
UV Disinfection Systems for Drinking Water - Overview

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Raymond Ehrhard, P.E., B.C.E.E.



Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

2. Overview of UV Disinfection

Chapter 2 provides an overview of UV disinfection. This overview includes discussion of basic chemical and physical principles, the components of UV equipment, and performance monitoring for UV facilities. The overview material in Chapter 2 is intended to present generally accepted facts and research results related to UV disinfection. The material is not intended to provide guidance or recommendations for designing, validating, or installing UV disinfection facilities. Some guidance is included in this chapter to enhance the information presented, but any guidance that appears in this section is also documented in the appropriate subsequent chapters in this manual.

Chapter 2 covers:

- 2.1 History of UV Light for Drinking Water Disinfection
- 2.2 UV Light Generation and Transmission
- 2.3 Microbial Response to UV Light
- 2.4 UV Disinfection Equipment
- 2.5 Water Quality Effects and Byproduct Formation

2.1 History of UV Light for Drinking Water Disinfection

UV disinfection is an established technology supported by decades of fundamental and applied research and practice in North America and Europe. Downes and Blunt (1877) discovered the germicidal properties of sunlight. The development of mercury lamps as artificial UV light sources in 1901 and the use of quartz as a UV transmitting material in 1906 were soon followed by the first drinking water disinfection application in Marseilles, France, in 1910. In 1929, Gates identified a link between UV disinfection and absorption of UV light by nucleic acid (Gates 1929). The development of the fluorescent lamp in the 1930s led to the production of germicidal tubular lamps. Considerable research on the mechanisms of UV disinfection and the inactivation of microorganisms occurred during the 1950s (Dulbecco 1950, Kelner 1950, Brandt and Giese 1956, Powell 1959).

Although substantial research on UV disinfection occurred during the first half of the 20th century, the low cost of chlorine and operational problems with early UV disinfection equipment limited its growth as a drinking water treatment technology. The first reliable applications of UV light for disinfecting municipal drinking water occurred in Switzerland and Austria in 1955 (Kruithof and van der Leer 1990). By 1985, the number of such installations in these countries had risen to approximately 500 and 600, respectively. After chlorinated disinfection byproducts (DBPs) were discovered, UV disinfection became popular in Norway and the Netherlands with the first installations occurring in 1975 and 1980, respectively.

As of the year 2000, more than 400 UV disinfection facilities worldwide were treating drinking water; these UV facilities typically treat flows of less than 1 million gallons per day (mgd) (USEPA 2000). Since 2000, several large UV installations across the United States have been constructed or are currently under design. The largest of these facilities includes a 180-mgd

facility in operation in Seattle, Washington, and a 2,200-mgd facility under design for the New York City Department of Environmental Protection (Schulz 2004). Because of the susceptibility of *Cryptosporidium* to UV disinfection and the emphasis in recent regulations on controlling *Cryptosporidium*, the number of public water systems (PWSs) using UV disinfection is expected to increase significantly over the next decade.

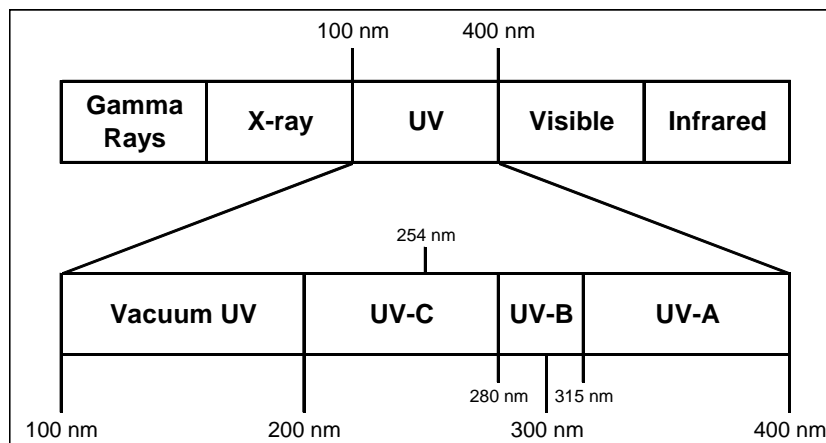
2.2 UV Light Generation and Transmission

The use of UV light to disinfect drinking water involves (1) generating UV light with the desired germicidal properties and (2) delivering (or transmitting) that light to pathogens. This section summarizes how UV light is generated and the environmental conditions that affect its delivery to pathogens.

2.2.1 Nature of UV Light

UV light is the region of the electromagnetic spectrum that lies between X-rays and visible light (Figure 2.1). The UV spectrum is divided into four regions: vacuum UV [100 to 200 nanometers (nm)]; UV-C (200 to 280 nm); UV-B (280 to 315 nm); and UV-A (315 to 400 nm) (Meulemans 1986). UV disinfection primarily occurs due to the germicidal action of UV-B and UV-C light on microorganisms. The germicidal action of UV-A light is small relative to UV-B light and UV-C light; therefore, very long exposure times are necessary for UV-A light to be effective as a disinfectant. Although light in the vacuum UV range can disinfect microorganisms (Munakata et al. 1991), vacuum UV light is impractical for water disinfection applications because it rapidly dissipates in water over very short distances. For the purposes of this manual, the practical germicidal wavelength for UV light is defined as the range between 200 and 300 nm. The germicidal range is discussed further in Section 2.3.1.

Figure 2.1. UV Light in the Electromagnetic Spectrum



Typically, UV light is generated by applying a voltage across a gas mixture, resulting in a discharge of photons. The specific wavelengths of light emitted from photon discharge depend on the elemental composition of the gas and the power level of the lamp. Nearly all UV lamps currently designed for water treatment use a gas mixture containing mercury vapor. Mercury gas is advantageous for UV disinfection applications because it emits light in the germicidal wavelength range. Other gases such as xenon also emit light in the germicidal range.

The light output from mercury-based UV lamps depends on the concentration of mercury atoms, which is directly related to the mercury vapor pressure. In low-pressure (LP) UV lamps, mercury at low vapor pressure [near vacuum; 2×10^{-5} to 2×10^{-3} pounds per square inch (psi)] and moderate temperature [40 degrees centigrade (°C)] produces essentially monochromatic (one wavelength) UV light at 253.7 nm. In medium-pressure (MP) UV lamps, a higher vapor pressure [2 – 200 psi] and higher operating temperature (600 – 900 °C) is used to increase the frequency of collisions between mercury atoms, which produces UV light over a broad spectrum (polychromatic) with an overall higher intensity. The characteristics of LP and MP lamps are discussed in Section 2.4.2 and summarized in Table 2.1.

2.2.2 Propagation of UV Light

As UV light propagates from its source, it interacts with the materials it encounters through absorption, reflection, refraction, and scattering. In disinfection applications, these phenomena result from interactions between the emitted UV light and UV reactor components (e.g., lamp envelopes, lamp sleeves, and reactor walls) and also the water being treated. When assessing water quality, UV absorbance or UV transmittance (UVT) is the parameter that incorporates the effect of absorption and scattering. This section briefly describes both the phenomena that influence light propagation and the measurement techniques used to quantify UV light propagation.

Absorption is the transformation of light to other forms of energy as it passes through a substance. UV absorbance of a substance varies with the wavelength (λ) of the light. The components of a UV reactor and the water passing through the reactor all absorb UV light to varying degrees, depending on their material composition. When UV light is absorbed, it is no longer available to disinfect microorganisms.

Unlike absorption, the phenomena of refraction, reflection, and scattering change the direction of UV light, but the UV light is still available to disinfect microorganisms.

Refraction (Figure 2.2) is the change in the direction of light propagation as it passes through the interface between one medium and another. In UV reactors, refraction occurs when light passes from the UV lamp into an air gap, from the air gap into the lamp sleeve, and from the lamp sleeve into the water. Refraction changes the angle that UV light strikes target pathogens, but how this ultimately affects the UV disinfection process is unknown.

Reflection is the change in direction of light propagation when it is deflected by a surface (Figure 2.3). Reflection may be classified as specular or diffuse. Specular reflection occurs from smooth polished surfaces and follows the Law of Reflection (the angle of incidence is equal to the angle of reflection). Diffuse reflection occurs from rough surfaces and scatters light in all

directions with little dependence on the incident angle. In UV reactors, reflection will take place at interfaces that do not transmit UV light (e.g., the reactor wall) and also at UV transmitting interfaces (e.g., the inside of a lamp sleeve). The type of reflection and intensity of light reflected from a surface depends on the material of the surface.

Figure 2.2. Refraction of Light

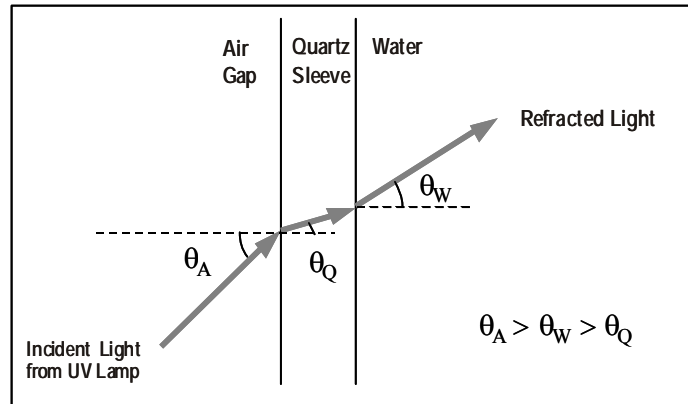
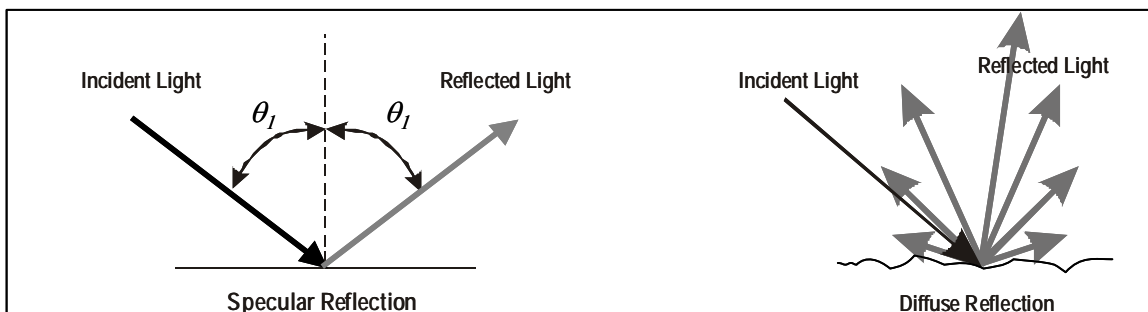
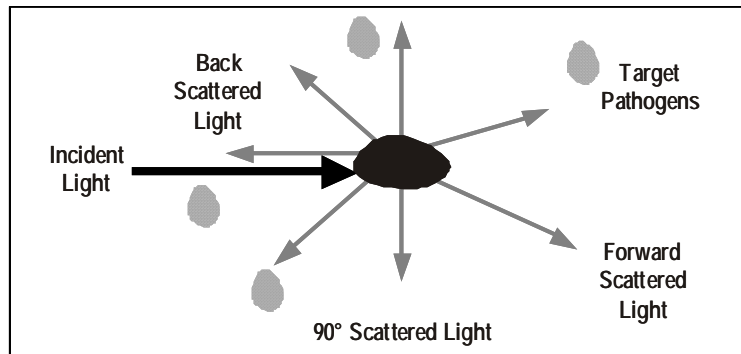


Figure 2.3. Reflection of Light



Scattering of light is the change in direction of light propagation caused by interaction with a particle (Figure 2.4). Particles can cause scattering in all directions, including toward the incident light source (back-scattering). Scattering of light caused by particles smaller than the wavelength of the light is called Rayleigh scattering. Rayleigh scattering depends inversely on wavelength to the fourth power ($1/\lambda^4$) and thus is more prominent at shorter wavelengths. Particles larger than the wavelength of light scatter more light in the forward direction but also cause some backscattering that is relatively independent of wavelength.

UV absorbance (A) quantifies the decrease in the amount of incident light as it passes through a water sample over a specified distance or pathlength. UV absorbance at 254 nm (A_{254}) is a water quality parameter commonly used to characterize the DBP formation potential of the water (e.g., specific UV absorbance calculations). In UV disinfection applications, A_{254} is used to measure the amount of UV light passing through the water and reaching the target organisms. A_{254} is measured using a spectrophotometer with 254 nm incident light and is typically reported on a per centimeter (cm^{-1}) basis.

Figure 2.4. Scattering of Light

Standard Method 5910B (APHA et al. 1998) calls for filtering the sample through a 0.45- μm membrane and adjusting the pH before measuring the absorbance. For UV disinfection applications, however, A_{254} measurements should reflect the water to be treated. Therefore, water samples should be analyzed without filtering or adjusting the pH. More information on collecting A_{254} data is provided in Section 3.4.4.1. Although Standard Methods defines this measurement as UV absorption, this manual refers to it as UV absorbance because the latter term is widely used in the water treatment industry.

UV Transmittance (UVT) has also been used extensively in the literature when describing the behavior of UV light. UVT is the percentage of light passing through material (e.g., a water sample or quartz) over a specified distance. The UVT can be calculated using Beer's law (Equation 2.1):

$$\% \text{ UVT} = 100 * \frac{I}{I_0} \quad \text{Equation 2.1}$$

where

- UVT = UV transmittance at a specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)
- I = Intensity of light transmitted through the sample [milliwatt per centimeter squared (mW/cm^2)]
- I_0 = Intensity of light incident on the sample (mW/cm^2)

UVT can also be calculated by relating it to UV absorbance using Equation 2.2:

$$\% \text{ UVT} = 100 * 10^{-A} \quad \text{Equation 2.2}$$

where

- UVT = UV transmittance at a specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)
- A = UV absorbance at a specified wavelength and pathlength (unitless)

UVT is typically reported at 254 nm because UV manufacturers and PWSs widely use A_{254} . This manual assumes UVT is at 254 nm unless specifically stated otherwise.

2.3 Microbial Response to UV Light

The mechanism of disinfection by UV light differs considerably from the mechanisms of chemical disinfectants such as chlorine and ozone. Chemical disinfectants inactivate microorganisms by destroying or damaging cellular structures, interfering with metabolism, and hindering biosynthesis and growth (Snowball and Hornsey 1988). UV light inactivates microorganisms by damaging their nucleic acid, thereby preventing them from replicating. A microorganism that cannot replicate cannot infect a host.

It is important that the assays used to quantify microorganism inactivation measure the ability of the microorganism to reproduce (Jagger 1967). For bacteria, assays measure the ability of the microorganism to divide and form colonies. For viruses, assays measure the ability of the microorganism to form plaques in host cells. For protozoan cysts, the assays measure the ability of the microorganism to infect a host or tissue culture. Assays that do not measure a response to reproduction may result in misleading information on the inactivation of microorganisms using UV light.

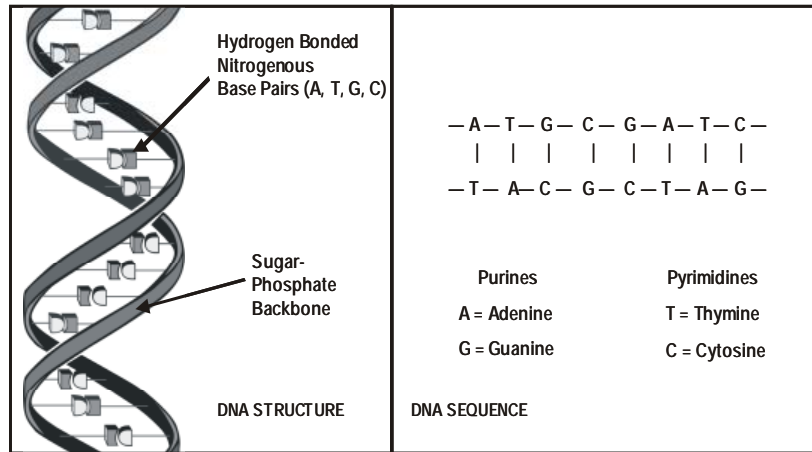
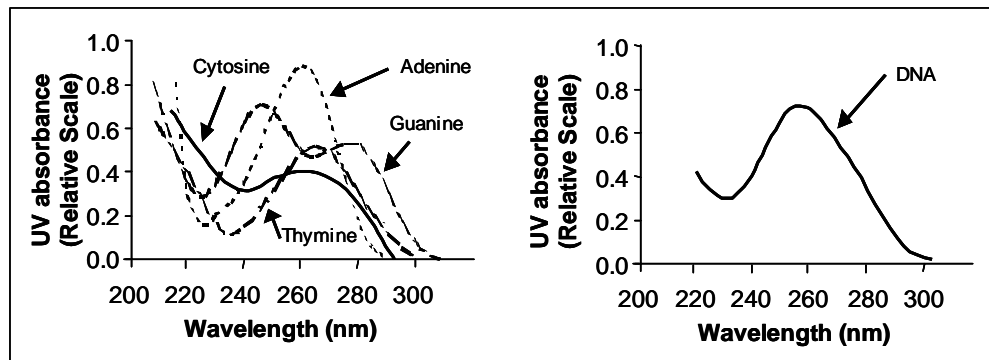
This section describes how UV light causes microbial inactivation, discusses how microorganisms can repair the damage, and introduces the concept of UV dose-response.

2.3.1 Mechanisms of Microbial Inactivation by UV Light

Nucleic acid is the molecule responsible for defining the metabolic functions and reproduction of all forms of life. The two most common forms of nucleic acid are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA and RNA consist of single- or double-stranded polymers comprising building blocks called nucleotides (Figure 2.5). In DNA, the nucleotides are classified as either purines (adenine and guanine) or pyrimidines (thymine and cytosine). In RNA, the purines are the same as in DNA, but the pyrimidines are uracil and cytosine.

As shown in Figure 2.6, the nucleotides absorb UV light at wavelengths from 200 to 300 nm. The UV absorption of DNA and RNA reflects their nucleotide composition and tends to have a peak near 260 nm and a local minimum near 230 nm.

All purines and pyrimidines strongly absorb UV light, but the rate of UV-induced damage is greater with pyrimidines (Jagger 1967). Absorbed UV light induces six types of damage in the pyrimidines of nucleic acid (Setlow 1967, Snowball and Hornsey 1988, Pfeifer 1997). The damage varies depending on UV dose. The following three types of damage contribute to microorganism inactivation:

Figure 2.5. Structure of DNA and Nucleotide Sequences within DNA**Figure 2.6. UV Absorbance of Nucleotides (left) and Nucleic Acid (right) at pH 7**

Source: Adapted from Jagger (1967)

- **Pyrimidine dimers** form when covalent bonds are present between adjacent pyrimidines on the same DNA or RNA strand, and they are the most common damage resulting from UV disinfection.
- **Pyrimidine (6-4) pyrimidone photoproducts** are similar to pyrimidine dimers and form on the same sites.
- **Protein-DNA cross-links** are covalent bonds between a protein and a DNA strand, and they may be important for the disinfection of certain microorganisms.

The other three types of damage do not significantly contribute to UV disinfection: pyrimidine hydrates occur much less frequently than dimers, and single- and double-strand breaks and DNA-DNA cross-links occur only at doses that are several orders of magnitude higher than the doses typically used for UV disinfection (Jagger 1967).

Pyrimidine dimers are the most common form of nucleic acid damage, being 1000 times more likely to occur than strand breaks, DNA-DNA cross-links, and protein-DNA cross-links. Of the three possible pyrimidine dimers that can form within DNA (thymine-thymine, cytosine-cytosine, and thymine-cytosine), thymine-thymine dimers are the most common. For RNA, because thymine is not present, uracil-uracil and cytosine-cytosine dimers are formed. Microorganisms with DNA rich in thymine tend to be more sensitive to UV disinfection (Adler 1966).

Pyrimidine dimer damage and other forms of nucleic acid damage prevent the replication of the microorganism. The damage, however, does not prevent the metabolic functions in the microorganism such as respiration. UV doses capable of causing oxidative damage that prevent cell metabolism and kill the microorganism (similar to the damage caused by chemical disinfectants) are several orders of magnitude greater than doses required to damage the nucleic acid and prevent replication.

2.3.2 Microbial Repair

Many microorganisms have enzyme systems that repair damage caused by UV light. Repair mechanisms are classified as either photorepair or dark repair (Knudson 1985). Microbial repair can increase the UV dose needed to achieve a given degree of inactivation of a pathogen, but the process does not prevent inactivation.

Even though microbial repair can occur, neither photorepair nor dark repair is anticipated to affect the performance of drinking water UV disinfection, as described below:

- Photorepair of UV irradiated bacteria can be prevented by keeping the UV disinfected water in the dark for at least two hours before exposure to room light or sunlight. Treated water typically remains in the dark in the piping, reservoirs, and distribution system after UV disinfection. Most facilities also use chemical disinfection to provide further inactivation of bacteria and virus and protection of the distribution system. Both of these common practices make photorepair unlikely to be an issue for PWSs.
- Dark repair is also not a concern for PWSs because the required UV doses shown in Table 1.4 are derived from data that are assumed to account for dark repair.

2.3.2.1 Photorepair

In photorepair (or photoreactivation), enzymes energized by exposure to light between 310 and 490 nm (near and in the visible range) break the covalent bonds that form the pyrimidine dimers. Photorepair requires reactivating light and repairs only pyrimidine dimers (Jagger 1967).

Knudson (1985) found that bacteria have the enzymes necessary for photorepair. Unlike bacteria, viruses lack the necessary enzymes for repair but can repair using the enzymes of a host cell (Rauth 1965). Linden et al. (2002a) did not observe photorepair of *Giardia* at UV doses typical for UV disinfection applications (16 and 40 mJ/cm²). However, unpublished data from the same study show *Giardia* reactivation in light conditions at very low UV doses (0.5 mJ/cm²,

Linden 2002). Shin et al. (2001) reported that *Cryptosporidium* does not regain infectivity after inactivation by UV light. One study showed that *Cryptosporidium* can undergo some DNA photorepair (Oguma et al. 2001). Even though the DNA is repaired, however, infectivity is not restored.

2.3.2.2 Dark Repair

Dark repair is defined as any repair process that does not require the presence of light. The term is somewhat misleading because dark repair can also occur in the presence of light. Excision repair, a form of dark repair, is an enzyme-mediated process in which the damaged section of DNA is removed and regenerated using the existing complementary strand of DNA. As such, excision repair can occur only with double stranded DNA and RNA. The extent of dark repair varies with the microorganism. With bacteria and protozoa, dark repair enzymes start to act immediately following exposure to UV light; therefore, reported dose-response data are assumed to account for dark repair.

Knudson (1985) found that bacteria can undergo dark repair, but some lack the enzymes needed for dark repair (Knudson 1985). Viruses also lack the necessary enzymes for repair but can repair using the enzymes of a host cell (Rauth 1965). Oguma et al. (2001) used an assay that measures the number of dimers formed in nucleic acid to show that dark repair occurs in *Cryptosporidium*, even though the microorganism did not regain infectivity. Linden et al. (2002a) did not observe dark repair of *Giardia* at UV doses typical for UV disinfection applications (16 and 40 mJ/cm²). Shin et al. (2001) reported *Cryptosporidium* does not regain infectivity after inactivation by UV light.

2.3.3 UV Intensity, UV Dose, and UV Dose Distribution

UV intensity is a fundamental property of UV light and has the units of watts per meter squared (W/m²) (Halliday and Resnick 1978). UV intensity has a formal definition that is derived from Maxwell's equations, which are fundamental equations that define the wavelike properties of light. The total UV intensity at a point in space is the sum of the intensity of UV light from all directions.

UV dose is the integral of UV intensity during the exposure period (i.e., the area under an intensity versus time curve). If the UV intensity is constant over the exposure time, UV dose is defined as the product of the intensity and the exposure time. Units commonly used for UV dose are joule per meter squared (J/m²), mJ/cm², and milliwatt seconds per centimeter squared (mWs/cm²), with mJ/cm² being the most common units in North America and J/m² being the most common in Europe.⁵

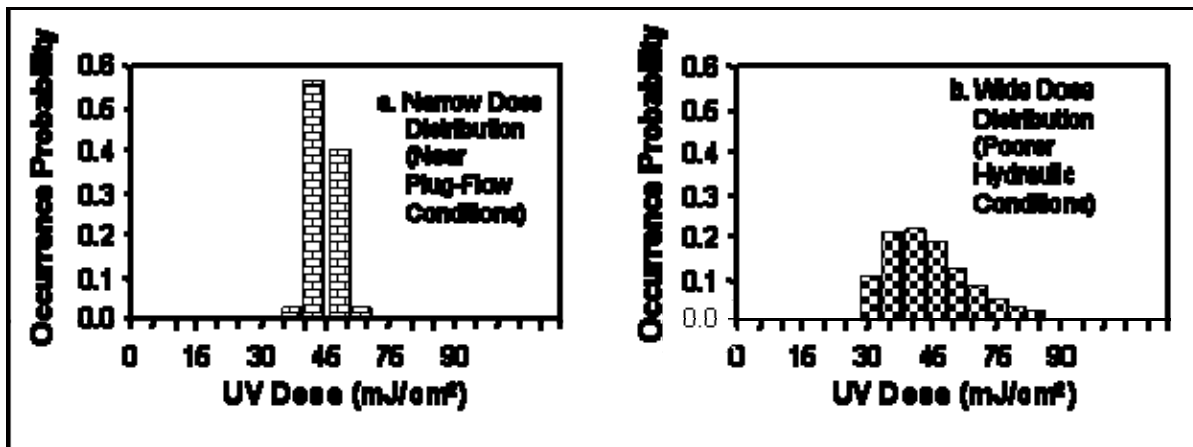
In a completely mixed batch system, the UV dose that the microorganisms receive is equal to the volume-averaged UV intensity within the system. An example of a completely mixed batch system is the collimated beam study in which a petri dish containing the stirred

⁵ 10 J/m² = 1 mJ/cm² = 1 mWs/cm²

microbial solution is irradiated by a collimated UV light beam (see Appendix C for details). In this case, the average UV intensity is calculated from the measured UV intensity incident on the surface of the microbial suspension, the suspension depth, and the UV absorbance of the water (see Appendix C for details). When using polychromatic light sources (e.g., MP lamps), UV dose calculations in batch system also incorporate the intensity at each wavelength in the germicidal range and the germicidal effectiveness at the associated UV wavelengths.

Dose delivery in a continuous flow UV reactor is considerably more complex than in a completely mixed batch reactor. Some microorganisms travel close to the UV lamps and experience a higher dose, while others that travel close to the reactor walls may experience a lower dose. Some microorganisms move through the reactor quickly, while others travel a more circuitous path. The result is that each microorganism leaving the reactor receives a different UV dose. Accordingly, UV dose delivered to the microorganisms passing through the reactor is best described using a dose distribution (Cabaj et al. 1996) as opposed to a single dose value. A dose distribution can be defined as a histogram of dose delivery (see Figure 2.7). Alternatively, the dose distribution can be defined as a probability distribution that a microorganism leaving a UV reactor will receive a given dose.

Figure 2.7. Hypothetical Dose Distributions for Two Reactors with Differing Hydraulics



The width of the dose distribution is indicative of the dose delivery efficiency of the reactor. A narrow dose distribution (Figure 2.7a) indicates a more efficient reactor, and a wider dose distribution (Figure 2.7b) indicates a less efficient reactor. In particular, the average log inactivation a reactor achieves with a given microorganism is strongly affected by microorganisms that receive the lowest UV doses.

The dose distribution a UV reactor delivers can be estimated using mathematical models based on computational fluid dynamics (CFD) and the light intensity distribution (LID). CFD is used to predict the trajectories of microorganisms as they travel through the UV reactor. LID is used to predict the intensity at each point within the UV reactor. UV dose to each microorganism is calculated by integrating the UV intensity over the microorganism's trajectory through the reactor. Biodosimetry (discussed below) is often used to verify these modeling results.

Currently, dose delivery is measured using a technique termed biosimetry. With biosimetry, the log inactivation of a surrogate microorganism is measured through the UV reactor and related to a dose value termed the reduction equivalent dose (RED) using the UV dose-response curve of the surrogate microorganism. Methods for conducting biosimetry are presented in Chapter 5. Although alternatives to biosimetry are being developed (e.g., the use of actinometric microspheres) for measuring the dose distribution of a reactor, such methods have not yet been proven for measuring dose delivery in UV reactors.

2.3.4 Microbial Response (UV Dose-Response)

Microbial response is a measure of the sensitivity of the microorganism to UV light and is unique to each microorganism. UV dose-response is determined by irradiating water samples containing the microorganism with various UV doses using a collimated beam apparatus (as described in Appendix C of this manual) and measuring the concentration of infectious microorganisms before and after exposure. The microbial response is calculated using Equation 2.3.

$$\text{Log Inactivation} = \log_{10} \frac{N_0}{N} \quad \text{Equation 2.3}$$

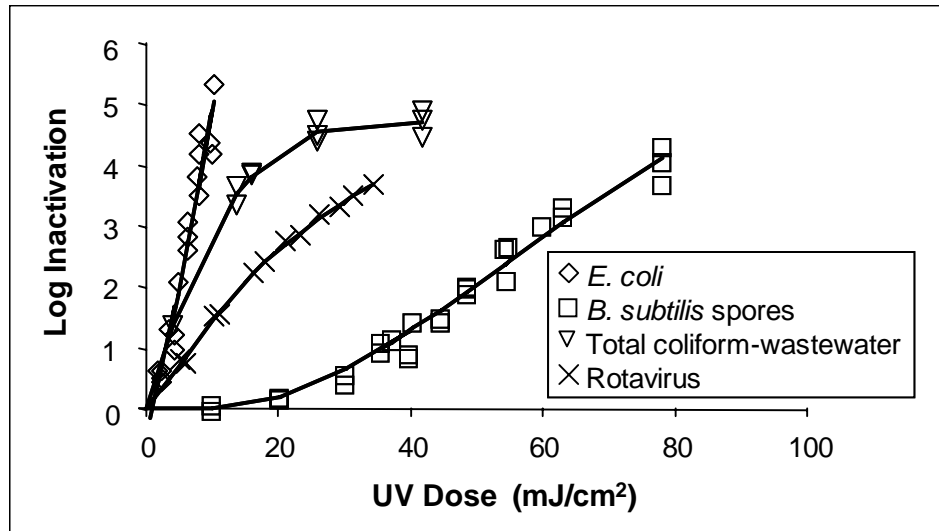
where

- N_0 = Concentration of infectious microorganisms before exposure to UV light
- N = Concentration of infectious microorganisms after exposure to UV light

UV dose-response relationships can be expressed as either the proportion of microorganisms *inactivated* or the proportion of microorganisms *remaining* as a function of UV dose. Microbial inactivation has a dose-response curve with a positive slope, while microbial survival has a dose-response curve with a negative slope. This manual presents microbial response as log inactivation because the terminology is widely accepted in the industry. Therefore, all dose-response curves presented (log inactivation as a function of dose) have a positive slope with log inactivation on a logarithmic (base 10) scale and UV dose on a linear scale.

Figure 2.8 presents examples of UV dose-response curves. The shape of the UV dose-response curve typically has three regions. At low UV doses, the UV dose-response shows a shoulder region where little if any inactivation occurs (e.g., *Bacillus subtilis* curve, Figure 2.8). The shoulder region has been attributed to dark repair (Morton and Haynes 1969) and photorepair (Hoyer 1998). Above some threshold dose level, the dose-response shows first-order inactivation where inactivation increases linearly with increased dose. In many cases, the dose-response shows first-order inactivation without a shoulder (e.g., *E. coli* curve, Figure 2.8). At higher UV doses, the dose-response shows tailing, a region where the slope of the dose-response decreases with increased dose (e.g., rotavirus and total coliform curves, Figure 2.8). Tailing has been attributed to the presence of UV-resistant sub-populations of the microorganism and the presence of particulate-associated and clumped microorganisms (Parker and Darby 1995). The shape of the dose-response curve can affect validation results, and information on how to account for tailing and shoulders in validation testing is included in Section C.6.

Figure 2.8. Shapes of UV Dose-Response Curves



Source: Adapted from Chang et al. (1985)

Microbial response to UV light can vary significantly among microorganisms. The UV sensitivity of viruses and bacteriophage can vary by more than two orders of magnitude (Rauth 1965). With bacteria, spore-forming and gram-positive bacteria are more resistant to UV light than gram-negative bacteria (Jagger 1967). Among the pathogens of interest in drinking water, viruses are most resistant to UV disinfection followed by bacteria, *Cryptosporidium* oocysts, and *Giardia* cysts.

UV dose-response is generally independent of the following factors:

- UV intensity:** In general, UV dose-response follows the Law of Reflectivity over an intensity range of 1 – 200 mW/cm², where the same level of inactivation is achieved with a given UV dose regardless of whether that dose was obtained with a high UV intensity and low exposure time or vice versa (Oliver and Cosgrove 1975, Rice and Ewell 2001). Non-reciprocity has been observed at low intensities where repair may compete with inactivation (Sommer et al. 1998, Setlow 1967).
- UV absorbance:** UV absorbance of the suspension is considered when calculating UV dose. Increasing intensity or exposure time, however, may be necessary to achieve a constant UV dose as the absorbance of a suspension changes.
- Temperature:** Temperature effects on dose-response are minimal and depend on the microorganism. For male-specific-2 (MS2) bacteriophage, inactivation is not temperature-dependent (Malley 2000). Severin et al. (1983) studied three microorganisms to determine the dose required to achieve 2-log inactivation as a function of temperature. For *E. coli* and *Candia parapsilosis*, the dose requires decreases by less than 10 percent as the temperature increases from 5 to 35 °C, and

for f2 bacteriophage, the dose requires decreases by less than 20 percent over the same temperature interval (Severin et al. 1983).

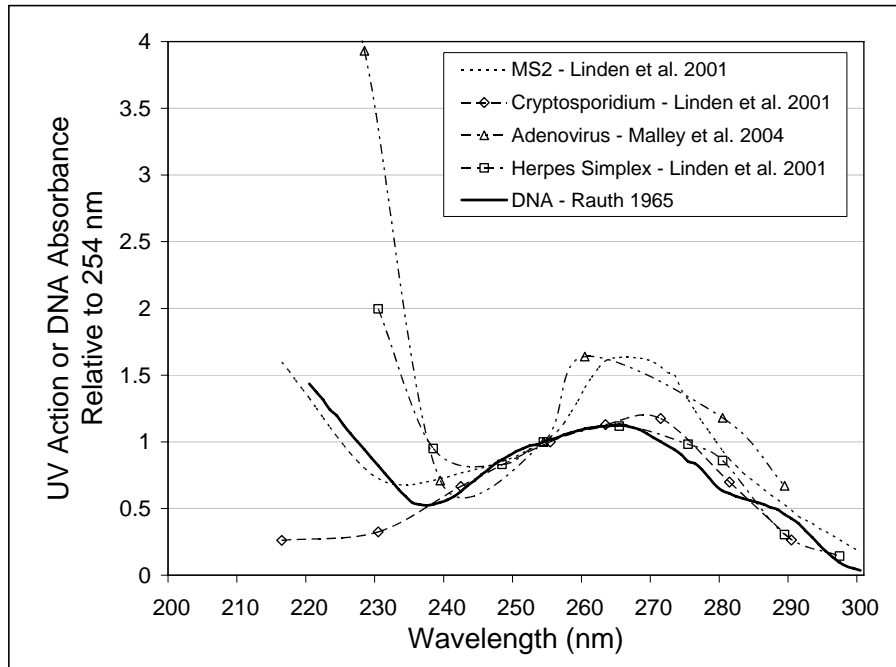
- **pH:** Dose-response is independent of the suspension pH from pH 6 to pH 9 (Malley 2000).

Particle association and clumping of microorganisms affects UV dose-response. Small floc particles can enmesh and protect MS2 bacteriophage, and potentially other viruses, from exposure to UV light (Templeton et al. 2003). Similarly, the inactivation rate of particle-associated coliforms is slower than that of non-particle-associated coliforms (Örmeçi and Linden 2003). The shielding effect of clumping or particle association can cause a tailing or flattening of the dose-response curve at higher inactivation levels (Figure 2.8, total coliform curve).

Several studies have examined the effect of particles on UV disinfection performance. Research by Linden et al. (2002b) indicated that the UV dose-response of microorganisms added to filtered drinking waters is not altered by variation in turbidity that meets regulatory requirements for filtered effluents. For unfiltered waters, source water turbidity up to 10 nephelometric turbidity units (NTU) did not affect the UV dose-response of separately added (seeded) microorganisms (Passantino et al. 2004, Oppenheimer et al. 2002). The effect of particle enmeshment on the UV dose-response of seeded microorganisms in water has been studied by adding clays or natural particles. When coagulating suspensions containing kaolinite or montmorillonite clay using alum or ferric chloride, no difference was observed in the log inactivation of the seeded microorganisms (Templeton et al. 2004, Mamane-Gravetz and Linden 2004). When humic acid particles and a coagulant were added to the suspensions, however, significantly less inactivation was achieved (Templeton et al. 2004). Further research is needed to understand fully the effect of coagulation and particles on microbial inactivation by UV light.

2.3.5 Microbial Spectral Response

Microbial response varies as a function of wavelength of the UV light. The action spectrum (also called UV action) of a microorganism is a measure of inactivation effectiveness as a function of wavelength. Figure 2.9 illustrates the UV action spectrum for three microbial species and the UV absorbance of DNA as a function of wavelength. Because of the similarity between the UV action and DNA absorbance spectra and because DNA absorbance is easier to measure than UV action, the DNA absorbance spectrum of a microorganism is often used as a surrogate for its UV action spectrum. In Figure 2.9, the scale of the y-axis represents the ratio of inactivation effectiveness at a given wavelength to the inactivation effectiveness at 254 nm.

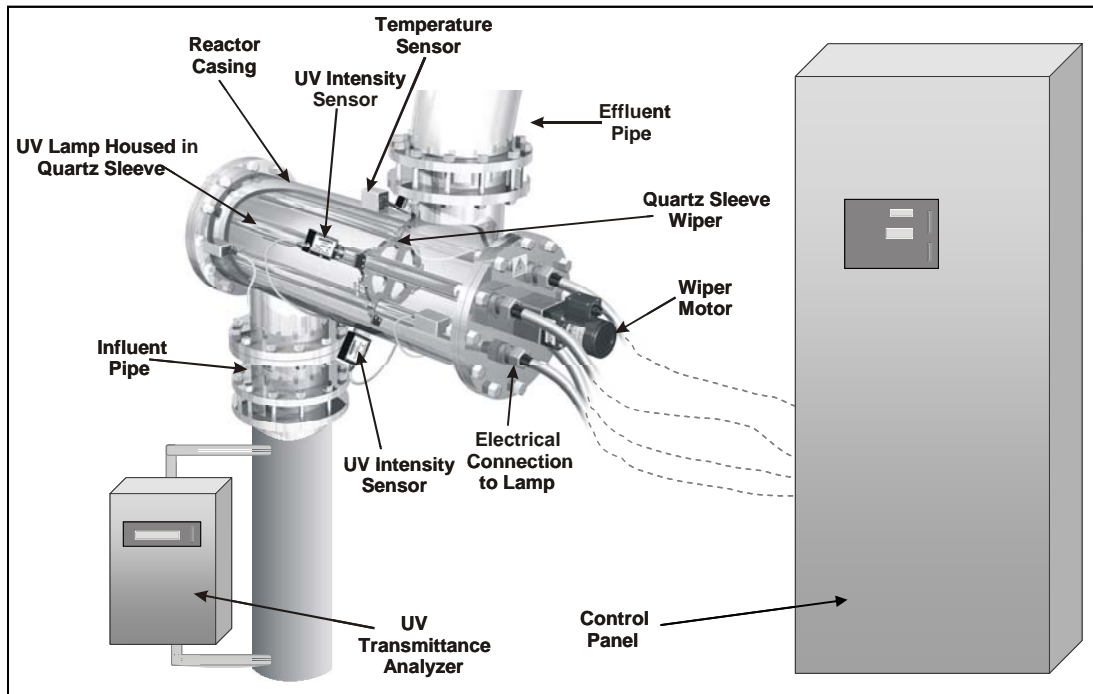
Figure 2.9. Comparison of Microbial UV Action and DNA UV Absorbance

Source: Adapted from Rauth (1965), Linden et al. (2001), and Malley et al. (2004)

For most microorganisms, the UV action peaks at or near 260 nm, has a local minimum near 230 nm, and drops to zero near 300 nm, which means that UV light at 260 nm is the most effective at inactivating microorganisms. Because no efficient way to produce UV light at 260 nm is available and mercury produces UV light very efficiently at 254 nm, however, the latter has become the standard. Although the action spectrum of various microorganisms is similar at wavelengths above 240 nm, significant differences occur at wavelengths below 240 nm (Rauth 1965).

2.4 UV Disinfection Equipment

The goal in designing UV reactors for drinking water disinfection is to efficiently deliver the dose necessary to inactivate pathogenic microorganisms. An example of UV equipment is shown in Figure 2.10. Commercial UV reactors consist of open or closed-channel vessels, containing UV lamps, lamp sleeves, UV sensors, and temperature sensors. UV lamps typically are housed within the lamp sleeves, which protect and insulate the lamps. Some reactors include automatic cleaning mechanisms to keep the lamp sleeves free of deposits. UV sensors, flow meters, and, in some cases, UVT analyzers, are used to monitor dose delivery by the reactor. This section briefly describes the components of the UV equipment and its monitoring systems.

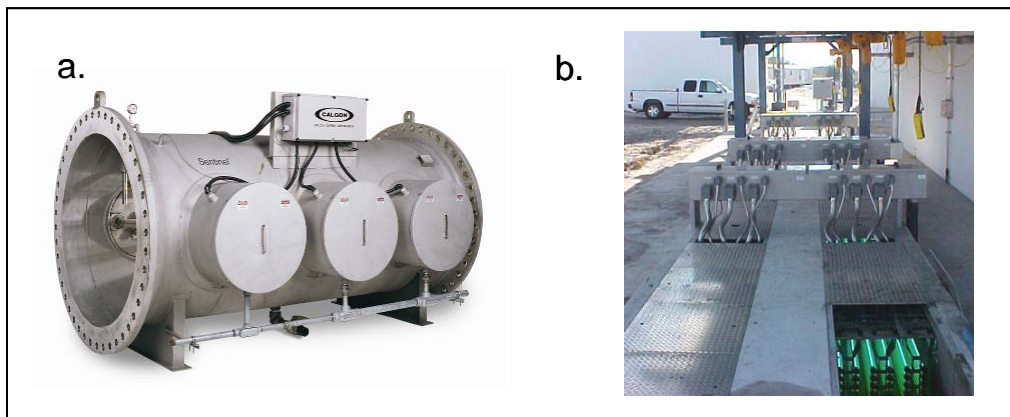
Figure 2.10. Example of UV Disinfection Equipment

Source: Courtesy of and adapted from Severn Trent Services
 Note: Not to scale

2.4.1 UV Reactor Configuration

UV reactors are typically classified as either closed or open channel. Water flows under pressure (i.e., no free surface) in closed-channel reactors (Figure 2.11a). Drinking water UV applications have used only closed reactors to date. Open-channel reactors (Figure 2.11b) are open basins with channels containing racks of UV lamps and are most commonly used in wastewater applications.

Figure 2.11. Examples of UV Reactors: (a) Closed-channel and (b) Open-channel



Source: (a) Courtesy of Calgon Carbon Corporation and (b) Courtesy of WEDECO UV Systems

UV equipment manufacturers design their UV reactors to provide efficient and cost-effective dose delivery. Lamp placement, baffles, and inlet and outlet conditions all affect mixing within a reactor and dose delivery. Individual reactor designs use various methods to optimize dose delivery (e.g., higher lamp output versus lower lamp output and improved hydrodynamics through increased head loss).

The lamp configuration in a reactor is designed to optimize dose delivery. In a reactor with a square cross-section, lamps are typically placed with lamp arrays perpendicular to flow. This pattern may be staggered to improve disinfection efficiency. With a circular cross-section, lamps typically are evenly spaced on one or more concentric circles parallel to flow. However, UV lamps may be oriented parallel, perpendicular, or diagonal to the flow direction. Depending on the reactor installation, lamps may consequently be oriented horizontally, vertically, or diagonally relative to the ground surface. Orienting MP lamps parallel to the ground prevents overheating at the top of the lamps and reduces the potential for lamp breakage due to temperature differentials.

The thickness of the water layer between lamps and between the lamps and the reactor wall influences dose delivery. If the water layer is too thin, the reactor wall and adjacent lamps will absorb UV light. If the water layer is too thick, water will pass through regions of lower UV intensity and experience a lower UV dose. The optimal spacing between lamps depends on the UVT of the water, the output of the lamp, and the hydraulic mixing within the reactor.

The flow through UV reactors is turbulent. Residence times are on the order of tenths of a second for MP lamps and seconds for LP lamps. In theory, optimal dose delivery is obtained with plug flow hydraulics through a UV reactor. In practice, however, UV reactors do not have such ideal hydrodynamics. For example, turbulence and eddies form in the wake behind lamp sleeves oriented perpendicularly to flow. Some manufacturers insert baffles to improve hydrodynamics in the reactor. Improvements to the hydraulic behavior of a reactor are often obtained at the expense of head loss.

Inlet and outlet conditions can significantly affect reactor hydrodynamics and UV dose delivery. For example, changes in flow direction of 90 degrees at inlets and outlets promote short-circuiting, eddies, and dead zones within the reactor. Straight inlet configurations with gradual changes in cross-sectional area will help create flow conditions for optimal dose delivery.

2.4.2 UV Lamps

UV light can be produced by the following variety of lamps:

- LP mercury vapor lamps
- Low-pressure high-output (LPHO) mercury vapor lamps
- MP mercury vapor lamps
- Electrode-less mercury vapor lamps
- Metal halide lamps

- Xenon lamps (pulsed UV)
- Eximer lamps
- UV lasers
- Light emitting diodes (LEDs)

Full-scale drinking water applications generally use LP, LPHO, or MP mercury vapor lamps. Therefore, this manual limits discussion to these UV lamp technologies. Table 2.1 lists characteristics of these lamps, and Table 2.2 lists operational advantages of the lamp types.

Table 2.1. Typical Mercury Vapor Lamp Characteristics

Parameter	Low-pressure	Low-pressure High-output	Medium-pressure
Germicidal UV Light	Monochromatic at 254 nm	Monochromatic at 254 nm	Polychromatic, including germicidal range (200 – 300 nm)
Mercury Vapor Pressure (Pa)	Approximately 0.93 (1.35x10 ⁻⁴ psi)	0.18 – 1.6 (2.6x10 ⁻⁵ – 2.3x10 ⁻⁴ psi)	40,000 – 4,000,000 (5.80 – 580 psi)
Operating Temperature (°C)	Approximately 40	60 – 100	600 – 900
Electrical Input [watts per centimeter (W/cm)]	0.5	1.5 – 10	50 – 250
Germicidal UV Output (W/cm)	0.2	0.5 – 3.5	5 – 30
Electrical to Germicidal UV Conversion Efficiency (%)	35 – 38	30 – 35	10 – 20
Arc Length (cm)	10 – 150	10 – 150	5 – 120
Relative Number of Lamps Needed for a Given Dose	High	Intermediate	Low
Lifetime [hour (hr)]	8,000 – 10,000	8,000 – 12,000	4,000 – 8,000

Note: Information in this table was compiled from UV manufacturer data.

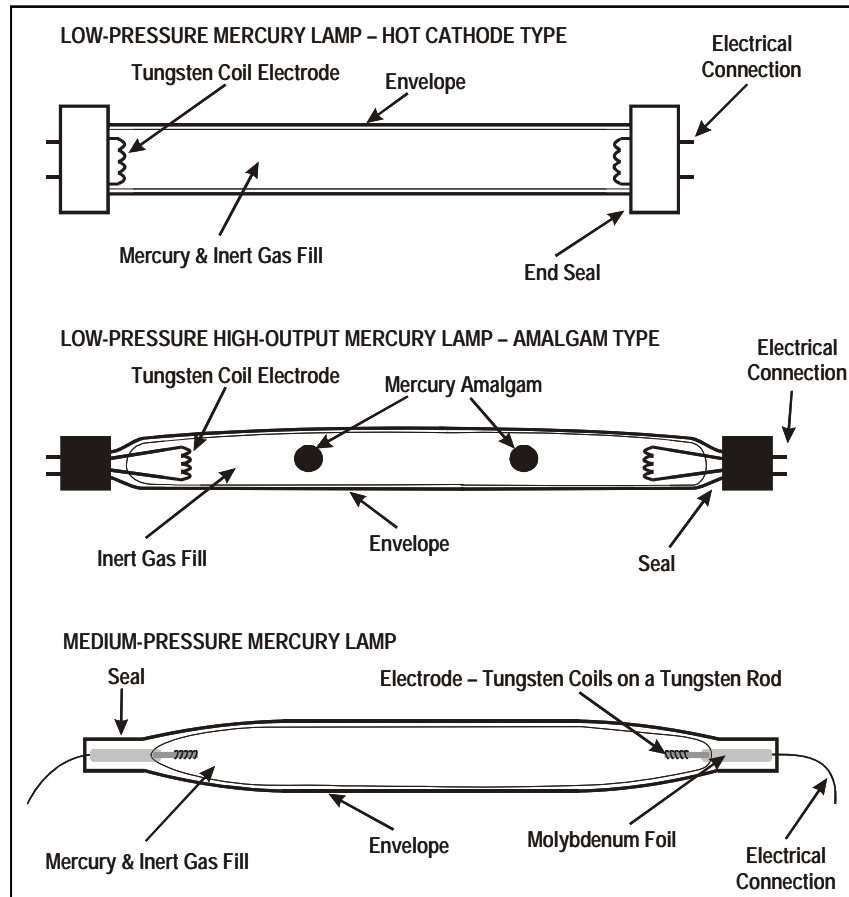
Table 2.2. Mercury Vapor Lamp Operational Advantages

Low-pressure and Low-pressure High-output	Medium-pressure
<ul style="list-style-type: none"> • Higher germicidal efficiency; nearly all output at 254 nm • Smaller power draw per lamp (less reduction in dose if lamp fails) • Longer lamp life 	<ul style="list-style-type: none"> • Higher power output • Fewer lamps for a given application

LP, LPHO, and MP lamps consist of the following elements, arranged as shown in Figure 2.12:

- **Lamp Envelope:** The envelope of the lamp is designed to transmit germicidal UV light, act as an electrical insulator, and not react with the lamp's fill gases. A non-crystalline form of quartz, vitreous silica, is often used for the lamp envelope because of its high UVT and its resistance to high temperatures. The UVT of the envelope affects the spectral output of lamps, especially with MP lamps at lower wavelengths. Because of this, lamp envelopes can be made from doped quartz (quartz that is altered to absorb specific wavelengths) to prevent undesirable non-germicidal photochemical reactions. Envelopes are approximately 1 – 2 millimeters (mm) thick, and the diameter is selected to optimize the UV output and lamp life.
- **Electrodes:** Electrode design and operation are critical for reliable long-term operation of lamps. Electrodes promote heat transfer so that lamps can operate at an appropriate temperature. The electrodes in LP and LPHO lamps are made of a coil of tungsten wire embedded with oxides of calcium, barium, or strontium. In MP lamps, electrodes consist of a tungsten rod wrapped in a coil of tungsten wire.
- **Mercury Fill:** The mercury fill present in UV lamps can be in the solid, liquid, or vapor phase. Amalgams (alloys of mercury and other metals such as indium or gallium in the solid phase) are typically used in LPHO lamps, while LP and MP lamps contain liquid elemental mercury. As the lamps heat, the vapor pressure of mercury increases. LP and LPHO lamps operate at lower temperatures and have lower mercury vapor pressures than MP lamps. In MP lamps, the concentration of mercury in the vapor phase is controlled by the amount of mercury in the lamp. In LPHO lamps, an excess of mercury is placed in the lamp, and the amount of mercury entering the vapor phase is limited by either a mercury amalgam attached to the lamp envelope, a cold spot on the lamp wall, or a mercury condensation chamber located behind each electrode.
- **Inert Gas Fill:** In addition to mercury, lamps are filled with an inert gas (typically argon). The inert gas aids in starting the gas discharge and reduces deterioration of the electrode. The vapor pressure of the inert gas is typically 0.02 – 1 psi.

In addition to amalgam LPHO lamps, another method is used to increase the output from LP lamps. In this application, a standard LP lamp with reinforced filaments is used, allowing for an increase in current through the lamp. The higher current increases the output from the lamp.

Figure 2.12. Construction of a UV Lamp

2.4.2.1 Lamp Start-up

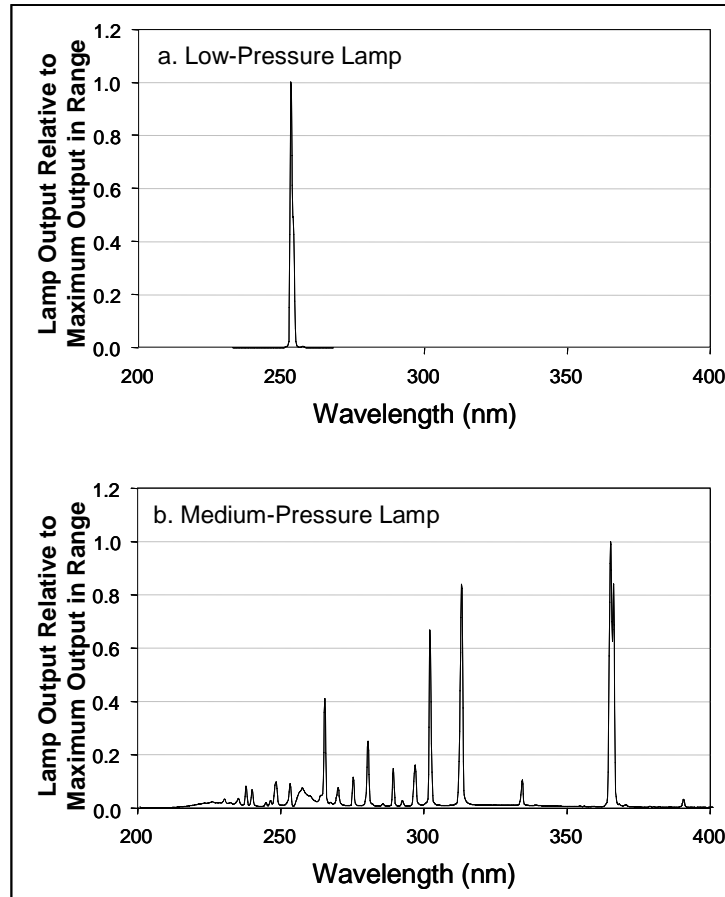
As lamps start up, the following series of events occurs to generate an arc (i.e., produce UV light). First, the electrode emits electrons that collide with the inert gas atoms, causing the inert gas to ionize. This creates a plasma that allows current to flow, which heats the gas. The mercury in operating lamps vaporizes in the presence of the hot inert gas, and collisions between the vapor-phase mercury and high-energy electrons in the plasma cause the mercury atoms to reach one of many excited states. As the mercury returns from a given excited state to ground state, energy is released (according to the difference in the state energies) in the wavelength range of the UV spectrum.

2.4.2.2 Lamp Output

The light that LP and LPHO lamps emit is essentially monochromatic at 253.7 nm (Figure 2.13a) in the ultraviolet range and is near the maximum of the microbial action spectrum. These lamps also emit small amounts of light at 185, 313, 365, 405, 436, and 546 nm due to higher energy electron transition in the mercury. Lamp output at 185 nm promotes ozone

formation. Because ozone is corrosive, toxic, and absorbs UV light, LP and LPHO lamps used in water disinfection applications are manufactured to reduce the output at 185 nm.

Figure 2.13. UV Output of LP (a) and MP (b) Mercury Vapor Lamps



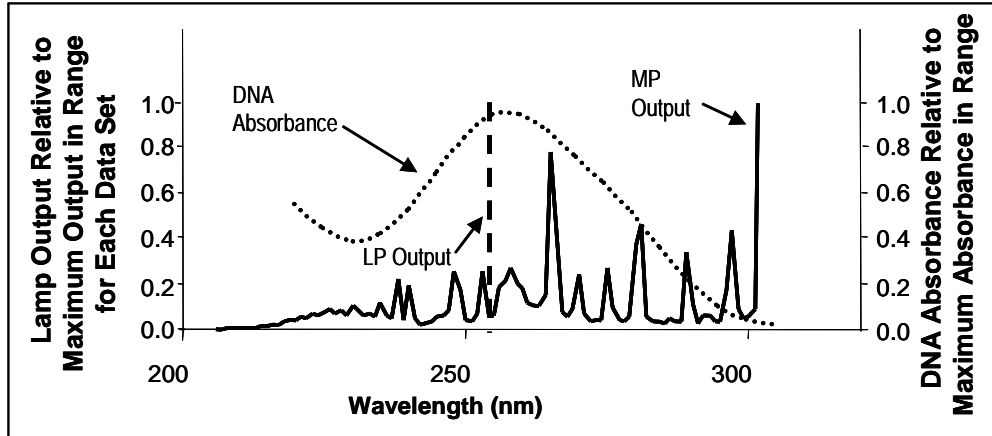
Source: Sharpless and Linden (2001)

MP lamps emit a wide range of UV wavelengths from 200 to 400 nm (Figure 2.13b). The combination of free electrons and mercury in the lamp creates a broad continuum of UV energy below 245 nm. Electron transitions in the mercury cause the peaks in the spectrum.

All UV lamps also emit light in the visible range. Visible light can promote algal growth as discussed in Section 2.5.1.5.

Figure 2.14 shows the output of LP and MP lamps superimposed on the DNA absorption spectrum. In Figure 2.14, the DNA absorbance is plotted relative to the maximum absorbance in the range (260 nm), and the lamp outputs are presented on a relative scale. In absolute terms, however, the intensity and power of LP and MP lamps differ significantly (see Table 2.1 for more information on lamp operating characteristics).

Figure 2.14. UV Lamp Output and its Relationship to the UV Absorbance of DNA



Source: Courtesy of Bolton Photosciences, Inc.

2.4.2.3 Lamp Sensitivity to Power Quality

A UV lamp can lose its arc if a voltage fluctuation, power quality anomaly, or power interruption occurs. For example, voltage sags that vary more than 10 – 30 percent from the nominal voltage for as few as 0.5 – 3 cycles (0.01 – 0.05 seconds) may cause a UV lamp to lose its arc.

The most common sources of power quality problems that may cause UV lamps to lose their arcs are as follows:

- Faulty wiring and grounding
- Off-site accidents (e.g., transformer damaged by a car accident)
- Weather-related damage
- Animal-related damage
- Facility and equipment modifications
- Starting or stopping equipment with large electrical needs on the same circuit at the water plant
- Power transfer to emergency generator or alternate feeders

LP lamps generally can return to full operating status within 15 seconds after power is restored. LPHO and MP reactors that are more typically used in drinking water applications, however, exhibit significant restart times if power is interrupted. The start-up time for lamps should be considered in the design of UV disinfection systems as start-up time can contribute to off-specification operations (see Section 3.4.1). The start-up and restart behaviors for LPHO and MP lamps are summarized in Table 2.3.

Table 2.3. Typical Start-up and Restart Times for LPHO and MP Lamps¹

Lamp Type	Cold Start ²	Warm Start ³
LPHO	total time: 4 – 7 minutes (min) (0 – 2 min warm-up plus 4 – 5 min to full power)	total time: 2 – 7 min (0 – 2 min warm-up plus 2 – 5 min to full power)
MP	total time: 1 – 5 min (No warm-up or cool down plus 1 – 5 min to full power ⁴)	total time: 4 – 10 min (2 – 5 min cool down plus 2 – 5 min to full power ⁴)

¹ Information shown in table is compiled from Calgon Carbon Corporation, Severn Trent, Trojan, and WEDECO. Contact the manufacturer to determine the start-up and restart times for specific equipment models.

² A cold start occurs when UV lamps have not been operating for a significant period of time.

³ A warm start occurs when UV lamps have just lost their arcs (e.g., due to voltage sag).

⁴ 60 percent intensity is reached after 3 min.

Source: Cotton et al. (2005)

The effects of temperature can increase or decrease the times listed in Table 2.3 and should be discussed with the UV manufacturer. Individual manufacturers report that colder water temperatures (below 10 °C) can result in slower start-ups for LPHO lamps than those listed in Table 2.3. Conversely, MP manufacturers report shorter restart times with colder temperatures because the cold water accelerates the condensation of mercury (i.e., cool down), which is necessary for re-striking the arc.

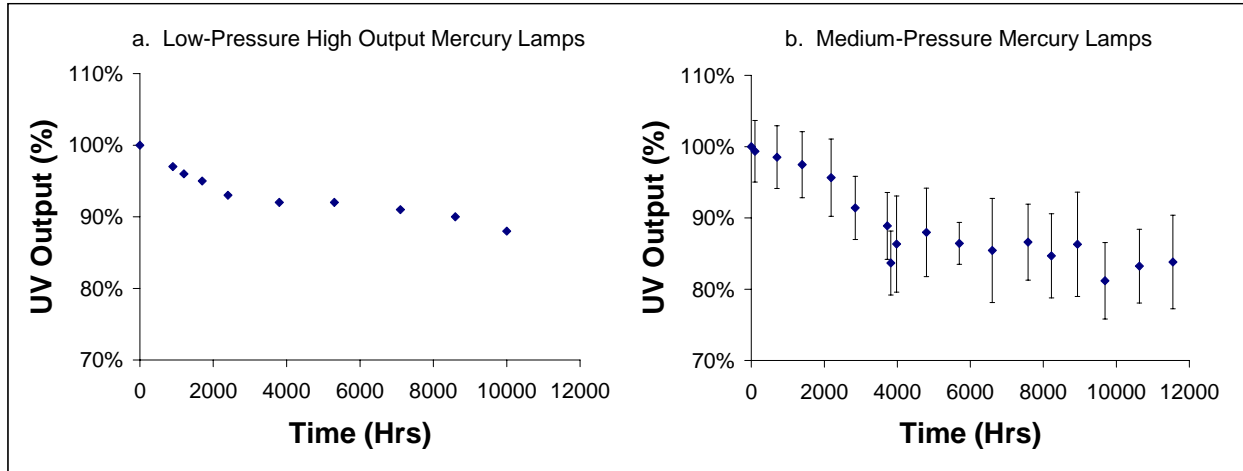
2.4.2.4 Lamp Aging

UV lamps degrade as they age, resulting in a reduction in output that causes a drop in UV dose delivery over time. Lamp aging can be accounted for with the fouling/aging factor (described in Section 3.4.5) in the design of the UV facility.

Lamp degradation occurs with both LP and MP lamps and is a function of the number of lamp hours in operation, number of on/off cycles, power applied per unit (lamp) length, water temperature, and heat transfer from lamps. The rate of decrease in lamp output often slows as the lamp ages (Figure 2.15). The reduction in output occurs at all wavelengths across the germicidal range as shown in Figure 2.16, which is an example of MP lamp output reduction after 8,220 hours of operation.

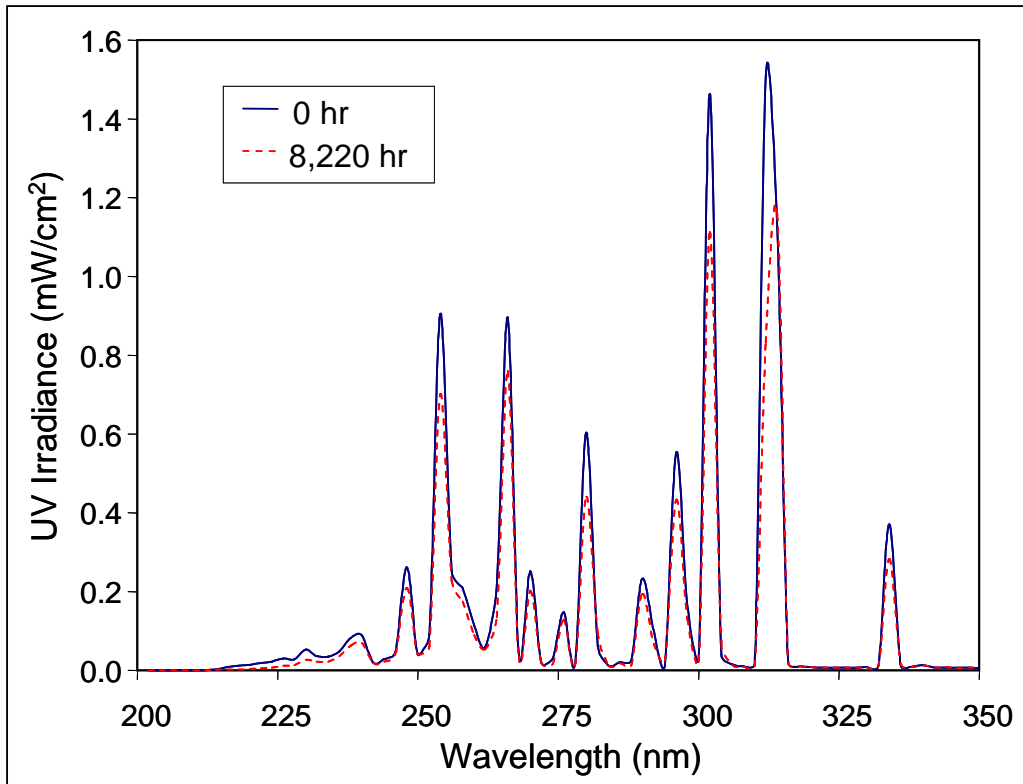
Preliminary findings from ongoing research into lamp aging at water and wastewater UV facilities shows that LPHO and MP lamp aging is non-uniform with respect to axial and horizontal output and varies greatly from lamp to lamp (Mackey et al. 2005). The lamp aging study by Mackey et al. is still ongoing, and any future findings from this or other studies should be evaluated and considered once results are available.

Figure 2.15. Reduction in UV Output of (a) LPHO and (b) MP Lamps Over Time



Source: (a) Adapted from WEDECO, (b) adapted from Linden et al. (2004)

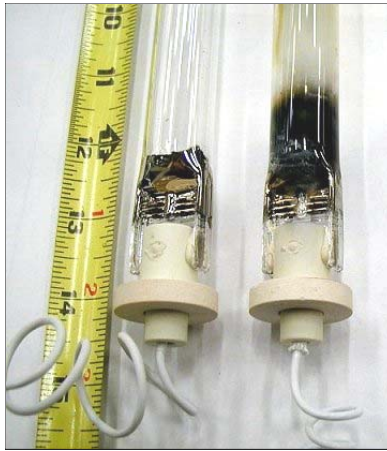
Figure 2.16. Lamp Aging for an MP Lamp



Source: Adapted from Linden et al. (2004)

Any deposits on the inner or outer surfaces of the lamp envelope and metallic impurities within the envelope can absorb UV light and cause premature lamp aging. In LP and LPHO lamps using UV-transmitting glass, mercury may combine with sodium in the glass to create a UV-absorbing coating. Electrode sputtering during start-up can also coat the inside surface of the lamp envelope with tungsten as the lamp ages. The tungsten coating is black, non-uniform, concentrated within a few inches of the electrode, and can absorb UV light (Figure 2.17). If the lamps are not sufficiently cooled during operation, electrode material in MP lamps may evaporate and condense on the inside of the envelope.

Figure 2.17. Aged UV Lamp (right) Compared to a New UV Lamp (left)



Source: Mackey et al. (2004)

UV lamp manufacturers can reduce electrode sputtering by designing lamps that pre-heat the electrode before applying the start voltage, are driven by a sinusoidal current waveform, or have a higher argon (inert gas) content. Electrode sputtering can be reduced by minimizing the number of lamp starts during operation.

2.4.3 Ballasts

Ballasts are used to regulate the incoming power supply at the level needed to energize and operate the UV lamps. Power supplies and ballasts are available in many different configurations and are tailored to a unique lamp type and application. UV reactors typically use magnetic ballasts or electronic ballasts.

Electronic and magnetic ballasts each have specific advantages and disadvantages. UV reactor manufacturers consider these advantages and disadvantages when determining what technology to incorporate into their equipment designs. Electronic and inductor-based magnetic ballasts can provide almost continuous adjustment of lamp intensity. Most transformer-based magnetic ballasts, however, allow only step adjustment of lamp intensity. Transformer-based magnetic ballasts are typically more electrically efficient than inductor-based ballasts but are less efficient than electronic ballasts. However, higher efficiency and additional features can increase

the electronic ballast cost. UV lamps that are powered by magnetic ballasts tend to have more lamp end-darkening (i.e., electrode sputtering) and have shorter lives compared to lamps powered by electronic ballasts due to the higher frequencies used by electronic ballasts. Electronic ballasts are generally more susceptible to power quality problems (Section 2.4.2.3) compared to magnetic ballasts; however, the power quality tolerances of both ballast types depend on the electrical design. A comparison of magnetic and electronic ballast technologies is shown in Table 2.4.

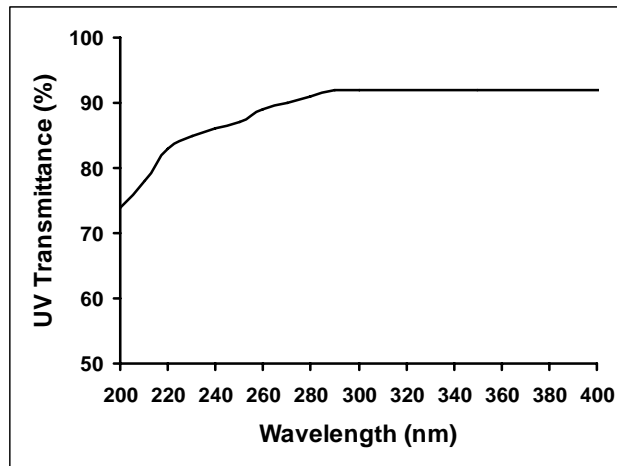
Table 2.4. Comparison of Magnetic and Electronic Ballasts

Magnetic Ballast	Electronic Ballast
<ul style="list-style-type: none"> • Less expensive • Continuous power adjustment occurs with inductor-based magnetic ballast (but not with transformer-based magnetic ballast) • More resistant to power surges • Proven technology (in use for nearly 70 years) • Greater separation distance allowed between the UV reactor and control panel 	<ul style="list-style-type: none"> • Continuous power adjustment and ability to adjust to lower power levels (e.g., 30 %) • More power efficient • Lighter weight and smaller size • Allows for longer lamp operating life and less lamp end-darkening

2.4.4 Lamp Sleeves

UV lamps are housed within lamp sleeves to help keep the lamp at optimal operating temperature and to protect the lamp from breaking. Lamp sleeves are tubes of quartz (vitreous silica) that are open at one or both ends. The sleeve length is sufficient to include the lamp and associated electrical connections. The sleeve diameter is typically 2.5 – 5.0 cm for LP and LPHO lamps and 3.5 – 10.0 cm for MP lamps. The distance between the exterior of the lamp and interior of the lamp sleeve is approximately 1 cm. The positioning of the UV lamp along the length of the sleeve can vary, depending on reactor configuration. Lamp sleeves absorb some UV light (Figure 2.18), which may influence dose delivery by the reactor.

Figure 2.18. UVT of Quartz that is 1 mm Thick at a Zero-degree Incidence Angle



Source: GE Quartz (2004a)

The lamp sleeve assemblies are sealed to prevent water condensation within the sleeve and contain any ozone formed between the lamp envelope and lamp sleeve. Components within the sleeve should withstand exposure to UV light, ozone, and high temperatures. If the components are not made of the appropriate material, UV light exposure can cause component deterioration and off-gassing of any impurities present in the quartz sleeve. Off-gassed materials can form UV-absorbing deposits on the inner surfaces of the lamp sleeve. Off-gassing and ozone formation are of greater concern with MP lamps because they operate at a higher temperature and emit low-wavelength ozone-forming UV light. Off-gassing can be minimized through proper manufacturing of the lamp sleeves.

Lamp sleeves are vulnerable to fractures. Fractures can occur from internal stress and external mechanical forces such as wiper jams, water hammer, resonant vibration, and impact by objects. Fractures may also occur if lamp sleeves are not handled properly when removed for manual cleaning. Most lamp sleeves are designed to withstand continuous positive pressures of at least 120 pounds per square inch gauge (psig) (Roberts 2000, Aquafine 2001, Dinkloh 2001). However, pressures of negative 1.5 psig have been shown to adversely affect sleeve integrity (Dinkloh 2001). Section 4.1.4 discusses design considerations to reduce the potential for pressure-related incidents. If a lamp sleeve fractures while in service, water can enter the sleeve. The temperature difference between the hot lamp and cooler water may cause the lamp to break. Lamp breaks are undesirable due to the potential for mercury release. Appendix E discusses the lamp sleeve and lamp breaks. The tolerance level of the sleeve depends on the quality of the quartz and the sleeve's thickness and length.

Lamp sleeves can also foul, decreasing the UVT of the lamp sleeve. Fouling on the internal lamp sleeve surface arises from the deposition of material from components within the lamp or sleeve due to temperature and exposure to UV light. The UV reactor manufacturer can control internal lamp sleeve fouling through appropriate material selection. For example, some UV reactors using LP or LPHO lamps have sleeves made of Teflon[®] or Teflon-coated quartz. Teflon sleeves have a lower UVT, however, and their transmittance reduces faster than quartz

sleeves without Teflon. Deposition of compounds in the water on the lamp sleeve surface cause fouling on external surfaces. A combination of thermal effects and photochemical processes causes the external fouling (Derrick and Blatchley 2005). Some compounds that may contribute to fouling are discussed in Section 2.5.1. External fouling can be removed by cleaning.

Solarization can also decrease the UVT of the sleeve. Solarization is photo-thermal damage to the quartz that increases light scattering and attenuation (Polymicro Technologies 2004). Quartz solarizes if exposed to prolonged high energy radiation such as UV light. Resistance to this type of solarization increases as the purity of the quartz increases. Solarization on quartz can be reversed by heating the quartz to about 500 °C (GE Quartz 2004b).

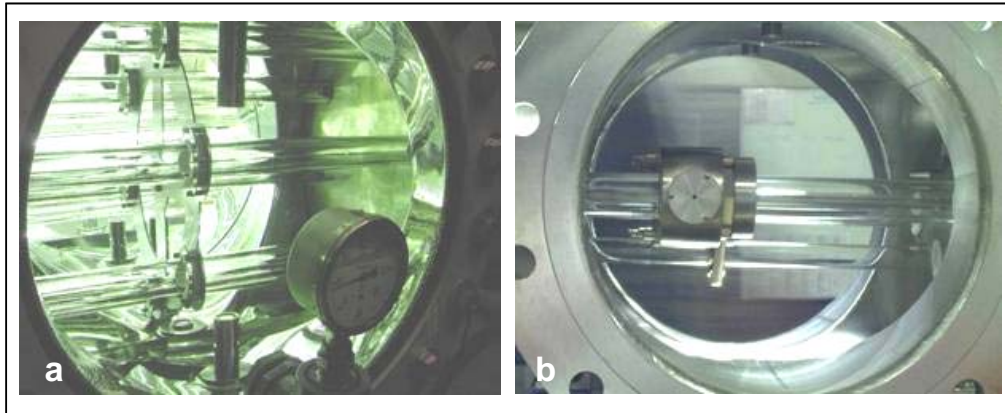
2.4.5 Cleaning Systems

UV reactor manufacturers have developed different approaches for cleaning lamp sleeves, depending on the application. These approaches include off-line chemical cleaning (OCC), on-line mechanical cleaning (OMC), and on-line mechanical-chemical cleaning (OMCC) methods.

For OCC systems, the reactor is shut down, drained, and flushed with a cleaning solution. Solutions used to clean lamp sleeves include citric acid, phosphoric acid, or a solution the UV reactor manufacturer provides that is consistent with National Sanitation Foundation International/American National Standards Institute (NSF/ANSI) 60 Standard (Drinking Water Treatment Chemicals – Health Effects). The reactor is filled with the cleaning solution for a time sufficient to dissolve the substances fouling the sleeves (approximately 15 minutes), rinsed, and returned to operation. The entire cleaning cycle typically lasts approximately 3 hours. Alternatively, instead of rinsing the UV reactor with a cleaning solution, the sleeves can be removed and manually cleaned. Some LPHO UV equipment uses OCC systems. The frequency of OCC can range from monthly to yearly and depends on the site-specific water quality and degree and frequency of fouling.

OMC and OMCC systems use wipers that are attached to electric motors or pneumatic piston drives. In OMC systems, mechanical wipers may consist of stainless steel brush collars or Teflon rings that move along the lamp sleeve (Figure 2.19a). In OMCC systems, a collar filled with cleaning solution moves along the lamp sleeve (Figure 2.19b). The wiper physically removes fouling on the lamp sleeve surface while the cleaning solution within the collar dissolves fouling materials.

Figure 2.19. Examples of (a) Mechanical Wiper System and (b) Mechanical-chemical Wiper System



Source: (a) Courtesy of Infilco Degremont, (b) Courtesy of Trojan Technologies

Draining the reactor is unnecessary when mechanical and mechanical-chemical wipers are used. Therefore, the reactor can remain on-line while the lamp sleeves are cleaned. MP equipment typically uses OMC or OMCC systems because the higher lamp temperatures can accelerate fouling under certain water qualities. The cleaning frequency for these OMC and OMCC systems ranges from 1 – 12 cycles per hour (Mackey et al. 2004).

2.4.6 UV Sensors

UV sensors measure the UV intensity at a point within the UV reactor (Figure 2.20) and are used with measurements of flow rate and, potentially, UVT to indicate UV dose delivery. The measurement responds to changes in lamp output due to lamp power setting, lamp aging, lamp sleeve aging, and lamp sleeve fouling. Depending on sensor position, UV sensors may also respond to changes in UVT of the water being treated. UV sensors comprise optical components, a photodetector, an amplifier, its housing, and an electrical connector. The optical components may include monitoring windows, light pipes, diffusers, apertures, and filters. Monitoring windows and light pipes deliver light to the photodetector. Diffusers and apertures reduce the amount of UV light reaching the photodetector, thereby reducing the sensor degradation that UV light causes. Optical filters modify the spectral response such that the sensor responds only to germicidal wavelengths (i.e., 200 – 300 nm). Verification of sensor performance is described in Chapter 5.

Figure 2.20. Example of a Dry UV Sensor Mounted on a UV Reactor



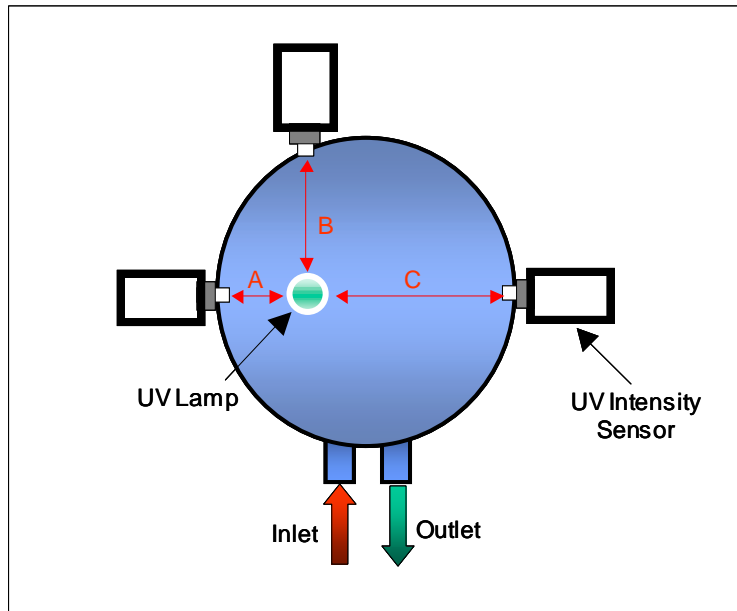
Source: Courtesy of WEDECO

UV sensors can be classified as dry or wet. Dry sensors monitor UV light through a monitoring window, whereas wet UV sensors directly contact the water flowing through the reactor. Monitoring windows and the wetted ends of wet sensors can foul over time and may require cleaning similar to lamp sleeves.

2.4.7 UVT Analyzers

As stated previously, UVT is an important parameter in determining UV dose delivery. UVT analyzers are essential if UVT is part of the dose-monitoring strategy (see Section 2.4.9 for a discussion of dose monitoring approaches). If UVT is not part of the dose-monitoring strategy, analyzers may be provided for the purpose of monitoring water quality and helping to diagnose operational problems. Several commercial UV reactors use the measurement of UVT to calculate UV dose in the reactor and, if necessary, change lamp output or the number of energized lamps to maintain appropriate UV dose delivery.

Two types of commercial on-line UVT analyzers are available. One analyzer calculates UVT by measuring the UV intensity at various distances from a lamp. This type of analyzer is schematically displayed in Figure 2.21. In this analyzer, which is external to the UV reactor, a stream of water passes through a cavity containing an LP lamp with three UV sensors located at various distances from the lamp. The difference in sensor readings is used to calculate UVT.

Figure 2.21. Example UVT Analyzer Design

Source: Courtesy of Severn Trent Services

The other type of on-line UVT analyzer is a flow-through spectrophotometer that uses a monochromatic UV light source at 253.7 nm. The instrument measures the A_{254} and calculates and displays UVT.

2.4.8 Temperature Sensors

The energy input to UV reactors that is not converted to light (approximately 60 – 90 percent, depending on lamp and ballast assembly) is wasted as heat. As it passes through a reactor, water can absorb the heat, keeping the reactor from overheating. Nevertheless, temperatures can increase when either of the following events occurs:

- Water level in the reactor drops and lamps are exposed to air.
- Water stops flowing in the reactor.

UV reactors can be equipped with temperature sensors that monitor the water temperature within the reactor. If the temperature is above the recommended operating range, the reactor will shut off to minimize the potential for the lamps to overheat. Because of the high operating temperature of MP lamps, dissipating heat can be more difficult than in reactors that use LP or LPHO lamps. As such, UV reactors with MP lamps typically have temperature sensors; however, reactors with LP or LPHO lamps may not because of the lower lamp operating temperature.

2.4.9 UV Reactor Dose-Monitoring Strategy

The dose-monitoring strategy establishes the operating parameters used to confirm UV dose delivery. This guidance manual focuses on UV reactors that use one of these two strategies, described below. Other existing dose-monitoring strategies or new strategies developed after this manual is published, however, may also be suitable for reactor operations provided they meet minimum regulatory requirements.⁶

1. **UV Intensity Setpoint Approach.** This approach relies on one or more “setpoints” for UV intensity that are established during validation testing to determine UV dose. During operations, the UV intensity as measured by the UV sensors must meet or exceed the setpoint(s) to ensure delivery of the required dose. Reactors must also be operated within validated operation conditions for flow rates and lamp status [40 CFR 141.720(d)(2)]. In the UV Intensity Setpoint Approach, UVT does not need to be monitored separately. Instead, the intensity readings by the sensors account for changes in UVT. The operating strategy can be with either a single setpoint (one UV intensity setpoint is used for all validated flow rates) or a variable setpoint (the UV intensity setpoint is determined using a lookup table or equation for a range of flow rates).
2. **Calculated Dose Approach.** This approach uses a dose monitoring equation to estimate the UV dose based on the flow rate, UV intensity, and UVT, as measured during reactor operations. The dose monitoring equation may be developed by the UV manufacturers using numerical methods; however, EPA recommends that water systems use an empirical dose monitoring equation developed through validation testing. During reactor operations, the UV reactor control system inputs the measured parameters into the dose monitoring equation to produce a calculated dose. The water system operator divides the calculated dose by the Validation Factor (see Chapter 5 for more details on the Validation Factor) and compares the resulting value to the required dose for the target pathogen and log inactivation level.

The dose-monitoring strategies are described in more detail in Section 3.5.2. Any dose monitoring strategy must be evaluated during reactor validation (as described in Section 5.1), and the outputs measured during validation will be part of the monitoring requirements described in Section 6.4.1 [40 CFR 141.720(d)].

2.5 Water Quality Effects and Byproduct Formation

Constituents in the water to be treated can affect the performance of UV disinfection. Additionally, all disinfectants can form byproducts, and the goal of the overall disinfection process is to maximize disinfection while controlling byproduct formation. This section

⁶ At a minimum, water systems must monitor flow rate, lamp status, and UV intensity plus any other parameters required by the State to show that a reactor is operating within validated conditions [40 CFR 141.720(d)(3)(i)].

discusses water quality characteristics affecting UV disinfection performance and the byproducts that may form during the UV disinfection process.

2.5.1 Effect of Water Quality on UV Reactor Performance

UVT, particle content, upstream water treatment processes, constituents that foul reactor components, and algae affect the performance of UV reactors. These effects can be adequately addressed through proper design of the UV disinfection equipment. The design guidelines are discussed in Section 3.4.

2.5.1.1 UVT

UVT has a strong effect on the dose delivery of a UV reactor. As UVT decreases, the intensity throughout the reactor decreases, which reduces the dose the reactor delivers. UV reactors are typically sized to deliver the required UV dose under specified UVT conditions for the application. Section 3.4.4.1 discusses approaches for selecting the UVT for UV facility design.

UV absorbers in typical source waters include soluble and particulate forms of humic and fulvic acids; other aromatic organics (e.g., phenols); metals (e.g., iron); and anions (e.g., nitrates and sulfites) (Yip and Konasewich 1972, DeMers and Renner 1992). UV absorbance will vary over time due to changing concentrations of these compounds and seasonal effects—rainfall, lake stratification and destratification (turnover), and changes in biological activity of microorganisms within the water source.

2.5.1.2 Particle Content

As described in Section 2.3.4, particle content can also affect UV disinfection performance. Particles in source waters are diverse in composition and size and include large molecules, microorganisms, clay particles, algae, and flocs. Sources of particles include wastewater discharges, erosion, runoff, microbial growth, and animal waste. The particle concentration will vary over time both seasonally and over the short term. Storm events, lake turnover, and spring runoff are some events that increase the concentration of particles.

2.5.1.3 Upstream Water Treatment Processes

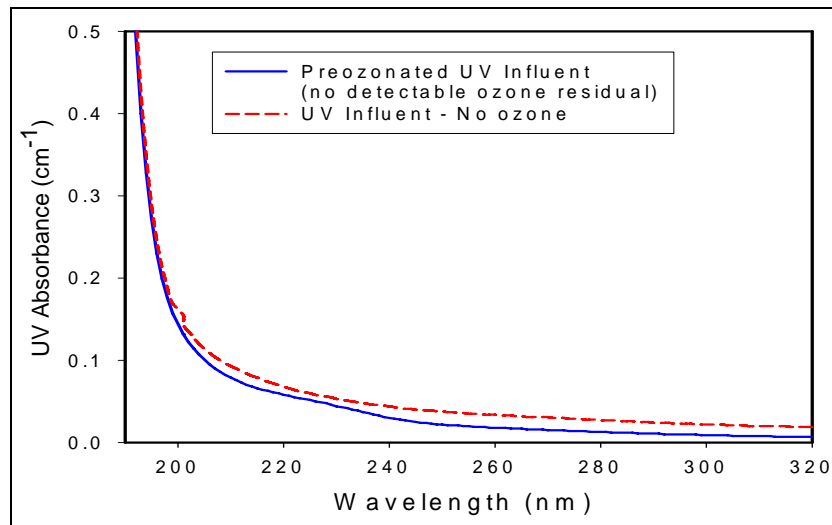
Unit processes and chemical addition upstream of UV reactors can significantly affect UV reactor performance because they can change the particle content and UVT of the water. Additionally, when UV disinfection is used in combination with another disinfectant, synergistic disinfection potentially may occur (i.e., the combination of disinfectants may be more effective than either disinfectant acting alone).

Water treatment processes upstream of the UV reactors can be operated to maximize UVT, thereby optimizing the design and costs of the UV reactor (Section 3.2.2). For example,

coagulation, flocculation, and sedimentation remove soluble and particulate material, and filtration removes particles. Activated carbon absorption also reduces soluble organics.

Adding oxidants (such as chlorine and ozone) can increase the UVT (APHA et al. 1998) by degrading natural organic matter, reducing soluble material, and precipitating metals. An example of the effect ozone has on decreasing UV absorbance is shown in Figure 2.22. Ozone is also a strong absorber of UV light, however, and will decrease the UVT if an ozone residual is present in significant concentrations in the water passing through a UV reactor. Quenching agents that do not absorb UV light (such as sodium bisulfite) can be used to destroy the ozone residual upstream of the UV reactors. Thiosulfate is not recommended as a quenching agent because it absorbs UV light and can decrease the UVT.

Figure 2.22. Example Effect of Ozonation on UV Absorbance if Ozone is Quenched Prior to UV Disinfection



Source: Malley (2002)

In addition to ozone, other chemicals used in water treatment such as ferric iron and permanganate also absorb UV light and can decrease UVT. Table 2.5 lists the UV absorption coefficients at 254 nm of several common water treatment chemicals along with their “impact threshold concentration,” which is the concentration that will decrease the UVT at 254 nm from 91 to 90 percent (Bolton et al. 2001). Note that these data are only for 254 nm, and the effect these chemicals have on UVT may be significantly different at other wavelengths generated by MP or other polychromatic lamps. The following chemicals were also evaluated in the same study (Bolton et al. 2001) and were found to have no significant absorbance: ammonia (NH₃), ammonium ion (NH₄⁺), calcium ion (Ca²⁺), hydroxide ion (OH⁻), magnesium ion (Mg²⁺), manganese ion (Mn²⁺), phosphate species, and sulfate ion (SO₄²⁻).

UV disinfection is often used in combination with other disinfectants, and the interaction of the disinfectants can affect the overall inactivation achieved. Research shows that applying ozone prior to UV disinfection is beneficial: the ozone increases the UVT, while the UV disinfection provides *Cryptosporidium* inactivation (Malley et al. 2003, Crozes et al. 2003).

Whether the effects of multiple disinfectants are synergistic (i.e., more inactivation observed when processes are used in combination than is expected from the sum of

Table 2.5. UV Absorbance Characteristics of Common Water Treatment Chemicals

Compound ¹	Molar Absorption Coefficient (M ⁻¹ cm ⁻¹)	Impact Threshold Concentration ² (mg/L)
Ozone (O ₃) (aqueous)	3,250	0.071
Ferric iron (Fe ³⁺)	4,716	0.057
Permanganate (MnO ₄ ⁻)	657	0.91
Thiosulfate (S ₂ O ₃ ²⁻)	201	2.7
Hypochlorite (ClO ⁻)	29.5	8.4
Hydrogen peroxide (H ₂ O ₂)	18.7	8.7
Ferrous iron (Fe ²⁺)	28	9.6
Sulfite (SO ₃ ²⁻)	16.5	23
Zinc (Zn ²⁺)	1.7	187

¹ The following chemicals were also evaluated in the same study (Bolton et al. 2001) and were found to have no significant absorbance: ammonia (NH₃), ammonium ion (NH₄⁺), calcium ion (Ca²⁺), hydroxide ion (OH⁻), magnesium ion (Mg²⁺), manganese ion (Mn²⁺), phosphate species, and sulfate ion (SO₄²⁻)

² Concentration in mg/L resulting in UVT decrease from 91 % to 90 % (A₂₅₄ increase from 0.041 cm⁻¹ to 0.046 cm⁻¹)

Source: Adapted from Bolton et al. (2001)

the disinfectants acting alone) is currently under debate. Two studies reported synergistic effects when using UV disinfection and free chlorine, monochloramine, or chlorine dioxide (Ballester et al. 2003, Lotierzo et al. 2003), while others did not observe synergism (Coronell et al. 2003, Oppenheimer et al. 2003). The importance of the sequence of the disinfectants is also a subject of debate. Ballester et al. (2003) obtained improved disinfection with UV disinfection followed by monochloramine addition than with chloramination followed by UV disinfection, while the sequence of disinfectants did not affect the disinfection effectiveness in the study by Lotierzo et al. (2003).

2.5.1.4 Fouling Potential

Compounds in the water can foul the external surfaces of the lamp sleeves and other wetted components (e.g., monitoring windows of UV sensors) of UV reactors. Fouling on the lamp sleeves reduces the transmittance of UV light through the sleeve into the water, thereby reducing the output from the UV lamp into the water. Also, fouling on the monitoring windows affects measured UV intensity and dose monitoring. Sleeve fouling can be accounted for with the fouling/aging factor (described in Section 3.4.5) in the design of the UV facility.

Hardness (as CaCO₃), alkalinity, temperature, ion concentration, oxidation reduction potential (ORP), and pH all influence the rate of fouling and, subsequently, the necessary frequency of sleeve cleaning. Fouling can occur for the following reasons:

- Compounds for which the solubility decreases as temperature increases may precipitate [e.g., CaCO₃, CaSO₄, MgCO₃, MgSO₄, FePO₄, FeCO₃, Al₂(SO₄)₃]. These compounds will foul MP lamps faster than LP or LPHO lamps because MP lamps operate at higher temperatures.
- Photochemical reactions that are independent of sleeve temperature may cause sleeve fouling (Derrick 2005).
- Compounds with low solubility may precipitate [e.g., Fe(OH)₃, Al(OH)₃].
- Particles may deposit on the lamp sleeve surface due to gravity settling and turbulence-induced collisions (Lin et al. 1999a).
- Organic fouling can occur when a reactor is left off and full of water for an extended period of time (Toivanen 2000).
- Inorganic constituents can oxidize and precipitate (Wait et al. 2005).

Fouling rate kinetics has been reported as independent of time following a short induction period (Lin et al. 1999b). Depending on the water quality and UV lamp type, significant fouling may occur in hours or take up to several months.

Pilot studies lasting 5 – 12 months using UV reactors with LP, LPHO and MP lamps found that standard cleaning protocols and wiper frequencies (1 – 12 cleaning cycles per hour) were sufficient to overcome the effect of sleeve fouling with water that had total and calcium hardness levels less than 140 milligrams per liter (mg/L) and iron less than 0.1 mg/L (Mackey et al. 2001, Mackey et al. 2004).

Inorganic fouling is a complex process, however, and is not related only to hardness and iron concentrations. The solubility of inorganic constituents depends on whether they are in an oxidized or reduced state, which can be affected by both the ORP and pH of the water (Wait et al. 2005). ORP is a measurement of the water's ability to oxidize or reduce constituents in the water. Both pH and ORP are needed to predict the oxidation state of an inorganic constituent. Studies have found that fouling rates increase as ORP increases (Collins and Malley 2005, Wait et al. 2005, Derrick 2005). In some waters with high ORP, however, fouling rates can be minimized if the iron and manganese are removed through oxidation, precipitation, and filtration (Wait et al. 2005, Derrick 2005, Jeffcoat 2005). Although ORP can provide valuable information, measuring it can be challenging and may not be possible in all instances.

Ultimately, the fouling potential is difficult to predict, but standard cleaning equipment can remove fouling and may need to be included. Also, pilot-scale or demonstration-scale testing can determine the fouling tendencies and cleaning regime if the PWS is concerned about fouling.

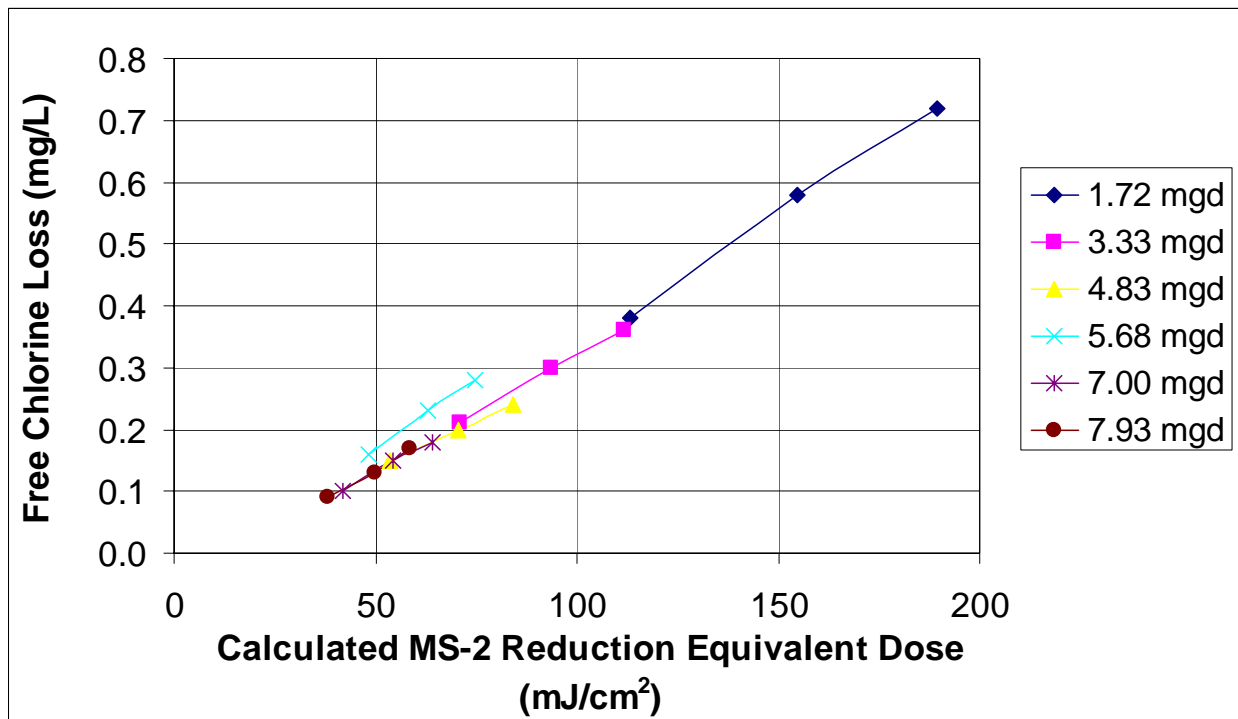
2.5.1.5 Algal Occurrence and Growth

The presence of algae in the water being treated may reduce UVT and interfere with the UV disinfection process. Algae also may grow upstream or downstream of UV reactors, which has been observed in MP pilot studies (Mackey et al. 2004). Visible light emitted from the lamps is transmitted through water farther than germicidal wavelengths. Algal growth depends on the concentration of nutrients in the water, hydraulics (i.e., dead spaces), and the amount of visible light transmitted beyond the reactor.

2.5.2 Chlorine Reduction through UV Reactors

When UV disinfection is applied to water with a free or total chlorine residual, some reduction of the residual may occur. The reduction in free chlorine residual is proportional to the delivered dose and independent of flow rate (Brodkorb and Richards 2004). The reduction in total chlorine residual is also proportional to the delivered dose (Wilczak and Lai, 2006). The reduction in chlorine residual further depends on the chlorine species, UV light source, and water quality characteristics (Örmeci et al. 2005, Venkatesan et al. 2003). An example of the effect of UV light on the free chlorine residual is shown in Figure 2.23. In other evaluations, a loss of about 0.3 mg/L of the free chlorine residual was observed in a WTP at a dose between 80 and 120 mJ/cm² (Kubik 2005), and a loss of 0.2 mg/L of the total chlorine residual was observed in bench-scale testing at doses up to 40 mJ/cm² (Wilczak and Lai 2006).

Figure 2.23. Example Effect of UV Disinfection on Free Chlorine Residual Loss



Source: Brodkorb and Richards (2004)

2.5.3 Byproducts from UV Disinfection

Studies indicate that UV disinfection at UV doses up to 200 mJ/cm² do not change the pH, turbidity, dissolved organic carbon level, UVT, color, nitrate, nitrite, bromide, iron, or manganese of the water being treated (Malley et al. 1996). Byproducts from UV disinfection, however, can arise either directly through photochemical reactions or indirectly through reactions with products of photochemical reactions. Photochemical reactions occur only when a chemical species absorbs UV light and the resulting excited state reacts to form a new species. The resulting concentration of new species depends on the concentration of the reactants and the UV dose. In drinking water, research on potential byproducts of UV disinfection has focused on the effect of UV light on the formation of halogenated DBPs after subsequent chlorination, the transformation of organic material to more degradable components, and on the potential formation of other DBPs (e.g., biodegradable compounds, nitrite, mutagenicity, and other byproducts).

2.5.3.1 Trihalomethanes, Haloacetic Acids, and Total Organic Halides

Trihalomethanes (THMs) and haloacetic acids (HAAs) are two categories of halogenated DBPs that EPA currently regulates. UV light at doses less than 400 mJ/cm² has not been found to significantly affect the formation of THMs or HAAs upon subsequent chlorination (Malley et al. 1996, Kashinkunti et al. 2003, Zheng et al. 1999, Liu et al. 2002, Venkatesan et al. 2003).

2.5.3.2 Biodegradable Compounds

Several studies have shown low-level formation of non-regulated DBPs (e.g., aldehydes) as a result of applying UV light at doses greater than 400 mJ/cm² to wastewater and raw drinking water sources (Liu et al. 2002, Venkatesan et al. 2003). At the doses typical for UV disinfection in drinking water (< 140 mJ/cm²), however, no significant change was observed (Kashinkunti et al. 2003). UV disinfection has not been found to significantly increase the assimilable organic carbon (AOC) of drinking water at UV doses ranging from 18 – 250 mJ/cm² (Kruithof and van der Leer 1990, Akhlaq et al. 1990, Malley et al. 1996).

2.5.3.3 Nitrite

The conversion of nitrate to nitrite is possible with MP lamps that emit at wavelengths below 225 nm [von Sonntag and Schuchmann (1992), Mack and Bolton (1999), IJpelaar et al. (2003), Peldszus et al. (2004)]. Sharpless and Linden (2001) reported a conversion rate from nitrate to nitrite of approximately 1 percent. Therefore, the nitrate-to-nitrite conversion is unlikely to be a significant issue for PWSs under current regulations. The nitrate levels would have to be higher than the nitrate MCL of 10 mg/L for the nitrite MCL of 1 mg/L to be exceeded.