
Introduction

WHAT IS ULTRAVIOLET DISINFECTION?

Ultraviolet (UV) lamps emit light in the 200–400 nm wavelength range (see Chapter 2 for more details on the nature of UV light). The 200–300 nm range is often called *germicidal* because this UV light is absorbed by the DNA and RNA of microorganisms. The absorption of UV photons causes changes in the structure of the DNA and RNA, rendering the microorganisms incapable of replicating. Because they cannot multiply, they cannot cause disease, even though technically they are still metabolically *alive*.¹ The degree of microorganism inactivation is determined by the UV dose (or fluence)² applied. More details on the mechanism of UV disinfection are given in Chapter 3.

UV light is usually delivered to drinking water as it flows through a UV reactor (Chapter 5 gives more description of the design of UV reactors). The UV equipment (including one or more UV reactors) is typically applied to filtered water and is often installed after the filter effluent piping recombining before the clearwell. It is very important that the operators are able to control the UV output in the reactor so that at least a minimum UV dose is applied at all times.

UV disinfection is a physical disinfection process. No chemicals are added and there is no residual effect once the water leaves the UV reactor.

HOW DOES UV DISINFECTION COMPARE TO CHEMICAL DISINFECTION?

Chemical disinfection is achieved by adding chemicals, such as chlorine, chloramines, chlorine dioxide, or ozone to the water and maintaining a chemical dose level for a sufficiently long period of time to achieve adequate disinfection. These chemical disinfection processes work quite well with bacteria and viruses, but most have limited efficacy with protozoa, such as *Cryptosporidium* and *Giardia*. Also, most of these chemical disinfectants produce disinfection by-products, which have regulatory limits.

1 It is for this reason that the word *kill* should not be used in regard to UV disinfection.

2 The correct term is *fluence*; however, the term *UV dose* is widely used, particularly in North America. Thus, in this handbook, the term *UV dose* is used in most places in this book. Nevertheless, see the discussion in Chapter 2.

UV disinfection does not significantly change the water quality and thus does not produce significant levels of regulated disinfection by-products (DBPs). Also, recent research (see following section) has demonstrated that UV light is effective for almost all bacteria, viruses, and protozoa. In contrast to chlorine-based chemical disinfectants, there is no residual disinfection capacity with UV disinfection. Thus, chlorine or chloramines are often used following UV disinfection to provide a disinfectant residual in the distribution system.

HISTORY OF ULTRAVIOLET DISINFECTION³

UV light has had a long and fascinating history in connection with its effects on microorganisms. The following is a brief chronology:

- 1801: Johann Ritter, a pharmacist in Silesia (now in Poland) discovered UV light by demonstrating that silver chloride is decomposed most efficiently by the invisible rays beyond the violet.
- 1842: Becquerel and Draper showed independently that a gelatin solution containing silver iodide darkened when exposed to sunlight (Hockberger 2002). This was the first indication of the spectral extent of UV light.
- 1877: Downes and Blunt (1877) observed that test tubes filled with a broth containing bacteria, when exposed to sunlight, eventually became sterile.
- 1878: Downes and Blunt (1878) further observed that, by using color filters, it is the blue and violet end of the spectrum that is responsible for the inactivation of bacteria.
- ~1900: The Danish physician Niels Finsen, considered the founder of modern phototherapy, discovered a UV treatment for *lupus vulgaris*, a form of skin tuberculosis. For this discovery, he received the Nobel Prize in Physiology or Medicine in 1904.
- 1903: Bernard and Morgan found that the most sensitive wavelengths for the inactivation of bacteria are around 250 nm (see Lorch 1987).
- 1904–1905: Hertel showed that UV light from arc lamps was far more powerful than sunlight in its effect on microorganisms. He showed that the order of efficacy was UVC > UVB > UVA light (see Chapter 2 for a definition of these UV ranges).
- 1904: The glassblower Richard Küch at Heraeus in Germany successfully learned how to blow quartz and was able to fabricate the first quartz enclosed mercury lamp.

³ Hockberger (2002) published a review of the history of UV light and UV disinfection prior to 1920. Sommer et al. (2002) provided a history of UV disinfection in Europe. Whitby and Scheible (2004) published a review of the history of UV in wastewater disinfection.

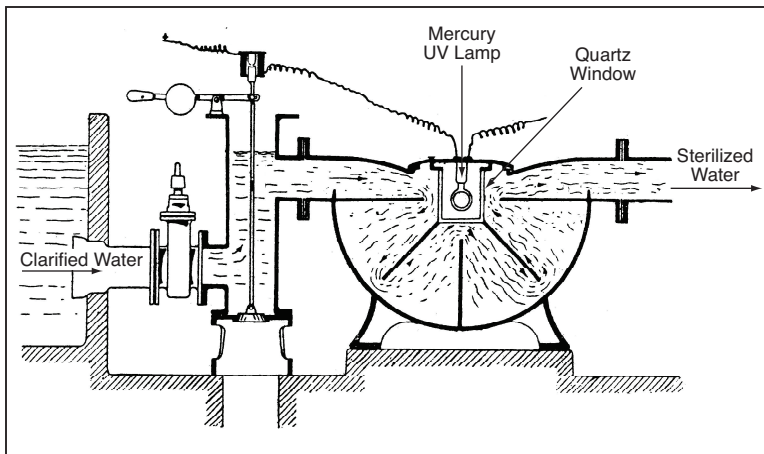


Figure 1-1 UV disinfection plant installed in 1910 in Marseilles, France (Henri et al. 1910a)

- Henri et al. (1910a,b) described the first commercial UV facility that used UV light to disinfect water in Marseilles, France. A diagram of this plant is shown in Figure 1-1. However, because of problems with technical failures, unreliable UV lamps, and instability of the electrical power supply, the system was shut down a short time after it was started.
- 1914: Henri and Moycho (1914) found that 280 nm is the most lethal of the wavelengths emitted from mercury arc lamps. (It is now known that the 254 nm emission is more effective.)
- 1920s: Chlorine disinfection was introduced. This technology was much cheaper than UV disinfection, so the latter went out of favor until the 1950s.
- 1938: Westinghouse introduced the first fluorescent gas discharge lamp.
- 1929, 1930: Gates (1929, 1930) was the first to carry out detailed investigations of the action spectrum of *E. coli*; he showed that the optimal wavelength for inactivation was about 260 nm.
- 1949: Kelner (1949a,b) was the first to discover *photoreactivation*. He found that bacteria stored for some time after UV exposure were able to recover; however, the effect was quite variable. On further investigation, he found that exposure of bacteria, previously inactivated by UV light, to visible or near UV light greatly enhanced the ability of the bacteria to recover.
- 1955: The first modern installations of UV disinfection systems using low-pressure UV lamps in water treatment plants occurred in Switzerland and Austria.

- 1960: Beukers and Berends (1960) irradiated frozen thymine solutions with UV light and were able to isolate thymine dimers. This was the basis of the currently accepted concept that UV inactivation is initiated by the formation of thymine dimers from adjacent thymines on a DNA strand.
- 1975: UV disinfection was introduced in Norway as a result of concern with the disinfection by-products from the use of chlorine disinfection.
- 1978: A full-scale UV system was successfully demonstrated at the N.W. Bergen wastewater treatment plant, Walfwick, N.J. (Scheible and Bassell 1981).
- By 1985: There were over 1,500 UV installations in Europe. Most were for the treatment of groundwater and bank-filtered water.
- Malley et al. (1996) found that regulated DBP formation was not affected by UV disinfection at UV doses lower than 400 mJ cm⁻².
- Prior to 1998: In North America, until the late 1990s, there was little drinking water application of UV disinfection except in small groundwater systems. This was the result of a perception that UV disinfection was not effective for the treatment of protozoa, such as *Cryptosporidium* or *Giardia*.
- 1998: Bolton et al. (1998) found that UV was very effective against *Cryptosporidium* (and later *Giardia*), contrary to the perception at that time that UV disinfection was not effective. Their paper, presented at the Annual Conference of the American Water Works Association (AWWA), changed this perception.⁴ They showed that earlier research on these protozoa was flawed and that if one used an assay that focused on the ability of these protozoa to infect hosts (i.e., neonatal mice), UV was found to be extremely effective in inactivating these organisms. This indicated that UV disinfection could be used as a broad spectrum disinfectant capable of inactivating almost all viruses, bacteria, and protozoa. Therefore, since 1999 there has been a remarkable increase in interest in UV disinfection for treating drinking water.
- 2001: Sommer et al. (2002) reported that the number of UV installations in Europe had risen to over 6,000, with most treating groundwater.
- 2003: USEPA issued the first draft Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), which included UV disinfection as a treatment technique. The USEPA also issued a draft *Ultraviolet Disinfection Guidance Manual* (UVDGM). This stimulated the installation of large UV disinfection systems throughout North America.
- 2006: USEPA issued the final versions of the LT2ESWTR (USEPA 2006a) and the UVDGM (USEPA 2006b).

⁴ This paper was subsequently published (largely unchanged) in the *Jour. AWWA* (Bukhari et al. 1999).

GOVERNMENT REGULATIONS

Several countries have now established regulations for UV disinfection.⁵ In 1996, Austria was the first country to introduce UV regulations [initially as guidelines but later enacted as binding regulations (ÖNORM 2001)] by requiring that UV reactors be certified, using biodosimetry testing (involving challenging a UV reactor with a nonpathogenic microorganism) to deliver a UV dose (fluence) of at least 40 mJ cm^{-2} (400 J m^{-2}) using a specific challenge microorganism. The first Austrian UV regulations were restricted to UV reactors containing LP UV lamps but were later extended to UV reactors containing medium-pressure (MP) UV lamps (ÖNORM 2003).

Germany followed a year later with the Deutsche Vereinigung des Gas- und Wasserfaches (DVGW) Standard (DVGW 1997). This standard is similar to that in Austria, in that it also requires a minimum UV dose of at least 40 mJ cm^{-2} (400 J m^{-2}) using a specific challenge microorganism. This standard was later revised (DVGW 2006) so that the German and Austrian standards are now almost equivalent.

The US Environmental Protection Agency (USEPA) has established several rules to address various issues of water treatment. The impacts on UV disinfection are as follows:

- Surface Water Treatment Rule (SWTR) (USEPA 1989).

These rules were based on the perception that UV disinfection is not effective in the treatment of *Giardia* but that it is effective for virus inactivation. These rules included UV dose tables for virus inactivation.

- A group of regulations collectively called the “Stage 1 Disinfectants and Disinfection Byproduct Rule” (USEPA 1998).

These rules did not consider UV light as a disinfectant technology largely because of the perception that UV disinfection was not effective in the treatment of protozoa (e.g., *Cryptosporidium* or *Giardia*), and UV disinfection does not leave a disinfectant residual.

- LT2ESWTR (USEPA 2006a). This rule lays out specific UV dose tables for *Cryptosporidium*, *Giardia*, and viruses. For UV disinfection applications, the companion *Ultraviolet Disinfection Guidance Manual* (USEPA 2006b) is a valuable source of UV information. This rule reversed the previous perception that UV disinfection was not highly effective for protozoa. In addition, this rule reversed the previous perception that it was highly effective for virus inactivation and requires a UV dose of 186 mJ cm^{-2} for 4-log virus inactivation.
- Stage 2 Disinfectant and Disinfection Byproduct Rule (Stage 2 DBPR) (USEPA 2006c).

5 Sommer et al. (2002) review the history of UV regulations, particularly those in Europe.

- Ground Water Rule (GWR) (USEPA 2006d).

This rule identifies UV disinfection as a promising technology for virus inactivation, although the UV dose levels for 4-log virus inactivation are much higher than what can currently be validated. Until validation procedures are available to validate the higher UV doses required for virus inactivation, UV disinfection can be used in series or in combination with other treatment techniques to meet the virus inactivation requirements. However, recent research studies show that validation of UV reactors for virus inactivation will be possible on a wide-scale in the next few years (See Chapter 4 for details).

In the LT2ESWTR and Stage 2 DBPR, UV disinfection is classified as one of the microbial options and is a *best available technology* because of the focus on *Cryptosporidium*. Thus, the USEPA has come full circle from rejecting UV disinfection as a viable treatment technology for protozoa to currently highlighting that it is a *best available* disinfection treatment technology. An important innovation in these rules is the classification of water utilities into *bins* according to the level of *Cryptosporidium* oocysts found in their source waters (Table 1-1). Water utilities in Bin 1, with source waters with relatively low levels are considered *safe* and do not require additional treatment, whereas water utilities in higher bins and *Cryptosporidium* levels have to introduce additional treatment. The various treatment technologies are gathered together into a *toolbox*, and each is assigned a log reduction credit. Therefore, utilities can combine treatment technologies to achieve the level of treatment required for their bin. UV disinfection becomes an attractive treatment option for water utilities with a high level of *Cryptosporidium* in their water, and accordingly these utilities are in bins 3 or 4.

The UV regulations are discussed in more detail in Chapter 4.

ADVANTAGES AND DISADVANTAGES OF UV DISINFECTION

There are many advantages and disadvantages for UV disinfection, as described in the following section.

Advantages

1. It is a very effective disinfection technology for *Cryptosporidium* and *Giardia*.
2. It does not significantly alter the water quality; that is, no change in total organic carbon (TOC), pH, corrosivity, DBP formation potential, or turbidity.
3. The technology is relatively inexpensive with low capital and operating costs, compared to other disinfection options for protozoa.
4. It is relatively easy to operate (i.e., turn up or turn down) the UV equipment based on changes in water flow, water quality, etc.
5. The UV equipment has a relatively small *footprint* and is usually amenable to retrofit into existing water treatment plants.

Table 1-1 LT2ESWTR bin classification for filtered public water systems (PWSs) (USEPA 2006a)

<i>Cryptosporidium</i> Concentration (oocysts/L)	Bin Classification	Additional Treatment Required			
		Conventional Filtration Treat- ment (includes softening)	Direct Filtration	Slow Sand or Diatomaceous Earth Filtration	Alternative Filtration Technologies
< 0.075	Bin 1	No additional treatment	No additional treatment	No additional treatment	No additional treatment
≥ 0.075 and < 1.0	Bin 2	1-log treatment*	1.5-log treatment*	1-log treatment*	As determined by the state* [‡]
≥ 1.0 and < 3.0	Bin 3	2-log treatment [†]	2.5-log treatment [†]	2-log treatment [†]	As determined by the state [‡] [§]
≥ 3.0	Bin 4	2.5-log treatment [†]	3-log treatment [†]	2.5-log treatment [†]	As determined by the state [‡] ^{**}

* PWSs may use any technology or combination of technologies from the microbial toolbox.

† PWSs must achieve at least 1 log of the required treatment using ozone, chlorine dioxide, UV light, membranes, bag/cartridge filters, or bank filtration.

‡ Total *Cryptosporidium* treatment must be at least 4.0 log.

§ Total *Cryptosporidium* treatment must be at least 5.0 log.

** Total *Cryptosporidium* treatment must be at least 5.5 log.

6. No chemicals are needed for UV disinfection.

7. Disinfection is very fast. Contact times are in the range of a few seconds.

Disadvantages

1. There is no residual disinfection capacity. Therefore, some level of chlorine or chloramines is usually added to maintain a disinfection residual in the distribution system.
2. At present, it is not possible to continuously monitor the UV dose, so operators have to rely on secondary measurements (sensor readings, UV transmittance, water flow rates, etc.).
3. Most UV reactors contain mercury lamps, so breakage of UV lamps represents a possible mercury hazard. However, calculations (USEPA 2006b) appear to show that even if the mercury in a lamp were to enter the water completely, the mercury level in the distributed water would still be well below maximum contaminant levels. More research is required to address this issue.
4. The electric power supply to the utility could be subject to interruptions, which could cause UV lamps to extinguish for time periods of 1–5 min. This could result in some water not being treated unless the water is diverted to waste.

5. There are times when water could be underdisinfected because of power interruptions or lamp warm-up. These situations are considered by the USEPA as *off-specification events* because the UV system would be operating outside of the verified limits of performance.

REFERENCES

- Beukers, R., and W. Berends. 1960. Isolation and Identification of the Irradiation Product of Thymine. *Biochim. Biophys. Acta*, 41: 550–551.
- Bolton, J.R., B. Dussert, Z. Bukhari, T.M. Hargy, and J.L. Clancy. 1998. Inactivation of *Cryptosporidium parvum* by Medium-Pressure Ultraviolet Light in Finished Drinking Water. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
- Bukhari, Z., T.M. Hargy, J.R. Bolton, B. Dussert, and J.L. Clancy. 1999. Medium-Pressure UV Light for Oocyst Inactivation. *Jour. AWWA*, 91(3):86–94.
- Downes, A., and T.P. Blunt. 1877. Researches on the Effect of Light Upon Bacteria and Other Organisms. *Proc. Res. Soc. London*, 26: 488–500.
- . 1878. On the Influence of Light Upon Protoplasm. *Proc. Res. Soc. London*, 28: 199–213.
- DVGW (Deutsche Vereinigung Gas- und Wasserfaches). 1997. UV-Desinfektionsanlagen für die Trinkwasserversorgung—Anforderungen und Prüfung (UV Systems for Disinfection in Drinking Water Supplies—Requirements and Testing). Technical Standard W294, October, 1997. Bonn, Germany: DVGW (German Association on Gas and Water).
- . 2006. *UV Devices for Disinfection in Drinking Water Supply: Part I: Requirements on Properties, Function and Operation; Part 2: Testing of Properties, Function and Disinfection Effectiveness; Part 3: Ports and Sensors for the Radiometric Monitoring of UV Disinfection Devices—Requirements, Testing and Calibration*. Deutsche Vereinigung des Gas- und Wasserfaches (German Association for Gas and Water), Bonn, Germany. [Online] Available only in German: http://www.wvgw.de/index.php?id=451&submit_gesamtsuche=&tx_indexedsearch%5Bsword%5D=W+294.
- Gates, F.L. 1929. A Study of the Bactericidal Action of Ultraviolet Light II: The Effect of Various Environmental Factors and Conditions. *Jour. Gen. Physiol.*, 13: 249–260.
- . 1930. A Study of the Bactericidal Action of Ultraviolet Light III: The Absorption of Ultraviolet Light by Bacteria. *Jour. Gen. Physiol.*, 14: 31–42.
- Henri, V., and V. Moycho. 1914. Actions des Rayons Ultraviolets Monochromatique dur les Tissus. Mesure de L'Énergie de Rayonnement Correspondant au Coup de Soleil. *Compt. rend. Hebd. Seances Acad. Sci.*, 158: 1509–1511.
- Henri, V., A. Helbronner, and M. de Recklinghausen. 1910a. Nouvelles Recherches sur la Sterilization de Grandes Quantités d'Eau par les Rayons Ultraviolets. *Compt. rend. Acad. Sci.*, 151: 677–683.
- . 1910b. Stérilization de Grandes Quantités d'Eau par les Rayons Ultraviolets. *Compt. Rend. Acad. Sci.*, 150: 932–934.
- Hockberger, P.E. 2002. A History of Ultraviolet Photobiology for Humans, Animals and Microorganisms. *Photochem. Photobiol.*, 76(6):561–579.
- Kelner, A. 1949a. Effect of Visible Light on the Recovery of *Streptomyces griseus conidia* From Ultraviolet Irradiation Injury. *Proc. Natl. Acad. Sci. US*, 35(2):73–79.

-
- . 1949b. Photoreactivation of Ultraviolet-Irradiated *Escherichia coli*, With Special Reference to the Dose–Reduction Principle and to Ultraviolet-Induced Mutation. *Jour. Bacteriol.*, 58: 511–522.
- Lorch, W. 1987. *Handbook of Water Purification*. 2nd ed. Chichester, UK: Ellis Horwood.
- Malley, J.P., J.P. Shaw, and J.R. Ropp. 1996. *Evaluation of By-products Produced by Treatment of Groundwaters With Ultraviolet Irradiation*. Denver, Colo.: Awwa Research Foundation.
- ÖNORM (Österreichisches Normungsinstitut). 2001. Austrian National Standard: ÖNORM M 5873-1 E. 2001. Plants for Disinfection of Water Using Ultraviolet Radiation: Requirements and Testing, Part 1: Low Pressure Mercury Lamp Plants. Vienna, Austria: ÖNORM (Austrian Standards Institute); www.on-norm.at.
- . 2003. Austrian National Standard: ÖNORM M 5873-2 E. 2003. Plants for Disinfection of Water Using Ultraviolet Radiation: Requirements and Testing, Part 2: Medium Pressure Mercury Lamp Plants. Vienna, Austria: ÖNORM; www.on-norm.at.
- Scheible, O.K., and C.D. Bassell. 1981. Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent. *EPA Report No. EPA-600/S2-B1-152*, Cincinnati, Ohio: US Environmental Protection Agency.
- Sommer, R., A. Cabaj, G. Hirschmann, W. Pribil, and T. Haidler. 2002. UV Disinfection of Drinking Water in Europe: Application and Regulation. In *Proc. of the First Asia Regional Conference on Ultraviolet Technology for Water, Wastewater, and Environmental Applications*. Scottsdale, Ariz.: International Ultraviolet Association. CDROM.
- USEPA (US Environmental Protection Agency). 1989. Surface Water Treatment Rule [Online]. Available: <http://www.epa.gov/ogwdw/therule.html#Surface>.
- . 1998. Stage 1 Disinfectants and Disinfection Byproduct Rule [Online]. Available: <http://www.epa.gov/ogwdw/mbp/dbp1.html>.
- . 2006a. Long Term 2 Enhanced Surface Water Treatment Rule (LT2) [Online]. Available: <http://www.epa.gov/safewater/disinfection/lt2/index.html>.
- . 2006b. *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule* [Online]. Available: http://www.epa.gov/safewater/disinfection/lt2/pdfs/guide_lt2_uvguidance.pdf.
- . 2006c. Stage 2 Disinfectants and Disinfection Byproducts Rule (Stage 2 DBP Rule) [Online]. Available: <http://www.epa.gov/safewater/disinfection/stage2/index.html>.
- . 2006d. Ground Water Rule (GWR) [Online]. Available: <http://www.epa.gov/safewater/disinfection/gwr/index.html>.
- Whitby, G.E., and O.K. Scheible. 2004. The History of UV and Wastewater. *IUVA News*, 6(3):15–26.