, and possibly with a detergent, will be necessary on an occasional basis to ensure that the Teflon tubes remain in a fairly clean state. It was also noted that many of the plants visited that had Teflon UV units had noticeable amounts of dust on the outside surfaces of the tubes. It is highly recommended that in all installations, a routine maintenance task must be to clean the outside with a rag and, possibly isopropyl alcohol or water; this will improve the transmission of the UV light through the Teflon into the wastewater.

#### **7.5.2.3 Other Design Elements for Effective Maintenance**

The following observations are made on the basis of current full-scale and pilot scale operating experiences. These are directed to considerations for design, fabrication, and installation which will ease maintenance tasks or provide for more effective maintenance:

- a. The reactors and related tankage should be equipped with drains which will allow for complete and rapid dewatering. Drainage should be to the main plant drainage system.
- b. A clean water supply should be permanently available, in addition to all requirements for chemical cleaning.

- c. The systems should be designed modularly with the ability to readily isolate a module from the plant flow.
- d. A bypass should be constructed around the entire UV disinfection system, particularly in plants which require only seasonal disinfection. This would allow for greater convenience for maintenance tasks during the non-disinfection season.
- e. The accessibility to the lamps, quartz sleeves, and Teflon tubes is critical to the ease of maintenance. Manways should be provided on larger scale systems.
- f. Strict inventories should be kept of the lamps in use, their relative output, and their estimated cumulative operating life. This should also apply to a more limited extent to the quartz sheaths, Teflon tubes, and ballasts.
- g. The reactors and all other accessory equipment should be installed in an area that is adequate to accomplish all the required maintenance tasks. The systems should not be so cramped that it is virtually impossible to work on the units.
- h. If reactors are taken out of service, they should always be drained; a clean water rinse would also be appropriate. The units should then be held in a drained, dry condition.

#### **7.5.3 System Components**

The major components of the UV systems are the lamps, enclosures, and the ballasts. Discussion of these have been interspersed throughout this text. The following observations are made to highlight the major points to consider when evaluating or designing a new system, or in the operations of an existing system.

- a. The low pressure mercury arc lamps are currently the most efficient source of UV radiation. Costwise, the longer arc length lamps are more efficient. Because of the negative effects of the ozone produced by the 185 nm light, lamps with fused quartz envelopes are not recommended. The lamps of vycor or other high transmission glass are appropriate.
- b. Care should be taken to minimize temperature effects. In quartz systems, O-ring spacers should be slipped over the lamps to prevent direct contact with the cooler quartz sleeve. These are generally provided in the newer systems.
- c. Fittings holding the quartz sleeve should be tight and leakproof. A number of plants have had problems with leaks at these points, causing

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electrical hazards and corrosion. Additionally, some designs are difficult to disassemble and reassemble, causing excessive labor, quartz breakage, and continuing leaks.

- d. The quartz sheaths are fairly standard in composition. Variations have been noted in the wall thickness; attention should be paid to the structural strength of the sleeve. Another variation is the single end quartz in which only one end of the quartz is open; the other end of the quartz is fused close. A plant which will use this type of quartz is the Nine Springs plant in Madison WI. The wiring from the lamp electrode at the fused end of the quartz will be snaked back to the open end of the quartz.
- e. Frequent on-off cycles for the lamps will shorten their life. More effective lamp control may be accomplished by voltage dimming, in conjunction with on-off control of banks of lamps.
- f. Control panels should be remote from the UV reactor.
- g. The ballasts must be properly mated with the lamps being used. It is strongly recommended that both the lamp and ballast manufacturers be consulted on this aspect. It would be appropriate to require certification that the ballast is correct for the UV lamp. The ballasts should be thermally protected; this forces the ballast to shutdown if it overheats.
- h. The power panel containing the ballasts must have adequate ventilation to discharge the heat generated by the ballasts. This has been a recurring problem at full-scale installations. The life of the ballast is greatly shortened and in several cases excessive heat build-up caused rapid failure of a number of ballasts. High volume ventilation fans should be installed in the power panels to cool the ballasts. During warm temperature months, this should be vented out of the building.
- i. Careful attention should be paid to the electrical wiring of the UV systems, at the points of both fabrication and installation. Improper wiring at several plants resulted in electrical hazards, component failures, and in some cases, small electrical fires. The wiring should be properly sized and the wire covering should be resistant to UV radiation effects. Typically, Teflon coated wiring is specified.
- j. The Teflon tubes are generally standard. The variables are the wall thickness and the tube diameter. The transmittance will decrease with increasing wall thickness; very thin walls will

limit the structural integrity of the tube, however, causing them to collapse. Greater intensities can be achieved with smaller diameter tubes; this will have to be weighed against increased head losses.

- k. Air bleeds should be considered on certain Teflon systems (in particular the pressure units) to minimize air binding in the Teflon tubes.
- l. Removeable screens should be placed upstream of the lamp reactor to prevent large debris from entering the system. This is especially important for quartz systems.

#### **7.5.4 Monitoring and Control**

**System Controls.** The sophistication of the monitoring and control systems for the UV process can vary from minimal to fully automated. This is no different from any other unit operation in a treatment facility. It is recommended that the minimum should always be provided; any increased capability should then be considered on a cost-benefit basis. The minimal requirements suggested for the UV disinfection process are flow metering per unit, individual lamp operating monitors, a portable radiometer, power panel temperature (with alarm), and the ability to turn portions of the system on and off on the basis of time. The following observations are made, again as points which should be considered when evaluating or designing a UV system:

- a. The units should be arranged such that banks of lamps can be shut off or on. In the simplest mode this can be controlled by timers. Modest adjustments can then be made on a diurnal basis to reflect the normal variation in the plant's flow. This can be further advanced by automatically slaving the lamp bank operations to the plant flow; some systems also will adjust the unit voltage, using bank shutoffs as a gross adjustment.
- b. Concurrent with the plant flow, the control of the system can be coupled to the water quality. This is done in some systems by use of an intensity monitor fixed to the reactor; this may cause problems if it cannot be effectively maintained. An alternative method is to utilize a continuous monitor of the wastewater UV absorbance.
- c. As had been discussed earlier, it is important that a continuing record be kept of the average output of the lamps, and the transmittance of the quartz and Teflon. Procedures have been given by which to monitor these parameters. It is strongly recommended that these become part of the system's routine O&M, and that the necessary equipment be available to accomplish these tasks.

- d. In-line pilot light monitors should be installed in the control panels to indicate each lamp operation. This is normally available on most UV systems. Alarms should be installed to alert the operator if a preset number of lamps fail.
- e. The flow to each module should be metered.
- f. Elapsed time monitors (non-resettable) should be installed for each bank of lamps. This will allow an accurate accounting of cumulative operating time and will allow the operator to balance the use of the various lamp banks in a system.
- g. The temperature in the ballast power panel should be monitored. An alarm system should be available to alert the operator if the panel temperatures exceed an acceptable level.
- h. A watt-meter would be useful, particularly in larger systems, to monitor on a continuous basis the power requirements relative to the remainder of the plant.

#### 7.5.4.2 Wastewater Monitoring for an Existing System

The UV disinfection process does not have the monitoring advantage of a measurable residual (as is the case with chlorine). As such, greater care is required in controlling operations efficiently and still maintaining performance. It is strongly recommended that this entail frequent sampling and analysis. A suggested protocol is to sample the system a minimum of three times per week (alternating days) between the hours of 10 a.m. and 3 p.m. The influent to the UV system should be analyzed for suspended solids, UV absorbance, and coliform density (i.e., the bacterial monitor prescribed by the plant's permit). Additionally, the flow rate should be recorded at the time of sampling, as well as the operating conditions of the reactor (number of lamps in operation, etc.). The effluent sample should be analyzed for coliform density.

An important note should be made with regard to the subsequent handling of the exposed UV effluent sample. All precautions should be taken to protect the sample from exposure to visible light (sunlight and normal fluorescent and incandescent light), before the sample has been set and put into incubation. This will prevent the occurrence of photoreactivation. Normal precautions include sampling in an opaque (and covered in foil) sample bottle, and keeping the sample covered during the procedure to set the sample (filtration and plating for the MF procedure, and dilutions and inoculation for the MPN procedure).

Alternatively, if photoreactivation is to be accounted for by the permit requirements, the effluent should be

taken with the transparent glass bottle and left in direct sunlight for approximately one hour. Enumeration would then be accomplished by routine procedures. Either the direct Membrane Filter (MF) or the Most Probable Number (MPN) procedures have been demonstrated to yield equivalent recoveries (65).

Collection of such a relatively comprehensive data set is felt to be important in controlling the operations of a UV system. It allows direct evaluation of the system performance under current wastewater conditions and provides a data base from which the disinfection model can be calibrated and/or refined. The model itself then becomes an excellent tool in controlling the system and optimizing operations for maximum use of lamps and minimal use of energy. The continuous collection of the appropriate data also allows a rational approach to troubleshooting the non-performance of a system.

#### 7.5.5 Safety Considerations

Ultraviolet disinfection is basically a safe process; the activity is generated on-site; thus, there are no transport concerns to or from the site, or concerns regarding storage of reactive material. Normal plant safety precautions apply relative to physical layout (railings, etc.) and to electrical hazards. Power supplies are high voltage, requiring the adherence to normal electrical safety codes. Electrical interlocks should be provided to shut off systems when opened (reactor end panels); particular attention should be paid to electrical wiring, groundings, and water-proofing.

The storage, handling, and disposal of the expendable components should also be considered from the standpoint of safety. Storage of lamps, quartz sleeves, and ballasts should be in a separate dry area. Adequate shelving should be designed to store the materials such that they are protected from breakage, and are easily and safely accessed. Used lamps, quartz sleeves, and ballasts which are to be discarded should be repackaged and overpacked for safe disposal.

Personnel safety training should address and require strict adherence to personal protection from excessive UV radiation. A lamp battery would not present a hazard while submerged and operational; the water absorbance will sufficiently attenuate the radiation. These lamp batteries should not be operated while in a dewatered and dry state. Similarly, "dry lamp" systems such as the Teflon unit, should have all covers in-place during operation. Plastic (e.g., plexiglas) will not transmit the 253.7 nm wavelength; this material can be used for the end plates (windows or end plates) or unit shields to protect against exposure but still allow visual inspection of the lamp ends. If it is necessary to engage a system without shields in

place (or with the lamp battery exposed) it is absolutely necessary that the proper protective gear be worn by all personnel in the area and that adequate warning signals be active during these operations to warn anyone entering the area. This will also apply during the routine lamp monitoring tasks discussed earlier.

The skin and eyes readily absorb UV radiation and are particularly vulnerable to injury. Sunburn (erythema) is a common example, although this effect is most pronounced with UV light between wavelengths 285 and 300 nm. Absorption by the mucous membranes of the eye and eyelids can cause conjunctivitis (commonly referred to as "welders flash"). The injury becomes apparent 6 to 12 hours after exposure; although painful and incapacitating, the damage is usually temporary.

Personal protection must include plastic goggles (wrap around), or face-shields. These must be rated to absorb the UV spectral lines. Protective clothing should be worn to prevent exposure to the hands, arms, and face.

#### **7.5.6 Facilities Requirements for Full Scale Installations**

The facilities needs are divided to two specific areas: equipment and the physical plant. The equipment elements include the hardware requirements directly associated with the installation of the UV process. The installation at a given plant site must then address the hookups and physical plant needs to install the system.

##### **7.5.6.1 Equipment**

The equipment generally supplied through the vendor include the UV reactor itself and the ancillary equipment used to control and monitor the system:

- a. UV lamp battery (UV reactor)
- b. Power supply and power panels (with single point hookup to the plant power)
- c. Instrumentation for the control and monitoring of the system; this generally includes a UV intensity monitor per module, pilot monitors for each lamp, controller to direct the number of lamp banks on as a function of flow (and/or water quality), and alarms to signal deficiencies in lamp operation and/or performance.
- d. Accessory cleaning equipment; this is generally in the form of chemical cleaning, mechanical wipers, or ultrasonics.
- e. Manufacturer's engineering and startup services are generally at the option of the buyer.
- f. Replacement parts supplied with purchase; this should include no more than 100 percent lamps,

50 percent ballasts, and 20 percent quartz or Teflon tubes. At minimum, this should be 20 percent, 10 percent and 10 percent, respectively.

When specifying a UV system, the design should analyze the cost of the ancillary monitoring and cleaning devices to be provided with the reactor against this need and benefit. These can account for 15 to 25 percent of the total equipment costs.

##### **7.5.6.2 Physical Plant**

The structural and installation requirements are sensitive to the specifics of the site and the equipment to be installed. It is difficult to give a detailed assessment of these needs; by way of guidance, however, a generic installation is considered.

There is a basic space requirement for the UV system at a plant, based on the number of lamp modules to be installed. The smallest plants would generally require only one module; the reactor itself is rather small. A minimum space of 10 m<sup>2</sup> (108 sq ft) should be allowed, however, for the unit. It is further suggested that this space allocation be increased to 25 m<sup>2</sup> (270 sq ft) for large modules which may contain several hundred lamps. Thus, a 500 kW system may contain approximately 6,000 lamps in 10 modules; the total space allocation would be approximately 250 m<sup>2</sup> (2,700 sq ft). In most cases, the system should be housed in a standard building. Certain configurations proposed by engineers/manufacturers (including existing full-scale systems), do not require such housing. The designs generally call for open channel installations of the UV equipment. The power supplies and instrumentation in this case require more stringent specifications with regard to weatherproofing and protection against water/electrical hazards.

Reactors which are housed are generally characterized by piped inlet and outlet structures. The reactors are typically sealed units or have integral influent and effluent tanks attached to the lamp battery. The housing itself may be shared with other unit operations in the plant. Power supplies and control systems are contained in the building, typically remote and elevated from the reactors. Storage for spare parts (lamps, ballasts, etc.) can also be accomplished within the building. The entire area should be adequately ventilated, particularly with regard to humidity control and venting from the power panels.

##### **7.5.7 Estimating O&M Requirements**

UV is a capital intensive process, with the equipment requirements directly proportional to the design peak hydraulic and performance needs. The operational and maintenance needs, however, are reflected more by the average utilization of the system. In fact, a key operational consideration is to use only that portion of the system necessary to meet current performance

demands. Over-utilization of the system, in an attempt to simplify operations, will have a significant impact on the costs to operate the process. The following discussions focus on the three major elements which comprise the costs associated with the operation and maintenance of a UV system.

#### 7.5.7.1 Labor Requirements

Estimating labor requirements is a subjective task, relying on current experiences and being selective in defining the tasks which should be assigned to the UV process. In estimating labor needs, Scheible et al. (54) assessed the experience in the operation of the Port Richmond plant, as well as previous studies, and the current experience at full scale facilities. The estimates are summarized in graphical form on Figure 7-56. As shown, the labor is divided to three major categories: direct UV operation and maintenance tasks; general maintenance; and system overhaul. It is important to note that the labor estimates are based on the O&M requirements for the entire installed system.

*Direct UV Operation and Maintenance.* The tasks which are considered in this category may be described as follows:

##### 1. Operations and Monitoring

- daily systems checks for proper operation;
- appropriate recording of data (lamps in operation, meter readings, power readings, flow rates, water quality readings, temperatures, etc.);
- sampling and analysis for SS, bacterial density, UV absorbance;
- direct manual control of the systems, or the monitoring and control of automatic operational instrumentation.

##### 2. Maintenance

- checking and maintaining system components (lubrication, etc.);
- storage and maintenance of appropriate parts inventory;
- routine systems cleaning, the labor associated with this task will include monitoring of the quartz/Teflon surfaces, switching systems during special cleaning cycles, and maintenance of the chemical feed systems;
- replacement of worn or broken components in the system.

The labor needs assigned to these direct O&M tasks are estimated to range from 2-3 hr/wk for small systems (less than 100 lamps) to 15-30 hr/wk for larger plants (greater than 1,500 lamps).

*General Maintenance.* As had been discussed, there are space, building, and ventilation requirements associated with the installation of a UV process. The general maintenance of these physical facilities will be required. For purposes of this discussion, the labor is assigned to the labor requirements for the disinfection process at a plant. It is suggested that approximately one-half the labor required for the direct O&M tasks discussed above be assumed for the general maintenance tasks.

*System Overhaul.* The reader is referred to the earlier discussions which dealt with the cleaning and direct measurement of the lamps and the quartz/Teflon which comprise the UV reactor. It is strongly recommended that the entire system be broken down on a yearly basis to accomplish the following tasks:

- a. clean the outside surface of each lamp;
- b. clean the inside surfaces of each quartz sleeve, and the outside surfaces of the Teflon tubes;
- c. measure each lamp for relative UV output; replace those which fall below a specified level;
- d. measure a representative sampling of the quartz/Teflon enclosures for transmittance, replace those which are worn excessively; and
- e. check internal components for wear and replace if necessary.

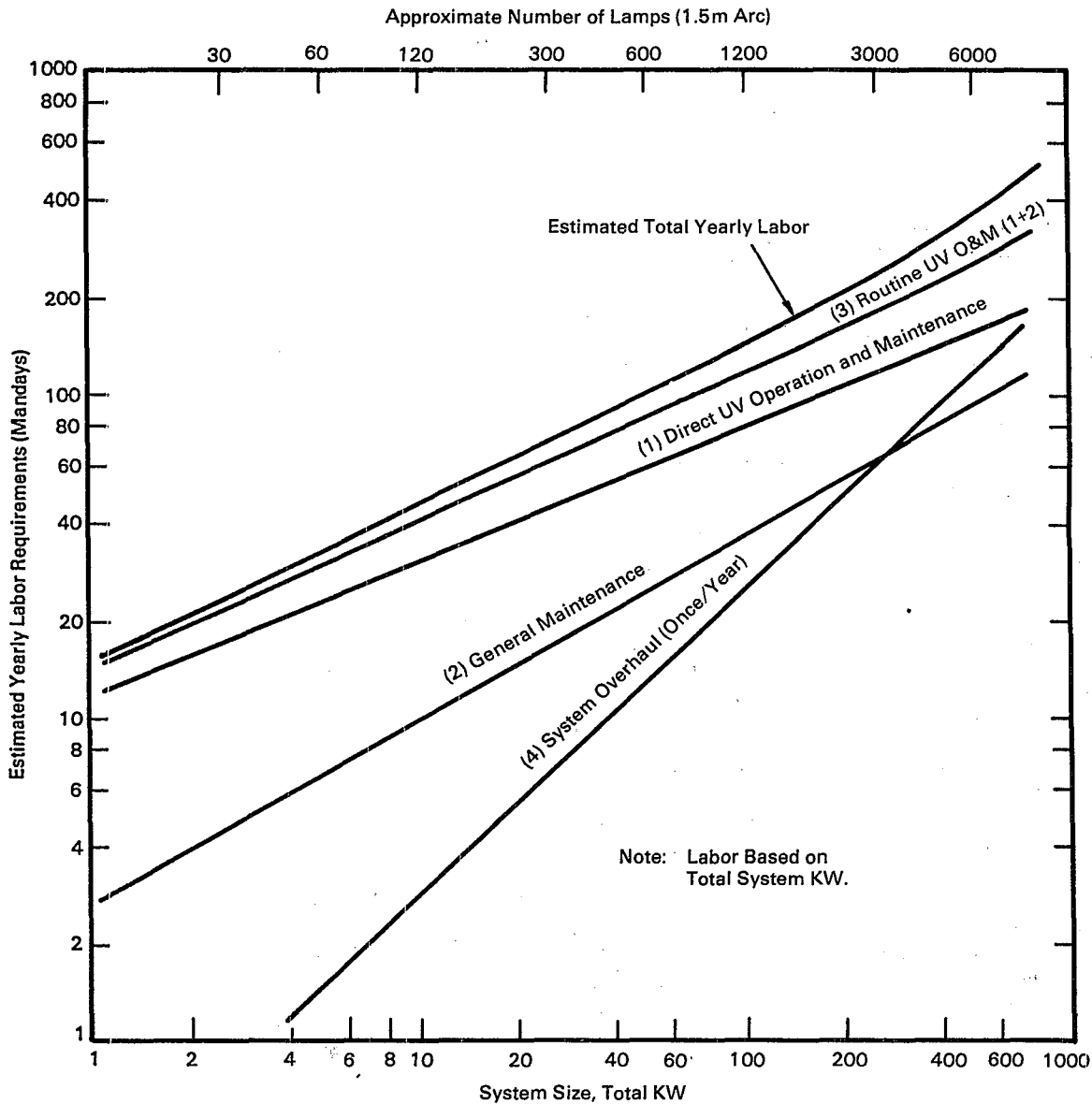
These tasks are suggested to serve as an efficient means to control the system's output and energy efficiency at acceptable levels. By having direct measurements of the unit's average output, the lamps can be utilized to their maximum life. Keeping the surface clean will allow for efficient use of the UV energy.

Based on the experiences of Port Richmond, the labor required to accomplish the system overhaul each year is estimated to be approximately 16 hr/100 lamps. Relative to the total labor requirements for the UV process, the system overhaul is small, but can yield significant overall O&M cost savings.

*Total Labor Estimates.* The total yearly estimated labor requirement is presented on Figure 7-56. Note that these are based on year-round disinfection. In cases where seasonal disinfection is allowed, the labor estimates for the direct O&M, and the general maintenance tasks would be reduced; the system overhaul is still recommended on a yearly basis. Overall, the labor needs for the UV process are relatively low, ranging from approximately 40 mandays/yr for a small 10 kW (120 lamps) system to approximately 400 mandays/yr for a 400 kW system (5,000 lamps).



Figure 7-56. Estimate of labor requirements for the operation and maintenance of UV systems (54).



### 7.5.7.2 Materials

The major materials cost associated with the UV system are the lamps, the ballasts, and the quartz or Teflon enclosures. Note that these requirements are considered as a function of the annual average system utilization (kW). Thus, although the system may be sized to meet the peak power demand, the need to replace the major expendable components of the system will depend on their actual use; this can be represented by the estimated annual average utilization of the system. To estimate the annual average requirement for material, the following suggestions are offered:

**Lamps.** Low pressure mercury arc (1.5 m/arc) are standard. This replacement cycle should be assessed at one year (8,700 hours). This is conservative; there are cases where considerably longer life cycles have been demonstrated.

**Ballasts.** A single ballast serves two lamps. The average life cycle is five years; this can be considered conservative if the ballast is properly mated and the power panel is properly ventilated to prevent overheating.

**Quartz/Teflon Enclosures.** The estimate should assume one quartz sleeve per lamp, and one Teflon

tube (3 m) per two lamps. An average life cycle of five years is suggested for both, although there is little demonstrated experience in this regard.

*Miscellaneous.* To account for miscellaneous parts replacement, a cost equivalent to five percent of the annual lamps, ballasts, and enclosures costs are suggested.

#### 7.5.7.3 Power Requirements

The third element, power, should also be estimated on the basis of the annual average system utilization. This requirement can be accounted for by addressing the lamps only. Ancillary power use is relatively insignificant, except in cases where ultrasonic devices are used for cleaning. The total power per lamp is 80 Watts (for 1.5 m arc lamps), including the ballast.

#### 7.5.7.4 Estimating Average Annual Utilization

As discussed, the materials and power requirements (and to a lesser extent, the labor needs) should be based on the annual average utilization. An example of this analysis was provided in Section 7.4 for the design example. It is based on the design needs for average wastewater conditions (flow, UV absorbance coefficient, initial density, and suspended solids). This can be significantly less than the peak system requirement (20 to 30 percent of peak), particularly with plants which are not at capacity and in cases when only seasonal disinfection is required.

## 7.6 References

1. Disinfection of Wastewater—Task Force Report, EPA-430/9-75-013, U.S. Environmental Protection Agency, Washington, DC, 1976.
2. Environment Canada. Wastewater Disinfection in Canada. A Background Paper Prepared by the WPC Directorate, Environmental Protection Service, Report No. EPS 3-WP-78-4, 1978.
3. International Joint Commission. IJC Chlorine Objective Task Force Final Report., 1976.
4. Kreft, P., Scheible, O.K. and A.D. Venosa. Hydraulic Studies and Cleaning Evaluations of Ultraviolet Disinfection Units. Presented at the 58th Annual Conference, Water Pollution Control Federation, Kansas City, MO, 1985.
5. J. M. Montgomery Engineers, Inc. Ultraviolet Disinfection; I/A Technology Assessment. Summary List of Facilities in the USA or Canada Utilizing UV Light Disinfection. Contract No. 68-03-1821, U.S. Environmental Protection Agency, Cincinnati, OH, 1984.
6. Venosa, Albert D. Current State-of-the-Art of Wastewater Disinfection. JWPCF 55(5), 1983.
7. Kohler, Lewis R. Ultraviolet Radiation, Second Edition. John Wiley & Sons, Inc., New York, NY, 1965.
8. Waymouth, J.F. Electric Discharge Lamps. The M.I.T. Press, Cambridge, MA, 1971.
9. Downes, A., and Blount, T. Research on the Effect of Light Upon Bacteria and Other Organisms. Proc. Roy. Soc., London, 26, 488, 1877.
10. Jagger, J. Introduction to Research in Ultraviolet Photobiology. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1967.
11. Setlow, R.B. and Setlow, J.K. Effect of Radiation on Polynucleotides. Annual Reviews of Biophysics and Bioengineering 1:293-346, 1972.
12. Smith, K.C. and Hanawalt, P.C. Molecular Photobiology, Inactivation and Recovery. Academic Press, New York, NY, 1969.
13. Harm, W. Biological Effects of Ultraviolet Radiation. Cambridge University Press, Cambridge, England, 1980.
14. Stanier, R., Doudoroff, M., and Adelburg, E. The Microbial World. Prentice-Hall, Englewood Cliffs, NJ, 1970.
15. Kirby-Smith, J.S. and Craig, D.L. Genetics 42:176-187, 1957.
16. Loofbourov, J.R. Effects of Ultraviolet Radiation on Cell Growth. 12:75-149, 1948.
17. Oda, A. Ultraviolet Disinfection of Potable Water Supplies. Ontario Water Resources Commission, Division of Research, Paper 2012, 1969.
18. Bernstein, I.A. Biological Influences on Environmental Toxicity. Deeds and Data, Water Pollution Control Federation, 18(5), 1981.
19. Jagger, J. and R.S. Stafford. Journal Biophysics 5:75, 1965.
20. Kelner, A. Proceedings of National Academy of Science, U.S. 35, 73, 1949.
21. Dulbecco, R. J. Bacteriology 59, 329, 1950.
22. Harm, W., Rupert C.S. and H. Harm. Photo-physiology, 6:279, 1971.
23. Harm, H. Contributor to Photochemistry and Photobiology of Nucleic Acids, Volume II. Academic Press, Inc., New York, NY, 1976.

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24. Novick, A. and L. Szilard. Proceedings National Academy of Science, U.S. 35, 591, 1949.
  25. Kelly, C.B. Disinfection of Sea Water by Ultraviolet Radiation, American Journal of Public Health 51(11), 1961.
  26. Huff, C.B., Smith, H.F., Boring, W.D. and N.A. Clarke. Study of Ultraviolet Disinfection of Water and Factors in Treatment Efficiency. Public Health Report 80(8), 1965.
  27. Hill, W.F., Akin, E.W., Benton, W.H. and F.E. Hamblet. Viral Disinfection of Estuarine Water by UV. Journal Sanitary Engineering Division, ASCE, SA5, 1971.
  28. Roeber, J.A. and F.M. Hoot. Ultraviolet Disinfection of Activated Sludge Effluent Discharging to Shellfish Waters. EPA-600/2-75-060, NTIS No. PB-249460, U.S. Environmental Protection Agency, Cincinnati, OH, 1975.
  29. Singer, M. and N. Nash. Ultraviolet Disinfection of a Step Aeration Effluent. Presented at Winter Meeting of the New York Water Pollution Control Association, 1977.
  30. Oliver, B.G. and J.H. Carey. A Scale-up Investigation of Ultraviolet Disinfection as an Alternative to Chlorination for Sewage Effluents. The Canadian Journal of Chemical Engineering, Volume 53, 1975.
  31. Oliver, B.G. and J.H. Carey. Ultraviolet Disinfection: An Alternative of Chlorination. JWPCF 48(11):2619, 1976.
  32. Oliver, B.G. and E.G. Cosgrove. The Disinfection of Sewage Treatment Plant Effluents Using Ultraviolet Light. The Canadian Journal of Chemical Engineering, 53, 1975.
  33. Drehwing, F.J., Oliver, A.J., MacArthur, D.A. and P.E. Moffa. Disinfection/Treatment of Combined Sewer Overflows, Syracuse, New York. Report of Project Number S802400, U.S. Environmental Protection Agency, Cincinnati, OH, 1978.
  34. Petrusek, A.C., Jr., Wolf, H.W., Elsmund, S.E. and D.C. Andrews. Ultraviolet Disinfection of Municipal Wastewater Effluents. EPA-600/2-80-102, NTIS No. PB81-111049, U.S. Environmental Protection Agency, Cincinnati, OH, 1980.
  35. Scheible, O.K. and C.D. Bassell. Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent. In: Proceedings of Wastewater Disinfection Alternatives—State-of-the-Art Workshop, 52nd Annual WPCF Conference, Houston, TX, 1979.
  36. Scheible, O.K., and C.D. Bassell. Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent. EPA-600/2-81-152, NTIS No. PB81-242125, USEPA, Cincinnati, OH, 1981.
  37. Severin, B.F. Disinfection of Municipal Wastewater Effluents with Ultraviolet Light. JWPCF 52(7), 1980.
  38. Johnson, J.D. and R.G. Qualls. Ultraviolet Disinfection of a Secondary Effluent: Measurement of Dose and Effects of Filtration. EPA-600/2-84-160, NTIS No. PB85-114023, U.S. Environmental Protection Agency, Cincinnati, OH, 1984.
  39. Qualls, R.G., Flynn, M.P. and J.D. Johnson. The Role of Suspended Solids in Ultraviolet Disinfection. JWPCF 55(10), 1983.
  40. Qualls, R.G. and J.D. Johnson. Bioassay and Dose Measurement in Ultraviolet Disinfection. Applied and Environmental Microbiology 45: 872, 1982.
  41. Bellen, Gordon E., Randy A. Gottler, Ronald Dormand-Herra. Survey and Evaluation of Currently Available Water Disinfection Technology Suitable for Passenger Cruise Vessel Use. National Sanitation Foundation report to Center for Prevention Services, Center for Disease Control, Atlanta, GA, Contract No. 200-80-0535, 1981.
  42. Haas, C.N. and G.P. Sakellaropoulos. Rational Analysis of UV Disinfection Reactors. Presented at ASCE National Conference of Environmental Engineers, San Francisco, CA, 1979.
  43. Severin, B.F., Suidan, M.T., Englebrecht, R.S. Mixing Effects in UV Disinfection. JWPCF 56(7), 1984.
  44. Severin, B.F., Suidan, M.T., Rittmann, B.E., Englebrecht, R.S. Inactivation Kinetics in a Flow-Through UV Reactor. JWPCF 56(2), 1984.
  45. Nehm, P.H. Operating Experience Disinfection Secondary Effluent with Pilot Scale Ultraviolet Units. In: Municipal Wastewater Disinfection Proceedings of Second National Symposium,

- Orlando, FL. EPA-600/9-83-009, NTIS No. PB83-263848, U.S. Environmental Protection Agency, Cincinnati, OH, 1983.
46. Ho, L.W.A. and P. Bohm. UV Disinfection of Tertiary and Secondary Effluents. *Water Pollution Research Journal, Canada*, 16, 33, 1981.
  47. Bohm, P., Ho, K.W.A. and J.E. Pagel. Application of UV Disinfection Technology in Ontario Water Pollution Control Plant Effluents. Ontario Ministry of the Environment, Toronto, 1981.
  48. Whitby, G.E., Palmateer, G., Cook, W.G., Maarschalkerweerd, J., Huber, D. and K. Flood. Ultraviolet Disinfection of Secondary Effluent. *JWPCF* 56(7), 1984.
  49. Kirkwold, D. Disinfecting with Ultraviolet Radiation. *Civil Engineering Magazine, ASCE*, pg. 62, December, 1984.
  50. Scheible, O.K., Forndran, A. and W.M. Leo. Pilot Investigation of Ultraviolet Wastewater Disinfection at the New York City Port Richmond Plant. In: *Municipal Wastewater Disinfection—Proceedings of Second National Symposium*, Orlando, FL. EPA-600/9-83-009, NTIS No. PB83-263848, U.S. Environmental Protection Agency, Cincinnati, OH, 1983.
  51. Scheible, O.K. Design and Operation of UV Disinfection Systems. In: *Proceedings of the Pre-Conference Workshop on Wastewater Disinfection*, 56th Annual WPCF Conference, Atlanta, GA, 1983.
  52. Scheible, O.K., Casey, M.C. and A. Forndran. Ultraviolet Disinfection of Wastewaters from Secondary Effluent and Combined Sewer Overflows. EPA-600/2-86/005, NTIS No. PB86-145182, U.S. Environmental Protection Agency, Cincinnati, OH, 1986.
  53. White, S.C., Jernigan, E.B. and A.D. Venosa. A Study of Operational Ultraviolet Disinfection Equipment at Secondary Treatment Plants. Presented at the 58th Annual Conference, Water Pollution Control Federation, Kansas City, MO, 1985.
  54. Scheible, O.K., Kreft, P. and A.D. Venosa. Demonstration of Process Design and Evaluation Procedures for Ultraviolet Disinfection. Summary prepared for U.S. Environmental Protection Agency, WERL, Cincinnati, OH, Contract No. 68-03-1821, 1985.
  55. Scheible, O.K. Pilot Studies of UV Disinfection at Several Wastewater Treatment Plants. Summary report, U.S. Environmental Protection Agency, WERL, Cincinnati, OH; Cooperative Agreement CR 808978, 1986.
  56. Scheible, O.K. Development of a Rationally Based Design Protocol for the Ultraviolet Light Disinfection Process. Presented at the 58th Annual Conference, Water Pollution Control Federation, Kansas City, MO, 1985.
  57. Rebhun, M. and Y. Argaman. Evaluation of Hydraulic Efficiency of Sedimentation Basins. *Journal SED, ASCE* 91(SA5):37, 1965.
  58. Levenspiel, O. *Chemical Reaction Engineering*, 2nd Edition. John Wiley and Sons, New York, NY, 1972.
  59. HydroQual, Inc. Evaluation of the UV Disinfection Process at the Northfield Water Pollution Control Plant. Report to the City of Northfield, MN, 1984.
  60. Baxendale, J.H. and N.R. Bridges. The Photo-reduction of Some Ferric Compounds in Aqueous Solutions. *Journal Physical Chemistry* 59:783, 1955.
  61. Parker, C.A. A New Sensitive Chemical Actinometer, Parts I and II. *Proc. Royal Soc. London Abs.* 235:518, 1956.
  62. HydroQual, Inc. Trip report to the USEPA, Cincinnati, OH, summarizing visit to Sents Creek WPCP, Pella, IA. Cooperative Agreement No. CR 808978, 1983.
  63. HydroQual, Inc. Trip report to the USEPA, Cincinnati, OH, summarizing visit to Tillsonburg WPCP, Tillsonburg, Ontario. Cooperative Agreement No. 808978, 1983.
  64. HydroQual, Inc. Trip report to the USEPA, Cincinnati, OH, summarizing visit to Vinton WPCP, Vinton, IA. Cooperative Agreement No. 808978, 1983.
  65. Qualls, R.G., Chang, J.C.H., Ossoff, S.F. and J.D. Johnson. Comparison of Methods of Enumerating Coliforms After UV Disinfection. *Applied and Environmental Microbiology* 48(4): 699-701, 1984.
  66. Jacob, S.M., and J.S. Dranoff. Light Intensity Profiles in a Perfectly Mixed Photoreactor. *Journal AIChE* 16(3), 1970.
  67. Rubert, J.S. *Journal General Physiology* 45:725, 1962.
  68. Luckieseh, M., Taylor, A., and G. Kerr. Germicidal Energy. *General Electric Review*, 1944.

