8. ULTRAVIOLET RADIATION

Unlike most disinfectants, ultraviolet (UV) radiation does not inactivate microorganisms by chemical interaction. UV radiation inactivates organisms by absorption of the light which causes a photochemical reaction that alters molecular components essential to cell function. As UV rays penetrate the cell wall of the microorganism, the energy reacts with nucleic acids and other vital cell components, resulting in injury or death of the exposed cells. There is ample evidence to conclude that if sufficient dosages of UV energy reach the organisms, UV can disinfect water to whatever degree is required. However, there has been some public health concerns with respect to the overall efficiency of UV to disinfect potable water.

Based on the available research literature, it appears that although exceptional for disinfection of small microorganisms such as bacteria and viruses, UV doses required to inactivate larger protozoa such as *Giardia* and *Cryptosporidium* are several times higher than for bacteria and virus inactivation (White, 1992; DeMers and Renner, 1992). As a result, UV is often considered in concert with ozone and/or hydrogen peroxide to enhance the disinfection effectiveness of UV or for ground water where *Giardia* and *Cryptosporidium* are not expected to occur.

8.1 UV Chemistry (Photochemical)

8.1.1 UV Radiation

UV radiation quickly dissipates into water to be absorbed or reflected off material within the water. As a result, no residual is produced. This process is attractive from a DBP formation standpoint; however, a secondary chemical disinfectant is required to maintain a residual throughout the distribution system, which may be subject to recontamination.

UV radiation energy waves are the range of electromagnetic waves 100 to 400 nm long (between the X-ray and visible light spectrums). The division of UV radiation may be classified as Vacuum UV (100-200 nm), UV-C (200-280 nm), UV-B (280-315 nm) and UV-A (315-400 nm). In terms of germicidal effects, the optimum UV range is between 245 and 285 nm. UV disinfection utilizes either: low-pressure lamps that emit maximum energy output at a wavelength of 253.7 nm; medium-pressure lamps that emit energy at wavelengths from 180 to 1370 nm; or lamps that emit at other wavelengths in a high intensity “pulsed” manner.

8.1.2 UV Disinfection Reactions

The degree to which the destruction or inactivation of microorganisms occurs by UV radiation is directly related to the UV dose. The UV dosage is calculated as:

$$D = I \bullet t$$

Where: D = UV Dose, $mW \cdot s/cm^2$

I = Intensity, mW/cm^2

t = Exposure time, s

Research indicates that when microorganisms are exposed to UV radiation, a constant fraction of the living population is inactivated during each progressive increment in time. This dose-response relationship for germicidal effect indicates that high intensity UV energy over a short period of time would provide the same kill as a lower intensity UV energy at a proportionally longer period of time.

The UV dose required for effective inactivation is determined by site-specific data relating to the water quality and log removal required. Based on first order kinetics, the survival of microorganisms can be calculated as a function of dose and contact time (White, 1992; USEPA, 1996). For high removals, the remaining concentration of organisms appears to be solely related to the dose and water quality, and not dependent on the initial microorganism density. Tchobanoglous (1997) suggested the following relationship between coliform survival and UV dose:

$$N = f \cdot D^n$$

Where: N = Effluent coliform density, /100mL

D = UV dose, $mW \cdot s/cm^2$

n = Empirical coefficient related to dose

f = Empirical water quality factor

The empirical water quality factor reflects the presence of particles, color, etc. in the water. For water treatment, the water quality factor is expected to be a function of turbidity and transmittance (or absorbance).

8.1.3 Process Variables

Since UV radiation is energy in the form of electromagnetic waves, its effectiveness is not limited by chemical water quality parameters. For instance, it appears that pH, temperature, alkalinity, and total

inorganic carbon do not impact the overall effectiveness of UV disinfection (AWWA and ASCE, 1990). However, hardness may cause problems with keeping the lamp sleeves clean and functional. The presence, or addition, of oxidants (e.g., ozone and/or hydrogen peroxide) enhances UV radiation effectiveness. The presence of some dissolved or suspended matter may shield microorganisms from the UV radiation. For instance, iron, sulfites, nitrites and phenols all absorb UV light (DeMers and Renner, 1992). Accordingly, the absorbance coefficient is an indication of this demand and is unique for all waters. As a result, specific "design" parameters vary for individual waters and should be determined empirically for each application.

UV demand of water is measured by a spectrophotometer set at a wavelength of 254 nm using a 1 cm thick layer of water. The resulting measurement represents the absorption of energy per unit depth, or absorbance. Percent transmittance is a parameter commonly used to determine the suitability of UV radiation for disinfection. The percent transmittance is determined from the absorbance (A) by the equation:

$$\text{Percent Transmittance} = 100 \times 10^{-A}$$

Table 8-1 shows corresponding absorbance measurements and percent transmittance measurements for various water qualities.

Table 8-1. Water Quality and Associated UV Measurements

Source Water Quality	Absorbance (absorbance units/cm)	Percent Transmittance
Excellent	0.022	95%
Good	0.071	85
Fair	0.125	75

Source: DeMers and Renner, 1992.

Continuous wave UV radiation at doses and wavelengths typically employed in drinking water applications, does not significantly change the chemistry of water nor does it significantly interact with any of the chemicals within the water (USEPA, 1996). Therefore, no natural physiochemical features of the water are changed and no chemical agents are introduced into the water. In addition, UV radiation does not produce a residual. As a result, formation of THM or other DBPs with UV disinfection is minimal (See Section 8.5, *Disinfection Byproducts of UV Radiation*).

8.2 Generation

Producing UV radiation requires electricity to power UV lamps. The lamps typically used in UV disinfection consist of a quartz tube filled with an inert gas, such as argon, and small quantities of mercury. Ballasts control the power to the UV lamps.

8.2.1 UV Lamps

UV lamps operate in much the same way as fluorescent lamps. UV radiation is emitted from electron flow through ionized mercury vapor to produce UV energy in most units. The difference between the two lamps is that the fluorescent lamp bulb is coated with phosphorous, which converts the UV radiation to visible light. The UV lamp is not coated, so it transmits the UV radiation generated by the arc (White, 1992).

Both low-pressure and medium-pressure lamps are available for disinfection applications. Low-pressure lamps emit their maximum energy output at a wavelength of 253.7 nm, while medium pressure lamps emit energy with wavelengths ranging from 180 to 1370 nm. The intensity of medium-pressure lamps is much greater than low-pressure lamps. Thus, fewer medium pressure lamps are required for an equivalent dosage. For small systems, the medium pressure system may consist of a single lamp. Although both types of lamps work equally well for inactivation of organisms, low-pressure UV lamps are recommended for small systems because of the reliability associated with multiple low-pressure lamps (DeMers and Renner, 1992) as opposed to a single medium pressure lamp, and for adequate operation during cleaning cycles.

Recommended specifications for low-pressure lamps (DeMers and Renner, 1992) include:

- L-type ozone-free quartz;
- Instant start (minimal delay on startup);
- Designed to withstand vibration and shock; and
- Standard nonproprietary lamp design.

Typically, low-pressure lamps are enclosed in a quartz sleeve to separate the water from the lamp surface. This arrangement is required to maintain the lamp surface operating temperature near its optimum of 40^{o}C. Although Teflon sleeves are an alternative to quartz sleeves, quartz sleeves absorb only 5 percent of the UV radiation, while Teflon sleeves absorb 35 percent (Combs and McGuire, 1989). Therefore, Teflon sleeves are not recommended.

8.2.2 Ballasts

Ballasts are transformers that control the power to the UV lamps. Ballasts should operate at temperatures below 60^{o}C to prevent premature failure. Typically, the ballasts generate enough heat to warrant cooling fans or air conditioning (White, 1992).

Two types of transformers are commonly used with UV lamps; namely, electronic and electromagnetic. Electronic ballasts operate at a much higher frequency than electromagnetic ballasts, resulting in lower lamp operating temperatures, less energy use, less heat production, and longer ballast life (DeMers and Renner, 1992).

Typical ballast selection criteria include (DeMers and Renner, 1992):

- Underwriter's Laboratories (UL) approval;
- Compatibility with UV lamps; and
- Waterproof enclosure in remote location.

8.2.3 UV Reactor Design

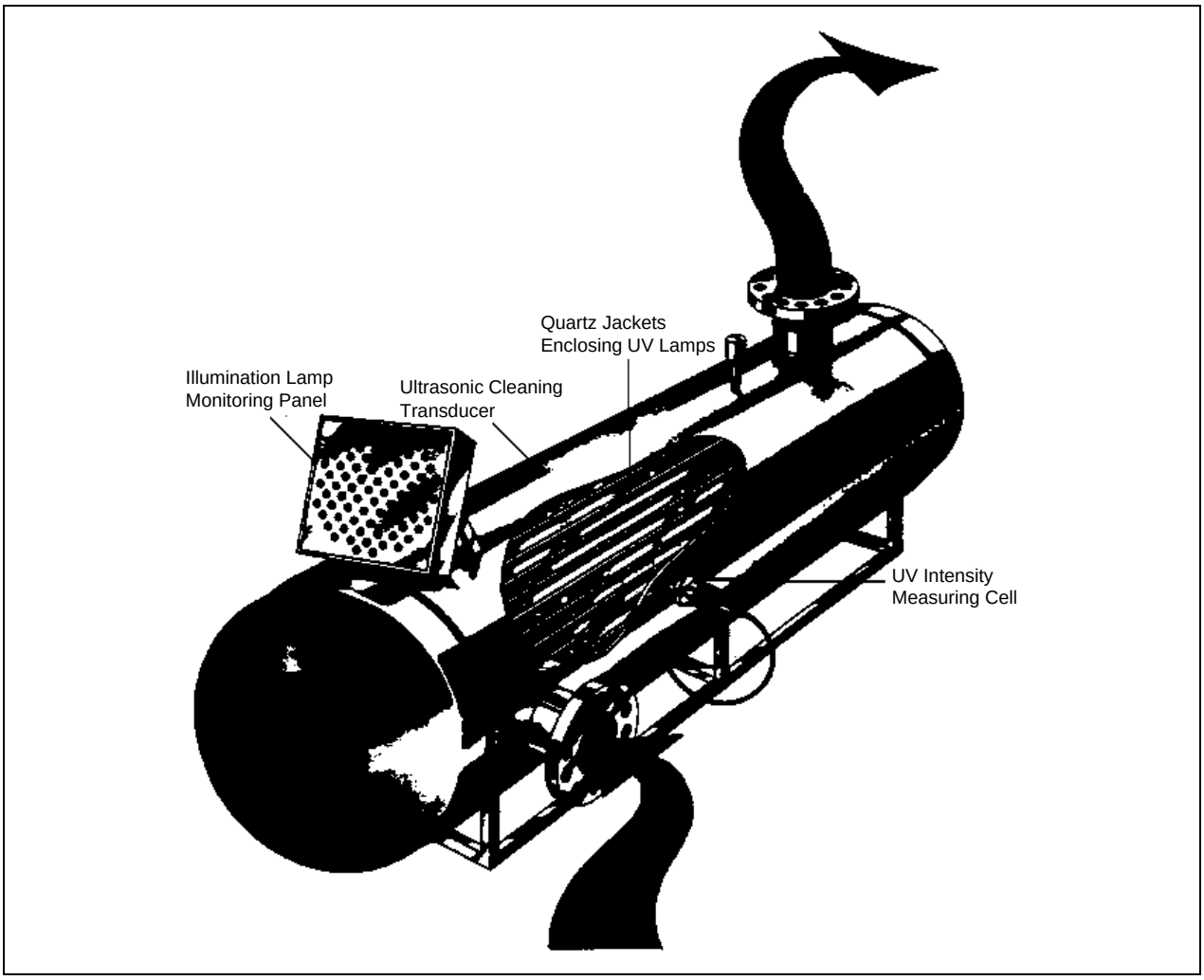
Most conventional UV reactors are available in two types; namely, closed vessel and open channel. For drinking water applications, the closed vessel is generally the preferred UV reactor for the following reasons (USEPA, 1996):

- Smaller footprint;
- Minimized pollution from airborne material;
- Minimal personnel exposure to UV; and
- Modular design for installation simplicity.

Figure 8-1 shows a conventional closed vessel UV reactor. This reactor is capable of providing UV dosages adequate to inactivate bacteria and viruses for flows up to 600 gallons per minute. However, it is incapable of the higher dosages required for protozoan cysts. To increase the dosage, either the number of UV lamps and/or the exposure time should be increased.

Additional design features for conventional UV disinfection systems include:

- UV sensors to detect any drop in UV lamp output intensity;
- Alarms and shut-down systems;
- Automatic or manual cleaning cycles; and
- Telemetry systems for remote installations.



Source: USEPA, 1996.

Figure 8-1. Closed Vessel Ultraviolet Reactor

In addition to conventional UV systems, two other UV processes are currently being evaluated for drinking water disinfection:

- Micro-screening/UV; and
- Pulsed UV

Both of these systems profess to provide sufficient UV dose to inactivate *Giardia* cysts and *Cryptosporidium* oocysts. See Section 8.2.3.2, *Emerging UV Reactor Designs*, for further discussion on these emerging technologies.

8.2.3.1 Hydraulic Design Considerations

The major elements that should be considered in the hydraulic design of a UV closed vessel reactor are: dispersion, turbulence, effective volume, residence time distribution, and flow rate (USEPA, 1996).

Dispersion

Dispersion is the characteristic of water elements to scatter spatially. The ideal UV reactor is plug flow, where water particles are assumed to discharge from the reactor in the same sequence they entered and each element of water passing through the reactor resides in the reactor for the same period of time. An ideal plug flow reactor has no dispersion and is approximated by a long tank with high length-to-width ratio in which dispersion is minimal (USEPA, 1996).

Turbulence

In addition to plug flow characteristics, the ideal UV reactor has a flow that is turbulent radially from the direction of flow, to eliminate dead zones. This radially turbulent flow pattern promotes uniform application of UV radiation. A negative of having a radially turbulent flow pattern is that some axial dispersion results, thus disrupting the plug flow characteristics. Techniques such as misaligning the inlet and outlet, and using perforated stilling plates, have been used to accommodate the contradicting characteristics of plug flow and turbulence (USEPA, 1996).

8.2.3.2 Emerging UV Reactor Designs

Two emerging technologies in UV reactor design are discussed below. All testing of these two systems to date has been under controlled laboratory or field conditions. Both of these technologies require demonstration of efficacy and applicability in real-world treatment operations.

Micro-Screening/UV

This unit consists of two treatment chambers, each containing a 2 μm nominal porosity metal screen. Each side of the screen has three 85 watt low pressure mercury lamps, with a total of six lamps per filter. The theoretical minimum dose is 14.6 mW·sec/cm^2 at the wavelength of 254 nm. The system is designed to capture *Cryptosporidium* oocysts from the water onto the first screen. The first cycle is set to establish the UV dose. The flow within the first screen chamber is then reversed to backflush to oocysts onto the second screen where the oocysts are trapped until the preset UV dose is reached. Using valves, the pattern of flow is designed to ensure that oocysts are temporarily captured on both filters so that they are exposed to a total preset UV dose, which is totally independent of treated water flowrate (Clancy et al., 1997). Johnson (1997) stated that such a system is capable of achieving total UV doses of 8,000 mW·sec/cm^2, sufficient to inactivate *Giardia* cysts and *Cryptosporidium* oocysts. One drawback of this type of reactor is the headloss created (up to 65 feet) by the 2 μm openings in the screen.

Pulsed UV

In the pulsed UV reactor, capacitors build up and deliver electricity in pulses to xenon flash tubes in the center of a 2 inch diameter flash chamber through which water flows. The unit is designed to provide microsecond pulses at 1 to 30 hertz (or per second). With each pulse, the flash tubes give off high intensity, broad band radiation, including germicidal UV radiation, which irradiates the flowing

water with irradiences of 75 mW·sec/cm^2 at 2 cm from the flash tube surface (Clancy et al., 1997). The UV dose can be adjusted by increasing or decreasing the frequency of the pulsing.

8.3 Primary Uses and Points of Application

The primary use of UV radiation is to inactivate pathogens to regulated levels. UV radiation is a physical disinfectant that leaves no residual. Therefore, it should be used only as a primary disinfectant followed by a chemical secondary disinfectant to protect the distribution system against coliform proliferation and biofilm formation. See Section 8.4, *Pathogen Inactivation and Disinfection Efficiency*," for a detailed discussion of disinfection efficiency and limitations.

The most common point of application for UV radiation is the last step in the treatment process train just prior to the distribution system and after filtration. The use of UV disinfection has no impact on other processes at the water treatment facility.

8.4 Pathogen Inactivation and Disinfection Efficiency

As opposed to most alternative disinfectants, UV is a physical process that requires a contact time on the order of seconds to accomplish pathogen inactivation (Sobotka, 1993). As with any disinfectant, UV has its limitations. For example, because it is a physical rather than a chemical disinfectant, it does not provide a residual to control pathogen proliferation and biofilm formation in the distribution system. When using UV for primary disinfection, some form of secondary chemical disinfectant is required to maintain water quality within the distribution system.

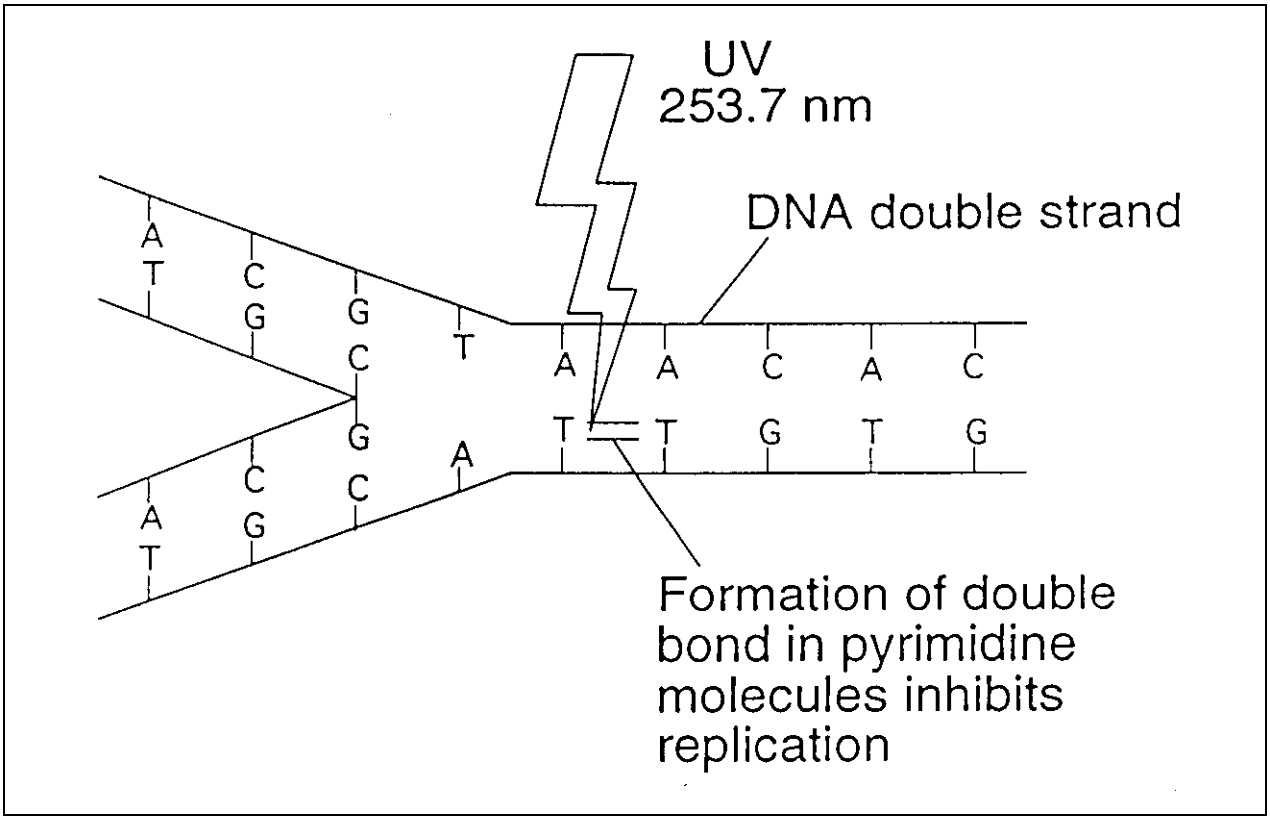
8.4.1 Inactivation Mechanism

UV radiation is efficient at inactivating vegetative and sporous forms of bacteria, viruses, and other pathogenic microorganisms. Electromagnetic radiation in the wavelengths ranging from 240 to 280 nanometers (nm) effectively inactivates microorganisms by irreparably damaging their nucleic acid. The most potent wavelength for damaging deoxyribonucleic acid (DNA) is approximately 254 nm (Wolfe, 1990). Other UV wavelengths, such as 200 nm, have been shown to exhibit peak absorbance in aqueous solutions of DNA (von Sonntag and Schuchmann, 1992); however, there is no practical application for UV inactivation of microorganisms in the wavelength range from 190 to 210 nm (USEPA, 1996).

The germicidal effects of UV light involve photochemical damage to RNA and DNA within the microorganisms. Microorganism nucleic acids are the most important absorbers of light energy in the wavelength of 240 to 280 nm (Jagger, 1967). DNA and RNA carry genetic information necessary for reproduction; therefore, damage to either of these substances can effectively sterilize the organism. Damage often results from the dimerization of pyrimidine molecules. Cystosine (found in both DNA and RNA), thymine (found only in DNA), and uracil (found only in RNA) are the three primary types of pyrimidine molecules. Replication of the nucleic acid becomes very difficult once the pyrimidine molecules are bonded together due to the distortion of the DNA helical

structure by UV radiation (Snider et al., 1991). Moreover, if replication does occur, mutant cells that are unable to replicate will be produced (USEPA, 1996). Figure 8-2 is a schematic of the germicidal inactivation observed with UV radiation.

Two phenomena of key importance when using UV disinfection in water treatment are the dark repair mechanisms and the capability of certain organisms to photoreactivate following exposure to certain light wavelengths. Under certain conditions, some organisms are capable of repairing damaged DNA and reverting back to an active state in which reproduction is again possible. Typically, photoreactivation occurs as a consequence of the catalyzing effects of sunlight at visible wavelengths outside of the effective disinfecting range. The extent of reactivation varies among organisms. Coliform indicator organisms and some bacterial pathogens such as *Shigella* have exhibited the photoreactivation mechanism; however, viruses (except when they have infected a host cell that is itself photoreactive) and other types of bacteria cannot photoreactivate (USEPA, 1980; USEPA, 1986; Hazen and Sawyer, 1992). Because DNA damage tends to become irreversible over time, there is a critical period during which photoreactivation can occur. To minimize the effect of photoreactivation, UV contactors should be designed to either shield the process stream or limit the exposure of the disinfected water to sunlight immediately following disinfection.



Source: Tchobanoglous, 1997.

Figure 8-2. Germicidal Inactivation by UV Radiation

8.4.2 Environmental Effects

To achieve inactivation, UV should be absorbed into the microorganism. Therefore, anything that prevents UV from reacting with the microorganism will decrease the disinfection efficiency. Scheible and Bassell (1981) and Yip and Konasewich (1972) reported that pH had no effect on UV disinfection. Several factors that are known to affect disinfection efficiency of UV are:

- Chemical and biological films that develop on the surface of UV lamps;
- Dissolved organics and inorganics;
- Clumping or aggregation of microorganisms;
- Turbidity;
- Color; and
- Short-circuiting in water flowing through the UV contactor.

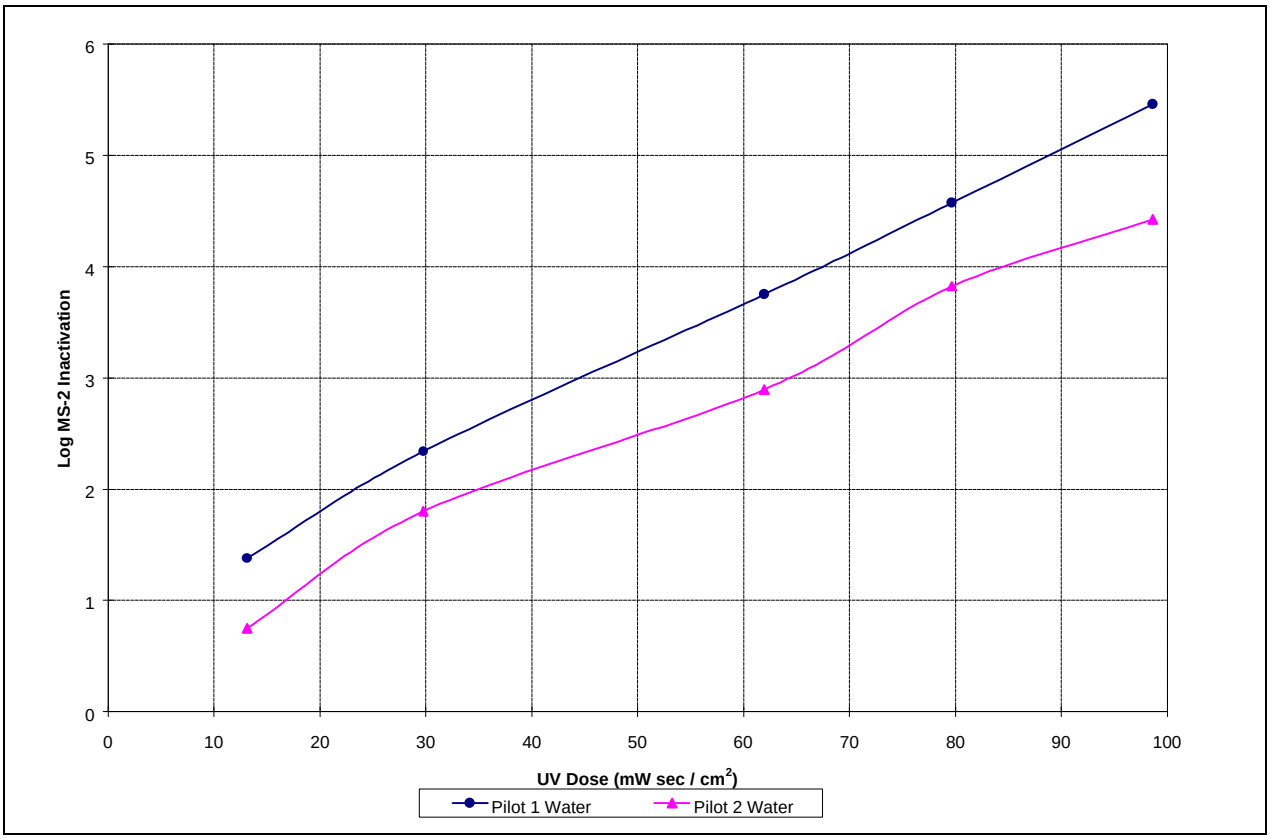
8.4.2.1 Chemical Films and Dissolved Organics and Inorganics

Accumulation of solids onto the surface of the UV sleeves can reduce the applied UV intensity and, consequently, disinfection efficiency. In addition to biofilms caused by organic material, buildup of calcium, magnesium, and iron scales have been reported (DeMers and Renner, 1992). Waters containing high concentrations of iron, hardness, hydrogen sulfide, and organics are more susceptible to scaling or plating (i.e., the formation of a thin coat on unit surfaces), which gradually decreases the applied UV intensity. Scaling is likely to occur if dissolved organics are present and inorganic concentrations exceed the following limits (DeMers and Renner, 1992):

- Iron greater than 0.1 mg/L;
- Hardness greater than 140 mg/L; and
- Hydrogen sulfide greater than 0.2 mg/L.

Figure 8-3 shows the UV dose required for inactivation of MS-2 coliphage at two pilot plants. Snicer et al. (1996) concluded that one possible explanation for higher UV dose for the same degree of inactivation required at pilot plant 2 could be the amount of scaling caused by higher iron concentrations experienced at this plant. Iron concentrations at pilot plant 2 were in the range of 0.45 to 0.65 mg/L, which exceed the limit shown above.

A variety of chemical substances can decrease UV transmission (Yip and Konasewich, 1972), including humic acids, phenolic compounds, and lignin sulfonates (Snider et al., 1991), as well as chromium, cobalt, copper, and nickel. It has been reported that coloring agents, such as Orzan S, tea, and extract of leaves reduce intensity within a UV contactor (Huff, 1965). In addition, iron, sulfites, nitrites, and phenols can absorb UV (DeMers and Renner, 1992).



Source: Snicer et al., 1996.

Figure 8-3. UV Dose Required for Inactivation of MS-2 Coliphage

8.4.2.2 Microorganism Clumping and Turbidity

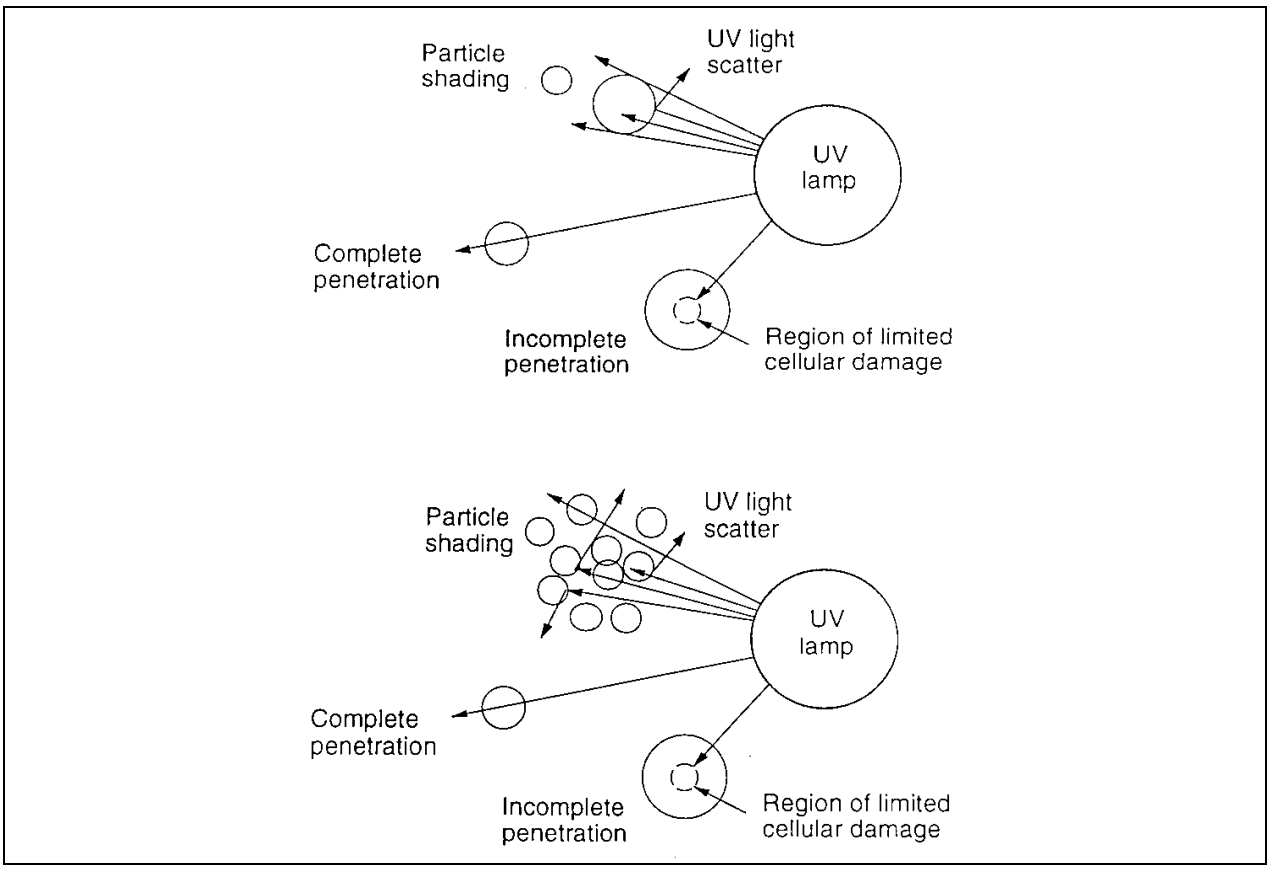
Particles can affect the disinfection efficiency of UV by harboring bacteria and other pathogens, partially protecting them from UV radiation, and scattering UV light (see Figure 8-4). Typically, the low turbidity of ground water results in minimal impact on disinfection efficiency. However, the higher turbidities of surface water can impact disinfection efficiency.

Similar to particles that cause turbidity, microorganism aggregation can impact disinfection efficiency by harboring pathogens within the aggregates and shade pathogens that would otherwise be inactivated.

8.4.2.3 Reactor Geometry and Short Circuiting

Poor geometry within the UV contactor (which creates spacing between lamps) can leave dead areas where inadequate disinfection occurs (Hazen and Sawyer, 1992). A key consideration to improving disinfection is to minimize the amount of dead spaces where limited UV exposure can occur. Plug flow conditions should be maintained in the contactor; however, some turbulence should be created between the lamps to provide radial mixing of flow. In this manner, flow can be uniformly distributed through the varying regions of UV intensity, allowing exposure to the full range of available UV radiation (Hazen and Sawyer, 1992).

As mentioned earlier, UV systems typically provide contact times on the order of seconds. Therefore, it is extremely important that the system configuration limit the extent of short circuiting.



Source: Tchobanoglous, 1997.

Figure 8-4. Particle Interactions that Impact UV Effectiveness

8.4.3 Disinfection Efficacy

UV disinfection has been determined to be adequate for inactivating bacteria and viruses. Most bacteria and viruses require relatively low UV dosages for inactivation, typically in the range of 2 to 6 mW·s/cm^2 for 1-log inactivation. Protozoan [oo]cysts, in particular *Giardia* and *Cryptosporidium*, are considerably more resistant to UV inactivation than other microorganisms. Results of several studies investigating the ability of UV to inactivate bacteria, viruses, and protozoa, are described in the following sections.

8.4.3.1 Bacteria and Virus Inactivation

UV doses required for bacteria and virus inactivation are relatively low. One study determined that UV was comparable to chlorination for inactivation of heterotrophic plate count bacteria following treatment using granular activated carbon (Kruithof et al., 1989).

A study of the ability of UV and free chlorine to disinfect a virus-containing ground water showed that UV is a more potent virucide than free chlorine, even after the chlorine residual was increased to 1.25 mg/L at a contact time of 18 minutes (Slade et al., 1986). The UV dose used in this study was 25 $mW \cdot s/cm^2$.

Table 8-2 shows results from a more recent pilot plant study (Snicer et al., 1996). As indicated by the different UV doses to obtain the same level of inactivation, water characteristics dramatically impact disinfection efficiency. They believed that the higher concentration of iron in pilot plant 2 water (Figure 8-3) interfered with UV or influenced the aggregation of MS-2 viral particles.

Snicer et al. (1996) also compared the susceptibility of MS-2 coliphage to hepatitis A virus, poliovirus, and rotavirus for 10 ground water sources. Results indicated that MS-2 was found to be approximately 2 to 3 times more resistant to UV disinfection than the three human pathogenic viruses.

Table 8-2. Doses Required for MS-2 Inactivation

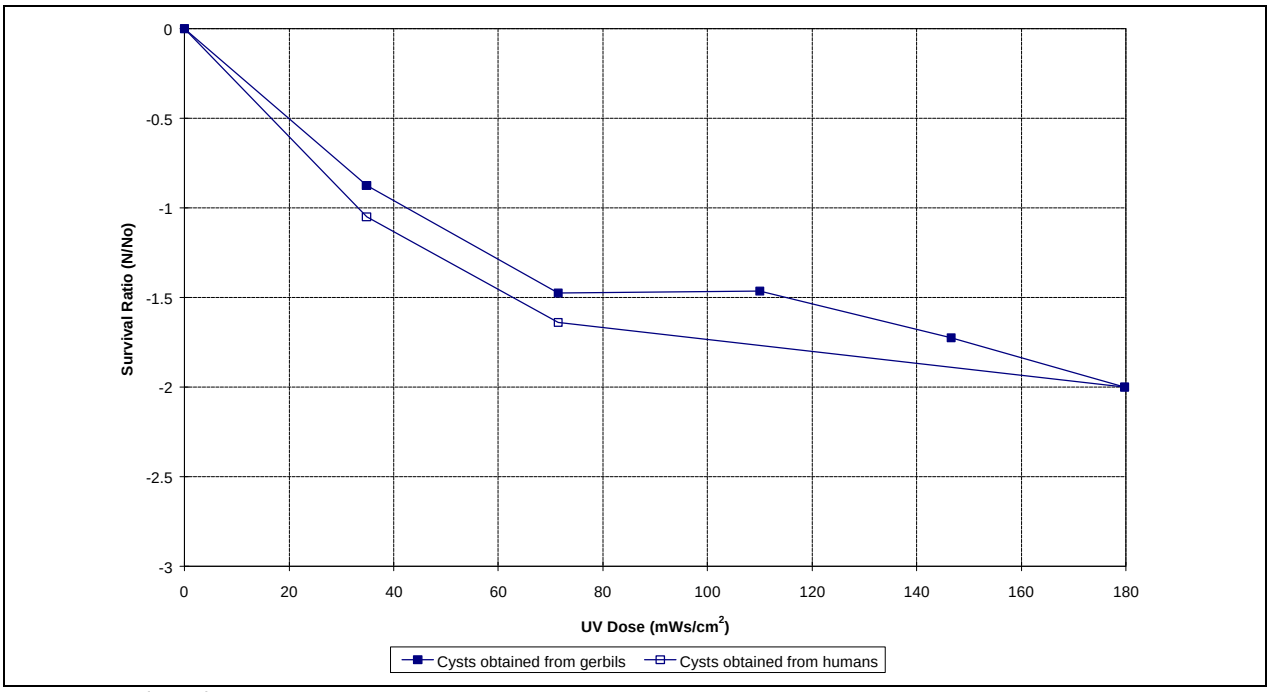
Log MS-2 Inactivation	Pilot Plant 1 ($mW \cdot s/cm^2$)	Pilot Plant 2 ($mW \cdot s/cm^2$)
1	3.9	15.3
2	25.3	39.3
3	46.7	63.3
4	68	87.4
5	89.5	111.4
6	111.0	135.5

Source: Snicer et al., 1996.

8.4.3.2 Protozoa Inactivation

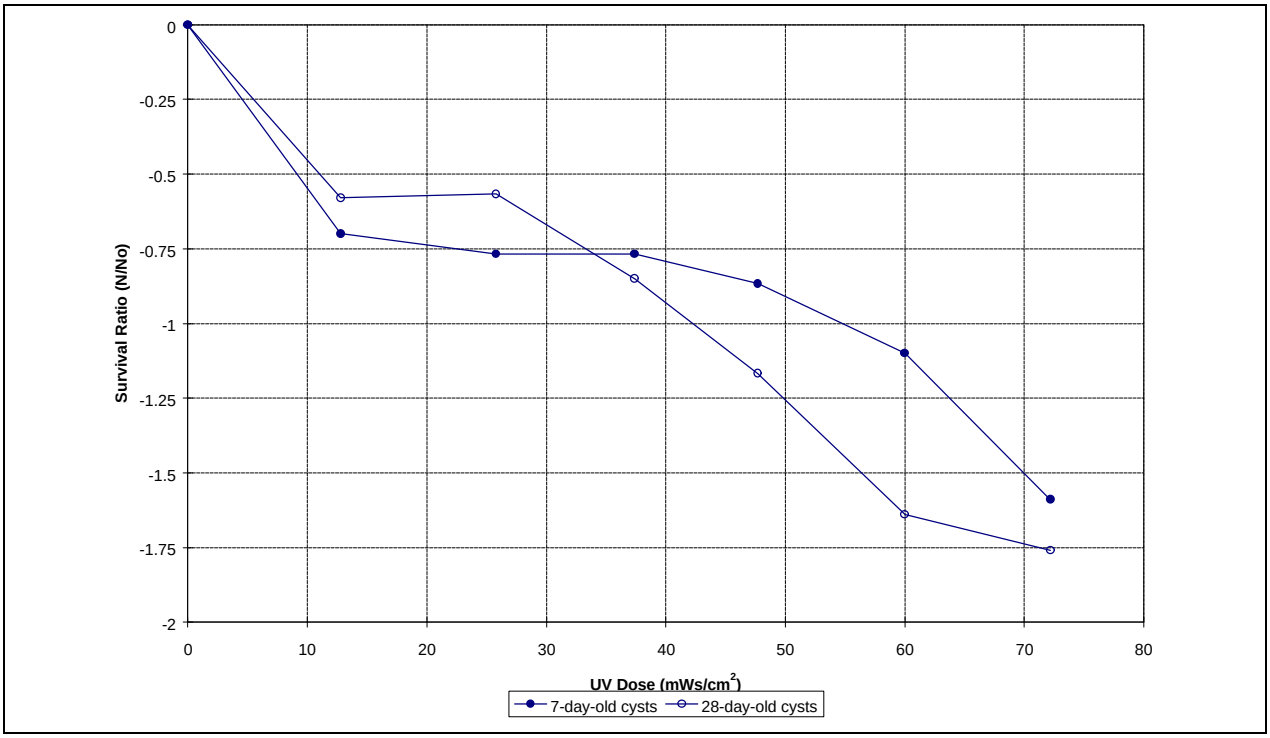
Even though protozoa were once considered resistant to UV radiation, recent studies have shown that ultraviolet light is capable of inactivating protozoan parasites. However, results indicate that these organisms require a much higher dose than that needed to inactivate other pathogens. Less than 80 percent of *Giardia lamblia* cysts were inactivated at UV dosages of 63 $mW \cdot s/cm^2$ (Rice and Hoff, 1981). A 1-log inactivation of *Giardia muris* cysts was obtained when the UV dose was increased to 82 $mW \cdot s/cm^2$ (Carlson et al., 1982).

To achieve 2-log inactivation of *Giardia muris* cysts, a minimum ultraviolet light dose of above 121 $mW \cdot s/cm^2$ is needed. Karanis et al. (1992) examined the disinfection capabilities of ultraviolet light against *Giardia lamblia* cysts extracted from both animals and humans (Karanis et al., 1992). Both groups suffered a 2-log reduction at UV doses of 180 $mW \cdot s/cm^2$. Two important factors to consider when determining dose requirements for *Giardia* inactivation are the parasite source and the growth stage of the microorganism (Karanis et al., 1992). Figure 8-5 shows that the source of the parasites is important in determining dose requirements. Figure 8-6 is from a study conducted in 1992 on *Acanthamoeba rhysodes* inactivation (Karanis et al., 1992). These data show that the age of the protozoa can dramatically affect the dose required to achieve a desired level of inactivation.



Source: Karanis et al., 1992.

Figure 8-5. UV Doses Required to Achieve Inactivation of *Giardia lamblia* Cysts Obtained from Two Different Sources



Source: Karanis et al., 1992.

Figure 8-6. Impact of Growth Stage of *A. rhysodes* on the Required UV Dosage to Achieve Inactivation

Results from recent studies show a potential for inactivating *Cryptosporidium parvum* oocysts using ultraviolet light disinfection. A 2 to 3-log reduction in the viability of *Cryptosporidium parvum* oocysts was achieved using a low-pressure ultraviolet light system with a theoretical minimum intensity of 14.58 mW/cm^2 and a contact time of 10 minutes (ultraviolet dose of 8,748 mW·s/cm^2) (Campbell et al., 1995). The combination filter-UV system described by Johnson (1997) is capable of delivering doses as high as 8,000 mW·s/cm^2, sufficient to achieve 2-log *Cryptosporidium* oocyst inactivation.

A pulsed UV process that delivered a minimum dose of 1,900 mW·s/cm^2 to any particle within the reactor was found to achieve *Cryptosporidium* oocyst inactivation levels in the range of 2-log. (Clancy et al., 1997). In this study, the reactor residence time was 4.7 seconds and the unit was operated to deliver 46.5 pulses per volume (10 Hz). Each pulse transfers power at the intensity rate of about 41 mW·s/cm^2 .

8.4.3.3 UV Dose Summary

UV radiation is considered effective for inactivating bacterial and viral pathogens. UV doses for 2 and 3-log inactivation of viruses are 21 and 36 mW·s/cm^2, respectively (AWWA, 1991). These doses are based on studies of hepatitis A virus inactivation and were derived by applying a safety factor of 3 to the inactivation data. Results from a more recent study on several ground water sources of hepatitis A virus, indicate that a 6 to 15 mW·s/cm^2 dose is required for a 4-log inactivation (Snicer et al., 1996). A safety factor was not applied to the doses. A 4-log inactivation of bacteriophage MS-2 is achieved at a dose of 93 mW·s/cm^2 (Snicer et al., 1996). In ground water containing high iron levels (0.65 ppm), applying a safety factor of 1.5 to the highest reported dose against viruses will yield a UV dose of 140 mWs/cm^2 for a minimum 4-log inactivation of viruses

In summary, ultraviolet radiation is effective against bacteria and viruses at low dosages. However, much higher dosages are required for *Cryptosporidium* and *Giardia* inactivation.

8.5 Disinfection Byproducts of UV Radiation

Unlike other disinfectants, UV does not inactivate microorganisms by chemical reaction. However, UV radiation causes a photochemical reaction in the organism RNA and DNA. The literature suggests that UV radiation of water can result in the formation of ozone or radical oxidants (Ellis and Wells, 1941; Murov, 1973). Because of this reaction, there is interest in determining whether UV forms similar byproducts to those formed by ozonation or advanced oxidation processes.

8.5.1 Ground Water

Malley et al. (1995) analyzed 20 ground water samples for aldehydes and ketones before and after UV radiation. Only one ground water sample, which contained 24 mg/L non-purgeable DOC and was highly colored, contained DBPs after exposure to UV. Low levels of formaldehyde were measure in duplicated experiments for this UV treated ground water sample mentioned above. GC-

ECD chromatographs before and after UV radiation for the other 19 ground waters studied showed significant shifts or unknown peaks after exposure to UV.

Malley et al. (1995) also determined the influence of UV on DBP formation during subsequent chlorination. To examine these effects, the 20 ground water samples were subjected to simulated distribution system (SDS) DBP tests with chlorine, before and after UV radiation. The data indicate that UV radiation did not significantly alter the SDS/DBP formation by chlorine in the ground waters studied.

To examine the effects of varying UV dosages on DBP formation, six new ground water samples (Malley et al., 1995) were subjected to UV dosages of 60, 130, and 200 $mW \cdot s/cm^2$. In this case, DBPs were not formed by UV radiation for any of the ground waters tested at any of the UV dosages. A comparison of chromatographs for samples before and after UV radiation, and for each UV dosage, showed no significant differences or appearances of unknown peaks.

8.5.2 Surface Water

UV radiation was found to produce low levels of formaldehyde in the majority of surface waters studied (Malley et al., 1995). The highest formaldehyde concentrations, ranging up to 14 μg/L, were observed in UV treatment of raw water, whereas trace levels (1 to 2 μg/L) were found in UV treatment of conventionally treated water. Since formaldehyde formation was also observed for one of the ground water samples, it appears that UV radiation of waters containing humic matter (i.e., color producing, UV absorbing organic macromolecules) will result in low levels of formaldehyde formation. Chromatographic examination of the surface water samples before and after UV radiation showed no other significant changes in the GC-ECD chromatograms.

Because of the chlorine demands of surface waters, higher chlorine dosages were required for post disinfection following UV radiation. This resulted in larger DBP concentrations than in the ground waters studied (Malley et al., 1995). However, the overall effect of UV radiation on SDS/DBPs was insignificant. As in the ground water studies, UV radiation did not significantly alter the total concentration or the speciation of the disinfection byproducts (e.g., THMs, HAA5, HANs, or HKs).

8.5.3 DBP Formation with Chlorination and Chloramination following UV Radiation

Research results suggest that UV radiation does not directly form DBPs or alter the concentration or species of DBPs formed by post-disinfection (Malley et al., 1995). However, the question of whether UV radiation influences the rate of DBP formation by post-disinfection is important. Several studies have addressed this question. Two surface waters that produced significant concentrations of a wide variety of DBPs in previous tests were chosen as samples. With the chlorine residuals carefully monitored to ensure they were consistent for pre-UV and post-UV samples, the results of the experiments suggested that UV radiation did not significantly affect the rate of DBP formation.

Studies were only performed to determine the pentane extractable DBP formation rate of a surface water sample for varying pH conditions. The results showed that UV radiation did not affect the rate of chloroform formation at pH 8.0 (Malley et al., 1995). Similarly, UV did not affect the DBP formation rate at pH 5.0. At pH 8.0, chloroform was the only pentane extractable detected, whereas at pH 5.0, chloroform, bromodichloromethane, chlorodibromomethane, and 1,1,1-trichloroacetone were formed.

The effects of UV radiation on the DBP formation rate following chloramination were also tested in this study using a surface water sample (Malley et al., 1995). Chloroform, trichloroacetic acid, dichloroacetonitrile (at low levels), and cyanogen chloride (at low levels) were the only detectable DBPs. Chloroform was the only compound formed at pH 8.0, and its rate of formation was not affected by UV radiation. At pH 5.0, chloroform and dichloroacetonitrile were formed, but their rate of formation was unaffected by UV radiation. Data showed that the effects of UV radiation on cyanogen chloride formation at pH 8.0 and pH 5.0 had no significant trends.

In summary, the DBP formation rate studies indicated that UV radiation did not significantly affect DBP formation rates when chlorine or chloramines were used as the post-disinfectant.

8.6 Status of Analytical Methods

Ultraviolet radiation intensity meter readings are taken to monitor the output of the UV disinfection system. These readings, coupled with the flow through the UV reactor, are used to determine the UV dosage applied. UV radiation leaves no residual disinfectant behind to monitor. Therefore, some form of secondary chemical disinfectant should be added to protect the distribution system against coliform proliferation and biofilm formation. Analytical methods for these chemical disinfectants are discussed elsewhere in this report.

8.6.1 Monitoring of Generated Ultraviolet Radiation

Ultraviolet intensity at 253.7 nm (the predominant wavelength emitted by low pressure mercury vapor lamps) is the water quality parameter used to monitor UV disinfection system output (Snider et al., 1991). The rate of disinfection is directly related to the average intensity of the UV light. Since UV intensity probes can only indicate UV intensity at a single point, there is no practical way to measure the average intensity of a UV system in the field by the operator.

The average intensity is dependent upon the three dimensional lamp geometry. Scheible (1983) developed a mathematical model that calculates the intensity at any point within the UV reactor. This Point Source Summation (PSS) method is used to estimate the average intensity emitted by any specific unit. UV disinfection system manufacturers use this method to design the system. The single point UV intensity probe reading is typically used for routine monitoring of the UV system only.

UV intensity sensors are typically photodiode sensors properly filtered to monitor the lamp intensity in the germicidal range only (DeMers and Renner, 1992). A minimum of two sensors (mounted near

separate lamps) located at the center of each lamp for each reactor is recommended as part of the system controls and instrumentation. White (1992) recommends installing the sensors in the wall of the disinfection chamber at the point of greatest distance from the tube or tubes.

The UV sensors should continuously sense the UV intensity produced in the bank of lamps. The sensor should be field calibrated to account for lamp geometry. Each UV sensor installed should provide a "low UV output" warning and a "low-low UV output" alarm indication that is field adjustable.

8.6.1.1 Ultraviolet Sensor Performance

To test electronic sensor performance, Snicer et al. (1996) placed a single electronic UV sensor at the center of a UV reactor. The UV sensor converted the UV energy into an electronic signal, which was used to indicate system performance. Initial results indicated that the sensor originally installed with the two UV reactors tended to wear or degrade in performance over time. The original sensor readings in the pilot facility were erratic and had a general downward trend over 6 months of operation. This loss in performance could not be attributed to UV lamp aging. In addition, these readings did not correlate well to actual system performance. After operation of these original sensors for 6 months, the manufacturer was consulted and a new type of sensor was installed into both pilot facilities. The new sensor design specifically addressed the problems encountered during the initial 6 months of the study. These new proprietary sensors performed consistently and sensor readings were shown to correlate well with actual MS-2 coliphage inactivation.

8.6.2 Disinfectant Interferences

Suspended solids may be the most important water quality parameter impacting UV intensity measurements. Particles can harbor bacteria and at least partially protect them from UV light. Particles can be completely penetrated, partially penetrated, or scatter UV light (Figure 8-4). All particles in water may not absorb UV light. Qualls et al. (1983) suggested that clays merely scatter UV light and, therefore, do little to inhibit performance.

Yip and Konasewich (1972) listed many chemical substances that interfere with UV transmission at 253.7 nm including phenolic compounds, humic acids, and ferric iron.

8.7 Operational Considerations

Onsite pilot plant testing is recommended to determine the efficiency and adequacy of UV disinfection for a specific quality of water. The efficiency test involves injecting select microorganisms into influent water and sampling effluent water to determine survival rates. The National Science Foundation's Standard 55 for ultraviolet water treatment systems recommends that UV disinfection systems not be used if the UV transmittance is less than 75 percent (NSF, 1991). If the raw water UV transmittance is less that 75 percent, the UV system should be proceeded by other treatment processes (to increase UV transmittance) or a different disinfectant should be used.

As previously discussed, some constituents that adversely interfere with UV disinfection performance by either scattering and/or absorbing radiation are iron, chromium, copper, cobalt, sulfites, and nitrites. Care should be taken with chemical processes upstream of UV disinfection process to minimize increasing concentrations of these constituents since disinfection efficiency may be adversely affected.

8.7.1 Equipment Operation

UV disinfection facilities should be designed to provide flexibility in handling varying flow rates. For lower flow rates, a single reactor vessel should be capable of handling the entire flow rate. A second reactor vessel with equal capacity of the first reactor vessel should be provided for redundancy should the first reactor vessel be taken out of service. For higher flow rates, multiple reactor vessels should be provided with lead/lag operation and flow split capacity to balance run time for each reactor vessel, if desired, and to avoid hydraulic overloading. Valves should be provided within the interconnecting piping to isolate one reactor vessel from another. There should also be a positive drainage system to remove water from within a reactor vessel when it is taken out of service.

8.7.1.1 UV Lamp Aging

The output of UV lamps diminishes with time. Two factors that affect their performance are: solarization which is the effect UV radiation has on the UV lamp that causes it to become opaque; and, electrode failure which occurs when electrodes deteriorate progressively each time the UV lamp is cycled on and off. Frequent lamp cycling will lead to premature lamp aging. When determining the requirement for UV disinfection, a 30 percent reduction of UV output should be used to estimate end of lamp. Average life expectancy for low pressure UV lamps is approximately 8,800 hours.

8.7.1.2 Quartz Sleeve Fouling

Fouling of the quartz sleeve reduces the amount of UV radiation reaching the water. The quartz sleeve has a transmissibility of over 90 percent when new and clean. Over time, the surface of the quartz sleeve that is in contact with the water starts collecting organic and inorganic debris (e.g., iron, calcium, silt) causing a reduction in transmissibility (USEPA, 1996). When determining the requirements for UV disinfection, a 30 percent reduction of UV transmission should be used to reflect the effect of quartz sleeve fouling.

8.7.2 Equipment Maintenance

8.7.2.1 UV Lamp Replacement

Adequate space should be provided around the perimeter of the reactor vessels to allow access for maintenance and replacement of UV lamps. With modular electrical fittings, lamp replacement consists of unplugging the pronged connection of the old lamp and plugging in the new.

8.7.2.2 Quartz Sleeve Cleaning

Quartz sleeve cleaning may be accomplished by physical or chemical means. Physical alternatives include:

- Automatic mechanical wiper;
- Ultrasonic devices;
- High water pressure wash; and
- Air scour.

Chemical cleaning agents include sulfuric or hydrochloric acid. A UV reactor vessel may contain one or more physical cleaning system with provision for an occasional chemical cleaning.

8.7.2.3 Miscellaneous

Effective maintenance of a UV system will involve:

- Periodic checks for proper operation;
- Calibration of intensity meter for proper sensitivity; and
- Inspect and/or clean reactor vessel interior.

8.7.3 Standby Power

Producing UV radiation requires electricity to power the electronic ballasts, which in turn power the UV lamps. Since disinfection is of utmost importance in producing potable water, the UV system should remain in service during periods of primary power failure. A dual power feed system or essential circuitry powered by a standby generator are typical ways to achieve the desired reliability. Each low pressure UV lamp requires approximately 100 Watts of standby power. A second precaution that should be considered is not powering the UV system from the same motor control center (MCC) that powers variable frequency drives (VFDs). The electronic ballasts produce harmonics that may require mitigation (active harmonic filters) for the VFDs.

8.8 Summary Table

Table 8-3. Summary of UV Disinfection

Consideration	Description
Generation	Low pressure and medium pressure UV lamps available.
Primary uses	Primary physical disinfectant; requires secondary chemical disinfectant for residual in distribution system.
Inactivation efficiency	Very effective against bacteria and viruses at low dosages (5-25 mW•s/cm^2 for 2-log removal and 90-140 mW•s/cm^2 for 4-log removal). Much higher dosage required for *Cryptosporidium* and *Giardia* (100-8,000 mW•s/cm^2 for 2-log removal).
Byproduct formation	Minimal disinfection byproducts produced.
Limitations	Limited experience and data with flows greater than 200 GPM. Water with high concentrations of iron, calcium, turbidity, and phenols may not be applicable to UV disinfection.
Point of application	Prior to distribution system.
Special considerations	Extremely high UV dosages for *Cryptosporidium* and *Giardia* may make surface water treatment impractical.

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