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# UV disinfection of small groundwater supplies

*Ultraviolet light treatment is safe, effective, and cost-competitive for small systems that do not require residual disinfection.*

**Marc J. Parrotta and Faysal Bekdash**

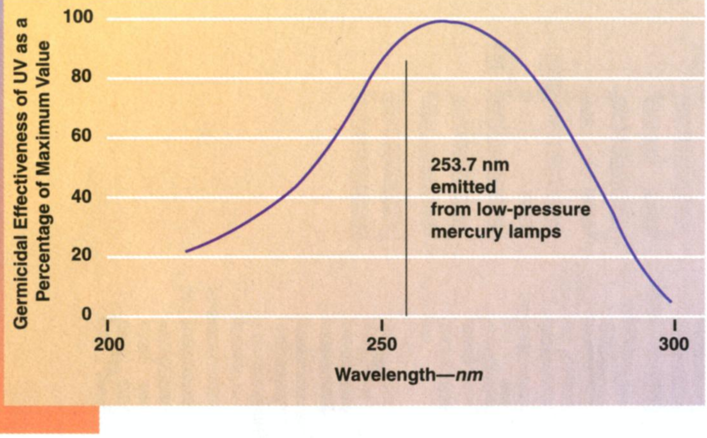
**The US Environmental Protection Agency has critically analyzed disinfection technologies available to small public water systems. Future groundwater disinfection requirements are expected to affect many public groundwater supplies, including a large number of very small noncommunity systems. Because small water systems generally have fewer technical and financial resources to cope with new requirements, they will need the simplest and lowest-cost techniques that enable them to comply with new drinking water standards. To address this issue, the agency studied ultraviolet light technology. This article summarizes availability, efficacy, operability, and costs of this technology as an option for small systems.**

The US Environmental Protection Agency (USEPA) is developing regulations to protect the microbiological quality of public groundwater supplies.

Small water utilities are the most likely to violate microbiological standards. Among the small public water systems in the United States are more than 100,000 transient–noncommunity (TNC) and nontransient–noncommunity (NTNC) groundwater systems, each serving fewer than 3,000 people. The TNC and NTNC systems serve restaurants, highway rest areas, airports, schools, camps, factories, rest homes, and hospitals.

***For executive summary, see page 172.***

**FIGURE 1** Relative germicidal effectiveness as a function of wavelength



Many of these systems lack the technical and financial resources needed to operate complicated treatment systems. Therefore, these systems will require the simplest and lowest-cost techniques that enable them to comply with new drinking water standards.

In addition, some larger systems may need to consider simpler disinfection technologies or combinations that include nonchemical treatment. Those that rely on remote wells or wellfields and those that may require a mix of treatment types to reduce disinfection by-products are candidates for such technologies.

Experience and recent surveys indicate considerable risk of well contamination, even at sites thought to be free of contaminants.[1] Viruses and bacteria are the most likely microorganisms to contaminate wells and associated water systems. Contamination of systems may be intermittent or chronic, and it may result from groundwater contamination or water distribution faults. Contaminants may migrate through fractured rock; aquifers and wellfields may be unprotected; wells may be poorly designed or constructed or they may simply have aged; sewers may leak; or distribution pipelines may operate at low pressures.

USEPA may permit water systems to ensure microbiological water quality through use of best management practices, in effect allowing protective measures, or "barriers," in place of actual water treatment. Nevertheless, many systems may require treatment at the wellhead, treatment of stored or distributed water, or both. Thus many systems, particularly small ones, need to explore practical disinfection methods. Because small systems need a disinfection process that is simple to install, maintain, and monitor and that has a low operating cost, USEPA must adequately document the costs and practical operation of these processes.

One disinfection technique that meets these requirements is ultraviolet (UV) light. It is safe, easy to use, and free of chemicals. UV technology has been used for several years to treat domestic wastewater and household water in North America;[2–6] it has been used in Europe for several decades in the water, food, and industrial sectors. Although it does not supply residual disinfection to protect distribution systems (as does chlorination), many small noncommunity water systems that serve restaurants, rest areas, camps, and schools may have short distribution systems—a single well may serve only one building. These situations are nearly analogous to a residential water supply. For these suppliers, UV may be a promising treatment.

This article summarizes the results presented in USEPA's report "Ultraviolet Light Disinfection Technology in Drinking Water Application—An Overview,"[7] which was first published in September 1996. This report describes one disinfection technique that may be used to meet the proposed Ground Water Disinfection Rule (GWDR). The final GWDR is to be issued by November 2000, as required by the 1996 amendments to the Safe Drinking Water Act (SDWA). Availability, operational characteristics, and economic considerations have been central in the early phases of GWDR treatment evaluation at USEPA.

This article, which follows the format of the USEPA report,[7] provides background information

**FIGURE 2** UV disinfection unit

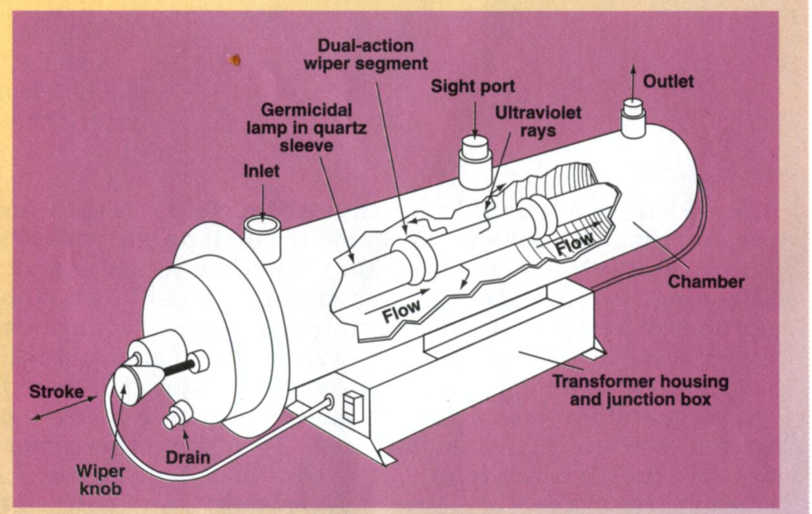
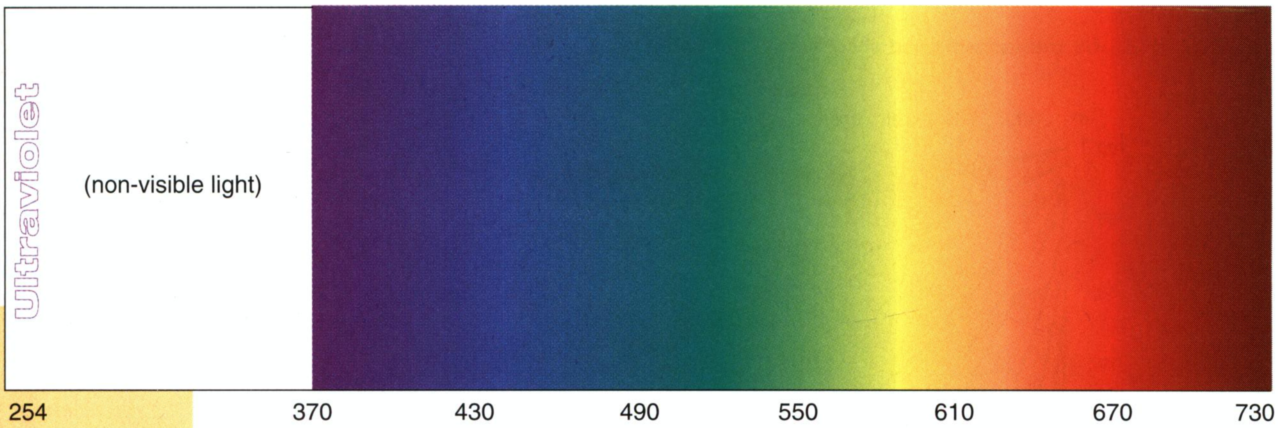


*Figure courtesy of Atlantic Ultraviolet Corp.*



***At 254 nm, the principal wavelength emitted by commercially available low-pressure mercury vapor lamps, UV light is strongly germicidal. The lamps generate UV light by striking an electrical arc through mercury vapor within the lamp.***

and assesses UV light efficacy, UV viability, and maintenance; describes case studies; and evaluates, in a preliminary fashion, the costs of UV treatment.

## UV mechanism of inactivation explained

Naturally occurring UV radiation in sunlight is situated beyond the visible spectrum. It has a wavelength shorter than that of visible light, 400–700 nm, and longer than that of X-rays, 0.1–100 nm. Some artificial UV radiation is emitted by regular incandescent light bulbs, halogen bulbs, high-efficiency light bulbs, and computer screens, among other sources. Special UV-emitting lamps are used to disinfect water. The wavelengths of interest for disinfection lie between 250 and 270 nm. At 254 nm, the principal wavelength emitted by commercially available low-pressure mercury vapor lamps, UV light is strongly germicidal (Figure 1).[7,8]

**Ultraviolet treatment typically employs a narrow band of electromagnetic radiation to penetrate and damage components of active microbial species.**

UV treatment typically employs a narrow band of electromagnetic radiation to penetrate and damage components of active microbial species. At a wavelength of approximately 254 nm, two components of genetic material—deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)—absorb ultraviolet light. UV alters the nitrogenous heterocyclic components within DNA and RNA, causing molecules to form new bonds; dimers such as thymine result. This effect can render microorganisms unable to replicate. The UV dosage, measured in milliwatt-seconds per square centimetre (mWs/cm$^2$), must either eliminate DNA replication or partially damage the genetic material. Partial damage may result in mutant progeny that are unable to replicate. Viruses living parasitically, such as bacteriophages, may be protected by the larger organism. Damage to the virus may range from total to insignificant. Also, under certain conditions, cells damaged by UV may repair and reactivate themselves through enzyme activity.

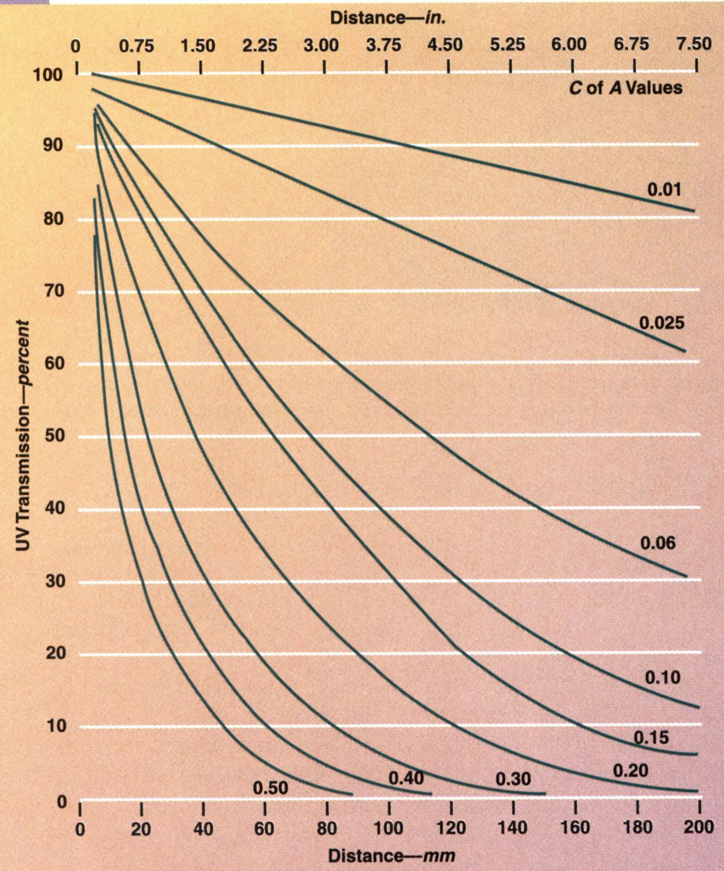
Such repair may also occur after chemical disinfection; this is commonly referred to as reactivation. Photoreactivation, the revival of organisms in visible light shortly after UV light exposure, may be a function of the intensity of visible light to which the organism is exposed as well as a function of pH and temperature.

Reactivation of microorganisms requires repair enzymes. Viruses do not have their own repair enzymes, but they can use repair enzymes in the host cell. Damaged viruses living outside bacteria or protozoa will not revive. Because they are exposed to UV briefly, possibly only for seconds, spores and slow-growing microorganisms are more likely to repair damage than fast-growing ones, whose DNA deteriorates rapidly on exposure to UV. Because undamaged DNA acts as a template in cell reconstruction, permanent inactivation requires damage to nucleic acids in many places.[5] The key is an appropriate UV dose. Under field conditions, reactivation of microorganisms through photoreactivation may not be significant in properly treated water.[9] However, additional tests, such as studies of increased UV intensity and attenuation time, will promote a better understanding of how to minimize photoreactivation.

## UV technology described

Commercially available UV lamps generate UV light by striking an electric arc through mercury vapor within the lamp, which is typically made of light-transmitting quartz, polymer, or silica. Mercury molecules excited by the electric current emit UV light

**FIGURE 3** UV transmission and absorbance coefficient



*High purity water—$\alpha = 0.01$, municipal drinking water—$\alpha = 0.06$, seawater—$\alpha = 0.15$; figure courtesy of Aquafine Corp.*

while much of the electricity is transformed into heat. Thus, when it is used to treat water, the hot lamp is separated from cool water by quartz sleeves.

The low-pressure 85-W mercury vapor lamps typically used to treat drinking water emit most of their UV light at 253.7 nm and a lesser amount at 184.9 nm. Medium-pressure mercury vapor lamps, which draw 7,500 W, emit light across a broad spectrum. They are more useful to treat water contaminated with a variety of organic compounds, and they may be more cost-effective if they replace several low-pressure lamps.

UV systems have been designed as closed- and open-channel systems. Closed systems, which can maintain pressure and are protected from recontamination, may be designed as a contact unit (UV lamps enclosed in a sleeve are in the water [Figure 2]) or as a noncontact unit (UV lamps transmit energy to PTFE pipes through which water flows). Open channel designs are more common at the 500 to 600 US wastewater plants that use UV treatment.[10]

UV has been used to treat water since the 1950s. In North America approximately 500 drinking water facilities employ this technology,[3] whereas in Europe there may be considerably more than 2,000 such facilities. In 1985, Switzerland, Norway, and Austria used UV in about 1,500 drinking water plants.[4]

In the beverage, food, pharmaceuticals, and electronics industries, and in centralized and household drinking water and Superfund cleanup applications, closed UV systems are clearly preferred. The rationale for this preference includes:

- more sanitary protection of water and minimal worker exposure to UV radiation;
- modular design and compact space requirements;
- minimal need to buy, handle, and store other post-treatment chemicals (only nonhazardous cleaning detergents); and
- cost containment because the pressurized system makes repumping of treated water unnecessary.

In the early years, both potable water and wastewater users found that UV lamps were difficult to keep clean and were easily broken. The quartz sleeves encasing lamps in contact systems tended to foul or become plated, which reduced the amount of UV transmitted and the effectiveness of disinfection. Calcium scale, silt, organic material, and iron have been reported to collect on sleeve surfaces. The frequency of manual inspection or cleaning will depend on the water source; it may range from monthly to annually.

UV systems have evolved in recent years. Some new units provide automatic mechanical wipers and other features that reduce maintenance. However, a responsible operator still needs a maintenance protocol that may entail periodic site inspections; changing of lamps approximately annually or when lamp transmission efficiency has decreased to 70 percent of its original level; inspection and cleaning of surfaces; and inspection and replacement of ballasts, O-rings, valves, and switches. A modern UV disinfection system supplied by a stable source of electricity may include the following:

- stainless-steel or some other type of chamber that will not corrode or otherwise be permeated by UV radiation;
- UV lamps secured within quartz sleeves but with easy access for maintenance;
- mechanical wipers, ultrasonic cleaners, or other self-cleaning mechanisms;
- sensors connected to alarm systems for monitoring UV intensity;

**TABLE 1** UV inactivation of microorganisms in water*

| Microorganism | Dose $\text{mWs/cm}^2$ | Log Inactivation | Reference | Comments |
|---|---|---|---|---|
| *E. coli* | 0.012–6.4 | 0.75 to 0.85 | Lea, 1947[18] | |
| *E. coli* | 6.5 | 3 | Chang et al, 1985* | Buffered distilled water |
| *Salmonella typhimurium* | 8 | 1 | Groocock, 1984[5] | |
| *Bacillus subtilis spores* | 12 | 1 | Groocock, 1984[5] | Test conditions uncertain |
| Bacteria | 2.1–12 | 1 | Meulemans, 1987[19] | Conditions uncertain |
| Total coliforms | 9.6–52 | 3.52 | Qualls et al, 1985* | Effluent water |
| Total coliforms | 5.7 | 2 | Qualls et al, 1985* | Filtered effluent |
| Fecal coliform | 33 | 4 | Whitby, 1989[20] | Conditions uncertain |
| Fecal coliform | about 275 | 3 | Zukovs et al, 1986* | Sewage |
| *Leg. pneumophila* | 30 | 3 | Muraca et al, 1987* | |
| Hepatitis A virus | 16 | 4 | Battigelli et al, 1993[21] | |
| Hepatitis A virus | 21 | 2 | USEPA, 1991[22] | Safety factor of 3 applied |
| Hepatitis A virus | 36 | 3 | USEPA, 1991[22] | Safety factor of 3 applied |
| Hepatitis A virus | 18.5 | 4 | Wiedenmann et al[23] | |
| Poliovirus | 21 | 3 | Chang et al, 1985* | Phosphate, buff, saline |
| Rota SA11 | 25 | 3 | Chang et al, 1985* | |
| Polio 1 | 29 | 3 | Harris et al, 1987* | Buffered distilled water |
| Reo 1 | 45 | 3 | Harris et al, 1987* | |
| MS-2 | 74 | 4 | Wiedenmann et al[23] | NaCl solution |
| MS-2 | 9 | 4 | Battigelli et al, 1993[21] | |
| *MS-2* | 64–93 | 4 | Snicer et al, 1996[24] | |
| *Giardia lamblia* | 63 | 0.52 | Rice and Hoff, 1981* | Buffered distilled water |
| *Giardia lamblia* | 180 | 2 | Karanis et al, 1992[25] | Distilled water, gerbil and human cysts |
| *Cryptosporidium* | >8,000 (maximum) | >3 | Safe Water Solutions, 1996[26] | Treated surface water; Safe Water Solutions' system exposes trapped oocysts |

*Referenced in Sobsey, 1989[17]

- safety shut-off in case of high or low flow rates, low lamp intensity, or elevated lamp or UV system component temperatures (ballasts and transformers may be more likely to overheat than the lamps, especially in warm climates or poorly ventilated buildings);
- lamp-out monitors; and
- electronic ballasts.

## Standards guide use of UV for disinfection

In order for designers of treatment systems to specify appropriate systems and for regulatory agencies to approve appropriate uses of UV disinfection, disinfection standards must be in place so that products can be tested and certified as meeting the standards. Several standards or guidelines already exist. In 1966 the Department of Health, Education, and Welfare set a minimum UV dose of 16 $\text{mWs/cm}^2$ at all points throughout the water disinfection chamber and a maximum distance of 3 in. (76 mm) between the lamp and the chamber wall.[11] The state of New Jersey issued a similar standard. The US Food and Drug Administration standard[12] relies on the Good Manufacturing Practice Code, which does not specify any minimum intensity or reduction of surrogate microorganism.

**Water quality determines how well UV is transmitted and how effective it is, but little controlled test data exist about this factor.**

American National Standards Institute/NSF Standard 55-1991,[13] which describes testing of point-of-use (POU) and point-of-entry (POE) UV light devices, specifies that systems using these devices should treat only water that is visually clear and does not have an obvious contamination source. Class A systems as defined in this standard may be used in POU or POE devices and must emit a minimum UV dose of 38 $\text{mWs/cm}^2$, which will inactivate *Bacillus subtilis* spores. Class A systems can be used on prefiltered surface water tested for cyst reduction in compliance with ANSI/NSF Standard 53. Class B systems are used in POU devices; they must emit a minimum UV dose of 16 $\text{mWs/cm}^2$, which will inactivate the yeast *Saccharomyces cerevisiae*. Class B systems are intended to supplement other bactericidal treatment and to reduce nuisance microorganisms.

States other than New Jersey also have criteria for water systems that want to use UV treatment. Wisconsin has published criteria for UV treatment at noncommunity and private water supplies[14] that apply specifically to microbiologically contaminated sources (positive total coliform or *Escherichia coli* bacteria test results more than once). Pretreatment is

**TABLE 2** **Characteristics of drinking water treatment plants studied that use UV light technology**

| System | Lebanon, N.J. | Washington, N.J. | Branchville, N.J. | Ringoes, N.J. | Phillipsburg, N.J. |
|---|---|---|---|---|---|
| Type | TNC* | TNC | TNC | TNC | CWS |
| Source of water | Groundwater | Groundwater | Groundwater | Groundwater | Groundwater |
| Population served | 50 | 5,000–10,000 | 40 | 312 | 30 |
| Type of installed unit | Closed | Closed | Closed | Closed | Closed |
| Year of installation | 1994 | 1988 | 1990-1991 | 1985 | 1995 |
| Minimum UV dose—*mWs/cm²* | 17 | Unknown | Unknown | Unknown | 30 |
| Type of alarm | Sound | None | Sound | None | Sound, light |
| Other treatment | | pH adjuster and hardness removal | | Paperlike filter | 5-µm filter |
| Design flow—*gpd (L/d)* | 21,600 (81,756) | Unknown | Unknown | Unknown | 29,000 (109,765) |
| Reported water use—*gpd (L/d)* | 200 (757) | Unknown | Unknown | Unknown | Unknown |
| Design flow per capita†—*gpd (L/d)* | 100 378.5) | Undetemined | Undetermined | Undetemined | 220 (833) |
| Coliform violations | None | None | None | One, 1992‡ | None |
| Frequency of service, time required | Annual, ½ h | 6 months, 2 h | Annual, 20 min | Annual | Weekly minor; annual, ½ h |
| Capital cost per unit—*$* | 2,500 | 4,500 | 1,500 | | 2,100 |
| Annual O&M cost per unit—*$* | 500§ | 150 | 135 | | 100 |

*TNC—transient–noncommunity, CWS—community water system

†Design per capita (gpd [L/d])—design flow/(population served)(4.3 peak design factor)

‡Ultraviolet light bulb was left in operation one half year beyond its service life.

§Includes costs of other treatments and water analyses for compliance purposes

required if any of several source water quality parameters exceeds a prescribed maximum level. The minimum dose is set at 38 mWs/cm²; automatic shutdown that triggers an alarm system is required below this level.

Some European countries have adopted minimum UV dosages for pretreated drinking water: Norway's minimum dose is 16 mWs/cm² and Austria's is 30 mWs/cm². The European Union (EU) uses drinking water directive 80/788/EEC, which does not specify treatments but sets maximum admissible concentrations (MAC) for microbes such as total coliforms (MAC <1/100 mL) and fecal coliforms (MAC <1/100 mL) using the multiple tube method.

Because coliforms and other vegetative bacteria (i.e., those that propagate by nonsexual means) are so susceptible to damage by UV radiation at a dose of 16 mWs/cm², other hardier organisms (such as *Bacillus subtilis* spores and *Saccaromyces cerevisiae*) must be used to quantify a UV unit's efficacy. The bacteriophage MS-2 has also been suggested as a possible surrogate test organism because it resists treatment and reacts to chemical and UV treatment similarly to enteroviruses such as Coxsackie, Norwalk, and polio viruses.[15]

USEPA must set specific microbial goals that assure safe drinking water before setting groundwater treatment requirements for community and noncommunity systems. USEPA will be able to use published data on viral or bacterial reductions to determine use and guidance for UV in a public water supply setting. As a benchmark at this time USEPA is considering a groundwater viral inactivation target of 4 logs, i.e., a 99.99 percent rate of reduction or inactivation of more-resistant organisms such as rotavirus. This inactivation target matches the current federal surface water treatment inactivation requirement for viruses. Furthermore, USEPA recently published a compliance technology list for the Surface Water Treatment Rule that includes detailed guidance for surface water UV applications.[16]

## Three factors determine the effectiveness of UV disinfection

Three principal factors determine the effectiveness of UV light inactivation of microorganisms: wavelength, intensity of radiation, and exposure time (or residence time distribution), in addition to the resistivity of target microoganisms and the water quality matrix. The wavelength is measured in nanometres. Intensity of UV light is measured in mW/cm², and exposure time in seconds—thus the dosage (intensity × time) unit of mWs/cm². The wavelength represents the energy at which a light particle is being transmitted, expressed in the following equation:

$$E = h\nu$$

in which $E$ = energy in Joules (W-s), $h$ = Planck's constant in J-s, $\nu$ = frequency in hertz or $s^{-1}$, and $\nu = c/\lambda$ ($c$ = speed of light in m/s = $2.9979 \times 10^8$ m/s and $\lambda$ = wavelength in m).

Therefore $E = h\, c/\lambda$. Accordingly, the energy of a photon is inversely proportional to the wavelength, and the shorter the wavelength, the greater the energy of the photon transmitted. For example, the energy of a photon at 253.7 nm is:

$$\begin{aligned} E &= h\, c/\lambda \\ &= \frac{(6.63 \times 10^{-34}\ \text{J-s})\ (3.0 \times 10^{8}\ \text{m/s})}{(2.537 \times 10^{-7}\ \text{m})} \\ &= 7.8 \times 10^{-19}\ \text{W-s} \end{aligned}$$

**TABLE 2** **Characteristics of drinking water treatment plants studied that use UV light technology, Continued**

| System | Harmony, N.J. | Ringoes, N.J. | Stewartsville, N.J. | Villadom, Ore. | Ft. Benton, Mont. |
|---|---|---|---|---|---|
| Type | NTNC* | NTNC | NTNC | CWS | CWS |
| Source of water | Groundwater | Groundwater | Groundwater | Groundwater | Surface water |
| Population served | 20 | 85 | 50 | 96 | 1,700 |
| Type of installed unit | Closed | Open | Closed | Closed | Open |
| Year of installation | 1994 | Unknown | 1991 | 1990 | 1987 |
| Minimum UV dose—*mWs/cm²* | Unknown | Unknown | Unknown | 30 | 25 |
| Type of alarm | Sound | Unknown | Unknown | Sound | Sound, light, telemetry |
| Other treatment | GAC filter | None | None | 120 mesh filter and chlorination | Chlorination |
| Design flow—*gpd (L/d)* | 34,600 (130,961) | Unknown | 29,000 (109,765) | 101,000 (382,285) | 2,300,000 (8,705,500) |
| Reported water use—*gpd (L/d)* | 10,000 (37,850) | Unknown | Unknown | Unknown | Unknown |
| Design flow per capita†—*gpd (L/d)* | 400 (1,514) | Unknown | 130 (492) | 240 (908) | 320 (1,211) |
| Coliform violations | None | Unknown | None | None | None |
| Frequency of service, time required | 6 months, 1 h | None | 6 months, several hours | Annual, 25 min | Annual |
| Capital cost per unit—*$* |  | Unknown | 1,000 | 5,000 | 74,587 |
| Annual O&M cost per unit—*$* | 1,000‡ |  | 200 | 140 |  |

*NTNC—nontransient–noncommunity, CWS—community water system
†Design per capita (gpd [L/d])—design flow/(population served)(4.3 peak design factor)
‡Includes costs of other treatments and water analyses for compliance purposes.

and the energy of a photon emitted at 185 nm is $E = 10.8 \times 10^{-19}$ W-s. Intensity is the power transmitted across a unit area; it corresponds to the number of light particles passing through a specific area.

Because energy must be transmitted throughout the entire volume of water to apply a sufficient dosage for microbial inactivation, the thickness of targeted water is a primary consideration. The convention of a 3-in. (76-mm) maximum depth to vessel wall is often cited.

Water quality determines how well UV is transmitted and how effective it is, but little controlled test data exist about this factor. Water quality may be the most complex variable because of the potential effects of soluble and insoluble UV-absorbing elements and compounds such as iron, manganese, and organic matter, as well as the effects of color, temperature, and pH. Although USEPA has found data on UV inactivation of microbes, water quality and methods used to measure UV intensity or dosage have not always been clearly defined. Therefore, comparison of results is often difficult because of the variety of prepared test media; the test organisms, which may include laboratory-cultured or natural specimens; and analytical procedures including dose measurements.

With these caveats, the better-qualified data from independent researchers and from manufacturers were examined. Studies that failed to report type of medium, source of microorganisms, and important quality concerns such as turbidity are not referenced in this article.

Table 1[17] summarizes information to date on UV inactivation of microorganisms, including some pathogenic protozoan cysts. Generally, pathogenic cysts do not threaten groundwater supplies unless groundwater is contaminated by surface water (which would trigger requirements under the 1989 Surface Water Treatment Rule). Comments in the table note the authors' observations on source of test water or other conditions. Some of the cited work was performed on laboratory-prepared water of various makeup, ranging from treated surface water (*Cryptosporidium* study)[26] to buffered distilled water and saline water (studies referenced on *E. coli*, polio 1 and Reo 1 viruses, and *Giardia lamblia*).

Different phyla of microorganisms resist UV light to differing degrees. Three-log inactivations of bacteria, viruses, and protozoan cysts occur in the neighborhood of 10, 20–45, and 8,000 mWs/cm$^2$ UV doses, respectively. A 4-log inactivation of bacteria species and bacterial indicators occurs at approximately 30 mWs/cm$^2$. These studies also indicate 4-log inactivations of hepatitis A viruses at 18.5 mWs/cm$^2$ and of MS-2 in the range of 64 to 93 mWs/cm$^2$[23,24] The latter study was performed on 10 groundwater sources of varying quality, one at a pilot treatment facility with up to 0.65 mg/L iron in groundwater. The authors concluded that the MS-2 bacteriophage is significantly more resistant to UV inactivation than the human pathogens poliovirus, hepatitis A virus, and rotavirus and that, therefore, MS-2 serves as a conservative indicator of effective treatment. (Because of a lack of culturing methods, such data are not available for Norwalk virus, an important human enteric virus, or other Norwalk-like viruses.)

UV efficacy may in part depend on water quality. This fact needs to be considered in future research and in design of new plants utilizing UV.

It has been suggested that even pure water exerts UV demand, and distilled water may absorb 8 percent of applied UV energy at a depth of 0.12 in. (3 mm). To describe UV demand, percent transmission, a mea-

**FIGURE 4** Comparison of capital costs of UV treatment

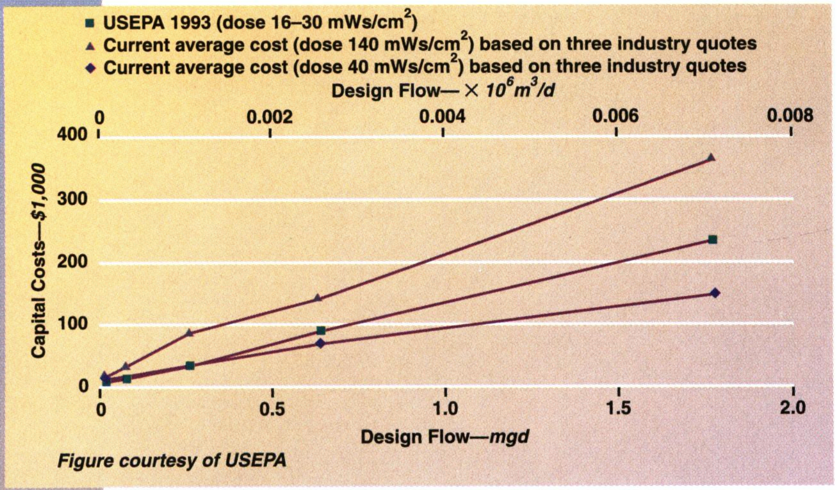


*Figure courtesy of USEPA*

**FIGURE 5** Comparison of operation and maintenance costs of UV treatment

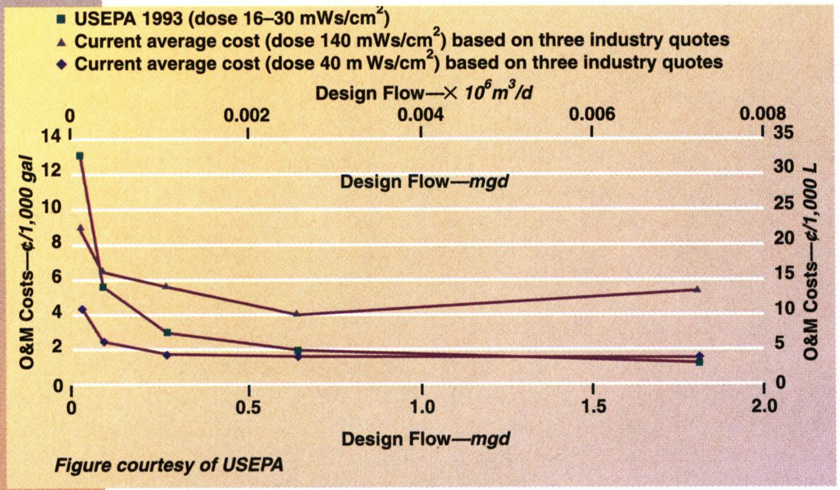


*Figure courtesy of USEPA*

**FIGURE 6** Comparison of total production costs of UV treatment

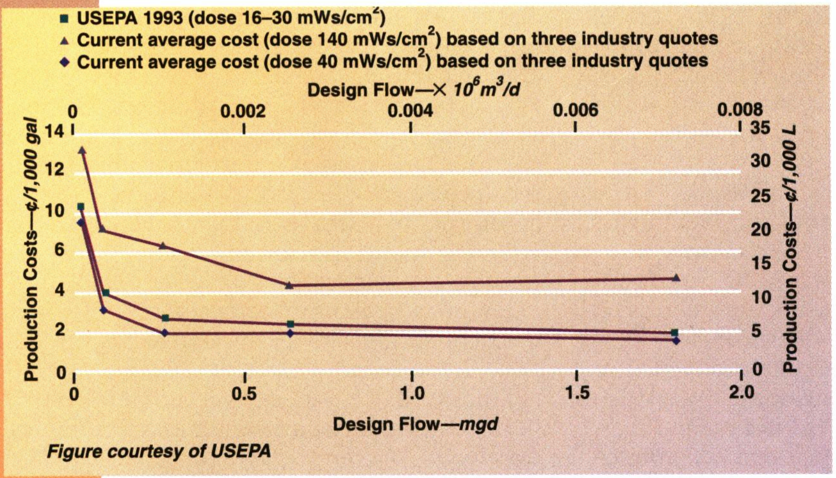


*Figure courtesy of USEPA*

sured characteristic of a given water sample, is expressed as

$$\text{percent transmission} = 100 \times 10^{-(\text{au/cm})d}$$

in which au = absorbance units and $d$ = distance (path length) in centimetres. The parameter most often used for design purposes is the coefficient of absorbance, or α, expressed as

$$\alpha = 2.3\ (\text{au/cm})$$

which considers water as a pure compound, i.e., not taking into consideration many interfering compounds.

Figure 3 illustrates UV transmission as a function of distance through various types of water, each having progressively higher coefficients of absorbance.

## How well does UV perform?

To determine how UV performed, USEPA interviewed personnel at several treatment plants, all but two located in New Jersey (Table 2).[7] The case studies thus developed mostly describe small noncommunity water systems supplied by groundwater. Severe site-specific conditions, such as high levels of dissolved iron or high hardness, required that water be pretreated. UV systems appeared easy to maintain and required only annual or biannual servicing. (At most plants, maintenance was contracted out.) The estimated service time ranged from 20 min to 2 h, depending on the number of units serviced, pretreatment, unit model, and water quality conditions. All UV units operated 24 h per day, and typically no backup units were available on site.

Operation and maintenance (O&M) costs were in the range of $100 to $200 per year, and cost was not a concern of system operators. Site

**FIGURE 7** Total cost of UV [40 mWs/cm²], chlorination, and ozonation at five flow rates

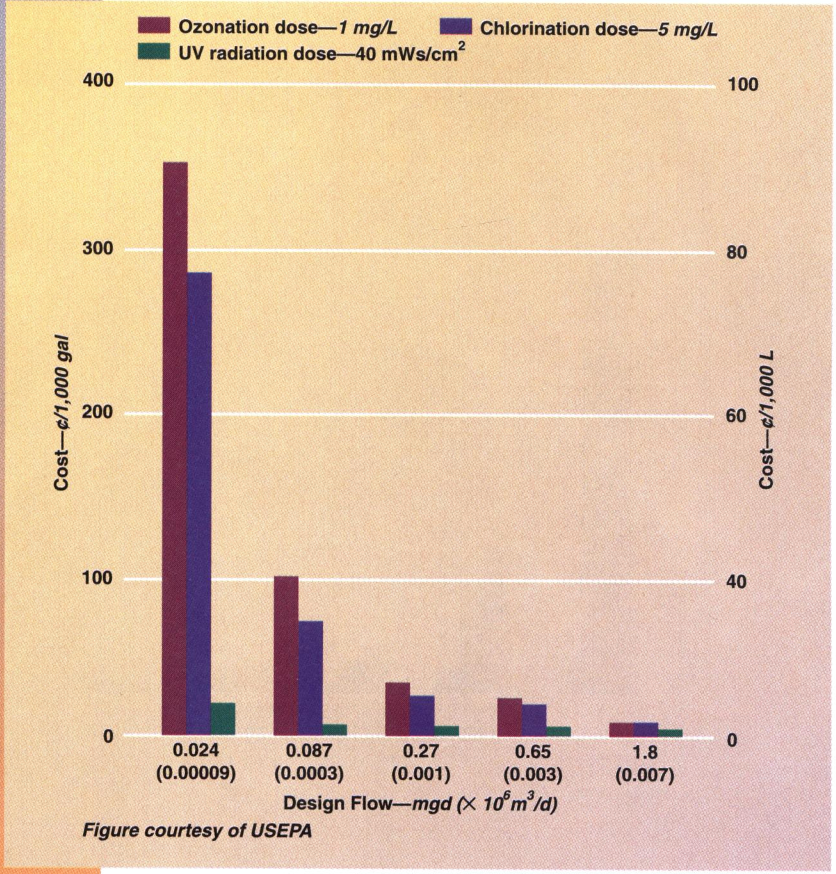


*Figure courtesy of USEPA*

modifications were either minimal or unnecessary, and installation costs were generally part of the equipment costs. Space requirements were also minimal, and the weight of a single unit was less than 25 lb (11 kg). Operators and users were satisfied with the performance of the installed UV units and with their simple operation and maintenance. Finally, operators of UV technology reported (with the exception of one system as tabulated) no coliform violations with UV treatment.

All the investigated systems that provided design flow information appeared to have UV units with capacities that exceeded actual water demand and likely any peak demand requirements. The per capita design flow at these systems far exceeded normal water demand (Table 2). The estimate of average water demand at the TNC system in Lebanon, N.J., was 4 gpcd (15 L/d per capita) (200 gpd [757 L/d] divided by population of 50), whereas the system's design capacity was at 100 gpcd (378.5 L/d per capita). Although some types of noncommunity systems may serve flows that nearly match community water use in excess of 100 gpcd (378.5 L/d per capita), the authors believe that many public systems, such as transient water supplies, may serve fewer than 20 gpcd.

## How much does UV treatment cost?

The 1996 USEPA report compares the cost of UV disinfection with more conventional chemical disinfectants. UV treatment costs may be very site-specific, and the cost analyses presented are preliminary. As of press time, USEPA was analyzing its methods of generating cost analyses; other factors previously not considered may be used in future USEPA regulatory impact assessments.

The 1996 UV report examined small system treatment costs for community groundwater systems serving on average less than 1 mgd (3.3 ML/d). Capital and operating costs for UV were based in part on information submitted by manufacturers; this information was supplemented by engineering and operational factors typically considered by USEPA in regulatory analyses. Costs developed reflect the assumption that a closed UV unit installation would likely resemble a turnkey (preengineered) rather than a fully engineered design and construction job. Engineering, site work, provision of a small enclosure, and minor construction costs are allowed for by a 20 percent markup of equipment cost, which includes shipping, to produce capital costs of UV installation. UV modules requiring one electrical connection and plumbing connections, racked modules with lamps and quartz sleeves, power supply distribution and ballasts, automatic cleaners, and a minimum of two units per facility (providing redundant peak capacity when one unit is not in service) were analyzed. Capital and O&M costs were computed at two UV doses, 40 and 140 mWs/cm², representing plausible low- and high-end requirements on the assumption that more resistant viruses are to be inactivated at a rate of approximately 4 logs. O&M costs assumed power consumption of lamps and ballasts using 70- to 85-W, low-pressure UV lamp units with lamp replacement after 8,000–14,000 h of continuous use (based on manufacturers' estimate of lamp life at 70 percent of initial lamp efficiency, i.e., 12 to 18 months), ballast replacement every 10 years and quartz sleeve replacement every 5 years (both worst-case assumptions), labor at one half hour per lamp per year for cleaning and repair, and additional minor chemical cleaning solutions and repair costs.

**FIGURE 8** Total cost of UV, chlorination, and ozonation at five flow rates

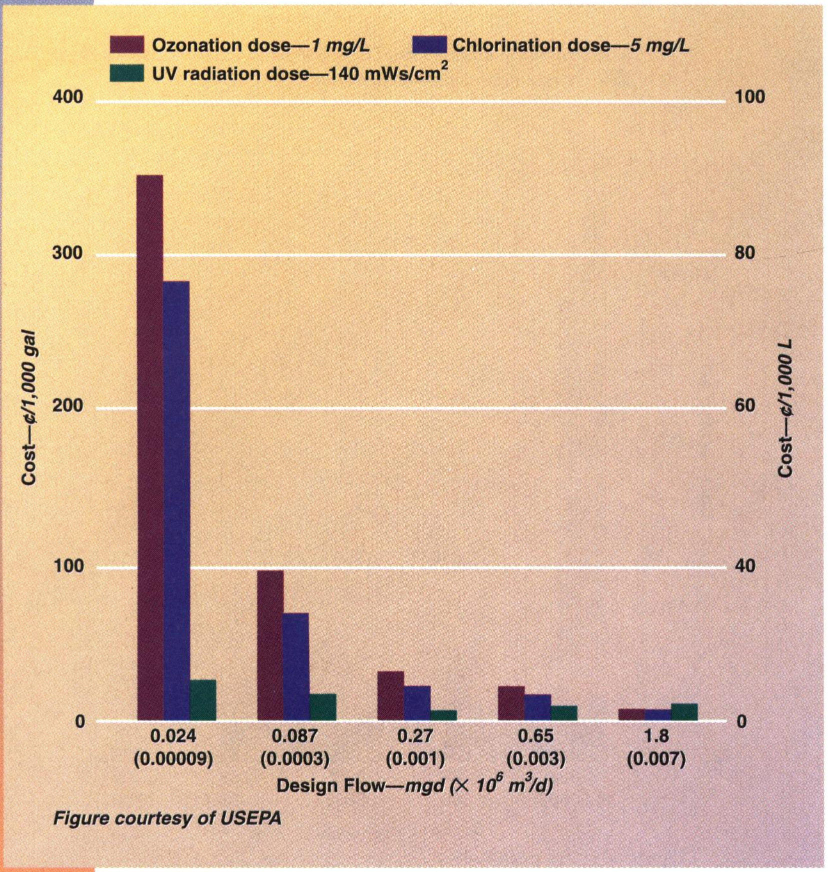


*Figure courtesy of USEPA*

Disposal of lamps and ballasts is assumed to be safe, i.e., consistent with the disposal of any electrical equipment. Some manufacturers are willing to recycle used UV lamps and ballasts at no extra cost to the water system.

USEPA calculated preliminary cost estimates of capital, O&M, and total production costs for UV disinfection of groundwater (Figures 4, 5, 6). The figures compare costs at doses of 40 and 140 mWs/cm$^2$, and at 16–30 mWs/cm$^2$, a dose used in a 1993 USEPA[27] cost analysis. Total production cost, according to these analyses, ranges from 5 to 20 ¢/1,000 gal (3,785 L) for the smaller systems represented—a cost likely affordable by most drinking water systems. USEPA also compared preliminary costs for UV disinfection and for ozonation and chlorination disinfection (Figures 7 and 8). At a UV dose of 40 mWs/cm$^2$, for all of the sizes considered, UV is clearly competitive; at the higher dose of 140 mW/cm$^2$, UV treatment appears to be competitive up to a service of approximately 1 mgd (3.8 ML/d).

## UV treatment is effective and affordable

As an initial step in the development of a Ground Water Disinfection Rule, USEPA has reviewed the applicability of UV disinfection in small groundwater treatment plants. Results are reported in Ultraviolet Light Disinfection Technology in Drinking Water Application—An Overview (EPA-811-R-96-002).[7] This report concludes the following:

- UV technology appears to be both available and affordable for use in the United States, particularly for smaller systems that produce up to approximately 1 mgd (3.8 ML/d).
- UV treatment provides an effective barrier to a variety of pathogenic microorganisms that will be targeted by a federal groundwater disinfection rule. Data from several sources conclude that inactivation of viruses is feasible in the range of UV dosages typically employed by commercial units and in a variety of tested source waters and likely can effect a 4-log reduction of viruses. However, UV does not provide a residual disinfectant to protect against recontamination. Other strategies are needed to protect distribution systems.
- Case studies and literature indicated that UV is easy to install in a closed, pressurized system in a variety of community and noncommunity systems and requires little space compared with other water treatment technologies, little O&M and operator attention (e.g., changing of lamps), and no on-site storage or use of potentially harmful chemicals. UV disinfection units may be fitted with shutdown systems, alarms, and redundancies to announce when units require unscheduled attention.
- Preliminary unit-cost estimates indicated UV is an affordable form of treatment relative to conventional disinfectants, particularly where a disinfectant residual is not needed, i.e., where no significant storage containment, piping, or other components would act as a source of recontamination. In plants that need a residual, conventional disinfection strategies would be more economical.
- Testing of UV units and criteria for UV disinfection in practice continue. Several states have adopted standards originally developed by ANSI/NSF (Standard 55) for POU and POE device certification, supplemented by specific operational criteria to ensure provision of a minimum dosage of 38 mWs/cm$^2$.

Progress is expected in researching UV efficacy under varying conditions and effects on microorganisms of interest, in developing test protocols, and in analysis of costs for small water system applications. These efforts are under way at USEPA and in the research community; it is hoped that they will lead to the safest and most cost-effective drinking water disinfection options. Issues related to potential benefits or tradeoffs of UV and other disinfectants, such as reducing exposure to disinfection byproducts, have not yet been addressed.

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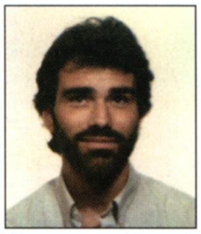
## References

1. Abbaszadegan, M.; Stewart, P.; & LeChevallier, M.W. Occurrence of Viruses in Groundwater. Proc. 1997 WQTC, Denver.
2. USEPA. UV Disinfection Technology Assessment. EPA 832-R-92-004. Washington (1991).
3. AWWA. Comments from J. Sullivan to USEPA on Draft USEPA Ground Water Disinfection Rule (1992).
4. Kruithof, J.C.; van der Leer, R.C.; & Hijnen, W.A.M. Practical Experiences With UV Disinfection in the Netherlands. *Aqua*, 41:2:88 (1992).
5. Groocock, N.H. Disinfection of Drinking Water by Ultraviolet Light. *Jour. Institution of Water Engrs. & Scientists*, 38:2:687 (1984).
6. Lund, V. & Hongve, D. Ultraviolet Irradiated Water Containing Humic Substances Inhibits Bacterial Metabolism. *Water Res.*, 28:5:1111 (1994).
7. USEPA. Ultraviolet Light Disinfection Technology in Drinking Water Application—An Overview. EPA 811-R-96-002 (1996). (Available through USEPA hotline at 800-426-4791.)
8. Oda, A. Ultraviolet Disinfection of Potable Water Supplies. Ontario Water Resources Commission Research Paper EO12 (1969). As cited in USEPA Design Manual: Municipal Wastewater Disinfection, EPA 625/1-86/021 (1986).
9. Ellis, K.V. Water Disinfection: A Review With Some Consideration of the Requirements of the Third World. *CRC Critical Reviews in Environmental Control*, 20:5/6:341 (1991).
10. USEPA. Draft Ground Water Disinfection Rule. *Fed. Reg.*, 57:33960 (July 31, 1992).
11. US Department of Health, Education, and Welfare Centers for Disease Control. Recommendations on Vessel Sanitation (1974) as cited in Witherall, L.; Solomon, R.; & Stone, K.M. *Ozone and Ultraviolet Radiation Disinfection for Small Community Water Systems.* (1979).
12. US Food and Drug Administration, CFR Part 129.8a (1995).
13. ANSI/NSF Standard 55-1991: Ultraviolet Microbiological Water Treatment Systems. NSF International, Ann Arbor, Mich. (1991).
14. Wisconsin Department of Natural Resources. DNR Criteria for Ultraviolet Water Treatment Devices for Private and Non-Community Public Water Supplies To Control Microbiological Contamination, November 17, 1995.
15. Wilson, B.R. et al. Coliphage MS-2 as a UV Water Disinfection Efficacy Test Surrogate for Bacterial and Viral Pathogens. Proc. 1992 AWWA WQTC, Toronto.
16. USEPA. Small System Compliance Technology List for the Surface Water Treatment Rule. EPA 815-R-97-002 (1997). (Available through USEPA hotline 800-426-4791.)
17. Sobsey, M.D. Inactivation of Health-related Microorganisms in Water by Disinfection Processes. *Water Sci. & Technol.*, 21:3:179 (1989).
18. Lea, D.E. *Actions of Radiations on Living Cells.* McMillan Co., New York (1947).
19. Meulemans, C.C.E. The Basic Principles of UV-Disinfection of Water. *Ozone Sci. & Engrg.*, 9:299 (1987).
20. Whitby, G.E. & Palmateer, G. The Effect of UV Transmission, Suspended Solids, and Photoreactivation on Microorganisms in Wastewater Treated with UV Light. *Water Sci. & Technol.*, 27:34:379 (1993).
21. Battigelli, D.A.; Sobsey, M.D.; & Lobe, D.C. The Inactivation of Hepatitis A Virus and Other Model Viruses by UV Irradiation. *Water Sci. & Technol.*, 27:34:339 (1993).
22. USEPA. Office of Drinking Water. Guidance Manual for Compliance With the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources (1991).
23. Wiedenmann, A. et al. Disinfection of Hepatitis A Virus and MS-2 Coliphage in Water by Ultraviolet Irradiation: Comparison of UV-Susceptibility. *Water Sci. & Technol.*, 27:3-4:335 (1993).
24. Snicer, G. et al. Evaluation of Ultraviolet Technology for Groundwater Disinfection, Draft Final Rpt. AWWARF (1996).
25. Karanis, P. et al. UV Sensitivity of Protozoan Parasites. *Jour. Water Supply Res. & Technol.—Aqua*, 41:2:95.
26. Safe Water Solutions. Evaluation of the Safe Water Solutions, L.L.C. *Cryptosporidium* Inactivation Device for Inactivation of *Cryptosporidium parvum* Oocysts. Clancy Environmental Consultants, St. Albans, Vt. Office of Ground Water and Drinking Water.
27. USEPA. Office of Ground Water and Drinking Water. Very Small Systems BAT Document (1993).



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