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ULTRAVIOLET LIGHT DISINFECTION TECHNOLOGY IN DRINKING WATER APPLICATION—AN OVERVIEW

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PRELUDE

The objective of this report is to support the United States Environmental Protection Agency's (USEPA) Office of Ground Water and Drinking Water (OGWDW) in its efforts to develop the Ground Water Disinfection Rule (GWDR). According to USEPA's databases on the number of public water systems in the United States, there are approximately 178,000 water supply systems serving fewer than 3,300 people. Of the 178,000 systems, approximately 130,000 systems are transient non-community (TNC) and non-transient non-community (NTNC) ground water supply systems with little or no distribution systems. These TNC and NTNC ground water systems may be amenable to alternative disinfection technology applications. This report presents a preliminary investigation of ultraviolet light (also called ultraviolet radiation) use as a ground water disinfection technology.

To investigate the availability, viability, and costs of ultraviolet equipment for use at potable water supplies and to obtain current information on equipment costs and operation and maintenance practices, the USEPA contacted equipment manufacturers or manufacturer representatives, the Water and Wastewater Equipment Manufacturer's Association, Inc. (WWEMA), the American Water Works Association (AWWA), the National Sanitation Foundation (NSF) International, the Water Quality Association (WQA), the Food and Drug Administration (FDA), the National Institute for Occupational Safety and Health (NIOSH), and universities involved in ultraviolet light research. The USEPA conducted an indepth literature search to determine ultraviolet light inactivation rates for specific microorganisms, including Rotavirus, poliovirus, hepatitis A virus, bacteria, and protozoa such as *Giardia lamblia*, and *Cryptosporidium parvum*. Information on inactivation rates provided by the ultraviolet light industry are presented next to the inactivation rates reported in the scientific literature. The juxtaposition of scientific and nonscientific information is intended to show points of agreement and disagreement between manufacturers' information and peer-reviewed research data. Information collected regarding ultraviolet light potential for destruction of volatile organic compounds (VOCs) and other priority organics is presented in Appendix B of this report.

This report contains a list of abbreviations, conversion units, and definitions; additionally, chapters 1, 2, 3, and 4 and appendices A and B have each a separate list of references. Subsequent to this Prelude, this report is arranged in the following format:

- EXECUTIVE SUMMARY

- CHAPTER 1. *BACKGROUND*—Presents historic and scientific background information and a general description of the technology. Also, the chapter provides an assessment of the availability of appropriate ultraviolet equipment in the United States of America, and presents information on existing use guidelines.

- CHAPTER 2. *ASSESSMENT OF ULTRAVIOLET LIGHT EFFICACY, VIABILITY AND OPERATIONAL FACTORS*—Discusses ultraviolet light disinfection efficacy (i.e., inactivation rates and issues that surround ultraviolet light applications for drinking treatment in a groundwater setting, and by-products formation). Issues related to the practicality of using ultraviolet light in a ground water setting with an emphasis on small systems are presented. Factors such as operating procedures and requirements, maintenance requirements, installation features, and design elements are considered. This chapter presents a description of ultraviolet light technology (including equipment operational factors, water quality considerations, hydraulic design considerations, and design considerations specific to small systems), as well as a summary with an emphasis on ultraviolet light viability for small drinking water systems based on the findings and data relative to operational factors.

- CHAPTER 3. *EVALUATION OF ULTRAVIOLET SYSTEMS COSTS AND COMPARISON TO OTHER DISINFECTION TECHNOLOGIES*—Provides an assessment of the costs of using ultraviolet light alone and in combination with, or in lieu of, other disinfectants. This chapter presents findings to date regarding costs associated with using ultraviolet light to disinfect ground water sources for five design flow categories (0.024 MGD, 0.087 MGD, 0.270 MGD, 0.650 MGD and 1.800 MGD).

- CHAPTER 4. *CASE STUDIES*—Presents information from sources in the field where ultraviolet light has been applied. The majority of the presented case studies are non-community ground water systems.

- CHAPTER 5. *SUMMARY OF FINDINGS*—Offers a summary of the findings on the issues discussed in the report.

- APPENDIX A. *OTHER ULTRAVIOLET-RELATED DRINKING WATER DISINFECTION TECHNIQUES*—Presents information available on newly applied ultraviolet-related disinfection techniques and other ultraviolet-related disinfection techniques that are at the experimental stage.

- APPENDIX B. *ORGANICS DESTRUCTION*—Presents an analysis of ultraviolet radiation's potential for the destruction of VOCs and other priority organics in drinking water.

- APPENDIX C. *QUESTIONNAIRE USED FOR STATE INQUIRY AND AS GUIDE IN TELEPHONE INQUIRIES*—Presents a list of questions used as a guide to collect information on ultraviolet systems, water quality, and costs.

- APPENDIX D. *REGULATIONS AND STANDARDS FOR DRINKING WATER DISINFECTION USING ULTRAVIOLET LIGHT*—Provides available regulations and standards regarding the use of ultraviolet light for drinking water disinfection.

ABBREVIATIONS LIST

α	Coefficient of Absorbance
ε	Molar decadic absorption coefficient in L/mol/cm
υ	Frequency in hertz or per second
λ	Wavelength in m
a.u.	Absorbance Units
AA	Activated Alumina
ANSI	American National Standards Institute
AOC	Assimilable Organic Carbon
APHA	American Public Health Association
AU Corp.	Atlantic Ultraviolet Corporation
ATCC	American Type Culture Collection
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
B(a)P	3,4-benzo(a)pyrene
BAT	Best Available Technology
BDCM	Bromodichloromethane
BOD	Biochemical Oxygen Demand
c	Speed of light
c/kgal	Cents per thousand gallons
C	Concentration of chemical disinfectant in mg/L
C/F	Coagulation/Filtration
C of A	Coefficient of Absorbance
CC	Corrosion Control
CDC	Centers for Disease Control
CFU	Colony Forming Units
CSTR	Continuous Flow Stirred Tank Reactor
CWS	Community Water Supply
d	Distance
DBCP	Dibromochloro propane
D/DF	Direct and Diatomite Filtration
DHEW	Department of Health, Education and Welfare
DOC	Dissolved Organic Carbon
DRCM	Differential Reinforced Clostridial Medium
eV	Electron volt
E	Energy
ENR	Engineering News Record
ENRCC	Engineering News Record Construction Cost
EU	European Union
FDA	Food and Drug Administration
GAC	Granular Activated Carbon
gmol	Gram Mole
gpm	Gallons per minute
GWDR	Ground Water Disinfection Rule
h	Planck's Constant Number
HAV	Hepatitis A Virus

HDPE	High Density Polyethlyene
HHS	Department of Health and Human Services
HPC	Heterotrophic Plate Count
i	Intensity of ultraviolet light
IE	Ion Exchange
J	Joule
k	Rate constant
k$	Thousand dollars
kgpd	Thousand gallons per day
kWhr	Kilowatt hour
KeV	Kilo electron volt
LED	Light-Emitting Diode
L/S	Liters per Second
LS	Lime Softening
M	Molar Concentration
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Levels Goal
mg/L	Milligrams per Liter
MGD	Million Gallons per Day
MIB	2-methylisoborneol
mol	Mole
MPN	Most Probable Number
MS	Male Specific
mWs/cm^2	Milliwatts Second per Square Centimeter
MX	3-chloro-4(dichloromethyl)-5-hydroxy-2(5H)-furanone
N	Surviving bacterial population after exposure to ultraviolet light
NG	No Growth
NCW	Non-Community Water
NIOSH	National Institute of Occupational Health and Safety
nm	Nanometer 10^{-9} meter
N_o	Initial bacterial population
NOM	Natural Organic Matter
NPDWR	National Primary Drinking Water Regulations
NSF	National Sanitation Foundation International
NTNC	Non-Transient Non-Community
NTU	Nephelometric Turbidity Units
NWRI	National Water Research Institute
ODHR	Oregon Department of Human Resources
OGWDW	Office of Ground Water and Drinking Water
ORP	Oxidation Reduction Potential
O&M	Operation and Maintenance
OX	Oxidation
PAH	Polyaromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCE	Perchloroethylene, tetrachloroethylene
PFR	Plug-Flow Reactor
PHCO	Photoassisted Heterogeneous Catalytic Oxidation
POE	Point of Entry
POM	Particulate Organic Matter
POU	Point of Use

PPPI	Producer Prices and Price Indexes
PSSM	Point Source Summation Method
PTA	Packed Tower Aeration
PVC	Polyvinyl Chloride
PWS	Public Water System
RAD	Radiation Absorbed Dose
RCRA	Resource Conservation and Recovery Act
RO	Reverse Osmosis
RTD	Residence Time Distribution
SAIC	Science Applications International Corporation
SDWIS	Safe Drinking Water Information System
sec	Second
SWTR	Surface Water Treatment Rule
t	Time
TCA	1,1,1-Trichloroethane, methyl chloroform
TCE	1,1,2-Trichloroethane, vinyl trichloride
THM	Trihalomethane
TiO_2	Titanium Dioxide
TNC	Transient Non-Community
TOC	Total Organic Carbon
TT	Treatment Technique
UFC	Uniform Fire Code
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VOC	Volatile Organic Compound
WERF	Water Environment Research Federation
WPCF	Water Pollution Control Federation
WQA	Water Quality Association
WWEMA	Water and Wastewater Equipment Manufacturer's Association, Inc.

CONVERSION UNITS AND DEFINITIONS

Watt is the power produced by a current (a flow of electrons) of one ampere across a potential difference of one volt.

Intensity is the power transferred across a unit area, e.g., watt/m^2. In practical terms, intensity is the flux or rate of delivery of photons to the target.

By-products precursor material is any material that reacts with disinfectants to form disinfection by-products.

Mineralization is the conversion of organic compounds into simple mineral acids and inorganic compounds such as CO_2 and H_2O.

Einstein is a unit of radiant energy equal to the energy of radiation that is capable of photochemically changing one mol of photosensitive substance.

Frequency is the number of cycles per second that passes a given point in space.

Radiation Absorbed Dose (RAD) is a unit of absorbed dose of ionizing radiation equal to an energy of 100 ergs per gram of irradiated material.

1 RAD = 100 ergs/gr of irradiated material.

1 Watt is the power produced by the work done by one joule per second.
1 Joule per second = 1 kg m^2 sec = 1 Newton Meter
1 Newton = 1 kg m/sec^2
1 Horsepower = 75 kgm/sec
1 Watt = 1 J/sec = 1 amp volt = (1/746) Horsepower = (75/746) kgm/sec = 0.1 kgm/sec

$$1 \text{ Watt/m}^2 = 1 \text{ J/m}^2 \text{ sec} = \frac{\text{mW} \times 10}{\text{cm}^2}$$

1 mWs/cm^2 = 10^4 ergs/cm^2
1 einstein of 254 nm quanta $\approx 4.72 \times 10^5$ J/mole

1 Joule = $(1/1.6) \times 10^{19}$ eV = 0.625×10^{16} KeV
1 Joule = 10^7 ergs
1 Joule = 1 kg m^2/sec^2
1 Joule = 0.23901 calorie
1 nm = 10^{-9} m

1 U.S. gallon = 3.7854 liters

1,000 L/hr = 1 m^3/hr = 6,340.15 gpd

To convert degrees Centigrade (°C) to degrees Fahrenheit (°F), apply the following equation:

$$°C = (°F–32)/1.8$$

Planck's constant $= 6.62608 \times 10^{-34}$ Joules second
$= 6.62608 \times 10^{-27}$ ergs
Speed of light $= 2.997925 \times 10^{8}$ m/sec

When ultraviolet light is transmitted, the energy transmitted is represented by the following formula:

$$E = h\nu$$

where:
E = Energy in Joules or Watt second
h = Planck's constant in Joules second
ν (nu) = Frequency in hertz or sec $^{-1}$

$$\nu = \frac{c}{\lambda}$$

c = speed of light in m/sec = 2.9979×10^{8} m/sec
λ = wavelength in m

The energy of a photon is inversely proportional to the wavelength.

The energy of a photon at 253.7 nm:

$$E = h\frac{c}{\lambda} = \frac{(6.63\times10^{-34}\,\text{Joules second})(3.0\times10^{8}\,\text{m/s})}{(2.537\times10^{-7}\,\text{m})} = 7.8\times10^{-19}\,\text{Watt second}$$

$$\text{Power} = \frac{\text{Work}}{\text{Time}} = \frac{\text{Energy Transferred}}{\text{Time}}$$

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EXECUTIVE SUMMARY

CHAPTER 1. BACKGROUND

Ultraviolet treatment in drinking water involves the direct exposure of the water stream to ultraviolet light. Exposure to the ultraviolet light damages nucleic acids and changes their mode of action in microorganisms, thus preventing microorganisms from propagating or remaining active. Ultraviolet light is generated by striking an electric arc through mercury vapor. The low-pressure mercury vapor lamp emits primarily at a wavelength of 253.7 nm with a lesser output at 184.9 nm. Research has shown that the optimum ultraviolet light wavelength range for bactericidal effect is between 250 nm and 270 nm and that maximum ultraviolet absorption by DNA occurs at about 200 nm wavelength. At shorter wavelengths (e.g., 185 nm), ultraviolet light is powerful enough to produce ozone, hydroxyl radicals, and other free radicals that have germicidal effects.

The use of ultraviolet light to disinfect drinking water in the United States dates back to 1916. Currently, several States have regulations that specifically allow the use of ultraviolet light to disinfect public non-community ground water supplies. Other States, like Montana and Oregon, recognize ultraviolet light as an acceptable technology for drinking water disinfection and permit its use on a case-by-case basis. At least four States forbid the use of ultraviolet light technology for water disinfection in public water systems.

Guidelines for the use of ultraviolet light for water disinfection, set by the U.S. Department of Health, Education, and Welfare (DHEW) in 1966, require a minimum dose of 16 mWs/cm^2 (milliwatts second per square centimeter) at all points throughout the water disinfection unit. The American National Standards Institute (ANSI) and the National Sanitation Foundation International (NSF) set the minimum ultraviolet light requirement to disinfect drinking water at 38 mWs/cm^2 for class A point of use (POU) and point of entry (POE) devices treating visually clear water. Also, the ANSI/NSF standard requires 16 mWs/cm^2 for class B POU treatment devices, which are for supplemental bactericidal treatment of disinfected or otherwise safe drinking water (i.e., to reduce nuisance bacteria only). Some European states have a minimum dose requirement for ultraviolet disinfection. In Austria, the minimum acceptable ultraviolet dose for pretreated drinking water disinfection is 30 mWs/cm^2.

At least 20 firms manufacture or are major distributors of ultraviolet light equipment in the United States. These firms market ultraviolet equipment for disinfection of water and other media. Of the 20 firms, six

are foreign companies. Some of these firms, including domestic firms, have been in the ultraviolet light equipment market for decades and have acquired tremendous experience and expertise in the field. The domestic ultraviolet industry claims that it can deliver closed system units in 4 to 8 weeks.

CHAPTER 2. ASSESSMENT OF ULTRAVIOLET LIGHT EFFICACY, VIABILITY, AND OPERATIONAL FACTORS

The inactivation of microorganisms in drinking water by means of ultraviolet light is a function of intensity of the radiation, proper wavelength, exposure time, water quality, flow rate, type and source of the microorganisms (natural or culture), and the distance from the light source to the targeted microorganisms. The intensity is measured in milliwatts per square centimeter and time is measured in seconds. Therefore, the dose is measured in milliwatts second per square centimeter (mWs/cm^2).

The data clearly show, with few exceptions, that the order of ultraviolet light disinfection resistance is as follows:

Bacteria < viruses < bacterial spores < protozoan cysts and oocysts.

Least resistant to ultraviolet light ⟷ Most resistant to ultraviolet light

Some ultraviolet light equipment manufacturers claim that bacteria can be greater than 99.9 percent inactivated by an ultraviolet dose of 26.4 mWs/cm^2 and that protozoa can be completely destroyed by a dose of 200 mWs/cm^2. The claims made by ultraviolet light equipment manufacturers for virus inactivation ranged from a 1 log reduction at a maximum dose of 11.3 mWs/cm^2 to complete destruction at 440 mWs/cm^2 for tobacco mosaic virus.

In general, and mainly under laboratory conditions using distilled water as a medium, the scientific literature shows that a 3 log reduction of bacteria is achieved using an ultraviolet light dose of 30 mWs/cm^2, a 3 log reduction of viruses is achieved at an ultraviolet light dose of 45 mWs/cm^2 (Reovirus 1), and a minimum 3 log reduction of bacterial spores is achieved at a dose of 60 mWs/cm^2. A 4 log reduction of bacteriophage MS-2 is achieved at a dose of 93 mWs/cm^2. A 4 log inactivation of rotavirus, poliovirus and Hepatitis A virus is achieved by an ultraviolet light dose of 50 mWs/cm^2, 29 mWs/cm^2, and 15 mWs/cm^2 respectively. A 2 log reduction of *Giardia lamblia* is achieved at a dose of 180

mWs/cm^2. For filtered secondary effluent, an ultraviolet light dose of 120 mWs/cm^2 can achieve a 4 log reduction in poliovirus.

Based on their study of the practical experience of ultraviolet disinfection in the Netherlands, Kruithof et al. (1992) recommended the use of ultraviolet light (without use of a secondary disinfectant) for disinfecting drinking water from all sources of water provided that two conditions are met: (1) the water has to be low in biodegradable compounds so regrowth would not occur, and (2) the distribution network does not need any additional protection (no biofilm growth is likely due to low AOC and no cross-contamination is likely). Multiple treatment steps in Dutch waterworks typically ensure protozoa, cysts, and organic compounds removal.

Ultraviolet Light Systems

There are two types of ultraviolet systems: closed systems and open systems. Closed systems are more commonly used in potable and sterile water applications and are assumed in this analysis to be the systems used for meeting small water systems requirements.

Equipment Operational Factors

The operational factors that affect adequate performance of an ultraviolet light system are lamp output, lamp aging, and plating and fouling of unit surfaces. To better control these operational factors, continuous dose measurement (i.e., accurate intensity and flow rate measurement) and proper maintenance (cleaning regimes and lamp and sleeve replacement regimes) are essential.

Water Quality Factors

The performance of an ultraviolet disinfection system is inversely related to ultraviolet light absorbance of the water being treated. This ultraviolet absorbance is analogous to chlorine demand in chemical disinfection processes. Microbial and chemical characteristics are the two major water quality factors that affect the performance of an ultraviolet unit in treating ground water (i.e., very low turbidity with no or very low silt and suspended matter content). Microbial water characteristics include type, source, age, and density. Chemical water characteristics include nitrites, sulfites, iron, hardness, and aromatic organic levels.

Hydraulic Design Considerations

The major hydraulic elements that need to be accounted for in the design and operation of an ultraviolet light disinfection system are dispersion, turbulence, effective volume, residence time distribution, and flow rate.

Small System Design Considerations

Multiple modular units are recommended for small systems. At a minimum, two units, each capable of carrying design flow, ought to be installed for the purpose of maintaining a continuous disinfection process while a unit is being serviced and to operate the appropriate number of units during low flow demand periods. Modular units designed for small drinking water systems should be easy to install (two plumbing connections per unit and one electrical hookup) and operate. They should be equipped with automatic cleaners and remote alarm systems. For systems in remote areas, a set of spare parts should be maintained and properly stored onsite, and a telemetry system for monitoring treatment may be a consideration.

Other Considerations Related to the Use of Ultraviolet Light for Drinking Water Disinfection

By-Products Formation and Removal of Organic Contaminants

Some organic contamination removal and breakdown occurs in ultraviolet-light-treated drinking water. At this point there are no significant by-products formed as a result of ultraviolet light disinfection, and there is no significant increase in assimilable organic carbon (AOC) and no significant nitrite formation from nitrate-containing treated water.

The Phenomena of Photoreactivation, Dark Reactivation, and Chemical Reactivation

Some microorganisms damaged by ultraviolet light may recover if they are exposed to visible light shortly after the exposure to ultraviolet light. In addition to such environmental factors as pH and temperature, the presence of certain compounds and the availability of repair enzymes are also important in the process of reactivation. Viruses do not have repair enzymes, so they do not photoreactivate on their own. However, viruses can use enzymes of the host cell to repair damages and resume activity. The experience gained from ultraviolet light application in wastewater disinfection shows a maximum repair rate of 1 to 2.5 log in coliforms. However, in drinking water application, recent research shows that reactivation does not occur and is not a significant issue. In addition, a variety of post treatment (i.e., storage, distribution) configurations may impact reactivation kinetics in drinking water application.

Ultraviolet Light and Residual Disinfection

Recent pilot studies show that ultraviolet-light-treated drinking water has an inhibitory effect on bacterial growth and replication in the distribution system; however, conditions within distribution systems and external sources of contamination may dictate the need for providing additional residual (e.g., free chlorine) disinfection.

The Search for a Surrogate

Traditional indicator surrogate microorganisms such as coliforms are sensitive to ultraviolet light. Therefore, a surrogate microorganism is needed to quantify the correlation of its inactivation rates to that of pathogenic microorganisms. Two challenge microorganisms, *Bacillus subtilis* spores and coliphage MS-2, are reviewed as indicators for ultraviolet light water disinfection efficiency. Both microorganisms are getting more research attention than other challenge microorganisms.

Comparison of Ultraviolet Light to Chemical Disinfection

When comparing ultraviolet light to traditional chemical disinfectants, the following issues stand out:

- Sensitivity to traditional microbiological parameters, such as coliforms
- Comparative relative effectiveness against specific pathogenic microorganisms
- Capital and operation and maintenance (O&M) costs and space requirements
- Risks associated with the formation of by-products or overdosing
- Effects on secondary water quality parameters, such as smell and taste
- Residual disinfection.

Traditional microbiological drinking water parameters (e.g., coliform) are sensitive to ultraviolet light. This fact complicates direct comparison of ultraviolet light to chemical disinfection. Studies of the comparative relative effectiveness of ultraviolet light versus chlorination and ozonation, using fecal coliform inactivation as the baseline, have been conducted by different researchers with mixed results. Also, unlike ozonation and chlorination processes, ultraviolet light application in drinking water is not associated with any negative smell or taste effect.

Disadvantages of ultraviolet light disinfection technology include the lack of a measurable disinfection residual, the lack of a firm technical database on system efficiency in various water quality conditions,

and the lack of an in-place standardized mechanism to measure, calibrate, and certify equipment for efficiency before and after installation. The general belief in the scientific community is that ultraviolet technology does not leave a disinfection residual, however, according to recent research, ultraviolet light does leave some residual disinfection effect in treated water.

CHAPTER 3. EVALUATION AND COMPARISON OF ULTRAVIOLET LIGHT TECHNOLOGY COSTS TO OTHER DISINFECTION PROCESSES

Cost estimates to disinfect five USEPA flow categories are presented in this chapter. These flow categories are Design Flows 0.024 MGD, 0.087 MGD, 0.270 MGD, 0.650 MGD, and 1.8 MGD. The ultraviolet light doses considered in these cost estimates are 40 mWs/cm^2 and 140 mWs/cm^2. Capital and O&M costs show that ultraviolet light is an economically feasible disinfectant, particularly in a ground water setting.

Ultraviolet Light Disinfection Costs

Capital costs considered are equipment and installation costs plus a 20 percent markup for engineering, site work, and other related items. Equipment costs considered are average costs obtained from ultraviolet light manufacturers. O&M costs include parts replacement, periodic cleaning, power consumption, labor, and miscellaneous equipment repair costs. Ultraviolet light disinfection system costs are presented in the following table, in this Executive Summary and are discussed in more detail in Chapter 3.

Ultraviolet Light System Costs (With and Without Secondary Disinfection) Compared to Chlorination and Ozonation Disinfection Technologies

Chlorination and ozonation costs for Flow Categories 1 through 5 were calculated using the USEPA 1993 document *Very Small Systems Best Available Technology Cost Estimates*. The cost comparisons of ultraviolet treatment with and without chlorination as secondary disinfectant are presented in the following figures, in this Executive Summary and are discussed in more detail in Chapter 3.

CHAPTER 4. OPERATIONAL CASE HISTORIES

The information collected from the case studies revealed satisfaction with the performance of ultraviolet equipment. The case studies also revealed that generally, ultraviolet systems receive little attention and require very little supervision. Minimum service time, low operation and maintenance costs, and the absence of a chemical smell and taste in finished water were the main cited factors for selecting ultraviolet technology over traditional disinfection technologies.

Ultraviolet Light Disinfection System Costs for USEPA Flow Categories 1-5 at 40 mWs/cm² and 140 mWs/cm² Doses

Dose 40 mWs/cm²

EPA Flow Category	Design Flow (MGD)	Cost per Year (k$)*			Cost (c/kgal)		
		Total Capital	Total O&M	Total Production Cost	Total Capital**	Total O&M	Total Production Cost***
1	0.024	1.3	0.4	1.7	15	4	19
2	0.087	1.7	0.8	2.5	5	2	8
3	0.27	3.7	1.7	5.3	4	2	5
4	0.65	7.7	3.7	11.4	3	2	5
5	1.8	16.6	9.7	26.3	3	1	4

Dose 140 mWs/cm²

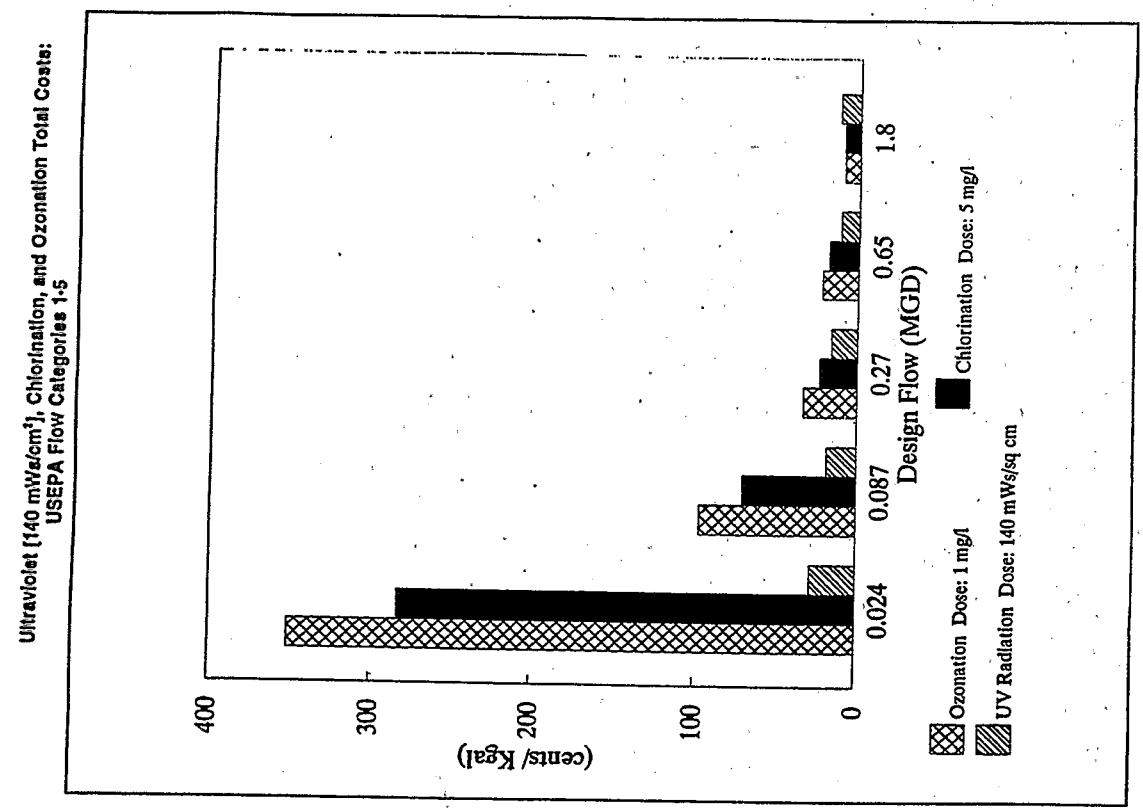
EPA Flow Category	Design Flow (MGD)	Cost per Year (k$)*			Cost (c/kgal)		
		Total Capital	Total O&M	Total Production Cost	Total Capital**	Total O&M	Total Production Cost***
1	0.024	1.7	0.8	2.5	19	9	28
2	0.087	3.6	2.1	5.7	11	7	18
3	0.27	10.0	5.5	15.5	10	6	6
4	0.65	16.5	9.4	25.8	7	4	11
5	1.8	42.1	34.0	76.0	6	5	12

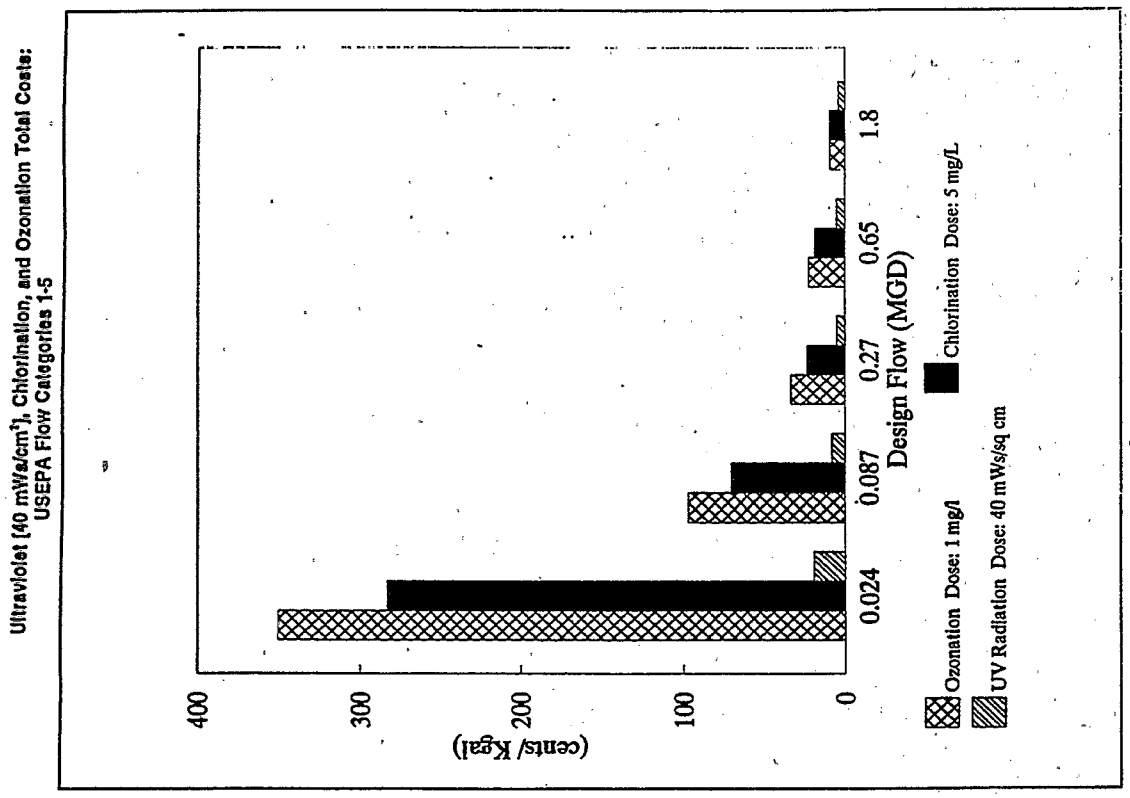
*August 1995 dollars
**Costs amortized at 10% for 20 years
***Figures might not add up because of rounding

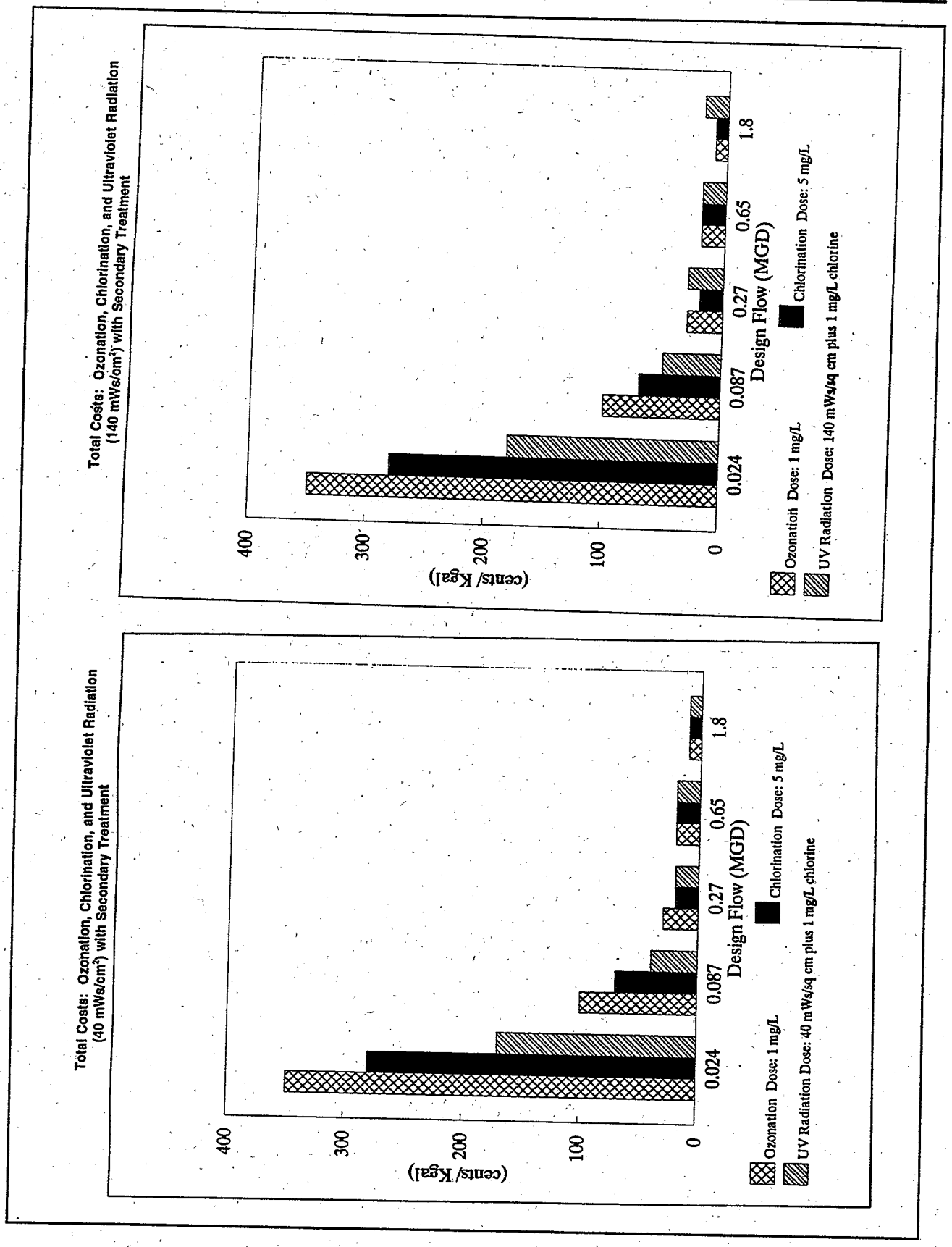
CHAPTER 5. SUMMARY OF FINDINGS

Ultraviolet light is an effective disinfection agent for drinking water at sufficient intensity and appropriate wavelength and exposure time. It is suitable for use on clean water sources more than it is for suspended matter-containing water. The order of disinfection resistance with few exceptions is bacteria (least resistant) < viruses < bacterial spores < protozoan cysts < protozoan oocysts (most resistant).

For the most resistant microorganisms, the literature shows that a 6 log reduction of *Bacillus subtilis* spores is achieved at 120 mWs/cm², a 5.5 log reduction at 90 mWs/cm², and a 4 log reduction at 60 mWs/cm²; for *Giardia lamblia*, a 2 log reduction is achieved at 180 mWs/cm². For bacteriophage MS-2 a 4 log reduction could be achieved at a dose of 93 mWs/cm². For viruses the literature shows that a 3 log reduction of Reovirus 1 is achieved at 45 mWs/cm² in a buffered distilled water.


Ultraviolet [140 mWs/cm²], Chlorination, and Ozonation Total Costs:
USEPA Flow Categories 1-5
(cents/ Kgal)
400
300
200
100
0
0.024
0.087
0.27
0.65
1.8
Design Flow (MGD)
Ozonation Dose: 1 mg/l
Chlorination Dose: 5 mg/l
UV Radiation Dose: 140 mWs/sq cm


Ultraviolet [40 mWs/cm²], Chlorination, and Ozonation Total Costs:
USEPA Flow Categories 1-5
(cents/ Kgal)
400
300
200
100
0
0.024
0.087
0.27
0.65
1.8
Design Flow (MGD)
Ozonation Dose: 1 mg/l
Chlorination Dose: 5 mg/L
UV Radiation Dose: 40 mWs/sq cm


Total Costs: Ozonation, Chlorination, and Ultraviolet Radiation
(40 mWs/cm²) with Secondary Treatment
(cents/ Kgal)
400
300
200
100
0
0.024
0.087
0.27
0.65
1.8
Design Flow (MGD)
Ozonation Dose: 1 mg/L
Chlorination Dose: 5 mg/L
UV Radiation Dose: 40 mWs/sq cm plus 1 mg/L chlorine
Total Costs: Ozonation, Chlorination, and Ultraviolet Radiation
(140 mWs/cm²) with Secondary Treatment
(cents/ Kgal)
400
300
200
100
0
0.024
0.087
0.27
0.65
1.8
Design Flow (MGD)
Ozonation Dose: 1 mg/L
Chlorination Dose: 5 mg/L
UV Radiation Dose: 140 mWs/sq cm plus 1 mg/L chlorine

According to USEPA data covering the years 1971 to 1977, 35 percent of outbreaks of waterborne diseases in the United States occur in non-community water supply systems. Thirty-three percent of waterborne disease outbreaks in ground water supply systems are caused by bacteria, 6 percent are caused by chemical agents, 3 percent by HAV viruses, less than 1 percent by *Giardia*, and about 58 percent by unknown agents. Therefore, using any form of disinfection in ground water systems will eliminate or greatly reduce the number of outbreaks caused by bacterial and viral agents and also may reduce the number of outbreaks caused by unknown agents.

The data on ultraviolet disinfection efficacy clearly show that many pathogenic bacteria and viruses (e.g., *Vibrio cholerae*, HAV, and polioviruses) associated with high morbidity and mortality around the world are very susceptible to ultraviolet light.

Operation and Maintenance

Technological advances have eliminated many of the O&M problems that were associated with earlier ultraviolet applications for disinfecting drinking water. Current systems are equipped with mechanical cleaners, ultrasonic cleaners, or some self-cleaning mechanism; lamps that are easy to install and replace; and alarm systems that indicate minor and major failure.

Evaluation and Comparison of Ultraviolet Costs to Other Disinfection Technologies

At a dose of 40 mWs/cm^2 and for systems treating design flows of 0.024 MGD through 1.8 MGD (USEPA Flow Categories 1 through 5), ultraviolet light systems are economically more feasible than chlorination at a 5 mg/L dose and ozonation at a 1 mg/L dose for the same flow categories, provided that a residual disinfectant is not required for distribution and/or storage.

At a dose of 140 mWs/cm^2, ultraviolet light systems are less expensive than ozonation at a dose of 1 mg/L in all flow categories but slightly more expensive than chlorination at a dose of 5 mg/L in flow category 1.8 MGD.

APPENDIX A—OTHER ULTRAVIOLET-RELATED DRINKING WATER DISINFECTION TECHNIQUES

Nonconventional techniques include pulsed ultraviolet light and Photoassisted Heterogeneous Catalytic Oxidation (PHCO). These techniques have been used, although on a limited scale, in water and wastewater applications. In the PHCO process, Titanium dioxide (TiO_2) is illuminated by near visible

ultraviolet light (long wavelengths). The energy absorbed by TiO_2 produces a redox potential sufficient to kill some microorganisms and mineralize organic compounds. The literature shows that under laboratory conditions, *Escherichia coli* can be destroyed completely with 30 minutes contact time and a dose of 1 g/L of TiO_2.

APPENDIX B—ORGANICS CONTROL

Ultraviolet light is used alone and in conjunction with ozone and hydrogen peroxide to treat ground water contaminated with organic compounds. However, the intensities and doses used in these treatment processes are far more than what might be necessary to disinfect drinking water. The current data show that ultraviolet light does not produce or leave any hazardous by-products in the treated water.

APPENDIX C—QUESTIONNAIRE OF ISSUES USED FOR STATE INQUIRY AND AS GUIDE IN TELEPHONE INQUIRIES

Twenty-seven questions were used to develop good case studies on ultraviolet use in drinking water disinfection. Eleven questions concentrated on systems and equipment, four questions were on water quality conditions, seven questions dealt with operation and maintenance, four questions were cost related, and one question was about the contact person and system manager.

APPENDIX D—REGULATIONS AND STANDARDS FOR DRINKING WATER DISINFECTION USING ULTRAVIOLET LIGHT

The presented standards show regulations from States that follow the 1966 guidelines published by DHEW and regulations from States that follow the ANSI/NSF international standards for ultraviolet light use in drinking water disinfection. The DHEW guidelines require a minimum ultraviolet dose of 16 mWs/cm^2. The ANSI/NSF standard for Class A units requires a minimum ultraviolet light dose delivery of 38 mWs/cm^2.

CHAPTER 1. BACKGROUND

This chapter discusses the history of artificial ultraviolet light and its application as a drinking water disinfectant in the United States. The chapter presents a general description of ultraviolet light technology and its mode of action on microorganisms. Existing guidelines for the use of ultraviolet equipment for the disinfection of drinking water are presented, and findings are introduced regarding the availability of ultraviolet light disinfection equipment in the United States and the use of ultraviolet light in water and wastewater treatment.

To investigate the availability of ultraviolet equipment for use at potable water supplies and to obtain current information on applications, the U.S. Environmental Protection Agency (USEPA) contacted equipment manufacturers or manufacturer representatives, the Water and Wastewater Equipment Manufacturer's Association, Inc. (WWEMA), the American Water Works Association (AWWA), the National Sanitation Foundation (NSF) International, the Water Quality Association (WQA), the Food and Drug Administration (FDA), the National Institute for Occupational Safety and Health (NIOSH), and universities involved in ultraviolet light research. Additionally, European and other nations' guidelines and experience in using ultraviolet light in drinking water disinfection were investigated. The European Union representation library in Washington, DC, provided available information on the European drinking water directive, and the literature search provided a wealth of scientific findings on ultraviolet light applications in drinking water.

This chapter is organized as follows: Section 1.1 presents an introduction to natural and artificial ultraviolet light, as well as a brief explanation of how ultraviolet light inactivates microorganisms and the wavelength range at which ultraviolet light is most effective. Section 1.1 also presents some historic background information on ultraviolet radiation treatment. Section 1.2 presents a general description of ultraviolet light technology and the types available for drinking water and wastewater disinfection applications. Section 1.3 presents existing official and non-official guidelines for ultraviolet disinfection in the United States and in Europe. Section 1.4 discusses the availability of ultraviolet light disinfection equipment in the U.S. market. Section 1.5 discusses the extent of ultraviolet technology applications in water and wastewater treatment.

1.1 INTRODUCTION TO ULTRAVIOLET LIGHT

Ultraviolet treatment in drinking water involves the direct exposure of the water stream to ultraviolet light. Exposure to the ultraviolet light damages and changes the nucleic acids of microorganisms present in the water, thus preventing them from propagating or remaining active (see **Exhibit 1-1**).

Naturally occurring ultraviolet light is situated beyond the visible spectrum at its violet end. It has a wavelength shorter than that of visible light (400 nm - 750 nm[1]) and longer than those of the X-ray wavelengths (0.1 nm - 100 nm). Ultraviolet radiation is subdivided into three regions: (1) near-ultraviolet (400 nm - 300 nm), which is present in sunlight as it reaches the earth and produces important biological effects; (2) middle-ultraviolet (300 nm - 200 nm), which is not present in sunlight as it reaches the earth (because of the ozone layer) but is transmitted through the air; and (3) the extreme-ultraviolet (200 nm - 100 nm[2]), which is not transmitted through the air (Van Nostrand, 1989 and Zumdahl, 1989). The division of the ultraviolet light spectrum described in the medical/pharmaceutical literature is (1) UV (100 nm - 200 nm), (2) UVA (200 nm - 290 nm), (3) UVB (290 nm - 320 nm), and (4) UVC (320 nm - 400 nm) (Fessenden and Fessenden, 1986; Sobotka, 1993). Meulemans (1987) puts the division as follows: UVa (400 nm - 315 nm), UVb (315 nm - 280 nm), UVc (280 nm - 200 nm), and Vacuum-UV (below 200 nm). Another ultraviolet light spectrum division used in the scientific literature is (1) UVA (400 nm - 320 nm), (2) UVB (320 - 290 nm), and (3) UVC (290 - 100 nm). Exposure to UVA and UVB (200 nm - 320 nm) for extended periods of time is known to cause mutation and skin cancer among humans and animals. In humans, at about 295 nm, ultraviolet light causes sunburn, between 280 and 300 nm it gives rise to Vitamin D, and between 300 and 400 nm it causes browning of the skin (Ellis, 1991). For purposes of clarity this report will treat ultraviolet light spectrum and other characteristics independently of the above classifications.

Artificial ultraviolet radiation is emitted by nearly all light sources (regular light bulbs, halogen bulbs, high-efficiency mercury-containing light bulbs, television and computer screens, and heat lamps). The transmission of ultraviolet light in the shorter wavelength region increases with the increase of excitation (current) or the temperature of the light source (heat lamps and halogen lamps emit more ultraviolet light

[1]nm = nanometer; 1 nm = 10^{-9} m

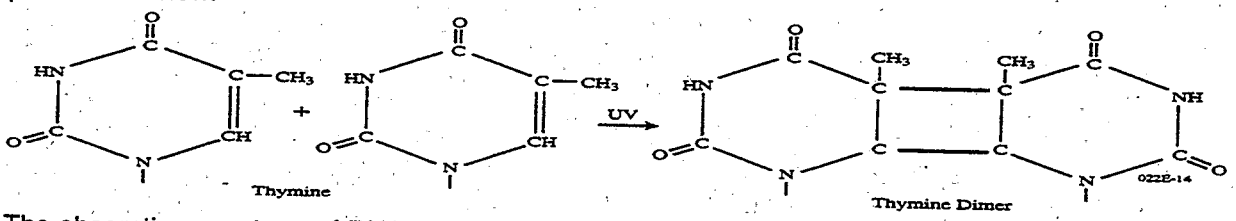
[2]The boundary between the ultraviolet region and the X-ray region at this point is rather arbitrary and could be seen in some references as 10 nm.

Exhibit 1-1. Ultraviolet Light Mode of Action on Microorganisms

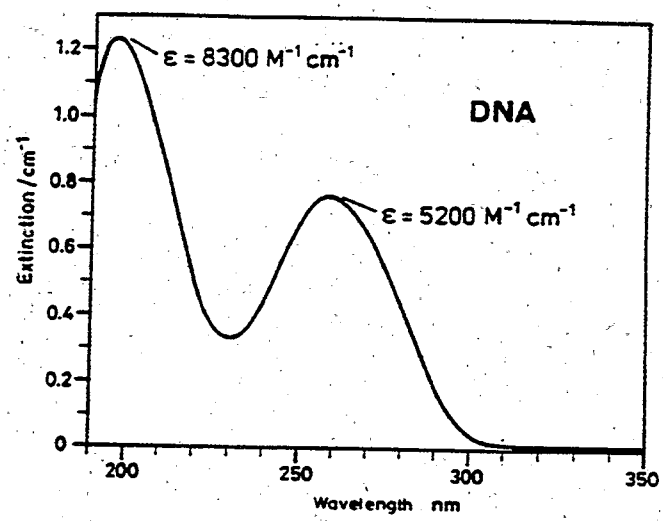
Molecules absorb specific wavelengths of electromagnetic radiation. At a wavelength of approximately 254 nm, some organic constituents of deoxyribonucleic acid (DNA) and of ribonucleic acid (RNA) in a cell absorb ultraviolet light.

DNA is the molecule in a cell that is unique to it and its species. The DNA molecule contains all genetic information that is needed for replication. RNA transcribes the genetic information encoded in the DNA so that the cell can make the enzymes needed to make the organic constituents of the cell. The monomeric units of DNA and RNA, called nucleotides, contain nitrogenous heterocyclic components. The nitrogenous heterocyclic components are uracil, thymine, cytosine, adenine, and guanine. Ultraviolet light causes the formation of dimers such as thymine-thymine dimers, cytosine-cytosine dimers, cytosine-thymine dimers, and uracil dimers (Gaudy and Gaudy, 1980). Dimers occur when the electrons in a covalent bond become out of phase (for further details, see Exhibit B-1 in Appendix B) and form a new bond with electrons from another molecule.

The formation of many dimers along a DNA strand may inhibit replication, which is lethal to the cell. If the ultraviolet light dose was insufficient to cause complete replication inhibition, then replication may occur with errors in the genetic code leading to mutant progeny that are unable to replicate (USEPA, 1986). An insufficient ultraviolet dose may cause limited damage to the DNA, which the cell, under favorable conditions, can repair using its repair enzymes. Viruses have no repair enzymes, so they use the repair enzymes of the host cell. The phenomena of cell reactivation is discussed further in Section 2.4.2 of this report. The effect of ultraviolet light on thymine is presented below.



The absorption spectrum of DNA in aqueous solution presented below show two peaks of maximum ultraviolet light absorption (von Sonntag and Schuchmann, 1992) at about 200 nm wavelength and at about 265 nm wavelength. Also, the absorption spectrum shows that ultraviolet light at above 300 nm is almost not absorbed by DNA.



ε - Molar decadic absorption coefficient in L/mol/cm.
M - Molar concentration.

than regular light bulbs). For example, "Tungsten lamps in quartz envelopes radiate in the ultraviolet range in accordance with Planck's law, slightly modified by the emissivity function of tungsten. Because of its high temperature (3,800°K), the crater of an open carbon arc is an excellent source of ultraviolet radiation, extending to violet emission, mainly in lines and bands. A widely used source of ultraviolet light is the quartz mercury arc" (Van Nostrand, 1989). The inverse relationship between light energy and wavelength is explained by the following formula:

$E = h\nu$
where:
E = Energy in Joules or in watt second
h = Planck's Constant in joules second
ν (nu) = Frequency in hertz or sec^{-1}

$$\nu = \frac{c}{\lambda}$$

c = speed of light in m/sec = 2.9979×10^8 m/sec
λ = wavelength in m.

Therefore $E = h\frac{c}{\lambda}$ and the shorter the wavelength, the greater is the energy of the photon transmitted. For example, the energy of a photon at 253.7 nm is

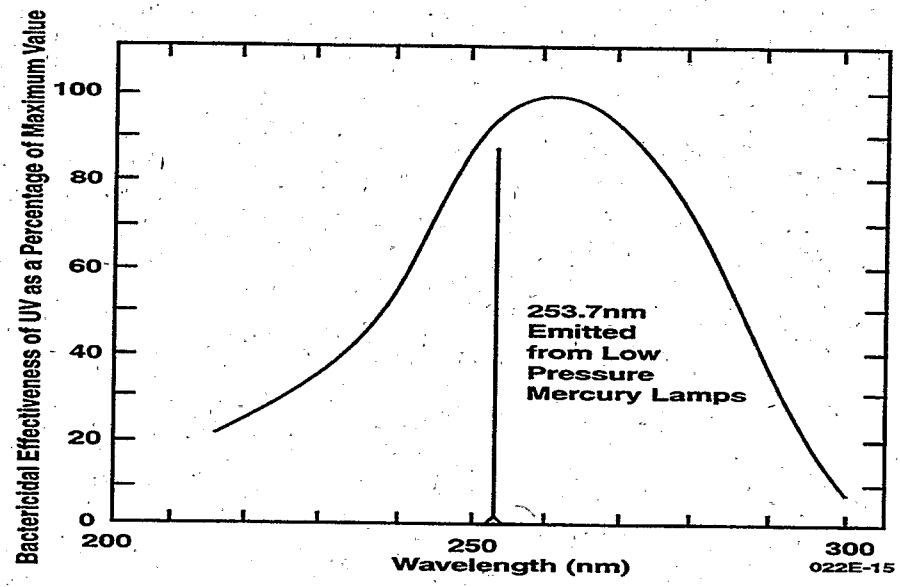
$$E = h\frac{c}{\lambda} = \frac{(6.63\times10^{-34}\text{Joules second})(3.0\times10^{8}\text{m/s})}{(2.537\times10^{-7}\text{m})} = 7.8\times10^{-19}\text{Watt sec or 4.9 eV.}$$

and the energy of a photon emitted at 185 nm is $E = 10.8 \times 10^{-19}$ Watt sec or 6.75 eV.

For water treatment applications two wavelengths are of interest. These wavelengths are 254 nm and 185 nm. These wavelengths are of interest because at these wavelengths ultraviolet radiation significantly affects microorganisms and certain organic chemicals, and because commercially available low-pressure mercury lamps omit most of their ultraviolet light energy at these wavelengths.

The optimum ultraviolet light wavelength range for bactericidal effect is between 250 nm and 270 nm. This was determined by measuring the inhibiting effect of ultraviolet light at different wavelengths on bacterial colony formation (Oda, 1969, as cited in USEPA, 1986). **Exhibit 1-2** shows the most effective spectrum of ultraviolet light for bacterial colony formation inhibition. As can be seen from Exhibit 1-2, the colony forming bacteria is more sensitive to ultraviolet light at a wavelength range of 250 nm to 270 nm than at shorten (high energy wavelengths). Microorganisms other than the tested colony forming bacteria might be more sensitive to ultraviolet light emitted at a different wavelength range. For example, nematodes, worm eggs and tobacco mosaic virus are more sensitive to ultraviolet light emitted at 220 nm (Legan, 1980 as cited in Masschelein, 1992). The literature search did not reveal any practical application of ultraviolet light microorganisms inactivation in the range of 190 nm to 210 nm wavelength, i.e., corresponding to DNA absorption spectrum finding by von Sonntag and Schuchmann, 1992.

Exhibit 1-2. Relative Bactericidal Effectiveness as a Function of Wavelength (Oda, 1969, as cited in USEPA, 1986)



The experimental use of artificial ultraviolet light-emitting low-pressure mercury vapor lamps dates back to 1835 in Europe (Bryant, Fulton, and Budd, 1992). The use of artificial ultraviolet light to disinfect drinking water in the United States dates back to 1916. Between 1916 and 1928, at least four water authorities in the United States used ultraviolet light for disinfection. The highest reported treated flows were 96 to 135 liters per second (l/s) (2.2 MGD to 3.1 MGD) serving a population of up to 12,000 (Jepson, 1972, as reported in Witherell, Solomon, and Stone, 1979). Today, the wide array of ultraviolet light treatment systems used for disinfection of water and wastewater, the increase in demand, and the experience gained over the years within the United States and abroad have led to a new generation of ultraviolet systems for water and wastewater disinfection applications. Many of the old problems that plagued the industry from its early years to the mid 1980s, such as costs and problems with operation and maintenance (O&M) (e.g., water leaks), have been solved or have become manageable (Witherell, Solomon, and Stone, 1979; Aquafine, 1995). Furthermore, ultraviolet technology is a major and essential element and component in the disinfection processes used in the food and the pharmaceutical industries and other specialized industries that require pathogen-free and chemical-free sterile water (NIOSH, 1995).

Cost trends show a decline as more ultraviolet light technology has been developed and used in water and wastewater disinfection processes (Hoehn, 1976, USEPA, 1992b, USEPA, 1993a, USEPA, 1993b). In its most recent study on ultraviolet use for disinfecting wastewater, the Water Environment Research

Foundation (WERF, 1995) provided annualized costs (capital and O&M) that clearly show the economic feasibility of ultraviolet technology for wastewater disinfection. The study shows that the costs of ultraviolet systems vary widely; nevertheless, these costs are considerably less than the costs of comparably designed chlorination systems for treating wastewater effluents. The costs provided in the WERF study reflect the costs of ultraviolet systems designed to deliver a minimum dose of 140 milliWatts second per square centimeter (mWs/cm^2) of ultraviolet light.

1.2 GENERAL DESCRIPTION OF ULTRAVIOLET LIGHT TECHNOLOGY

Ultraviolet radiation is generated by striking an electric arc through mercury vapor contained in a lamp. Because ordinary glass absorbs ultraviolet light, the lamp is made of special ultraviolet light transmitting quartz, polymer or silica. There are several types of ultraviolet lamps, including the low-pressure mercury vapor lamp, which emits primarily at a wavelength of 253.7 nm (approximately 85% of the light energy emitted) with a lesser output at 184.9 nm. The low-pressure mercury vapor lamp is the lamp that is used primarily for drinking water treatment. **Exhibit 1-3** shows the emission spectrum of a low-pressure mercury lamp and a medium-pressure mercury lamp, demonstrating that in low-pressure lamps, most of the ultraviolet light energy is emitted at 254 nm wavelength, while in a medium-pressure lamp, the ultraviolet light energy is emitted across a broad range of the visible light and ultraviolet light portion of the spectrum. Exhibit 1-3 was constructed from spectrum tables cited in Legan, 1982. The medium-pressure mercury vapor lamp is used primarily for treatment of wastewater and water contaminated with organic compounds, typically for contaminated groundwater.

When the electrons in the electric current run through the mercury vapor, the excited mercury molecules emit ultraviolet light. A good portion of the electric energy is transformed into heat, which necessitates quartz sleeves that are larger in diameter than the lamp itself (1.5 to 2.5 cm in diameter) to encase the lamp. This quartz sleeve serves as an important barrier between the cool water flow and the hot lamp. Ultraviolet technology applications in water and wastewater fall into two categories: closed systems and open channel systems. The closed systems can be further subcategorized as either contact units or non-contact units. Contact units consist of ultraviolet lamps encased in quartz around which the water or liquid to be disinfected flows. Non-contact units are designed such that the ultraviolet lamps transmit energy to Teflon pipes through which the water or liquid to be disinfected flows. The open channel systems consist of submerged ultraviolet lamps either vertically or horizontally suspended in an open channel. **Exhibits 1-4, 1-5, 1-6, 1-7,** and **1-8** present schematic drawings of different types of ultraviolet systems

Exhibit 1-3. Emission Spectra of Low-Pressure and Medium-Pressure Mercury Lamps (based on Legan, 1982)

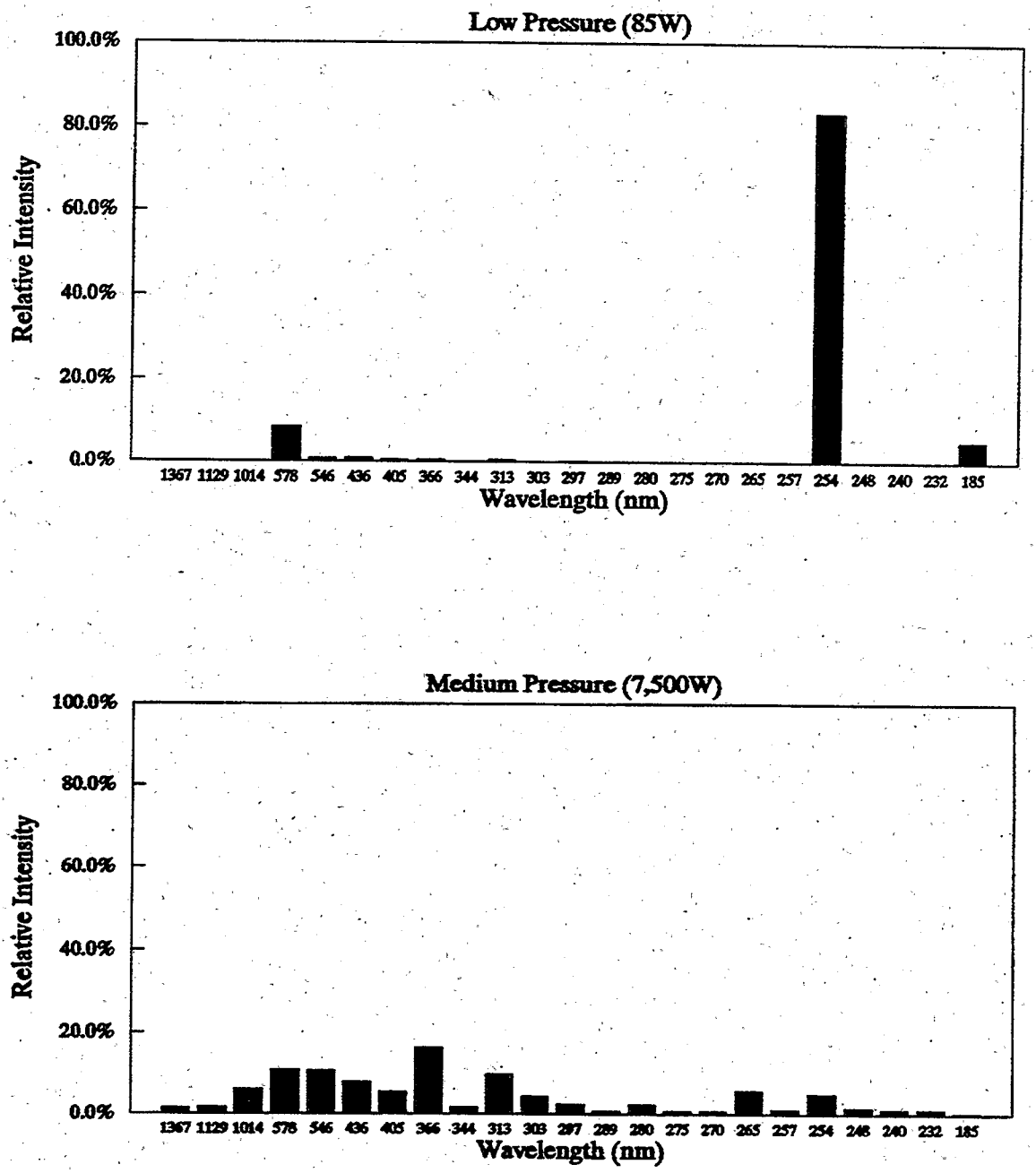


Exhibit 1-4. Non-Contact Ultraviolet Disinfection Unit (USEPA, 1986)

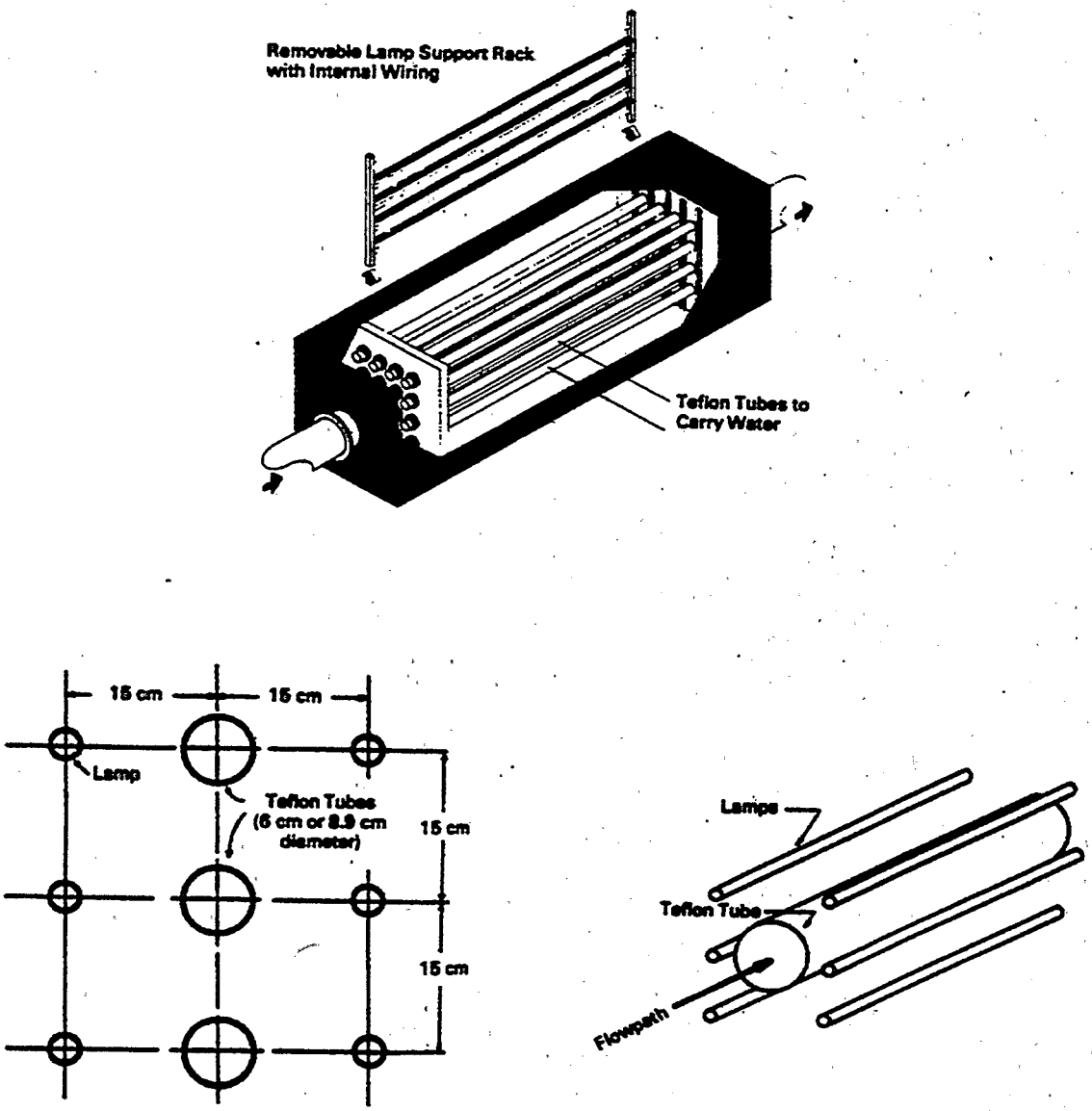


Exhibit 1-5. Closed Vessel Ultraviolet Reactor (USEPA, 1986)

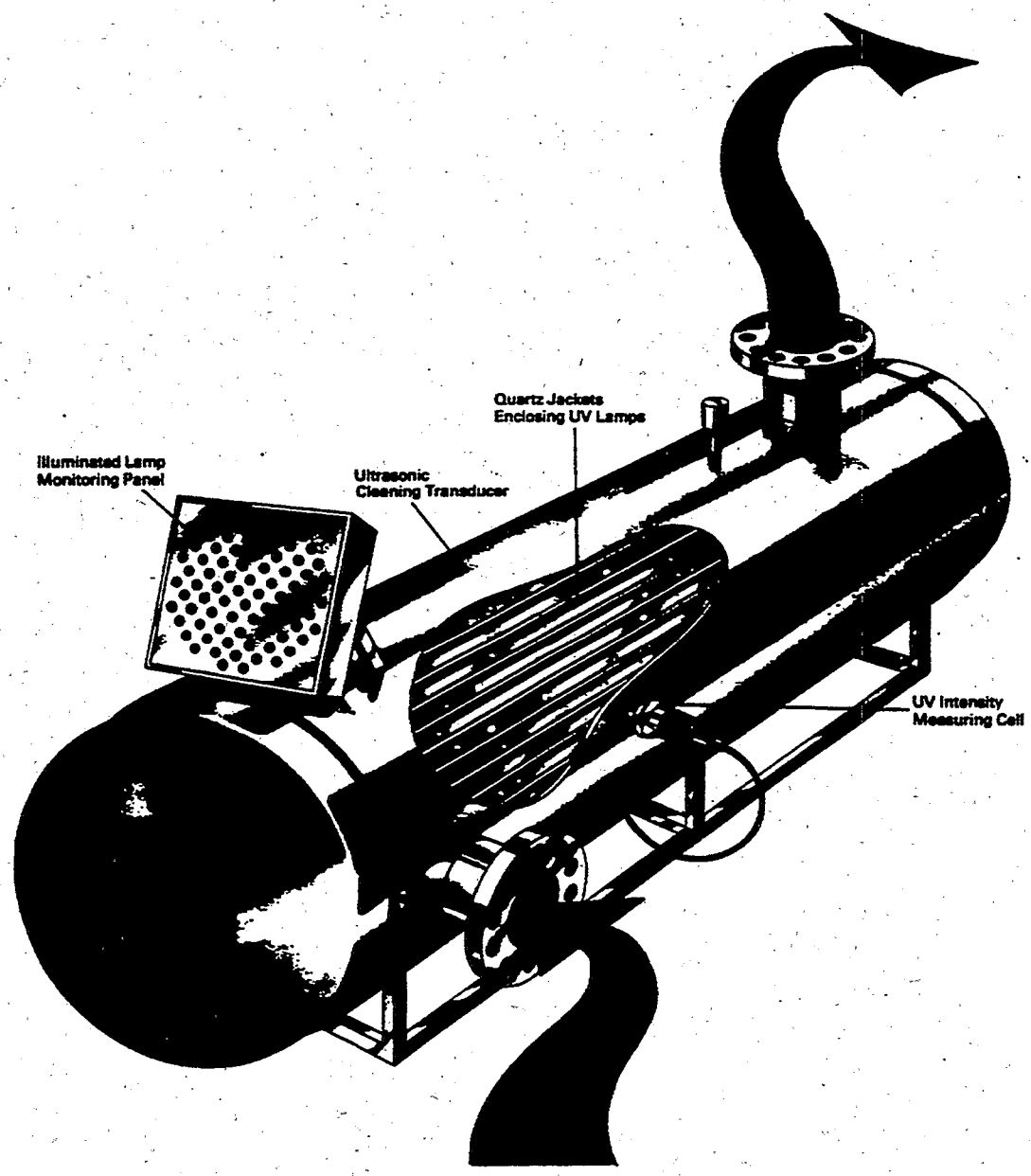
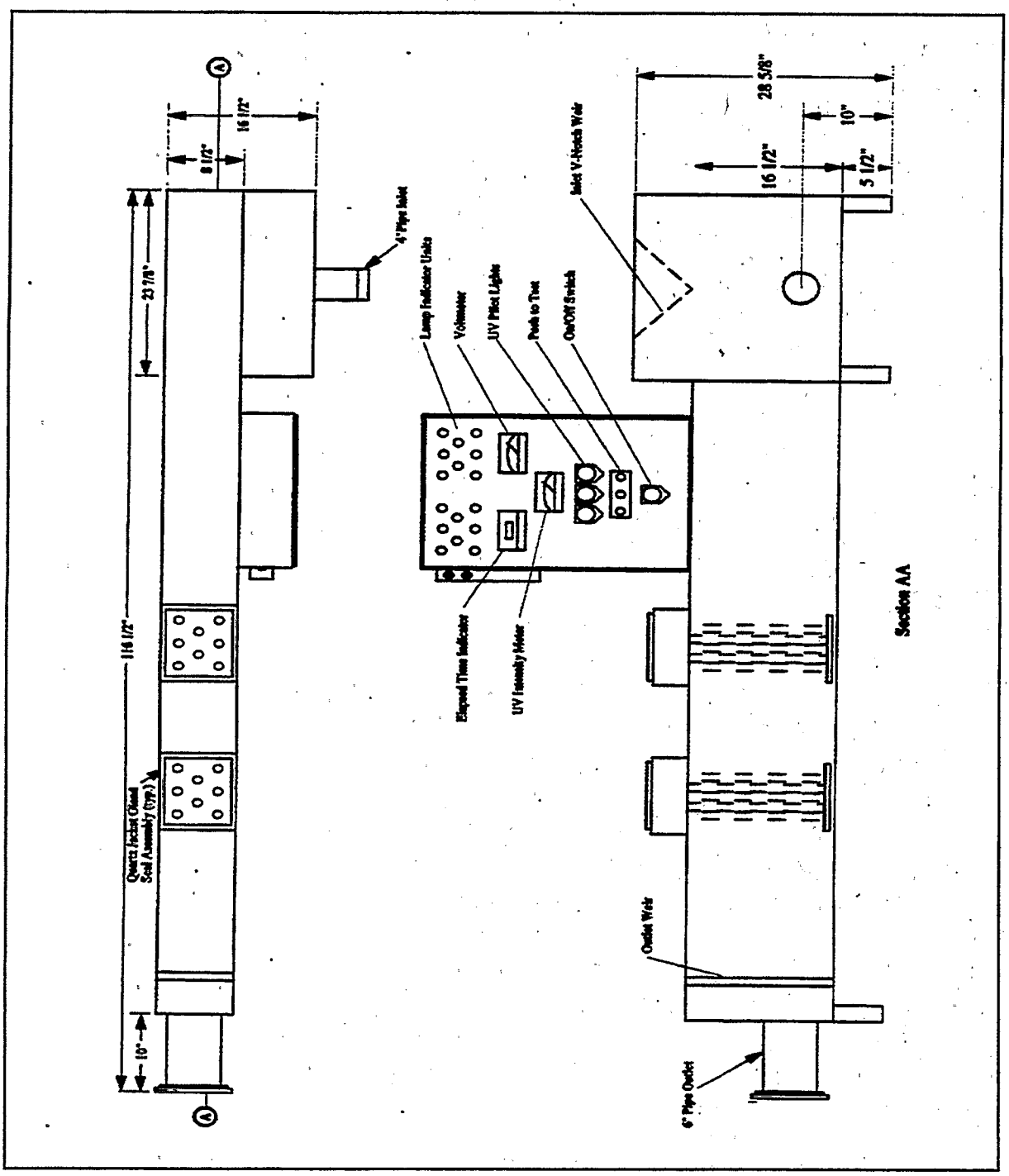


Exhibit 1-6. Vertically Mounted Ultraviolet Lamps in an Open Channel System (WERF, 1995)



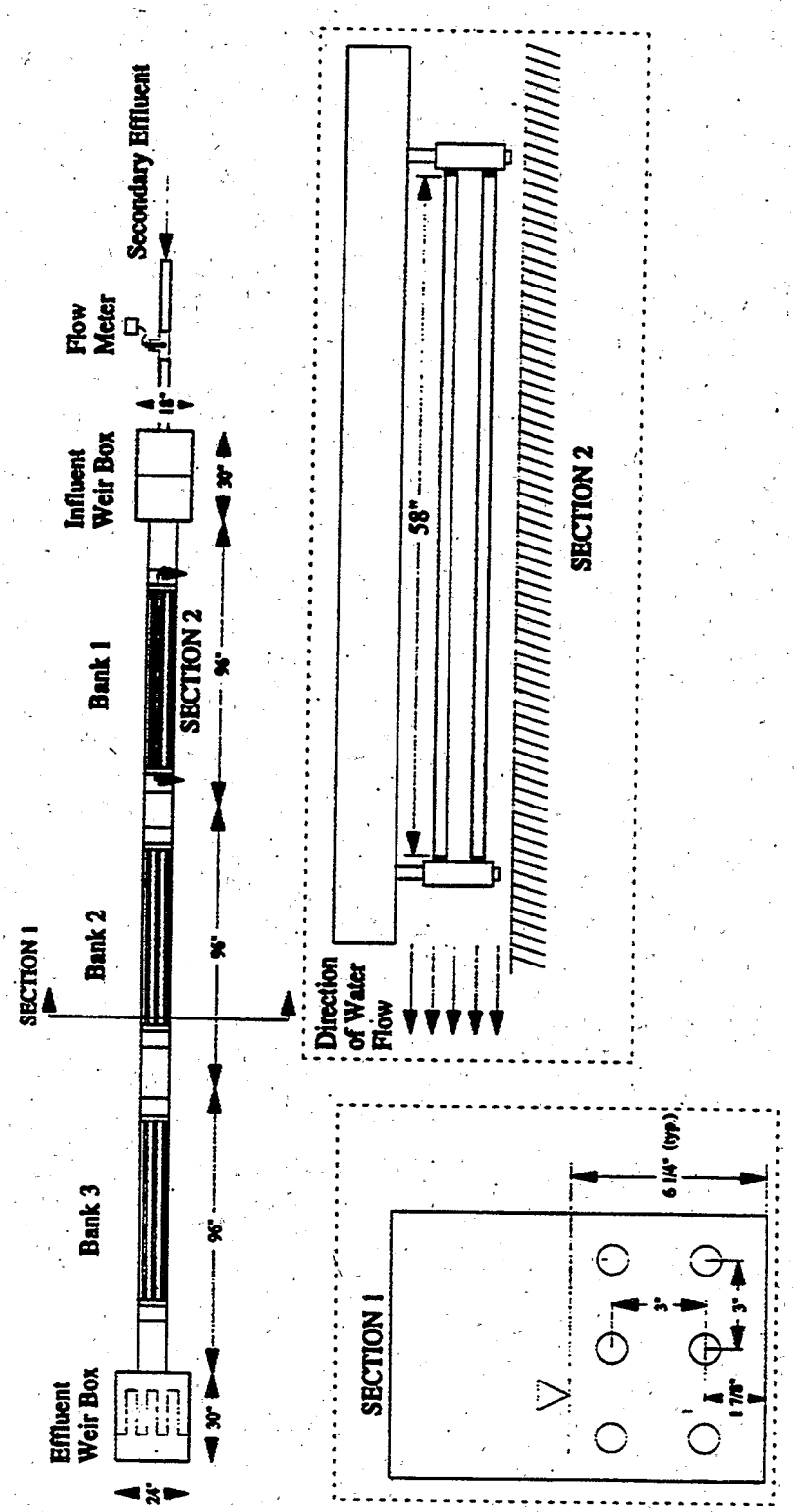
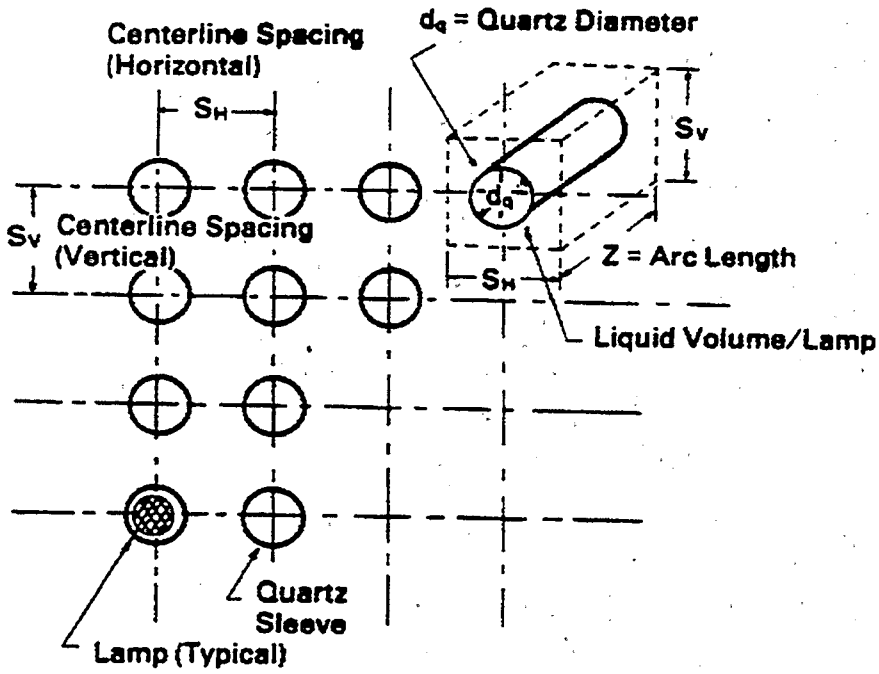
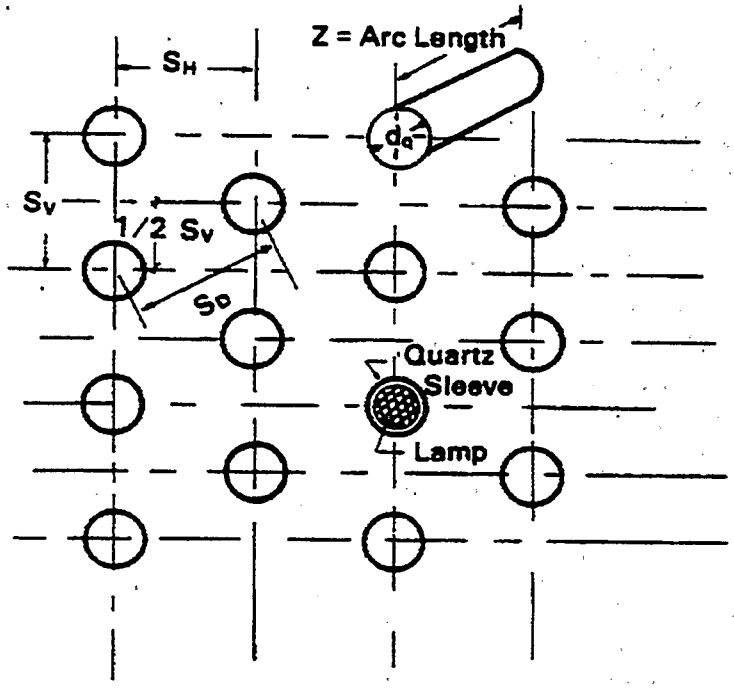


Exhibit 1-7. Horizontally Mounted Ultraviolet Lamps in an Open Channel System (WERF, 1995)

Exhibit 1-8. Example of Lamp Arrangement in an Ultraviolet Reactor (USEPA, 1986)



(a) Uniform Array



(b) Staggered Uniform Array

and lamp arrangements. Open systems are commonly used in wastewater applications, while closed systems are commonly used in drinking water applications to maintain positive pressure thus avoiding the need to repump and to minimize contamination.

1.3 EXISTING GUIDELINES FOR ULTRAVIOLET LIGHT DISINFECTION IN DRINKING WATER APPLICATIONS

In this section, standards and guidelines set by Federal and State agencies and nationally recognized institutions are presented. In addition, the available standards from Europe are presented. The current guidelines in place for the use of ultraviolet radiation for drinking water disinfection on ships were released by the U.S. Department of Health, Education, and Welfare (DHEW), Public Health Division of Environmental Engineering and Food Protection, in 1966. The guidelines require a minimum dose of 16 milliwatts second per square centimeter (mWs/cm^2) at all points throughout the water disinfection chamber. The policy statement requires that a 3-inch maximum distance be kept between the surface of the lamp and the walls of the chamber. Evidently, this low dose requirement, as well as other early O&M issues, led to problems that were evident on vessels using ultraviolet light for water disinfection (DHEW CDC, 1974).

Several States in the United States recognize ultraviolet light technology as an acceptable technology for disinfecting ground water. The State of New Jersey, and the State of Pennsylvania as stated in their drinking water regulations and following the guidelines of DHEW, require a minimum dose of 16 mWs/cm^2 (NJ, 1985) to be applied to disinfect ground water sources. Other States, allow the use of ultraviolet light in disinfecting drinking water on a case-by-case basis. At least five States' codes (Arizona, Delaware, Massachusetts, North Carolina, and Wisconsin) require that an ultraviolet light disinfection system meet ANSI/NSF Standard 55-1991 (discussed below), while at least four other States (Alaska, Idaho, Kansas, and Vermont) forbid the use of ultraviolet light for water disinfection in public water systems.

Appendix D of this report contains samples of State criteria for ultraviolet treatment for non-community public and private water supplies. Appendix D also includes the main section of ANSI/NSF Standard 55-1991. The State of Wisconsin requires that systems meet the ANSI/NSF Standard 55-1991 for Class A treatment units. It also has set criteria for ultraviolet water treatment devices used at non-community public water supplies to control microbiological contamination (Wisconsin Department of Natural Resources [DNR], Nov. 17, 1995). In the State of Wisconsin, eligibility is based on a finding of

microbiological contamination, based on positive total coliform or *Escherichia coli* tests, failure of system batch chlorination to eliminate the problem, and a decision that well reconstruction or replacement would not correct the problem. Water quality characteristics (with "maximum" and "preferred" levels) have been specified in addition to detailed design and operational criteria, among which are the following:

- Ultraviolet radiation at 253.7 nanometers wavelength with minimum dose of 38 mWs/cm^2.
- Quartz or high silica glass jacket and stainless steel housing materials.
- Assemblies must provide accessibility for viewing, cleaning and replacements.
- An alarm and automatic shutdown valve triggered by lamp failure or dose deficiency.
- Identical parallel ultraviolet systems.
- $5\mu_m$ sediment prefilter and a cyst reduction filter.

Coliform monitoring, turbidimeter installation on systems exhibiting turbidity variation, and record keeping provisions are also included (WI, 1995). As stated earlier, Appendix D contains the Wisconsin DNR criteria in addition to other States criteria for ultraviolet drinking water disinfection systems.

Ultraviolet light equipment installed in water vending machines is regulated by the FDA. The FDA "standard" for the use of ultraviolet light for disinfecting water sold in these machines is part of the Good Manufacturing Practice Code. The Code is somewhat vague in that it requires only that the equipment disinfect the water; it does not specify a minimum intensity, dose, or log reduction of a surrogate microorganism (FDA, 1995).

The ANSI/NSF standard 55-1991, which covers Point-of-Use (POU) and Point-of-Entry (POE) ultraviolet light applications, clearly states that these ultraviolet systems are not intended to be used with water that has an obvious contamination source or to reuse treated wastewater in drinking activities (ANSI/NSF, 1991). ANSI/NSF 55-1991 differentiates between POU and POE systems. Class A systems can be used as POU or POE and require a minimum ultraviolet light dose of 38 mWs/cm^2, based on the inactivation of *Bacillus subtilis* spores. Class B systems are POU systems with a minimum ultraviolet light dose of 16 mWs/cm^2. This dose was determined based on the inactivation of *Saccharomyces Cerevisiae* yeast. Because most vegetative bacteria (i.e., bacteria that propagate by non-sexual processes), including coliform species, are too susceptible to ultraviolet radiation at the dose range of 16 mWs/cm^2 to allow for measurable testing, *Saccharomyces cerevisiae* was chosen as the test challenge to allow for a reasonable influent concentration and an easily measured reduction in the effluent (ANSI/NSF, 1991).

The protocol detailed in ANSI/NSF standard 55-1991 for sensitivity calibration of challenge organisms requires that laboratory cultured microorganisms be suspended in buffered water. The ANSI/NSF standard clearly states that the systems are intended to be used on visually clear water. 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 intended to be used as supplemental bactericidal treatment and to reduce non-pathogenic or nuisance microorganisms only.

The European Union (EU) drinking water directive 80/788/EEC does not specify a treatment technology or technologies for public water systems to achieve levels below the Maximum Admissible Concentrations (MAC) specified for microbiological parameters. The EU directive 80/788/EEC microbiological parameters include total coliforms, fecal coliforms, fecal streptococci, sulphite-reducing clostridia, and total bacteria counts. (OJC, 1990, Eureau, 1992). The EU microbiological parameters are presented in **Exhibit 1-9**.

Also, the EU drinking water directive does not specify disinfection procedures or set a minimum ultraviolet dose requirement. However, the directive specifies certain microorganisms for testing and requires in a general statement that the water intended for human consumption be pathogen-free. Some EU member states have a minimum dose requirement for ultraviolet light systems. In Norway, for example, the minimum acceptable ultraviolet light dose for pretreated drinking water is 16 mWs/cm^2 measured at the chamber wall (NIPH, 1989). In Austria, the minimum acceptable ultraviolet light dose level for pretreated drinking water disinfection is 30 mWs/cm^2 (Sommer and Cabaj, 1993).

1.4 AVAILABILITY OF ULTRAVIOLET TECHNOLOGIES FOR GROUND WATER DISINFECTION

To determine the availability of ultraviolet systems hardware in the U.S. market, with emphasis on systems used in water disinfection, USEPA attempted to obtain information to address the following questions:

- Is there enough experience and knowledge about the technology to render the risks of using it calculable or acceptable?
- Is the technology currently available, and can it be delivered in a reasonable time? Are the equipment and spare parts available to the consumer in a reasonable time?
- Is the use of the technology economically feasible?

Exhibit 1-9. EU Microbiological Parameters Drinking Water Directive 80/778/EEC

Water intended for human consumption should not contain pathogenic organisms. If it is necessary to supplement the microbiological analysis of water intended for human consumption, the samples should be examined not only for the bacteria referred to below but also for pathogens including the following:

- Salmonella
- Pathogenic staphylococci
- Fecal bacteriophages
- Enteroviruses.

Nor should such water contain the following:

- Parasites
- Algae
- Other organisms such as animalcules (worms-larvae).

Parameters	Results: Volume of the Sample in ml	Guide Level (GL)	Maximum Admissible Concentration (MAC)	
			Membrane Filter Method	Multiple Tube Method (MPN)
Total Coliforms[a]	100	--	0	MPN < 1
Fecal Coliforms	100	--	0	MPN < 1
Fecal streptococci	100	--	0	MPN < 1
Sulphite-reducing Clostridia	20	--	--	MPN ≤ 1

Parameters	Temperature	Results: Volume of the Sample in ml	Guide Level (GL)	Maximum Admissible Concentration (MAC)
Total bacteria counts for water supplied for human consumption	37°C	1	10[b,c]	--
	22°C	1	100[b,c]	--
Total bacteria counts for water in closed containers	37°C	1	5	20[d]
	22°C	1	20	100[d]

[a] Provided a sufficient number of samples is examined (95% consistent results).

[b] For disinfected water the corresponding values should be considerably lower at the point where it leaves the processing plant.

[c] If, during successive sampling, any of these values is consistently exceeded, a check should be carried out.

[d] MAC values should be measured within 12 hours of being put into closed containers with the sample water being kept at a constant temperature during that 12-hour period.

Exhibit 1-9. EU Microbiological Parameters Drinking Water Directive 80/778/EEC (Continued)

Parameter	Analytical Method	Incubation Period
Total Coliforms	Fermentation in multiple tubes. Subculturing of the positive tubes on a confirmation medium. Count according to MPN (most probable number).	24 to 48 hours
Fecal Coliforms	Membrane filtration and culture on an appropriate medium such as Tergitol lactose agar, endo agar, 0.4% Teepol broth, subculturing and identification of the suspect colonies • Incubation temperature for total coliforms: 37°C • Incubation temperature for fecal coliforms: 44°C	24 to 48 hours
Fecal Streptococci	Sodium azide method (Litsky). Count according to MPN—Membrane filtration and culture on an appropriate medium.	24 to 48 hours
Sulphite-Reducing Clostridia	A spore count, after heating the sample to 80°C by: • Seeding in a medium with glucose, sulphite and iron, counting the black-halo colonies • Membrane filtration, deposition of the inverted filter on a medium with glucose, sulphite and iron covered with agar, count of black colonies • Distribution in tubes of Differential Reinforced Clostridial Medium (DRCM), subculturing of the black tubes in a medium of litmus-treated milk, count according to MPN.	24 to 48 hours
Total Counts	Inoculation by placing in nutritive agar.	48 to 72 hours
Salmonella	Concentration by membrane filtration. Inoculation on a pre-enriched medium. Enrichment, subculturing on isolating agar. Identification.	
Pathogenic Staphylococci	Membrane filtration and culture on a specific medium (e.g., Chapman's hypersaline medium). Test for pathogenic characteristics.	
Fecal Bacteriophages	Guelin's process.	
Enteroviruses	Concentration by filtration, flocculation or centrifuging, and identification.	
Protozoa	Concentration by filtration on a membrane, microscopic examination, test for pathogenicity.	
Animalcules (worms - larvae)	Concentration by filtration on a membrane, microscopic examination, test for pathogenicity.	

This study identified 14 firms in the United States that manufacture and/or distribute ultraviolet light equipment for disinfection of water and other media. Ultraviolet light technology is used extensively for disinfection and sterilization in the food industry, electronics industry, spas and swimming pools, ships, the health industry (hospitals, clinics, and pharmaceutical manufacturing facilities), wastewater facilities and laboratories. Other applications of ultraviolet technology include special applications in the space and defense industries, testing and monitoring equipment industry, and chemical manufacturing industry. (Zumdahl, 1989).

Ultraviolet light is not used extensively at drinking water facilities in the United States. According to the American Water Works Association (AWWA, 1992), about 500 drinking water treatment facilities use ultraviolet light for disinfection in North America. More recent data show that more than 1,000 drinking water treatment facilities in the United States use ultraviolet light for disinfection, alone or in combination with a secondary disinfectant (PA, 1996 and NY, 1995).

Ultraviolet light for drinking water disinfection is also used in POU systems, water-vending machines, and private homes (McSwane, 1994). **Exhibit 1-10** presents a list of manufacturers/distributors of ultraviolet light equipment in the United States. Most of these firms are located on the East Coast, and a few are in California. Exhibit 1-10 includes six foreign firms (Swiss, Canadian, and British) that export ultraviolet equipment to the United States. The list provided in Exhibit 1-10 was compiled from different sources and is believed to be a comprehensive list of ultraviolet light manufacturers of products for water and/or wastewater disinfection or remediation from organic contamination (NIOSH, 1995).

In public facilities (water and wastewater), most of the current ultraviolet light disinfection market is in the wastewater treatment field. The ultraviolet equipment designed and manufactured to disinfect wastewater delivers intensities that are much higher than the intensities generally used for drinking water disinfection.

There are three available types of ultraviolet light disinfection systems in the U.S. market. The two most widely used types are (1) the closed chamber ultraviolet disinfection system and (2) the open channel ultraviolet disinfection system. A third closed system called the non-contact reactor is also available but not as popular as the other two. The open channel system is used mainly for large flows (roughly 2,000 GPM or 2.9 MGD). This system does not require pumping and usually is custom designed. The closed chamber system is used for small flows (with units that can handle up to 600 GPM per unit). This system

Exhibit 1-10. List of Companies and Individuals That Are Actively Involved in the Ultraviolet Industry, Either as Manufacturers or as Major Distributors[a]

Mr. De Vos, President
AMWAY Corporation
7575 East Fulton Road
Ada, MI 49355
(616) 787-6279

Ms. Roberta Veloz, President
Mr. Bak Srikanth, Senior Applications Engineer
Aquafine, Corporation
25230 West Avenue Stanford
Valencia, CA 91355
(800) 423-3015 ext. 651 or
(805) 257-4770; fax: (805) 257-2489

Ms. Colleen O'Neil
Aquafine Wedeco Environmental Systems, Inc.
25647 Rye Canyon Road
Valencia, CA 91355
(800) 992-1314
fax: (805) 257-5870

Mr. David McCarty, President
Aquionics, Inc.
21 Kenton Lands Road
P.O. Box 18395
Erlanger, KY 41018
(606) 341-0710; fax: (606) 341-2302

Mr. Hilary Boehme, President
Contact person: Ms. Ann Wysocki, Marketing Director
Atlantic Ultraviolet Corporation
375 Marcus Boulevard
Hauppauge, NY 11788
(516) 273-0500; fax: (516) 273-0771

Mr. Steven W. Fierce, President
Contact person: Mr. Leon Martin
Capital Controls Company
3000 Advance Lane
P.O. Box 211
Colmar, PA 18915
(215) 997-4000; fax: (215) 997-4062

Mr. Karl Scheible, President
Hydroqual, Inc.
1 Lethbridge Plaza
Mahwah, NJ 07430
(201) 529-5151; fax: (201) 529-5728

Mr. Mark Kurtz
Contact person: Jesse Rodriquez
Ideal Horizons
1 Ideal Way
Putney, VT 05764
(802) 287-4488; fax: (802) 287-4486

Mr. Art Shapiro
Contact persons: Mr. Geronomo Balallo,
Mr. Kevin Smith, Mr. Mervyn Bowen
Infilco-Degremont
8924 Emerywood Parkway
Richmond, VA 23294
(800) 446-1150; fax: (804) 756-7643

Mr. John Kenin
Contact person: Mr. Peter Waldrin ext 434
Ionic Corporation
65 Grove Street
Watertown, MA 02172
(617) 926-2500; fax: (617) 926-4304

Mr. Donald Lander, Vice President
Pure Pulse
8888 Balboa Avenue
San Diego, CA 92123
(619) 496-4100; fax: (619)576-1377

Mr. Charles R. Reading, Jr., Director
Safe Water Solutions L.L.C.
20 Hollow Horn Road
Erwinna, PA 18920
(610) 294-9376; fax: (610) 294-9590

Mr. Jim Donallen, President
Ultra Dynamics Corporation
299 W. Fort Lee Road
Bogata, NJ 07603
(800) 727-6931; fax: (201) 489-9229

Mr. Bill Himebaugh
Ultrox Division of Zimpro Environmental
7755 Center Avenue, #1100
Huntington Beach, CA 92647
(714) 545-5557; fax: (714) 557-5396

Foreign Companies Involved in Ultraviolet Applications in the United States

Mr. Marc Parella
Bailey, Fischer & Porter
134 Norfinch
Downsview, Ontario M3N 1X7, Canada
(416) 667-9800; fax: (416) 667-8469

Katadyn Products Switzerland
Oberwiessen Strasse
CH-8304 Wallisellen, Switzerland
Tel 011-41-1-839-2111; fax: 011-41-1-830-7942

Mr. Brian Butters
Mr. Tony Powell
Purifics
Ontario, Canada
(519) 473-5788; fax: (519) 473-0934

Amway (JAPAN) Ltd.
Nihon Seimei
Minami Azabu Building 2-8-12
Minami Azabu Minatoku
Tokyo, 106 JAPAN

Mr. Mike Farrimond
Severn Trent Water
2297 Coventry Road
Birmingham B26 3PU, UK
011-44-21-722-4000; fax: 011-44-21-722-4597

Mr. Hank Vanderlann, President
Contact person: Mr. Gary Vanderlann
Trojan Technologies
3020 Gore Road
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[a]This list was compiled from the AWWA manufacturers catalogue, EPA documents on ultraviolet light technologies that date back to 1983, Water & Wastewater Equipment Manufacturers Association (WWEMA), National Sanitation Foundation (NSF) International, GWDR Docket records, and the National Drinking Water Clearinghouse Treatment Technology database. This list was verified and updated as of September 1996.

requires pumping but is more readily available and is easier to install. The ultraviolet industry can deliver standard closed system units in less than 4 weeks. The ultraviolet industry claims that it can assess the requirements (or design), ship, and install a closed system in 4 to 8 weeks on average and an open channel system in about 12 weeks.

The ultraviolet units available in the market are used as stand-alone treatment systems or as a part of a series of other drinking water treatment processes. A common treatment train using ultraviolet light for contaminant removal and disinfection of ground water sources involves a combined ozone or hydrogen peroxide process along with ultraviolet application. Therefore, it is common to find that the manufacturers of ultraviolet equipment are ozone equipment manufacturers as well. Furthermore, the industry also provides ultraviolet equipment (mainly the closed chamber units) for short-term uses. Rental units are used in cleanup and emergency situations, such as ground water contaminated with spilled toxic organic compounds.

1.5 ULTRAVIOLET LIGHT SYSTEMS IN WATER AND WASTEWATER APPLICATIONS

The American Water Works Association (AWWA, 1992) reported that more than 2,000 water treatment facilities in Europe use ultraviolet light for disinfection.

In the United States, more than 1,000 drinking water treatment facilities use ultraviolet light for disinfection, alone or in combination with a secondary disinfectant. For example, in the State of New York, 6.4 percent of ground water systems with some kind of treatment (264 ground water systems out of 4,141 ground water systems with treatment records) use ultraviolet light for drinking water disinfection (NY, 1995).

In the State of Pennsylvania, of the 10,700 PWS systems, 761 systems use ultraviolet light for disinfection alone or in combination with a chlorine disinfectant at 843 treatment facilities. All the systems using ultraviolet light for disinfection are ground water systems. Out of the 843 treatment facilities, only 26 treatment facilities use ultraviolet light in combination with a chlorine disinfectant. These figures do not include bottled water systems, vending water systems, bulk water hauling, or retail systems that often use ultraviolet light for disinfection. About 77 percent of the systems using ultraviolet light for disinfection are TNC ground water systems, 18 percent are NTNC ground water systems, and 4 percent CWS ground water systems (percentages do not add to 100 because of rounding). The statistics of population served by these systems show that 82 percent of the systems serve less than 200 people and 96 percent of the

systems serve less than 500 people. During Pennsylvania State fiscal year 1995, less than 3 percent of the drinking water systems using ultraviolet light for disinfection experienced MCL bacteriological violation (PA, 1996). The State of Pennsylvania requires a minimum ultraviolet light dose of 16 mWs/cm^2 for drinking water disinfection (see appendix D).

Ultraviolet disinfection has been employed in European drinking water treatment plants since 1955. Ultraviolet disinfection became very popular following the awareness about the dangers of trihalomethanes (THM) formation during chlorination (Zoeteman et al., 1982). **Exhibit 1-11** shows a profile of ultraviolet light applications in drinking water in three European countries. As can be seen from Exhibit 1-11, the number of water treatment plants using ultraviolet light for drinking water disinfection in Norway rose from no plants to 400 plants in a period of 10 years. This indicates that, in Norway, ultraviolet technology is a feasible and demonstrated technology when compared to other disinfection technologies.

Exhibit 1-11. Application of Ultraviolet Disinfection in Three European Countries (Kruithof, 1992)

Country	First Application	Number of Installations in 1985	Maximum Capacity m^3/hr (gpd)
Switzerland	1955	500	400 (2,536,060)
Austria	1955	600	500 (3,170,075)
Norway	1975	400	1,000 (6,340,149)

In the Netherlands, ultraviolet light has been applied to disinfect drinking water. Ultraviolet technology is used to destroy *Escherichia coli* and Aeromonas bacteria or to decrease colony counts in ground water, as well as in bank-filtered water following GAC filtration. Ultraviolet light also is used to replace post chlorination in extensively pre-treated surface water (Kruithof et al., 1992). The capacity of treatment plants that use ultraviolet light for disinfection in the Netherlands is between 80 and 2,700 m^3/hr (0.5 MGD to 17.1 MGD) with the majority between 0.5 and 5.1 MGD. Kruithof et al. (1992) reported that the largest surface water plant in the Netherlands (18,000 m^3/hr [114 MGD]) is considering the use of ultraviolet disinfection with medium pressure mercury lamps for organics control and disinfection. The purpose of employing ultraviolet light for disinfection in three out of four under construction and planned water treatment plants in the Netherlands (Kruithof et al., 1992) is to reduce bacterial colony counts (plate count agar at 37°C) in the finished water. The water sources for these under construction and planned plants are surface and bank-filtered water.

Wolfe (1990) reported that a 14.5 MGD drinking water treatment in London, England, uses ultraviolet light for primary disinfection and chlorine for residual disinfection. The treatment plant uses an array of low-pressure ultraviolet lamps in combination with 16 medium pressure lamps.

Unlike chemical disinfectants, continuous use of ultraviolet light and overdosing does not pose any known health risks. Gilpin et al. (1985) investigated the applicability of ultraviolet light to disinfect recirculating water in systems such as whirlpools and hydrotherapy tubs in hospitals. Gilpin et al. (1985) found that at ultraviolet light intensity of 0.001 mW/cm^2 and for a period ranging from 45 minutes to 90 minutes (dose range 2.25 mWs/cm^2 to 4.5 mWs/cm^2) all tested *Legionella spp.* and *pseudomonas aeruginosa* were completely destroyed. The same inactivation results were obtained by chemical disinfection using a free chlorine concentration of 2 mg/l for 30 minutes. For recirculating water systems, continuous ultraviolet light disinfection has the advantage of not requiring repeated chemicals additions and the advantage of not altering the chemical nature of the water.

Sobotka (1992) studied the application of ultraviolet light in combination with ceramic filtration to disinfect water in swimming pools, health facilities' pools, and water works. Sobotka (1992) reported that ultraviolet disinfection capability improved when ceramic filters were used prior to ultraviolet treatment. Also, Sobotka reported that ultraviolet treatment made it possible to reduce chlorine residue in therapeutic pools in hospitals from 0.4 mg/l to 0.2 mg/l.

In 1990, approximately 500 to 600 ultraviolet systems were operating in wastewater plants in the United States (USEPA, 1992). The majority of ultraviolet operating systems were open-channel systems. **Exhibit 1-12** presents a comparison by category of ultraviolet systems in operation at wastewater treatment plants between 1984 and 1990. As can be seen from Exhibit 1-12, a significant shift from closed systems to open-channel systems occurred in wastewater application. The greatest share loss in system type application was in the Teflon systems. This decrease in use is due to problems related to Teflon degradation and cleaning considerations.

However, unlike wastewater application, ultraviolet light systems used in potable and sterile water applications are more commonly closed systems. The ultraviolet industry representatives contacted indicated that closed-chamber systems are the only systems used to disinfect and purify water in the beverage and food industry, pharmaceutical industry, power generation industry, electronics industry,

Exhibit 1-12. Ultraviolet Systems in Wastewater Applications in 1984 and 1990

Year	1984	1990
Number of Plants	50-60	500-600
Flows <1 MGD	80%	50%
1-20 MGD	20%	47%
> 20 MGD	--	3%
Closed Systems	84%	32%
Non-Contact (Teflon)	35%	7%
Contact	49%	25%
Open Channel	8%	66%
Horizontal Lamp Configuration	100%	85%
Vertical Lamp Configuration	--	15%
Other	8%	2%

(Source: USEPA, 1992)

household-type potable water applications, and total organic carbon (TOC) reduction applications in contaminated ground water at Superfund sites.

The reasons for industry's preference for using the closed ultraviolet light system versus the open system in water purification applications are the following:

- Minimal or no exposure hazard to workers as compared to open-channel systems.
- Very small space requirement and low or no construction costs. For example, the dimensions of a treatment chamber required to treat a 475 gpm (0.68 MGD) flow of water are 67×16×25 inches (Aquafine, 1995).
- Simplicity of installation because of modular design.
- Low maintenance, particularly with systems equipped with automatic mechanical wipers and/or ultrasonic cleaners.
- The array of alarm systems that would alert an operator to minor or major problems. (With monitoring systems mounted on the ultraviolet unit and/or connected to other remote monitoring devices, a water treatment plant operator will always be alerted to any malfunction.)
- Minimal need to store chemicals (nonhazardous cleaning detergents or chemicals).

The components of an ultraviolet light unit that is used in a typical potable water disinfection application are as follows:

- A stable source of electricity. Low line voltage would result in a lower ultraviolet dose.
- A chamber made of stainless steel or any other material that is opaque and would not corrode by the action of ultraviolet light or water passing through it.
- Ultraviolet lamps that are properly secured inside quartz sleeves with ease of access for installation, replacement, or maintenance.
- Quartz sleeves that deliver the ultraviolet energy produced by the ultraviolet lamps with sufficiently high transmission rates.
- Mechanical wipers to maintain optimum transmission between scheduled cleaning and maintenance work.
- Sensors to monitor the ultraviolet intensity passing through the water. These sensors need to be connected to alarm systems to alert the operator in case of low ultraviolet intensity. Easy access to these sensors is necessary for installation, replacement, calibration, and maintenance.
- Safety control to shut off ultraviolet lamps in case of low flow levels and elevated lamp temperature.
- Arc condition and lamp-out monitors to detect any fault condition and alert the operator.
- Electronic ballasts.

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CHAPTER 2. ASSESSMENT OF ULTRAVIOLET LIGHT EFFICACY, VIABILITY, AND OPERATIONAL FACTORS

This chapter presents reported doses and corresponding inactivation rates achieved for various microorganisms. It briefly describes methods for ultraviolet light intensity and dose measurements. Also, it presents information provided by the ultraviolet light industry and AWWA on inactivation rates and dose requirements next to the inactivation rates and dose requirements reported in the scientific literature. This juxtaposition is intended to show points of agreement and disagreement between manufacturers' information and peer-reviewed research data.

The inactivation rates reported in this chapter and corresponding dose requirements may be used as a guide for ultraviolet light application in ground drinking water disinfection. However, it is important to consider the conditions under which these inactivation rates were achieved. These conditions include laboratory conditions, water quality or media used, microorganism type and source, method used to estimate ultraviolet light intensity and dose, and reliability of the method used to count the microbial population that survived the ultraviolet treatment. Additionally, it is important to consider the ambient conditions where the ultraviolet light treatment will be used before deciding on a specific dose for disinfection.

This chapter discusses equipment operational factors, water quality, and hydraulic design considerations. General and specific small systems design considerations are suggested. Moreover, ultraviolet light operational case histories are presented to provide information on the practical aspects of various ultraviolet light disinfection field applications. Other considerations related to the use of ultraviolet light, such as by-products formation and the phenomena of reactivation, are presented. Finally, the issue of finding a suitable challenge surrogate microorganism is discussed, as well as attempted comparisons of ultraviolet light disinfection efficiency to chemical disinfectants.

This chapter is organized as follows: Section 2.1 is an introduction to drinking water disinfection by means of ultraviolet light. It briefly explains how doses and intensities are estimated. Section 2.2 presents inactivation rates of various microorganisms by means of ultraviolet light in water and wastewater. It presents microorganism reduction rates attained through the use of ultraviolet light as provided by the ultraviolet light industry and AWWA (section 2.2.1) and inactivation rates reported in the scientific literature (section 2.2.2 and section 2.2.3). Section 2.2.4 provides a brief overview of the inactivation rates achieved in applying ultraviolet light in wastewater effluent treatment, combined sewer overflow treatment,

and recycled water treatment. This section (2.2.4) describes what ultraviolet light disinfection technology can achieve in microorganism inactivation under worst-case conditions, such as floods, failure of a well casing, an undetected cesspool failure, or a ground water system coming under the direct influence of surface water. Section 2.3 gives an insight to the operational factors that govern the application of ultraviolet light technology in drinking water (section 2.3.1 through section 2.3.4). Section 2.4 discusses issues related to the use of ultraviolet light in drinking water applications, such as by-products formation and organics removal (section 2.4.1); the phenomena of photoreactivation, dark reactivation, and chemical reactivation (section 2.4.2); the issue of disinfectant residual (section 2.4.3), and the availability of a monitoring and challenge surrogate microorganism (section 2.4.4). Section 2.4.5 discusses the attempts to compare ultraviolet light disinfection efficacy to chemical disinfection efficacy. Section 2.5 presents a summary of findings.

2.1 INTRODUCTION TO INTENSITIES AND DOSES

The inactivation of microorganisms in drinking water by means of ultraviolet light is a function of the intensity of radiation at the proper wavelength, the exposure time, the water quality, and the thickness of targeted water. The intensity is measured in milliwatts per square centimeter (mWs/cm^2). The time is the theoretical exposure time calculated or measured as the hydraulic detention time in seconds in the ultraviolet chamber. The proper wavelength is a range (200 nm to 300 nm) with a maximum biocidal effectiveness at 250 nm to 265 nm. The thickness of the targeted water is the perpendicular distance from the light source to the wall of the chamber.

Similar to the hydraulic consideration needed in chemical disinfection processes, a primary consideration in the application of ultraviolet light for disinfection is to ensure that sufficient energy is delivered to the entire volume of water to be disinfected. The concept of dose in ultraviolet light disinfection is comparable to the dose concept in chemical disinfection. In chemical disinfection, dose "Ct" is the product of "C" the concentration of the chemical disinfectant in mg/L and contact time "t" in minutes. Under the Surface Water Treatment Rule (SWTR), "t" is defined as the contact time measured from the point of disinfectant application to the point of residual measurement or between points of residual measurements (USEPA, 1991). Because there is no ultraviolet light residual measurement beyond the light emitting lamp, contact time in an ultraviolet light application is the hydraulic detention time. **Exhibit 2-1** is intended to provide a brief description of the methods used to estimate ultraviolet light intensity and dose measurements.

Exhibit 2-1. Dose and Intensity Measurements

Dose is intensity multiplied by time. It is usually represented in milliwatts second per square centimeter units (mWs/cm^2). Time is calculated as the hydraulic residence time of the water in the ultraviolet light reactor. Determining intensity of ultraviolet light at any point in an ultraviolet light reactor is not as simple as measuring time. The intensity of ultraviolet light at 253.7 nm is a function of the light source, the physical arrangement of the lamps, and energy absorbing elements in the water that will absorb the light or attenuate it before it reaches the microorganism to be disinfected or the point of intensity measurement.

Diodes[1] employed to measure ultraviolet light intensity at the farthest point from the light source provide continuous monitoring of the ultraviolet reactor. However, these sensors are planar receptors; therefore, only light that strikes the surface of the receptor orthogonally (at a right angle) will be fully measured. Moreover, the ultraviolet light-emitting lamp emits light at wavelengths that are visible or does not have germicidal effect. Diodes might be sensitive to these non-ultraviolet rays. For drinking water disinfection and in a multi-lamp ultraviolet light reactor, measuring light intensity becomes more complex because light flux and target microorganisms are all three-dimensional.

Currently, there are three methods to estimate ultraviolet light intensity. According to these estimates, ultraviolet light disinfection reactors are designed, tested, and calibrated. These methods are biological assays, chemical actinometer, and calculation.

In the biological assays method, collimated ultraviolet light (light directed in a straight line) intensity is measured by a radiometer (USEPA, 1986). Challenge bacteria is then exposed to the measured intensity for equal intervals of time, thus yielding specific doses. The surviving bacterial population is plotted against the dose, and a dose-response relationship is established (Johnson and Qualls, 1984, Qualls and Johnson, 1982). This biological assay method offers an independent verification of the ultraviolet system, thus serving as a design tool and as a post-construction performance test. However, this method can be costly, time consuming and cumbersome. Moreover, there is no consensus among scientists about which challenge microorganism to use to make this method more standardized.

Actinometry is the measurement of radiation intensity by the speed of a photochemical reaction. In practical terms related to drinking water, chemical actinometry is the measurement of the disinfecting power of ultraviolet light by chemical means (von Sonntag and Schuchmann, 1992). In an actinometry method, chemicals that are insensitive to visible light but sensitive to ultraviolet light at 254 nm are exposed to ultraviolet light. The change in the chemical brought about by the effect of ultraviolet light or the formation of some ions, such as H^+, is measured. The quantum yield of the H^+ formed is known and constitutes the calibration factor. For example, the quantum yield of formed H^+ at 20°C is 1.8 mol/einstein[2] or 1.8 mol/4.72 x 10^5J or 1.8 mol/4.72 x 10^5 watt second (Hoyer et al., 1992, Mark et al., 1990). Actinometry can be used for photocell calibration or for evaluating the radiation input over the entire volume of the reactor. To calibrate ultraviolet light sensors, two procedures are suggested. The first involves substituting for the photocell a quartz cell that contains actinometer solution and then measuring the chemical change in the solution. The second is accomplished by irradiating the photocell with an ultraviolet lamp whose flux has been determined by an actinometer and adjusting the reading of the photocell accordingly.

Calculation of the average intensity by Point Source Summation Method (PSSM) is based on the assumption that the lamp is a finite series of point sources that emit light energy radially in all directions. Therefore, the intensity at any point is the sum of intensities emanating from each point source. The summation model assumes two basic mechanisms, light dissipation and light absorption, and neglects reflection, refraction, and diffraction.

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[1] Diodes are semiconductors in which an absorbed photon will liberate a bound electron. The flow of liberated electrons from the receptor surface to the "collector" electrode in the diode will generate an electric current that easily could be measured with an ammeter.

[2] Einstein is a unit of radiant energy equal to the energy of radiation that is capable of photochemically changing one mol of photosensitive substance.

The information collected on inactivation rates from the industry and the scientific literature provide important information on targeted microorganisms and applied doses. However, data on factors that can affect disinfection rate and effectiveness of ultraviolet light application are seldom mentioned in the published literature. Very little data are available on light intensity and method of measurement, ultraviolet light transmission efficiency, water or medium absorbance coefficient. Also, very little data are available on the effects of time, temperature, pH, total dissolved solids, high ultraviolet light absorbing inorganic compounds such as iron and manganese, total organic carbon or assimilable organic carbon, color, and turbidity on disinfection efficacy.

2.2 INACTIVATION RATES (EFFICACY)

This section presents microorganism reduction rates attained through the use of ultraviolet light as provided by the ultraviolet light industry and AWWA. Also provided is a literature review of various microorganism inactivation rates attained in water and wastewater disinfection experiments. This section is intended to present the spectrum of ultraviolet light inactivation rates for various microorganisms under different conditions.

2.2.1 Inactivation Rates Provided by Ultraviolet Light Equipment Manufacturers

Commercial ultraviolet light lamps produce greater than 85 percent of the ultraviolet light output at 254 nm wavelength (Aquafine, 1995, USEPA, 1986, Von Sonntag and Schuchmann 1992, Legan, 1982). However, the intensity of light the lamps transmit and the length of lamps are not uniform; therefore, the doses provided by these commercial lamps to disinfect water with similar quality and flow rate are not the same.

Manufacturers provided data on dose levels for ultraviolet inactivation rates of some microorganisms. Atlantic Ultraviolet Corporation provided tables containing information on the doses necessary to inactivate general and specific microorganisms (Atlantic Ultraviolet Corporation, 1995, 1996). A sample of the information is presented in **Exhibits 2-2** and **2-3**.

Trojan Technologies Incorporated (Trojan, 1992) provided bacteria inactivation rates that are similar in some respects to those provided by Atlantic Ultraviolet Corporation. Aquafine Corporation (Aquafine, 1995) provided inactivation rates identical in most respects to those provided by Atlantic Ultraviolet Corporation (presented in Exhibit 2-3 under the heading >99.9%).

Exhibit 2-2. Doses Required for "Complete Destruction" (>99.9%) of Microorganisms* (Atlantic Ultraviolet Corporation, 1995)

Organism	Dose mWs/cm^2
Streptococcus	3.8
Dysentery bacilli	4.2
Influenza	6.6
Staphylococcus	6.6
Fecal Coliform	6.6
Salmonella	10.0
Legionella pneumophila	12.3
Bacteriophage (*E. coli*)	6.6

*Atlantic Ultraviolet Corporation has defined its "complete destruction" term to mean greater than 99.9% inhibition of colony formation based upon research conducted by Rudolf Nagy, Westinghou se Corp., in the 1950s.

Capital Controls Company, Inc., provided information on inactivation rates for various microorganisms with names of authors who reported the rates (Capital, 1995). Infilco Degeremont, Inc. (IDI, 1995) provided inactivation rates for some general microorganisms and one specific microorganism (*Escherichia coli*). The ultraviolet light doses specified by Infilco Degeremont, Inc., to achieve 2 log reduction for various general microorganisms are difficult to verify. The dose reported by Infilco Degeremont, Inc., to be sufficient to achieve 2 log reduction in *Escherichia coli* (6.6 mWs/cm^2) is the same dose reported by Atlantic Ultraviolet Corporation and Aquafine Corporation, to be sufficient to achieve a minimum of 3 log reduction in the same microorganism.

Both Capital Controls Company, Inc. and Infilco Degeremont, Inc. claimed to contract out bioassay studies to independent laboratories, however, both companies did not provide detailed information or data from the studies conducted.

The inactivation rates provided by the industry are difficult to verify at this point. In addition, industry-provided information on inactivation rates did not include information on the type of medium in which the organisms were targeted, the source of the organisms, and other parameters, such as turbidity. The inactivation dose ranges provided by the five companies are summarized in **Exhibit 2-4**.

The ultraviolet light dose requirements provided by the ultraviolet light industry (>99.9% inactivation for some microorganisms) are lower than the doses reported in the scientific literature for water disinfection. For example, two industry sources claimed that 22 mWs/cm^2 is sufficient for >99.9% inactivation of *B. Subtilis*; the research by Chang et al., 1985, shows 3 log reduction at an ultraviolet dose of 60 mWs/cm^2.

Exhibit 2-3. Dose Required at 253.7 Nanometers to Inhibit Colony Formation in 90 Percent of the Organisms and for Complete Destruction (>99.9%) (Atlantic Ultraviolet Corporation, 1995)

Organism	(mWs/cm^2)	
	90%	>99.9%
Bacillus anthraces	4.52	8.7
B. Megaterium spp. (veg.)	1.3	2.5
B. Megaterium spp. (spores)	2.73	5.2
B. paratyphosus	3.2	6.1
B. subtilis	5.8	11.0
B. subtilis spores	11.6	22.0
Corynebacterium diphtheria	3.37	6.5
Dysentery bacilli	2.2	4.2
Eberthella typos	2.14	4.1
Escherichia coli	3.0	6.6
Micrococcus candidus	6.05	12.3
Micrococcus sphaeroides	10.0	15.4
Neisseria catarrhalis	4.4	8.5
Phytomonas tumafaciens	4.4	8.5
Proteus vulgaris	3.0	6.6
Pseudomonas aeruginosa	5.5	10.5
Pseudomonas fluorescens	3.5	6.6
S. enteritidis	4.0	7.6
S. typhimurium	8.0	15.2
Sarcina lutea	19.7	26.4
Serratia marcescens	2.42	6.16
Shigella paradysenteriae	1.68	3.4
Spirillum rubrum	4.4	6.16
Staphylococcus albus	1.84	5.72
Staphylococcus aureus	2.6	6.6
Streptococcus hemolyticus	2.16	5.5
Streptococcus lactis	6.15	8.8
Streptococcus viridans	2.0	3.8
Yeast		
Saccharomyces ellipsoideus	6.0	13.2
Saccharomyces spp.	8.0	17.6
Saccharomyces cerevisiae	6.0	13.2
Brewer's yeast	3.3	6.6
Baker's yeast	3.9	8.8
Common yeast cake	6.0	13.2
Mold Spores (Color)		
Penicillium rogueforti (Green)	13.0	26.4
Penicillium expansum (Olive)	13.0	22.0
Penicillium digitatum (Olive)	44.0	88.0
Aspergillus glaucus (Bluish green)	44.0	88.0
Aspergillus flavus (Yellowish green)	60.0	99.0
Aspergillus niger (Black)	132.0	330.0
Rhisopus nigricans (Black)	110.0	220.0
Mucor racemosus A (White gray)	17.0	35.2
Mucor racemosus B (White gray)	17.0	35.2
Oospora lactis (White)	5.0	11.0

Exhibit 2-4. Summary of Ultraviolet Light Microorganisms Inactivation Dose Requirements in mWs/cm^2

Source	Bacteria	Virus	Protozoa	Inactivation
Aquafine	2.5 - 26.4	6.6 – 440*	200	≥3 log
Atlantic Ultraviolet Corporation	2.5 - 26.4 1.3 - 19.7	-- --	-- --	>3 log 1 log
Capital Controls Company	1 - 54.5**	2.6 – 240***	60 – 200	1 log
Infilco Degeremont, Inc.	2.9 – 15.2	6.6 – 8	--	2 log
Trojan	1 - 54.5**	3.6 – 11.3	60 – 200	1 log

*440 mWs/cm^2 was reported for tobacco mosaic virus; the second highest dose reported by Aquafine was 8 mWs/cm^2.
**54.5 mWs/cm^2 was reported for bacterial spores; the second highest dose reported for a bacteria was 20.5 mWs/cm^2.
***240 mWs/cm^2 was reported for tobacco mosaic virus; the second highest dose reported for a virus was 3.6 mWs/cm^2.

The inactivation rates provided by the industry appear to be adopted from European literature. A list of energies required to achieve 90 and 100 percent reduction in microorganism by means of ultraviolet light at 253.7 nm wavelength published in *Developments in Food Microbiology* Vol. 3 (Snowball and Hornsey, 1988) shows dose requirements identical for the most part to those provided by the ultraviolet industry for drinking water disinfection. However, the list provided by Snowball and Hornsey, 1988, clearly states that all dose requirements data were collected under laboratory conditions and in *a static air medium* (emphasis added) and that the relevance of such data when applied to the same listed microorganisms in water must be suspect (Snowball and Hornsey, 1988).

In its comment to the USEPA on the 1991 draft Ground Water Disinfection Rule (GWDR), the American Water Works Association (AWWA) referred to studies conducted at the University of New Hampshire involving inactivation rates of surrogate microorganisms for drinking water disinfection using ultraviolet light. AWWA, 1992, provided preliminary results for the inactivation of bacteriophage MS-2. According to AWWA, a 4 log reduction of MS-2 was achieved at a 150 mWs/cm^2 dose at 10°C and pH 7.0. At pH of 5.5 and at 10°C, a dose of 152 mWs/cm^2 was required to achieve a 4 log reduction. These preliminary results suggest that ultraviolet light treatment is pH independent in that range. Malley, Shaw and Ropp, 1996 (as cited in Snicer et al., 1996) examined MS-2 inactivation under different temperature and pH levels in ground waters containing less than 0.15 ppm iron. The test results showed that temperature had little effect on MS-2 inactivation, but a significant difference in inactivation was detected between the tests at pH levels of 7.0 and 8.5 and that of tests at a pH level of 5.5. The researchers attributed the detected difference to morphological changes int he nature of the protein coat that caused clumping of

microorganisms. Other technical references (Montgomery, 1985 and USEPA, 1986) conclude that ultraviolet light treatment is pH insensitive. The doses reported in the preliminary results of bacteriophage MS-2 4 log inactivation as reported by AWWA, 1992, are about twice the doses reported by Wilson et al., 1993, and Weidenmann et al., 1993, for 4 log inactivation of the same microorganisms.

2.2.2 Inactivation Rates in Drinking Water Treatment as Compiled from the Scientific Literature

Based on the literature search, Lea (1947) provided mean lethal dose values for *Escherichia coli* at different ultraviolet intensities. Using an ultraviolet light at 253.6 nm of wavelength, he reported the results presented in **Exhibit 2-5**.

Exhibit 2-5. Light Intensities and Mean Lethal Doses for *E. Coli* (Lea, 1947)

Intensity ergs/cm²/sec	Mean Lethal Dose ergs/cm²
1.2×10^2 (0.012 mW/cm²)	7.5×10^3 (0.75 mWs/cm²)
3.1×10^3 (0.31 mW/cm²)	8.5×10^3 (0.85 mWs/cm²)
6.4×10^4 (6.4 mW/cm²)	8.5×10^3 (0.85 mWs/cm²)

- Mean lethal dose here is defined as the dose required for the reduction of *E. coli* to 37% (i.e., .43 log reduction)
- 1 erg = 10^{-7} joules
- 1 joule = 1 watt second
- mWs/cm² = milliwatts second per square centimeter = 10^4 ergs/cm²

Lea (1947) concluded that bacterial disinfection using ultraviolet light is a first-order reaction. This conclusion was based on data compiled by Lea using ultraviolet light of 280.3 nm wavelength on *Bacillus megaterium* (see **Exhibit 2-6**). Lea (1947) also concluded that the mean lethal dose is independent of intensity (as reported in Lamanna and Mallette, 1965). The measurements of the intensity of ultraviolet light and the efficiency of light transmission at the reported wavelengths were not reported.

Therefore, the reliability of these low doses compared with current experience is questionable. Also, the determination that this is a first-order reaction was based on data with less than 1 log reduction of the targeted bacteria.

Groocock (1984) of the Derwent Division of the Severn-Trent Authority in the United Kingdom reported ultraviolet light doses required to achieve one log reduction (90 percent inactivation) for several microorganisms. The reported doses are presented in **Exhibit 2-7**. Groocock (1984) did not report specific information on the types of protozoa reduced, methods used to estimate doses, test setting, or

Exhibit 2-6. Survival Curve of Bacillus Megaterium Irradiated Using Ultraviolet Light at 280.3 nm (Lea, 1947)

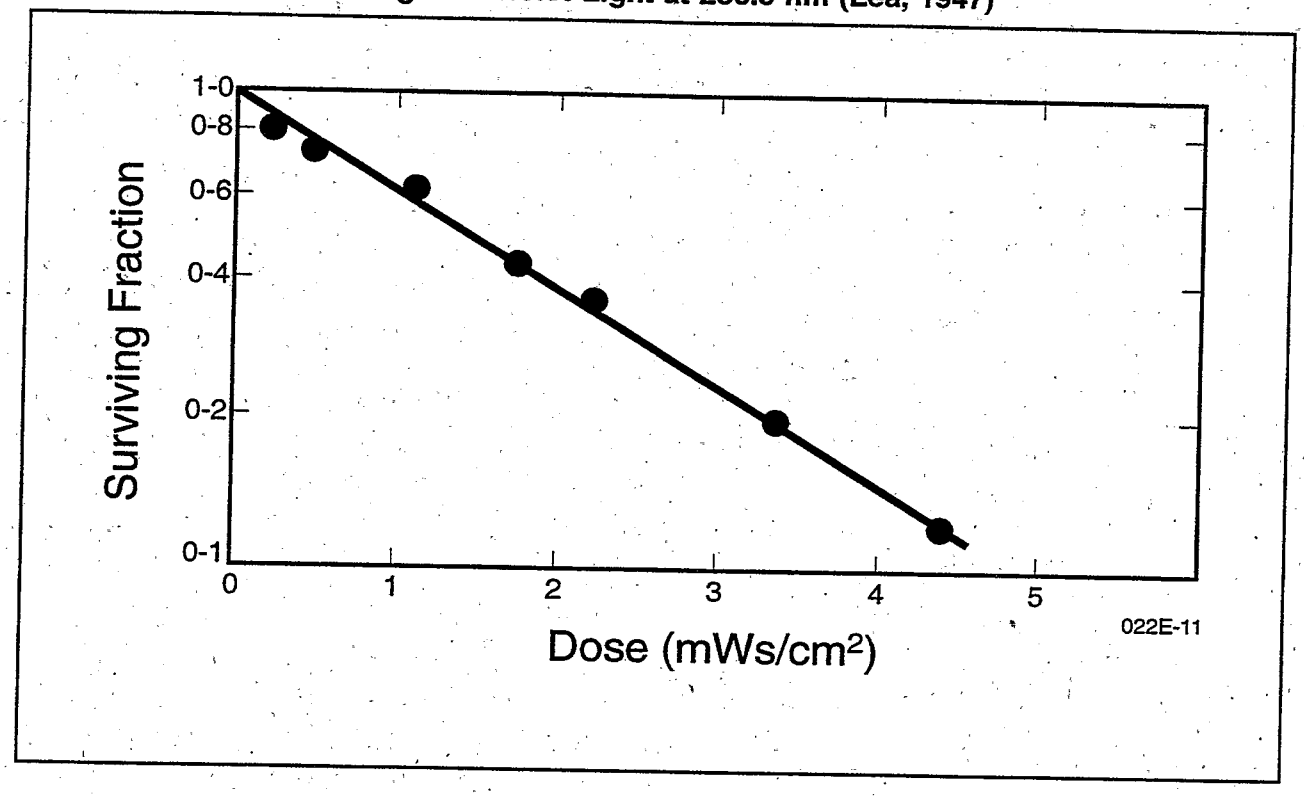


Exhibit 2-7. Ultraviolet Light 254 nm Dose (mWs/cm^2) Required for a 90 Percent Killing of Various Microorganisms (Groocock, 1984)

Microorganism	Dose	Microorganism	Dose
Serratia marlescens	2.42	*Bacillus subtilis* (spores)	12.00
Pseudomonas aeruginosa	5.50	*Clostridium tetani*	4.90
Mycobacterium tuberculosis	6.00	*Staphylococcus aureus*	2.18
Salmonella enteritidis	4.00	*Streptococcus viridans*	2.00
Salmonella paratyphi	3.20	*Streptococcus pyogenes*	2.16
Salmonella typhi (1)	2.14	*Micrococcus candidus*	6.05
Salmonella typhimurium	8.00	*Micrococcus sphaeroides*	10.00
Shigella dysenteriae (2)	2.20	*Sarcina lutea (M. luteus)*	19.70
Shigella paradysenteriae	1.68	*Micrococcus lysodeikticus (M. luteus) ATCC 12698*	23.00
Escherichia coli	3.00	*Mictococcus radiodurans* (Phosphate buffer)	20.50
Proteus vulgaris	2.70	Yeast (average)	4.00
Bacillus anthracis	4.52	Protozoa	60-100
Bacillus megaterium (cells)	3.75	Algae, blue-green	300-600
Bacillus megaterium (spores)	9.07	*Aspergillus niger* (bread)	100
Bacillus subtilis (cells and spores)	7.10		

water quality parameters under which the reduction occurred. However, Groocock's paper has often been used as a reference in the scientific literature and is often used as a testament to the efficacy of ultraviolet light. Many of the dose figures provided in Groocock (1984) are the same figures provided in the literature published by the ultraviolet light industry.

Meulemans, 1987, as cited in Ellis, 1991, shows a 1 log reduction in bacteria at a dose range of 2.1 mWs/cm^2 to 12 mWs/cm^2 and a 1 log reduction in protozoa at a range of 64 to 100 mWs/cm^2. Whitby, 1989, reported more than a 4 log reduction in fecal coliform at an estimated dose of 33 mWs/cm^2.

The guidance manual for compliance with the filtration and disinfection requirements for public water systems using surface water sources (USEPA, 1991) listed a 2 log reduction in Hepatitis A virus (HAV) at a dose of 21 mWs/cm^2 and a 3 log reduction of HAV at a dose of 36 mWs/cm^2. The dose values were derived by applying a safety factor of 3 to the HAV inactivation data that were reported by Sobsey (1988). The HAV has been established as an important cause of waterborne disease (USEPA 1991).

Wiedenmann et al., 1993, achieved an inactivation rate of 4 logs for MS-2 in a 0.9 percent NaCl solution with an ultraviolet dose of approximately 74 mWs/cm^2 (intensity 0.184 mW/cm^2, time 400 seconds) and a 4 log reduction in HAV with an ultraviolet dose of approximately 18.5 mWs/cm^2 (intensity 0.184 mW/cm^2, time 100 seconds). The Wiedenmann et al. (1993) test results suggest that MS-2 is four times more resistant to ultraviolet light than HAV. The incomparability of Sobsey's (1988) results with the Wiedenmann et al. (1993) figures can be attributed to the source of microorganisms, medium difference, and ultraviolet intensity estimates. The same reasons can be given when comparing the Battigelli, Sobsey, and Lobe, 1993, 4 log reduction of HAV achieved with 16 mWs/cm^2 of ultraviolet light dose to the reductions mentioned previously.

In their recent research, Battigelli, Sobsey, and Lobe (1993) confirmed in a lab setting what other researchers have found. The researchers' ultraviolet light disinfection test results showed that MS-2 bacteriophage is more resistant to ultraviolet light than rotavirus strain SA 11, coxsackie virus type B 5, HAV virus strain HM-175, and bacteriophage ΦX174. The 4 log reduction doses for HAV strain HM-175 and bacteriophage ΦX174 were 16 and 9 mWs/cm^2, respectively. The 3 log reduction doses for coxsackie virus type B-5 and rotavirus strain SA-11 were 20 and 25 mWs/cm^2, respectively. The bacteriophage MS-2 showed the highest resistance to ultraviolet radiation with less than 1 log reduction at 25 mWs/cm^2.

Sobsey (1989) summarized data on inactivation of pathogens in water and wastewater by ultraviolet light. He noticed that vegetative bacteria (i.e., bacteria that propagate by nonsexual processes, such as coliforms) are inactivated (>3 log reduction) at doses below the DHEW-recommended minimum level of 16 mWs/cm^2 and that higher doses are required to achieve 3 log reductions in viruses, bacterial spores, and protozoan cysts. Data show that all bacteria and viruses (including Simian rotavirus SA-11), with the exception of Reovirus 1, suffered 3 log reduction at doses below the ANSI/NSF-recommended level of 38 mWs/cm^2, regardless of the liquid medium except for sewage medium. Data compiled by Sobsey (1989) are presented in **Exhibit 2-8**.

As can be seen from Exhibit 2-8, bacterial sensitivity to ultraviolet light varies from one species to another. Even the same species exhibit nonuniform sensitivity. This variation is a function of medium quality, source of microorganism, age of the microorganisms, microorganism population, and possible measurement errors or inconsistent methods in measuring the applied average ultraviolet light dose. The range of ultraviolet light doses to disinfect bacteria (3 to 4 log reduction) in media other than sewage is 0.14 for *Escherichia coli* to 60 mWs/cm^2 for *B. subtilis* spores.

The range of sensitivity within tested viruses as reported in Exhibit 2-8 is 21 to 45 mWs/cm^2 at 3 log reduction. Also, the data presented above show that ultraviolet light is effective against protozoa at high doses. The 3 log removal of a protozoa (*Acanthamoeba Castellanii)* reported in Exhibit 2-8 at a dose of 100 mWs/cm^2 and that of a 1 log removal of another protozoa (*paramecium*) at the same dose as reported by Meulemans, 1987, show that inactivation rates for some groups of microorganisms vary considerably.

Sobotka (1993) concluded that a bactericidal dose of 25 mWs/cm^2 is sufficient for most pathogenic organisms; however, Sobotka (1993) did not provide any specific evidence or cites for his conclusion.

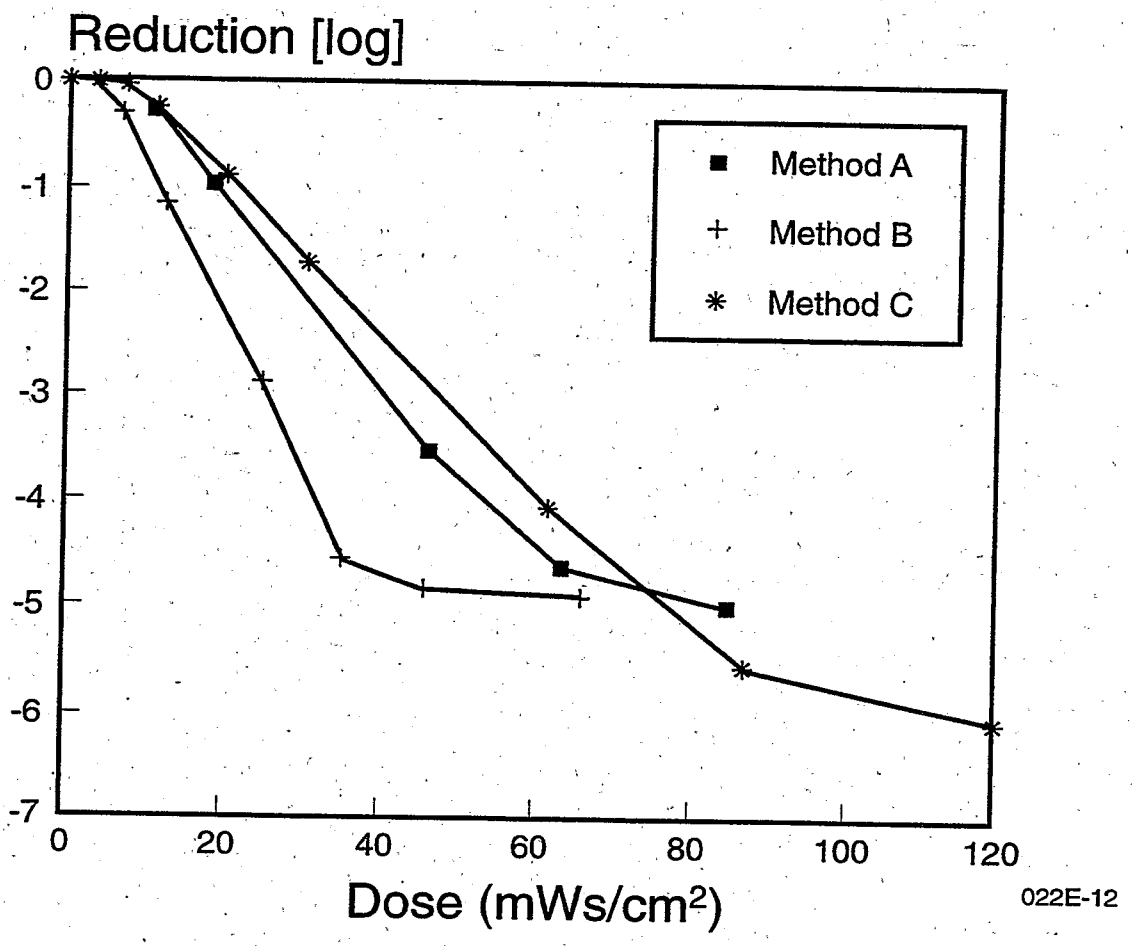
Sommer and Cabaj (1993), using three different cultural techniques of *Bacillus subtilis* spores, concluded that one of the three methods gave consistent inactivation rates between a dose of 200 j/m^2 to 900 j/m^2 (20 mWs/cm^2 to 90 mWs/cm^2) with 5.5 log reduction at 90 mWs/cm^2 and 6 log reduction at 120 mWs/cm^2. In their experiment, *Bacillus subtilis* spores were suspended in potable water and irradiated in a commercially available drinking water ultraviolet disinfection unit. The results of inactivation of *Bacillus subtilis* spores depending on cultural methods are presented in **Exhibit 2-9**. Sommer and Cabaj (1993) recommended the use of cultural method C because it yielded *Bacillus subtilis* spores that were

Exhibit 2-8. Inactivation of Health-Related Microbes in Water by Ultraviolet Radiation (Sobsey, 1989)

Microbe	Medium	UV Dose (mWs/cm²)	Temp. (°C)	pH	Reduction Log	Reduction (%)	Reference[b]
Bacteria:							
E. coli	BDW[a]	6.5	room	?[f]	3	99.90	Chang et al., 1985
Total Coliforms	effl.[c]	8.2	room	?	3	99.90	"
HPC	effl.	14	room	?	3	99.90	"
B. subtilis spores	BDW	60	room	?	3	99.90	"
Total coliforms	effl.	6.5	?	?	2	99.00	Qualls et al., 1985
Total coliforms	effl.	9.6-52	?	?	3.52	99.97	"
Total coliforms	filt. effl.[d]	5.7	?	?	2	99.00	"
Total coliforms	tea	7.2-28	?	?	>3.3	>99.95	Tobin et al., 1983
HPC	tea	7.2-28	?	?	0.96	88.96	"
Fecal Coliforms	sewage	ca. 275	?	?	3	99.90	Zukovs et al., 1986
Enterococci	sewage	ca. 275	?	?	3	99.90	"
P. aeruginosa	sewage	ca. 280	?	?	3	99.90	"
E. coli recA-, uvrA-	on medium	10.3	?	?	3	99.90	Knudson, 1985
E. coli, B/r	"	.14	?	?	3	99.90	"
Legionella (6 sp.)	"	0.8-5.5	?	?	3	99.90	"
L. pneumophila	tap	30	25	?	3	99.90	Muraca et al., 1987
L. pneumophila	dist. water[e]	1.8	room	?	3	99.90	Butler et al., 1987
Y. enterocolitica	dist. water	2.7	room	?	3	99.90	"
C. jejuni	dist. water	5.0	room	?	3	99.90	"
Viruses:							
Polio 1	PBS[a]	21	room	7.5	3	99.90	Chang et al., 1985
Rota SA11	PBS	25	room	7.5	3	99.90	"
Polio 1	BDW	29	?	7.2	3	99.90	Harris et al., 1987
Reo 1	BDW	45	?	7.2	3	99.90	"
Protozoan Cysts:							
Giardia Lamblia	BDW	63	?	?	0.52	70.00	Rice and Hoff, 1981
A. castellanii	BDW	100	room	?	3	99.90	Chang et al., 1985

[a]BDW = buffered distilled water; PBS = phosphate buffered saline
[b]As cited in Sobsey, 1989.
[c]Effl = effluent
[d]Filt. Effl. = Filtered Effluent
[e]Dist. Water = Distilled water
[f]? = Unknown

Exhibit 2-9. Inactivation of *B. subtilis* Spores Depending on Laboratory Cultural Methods (Sommer and Cabaj, 1993)



Bacillus subtilis (ATCC 6633) spores were cultured with three different methods.

Method A: Bacteria were inoculated on Columbia agar plates (Oxoid) with 2% $CaCl_2$, incubated at 37°C for 7 days, harvested, and suspended in sterile aqua dest.

Method B: Bacteria were inoculated on Schaeffer sporulation agar plates (Munaka and Rupert, 1972), incubated at 37°C for 6 days, harvested, and suspended in sterile aqua dest.

Method C: Schaeffer medium was modified as a liquid enrichment bouillon. Bacteria were inoculated, incubated at 37°C for 3 days, harvested by centrifugation (4,000 g, 15 min, 10°C), and suspended in sterile aqua dest.

more resistant to ultraviolet light treatment and showed a linear relationship between dose and log reduction over a wider dose range than Methods A and B. Sommer and Cabaj's study is discussed further under section 2.4.4.

Wilson et al. 1993 tested the sensitivity of pathogenic water borne microorganisms to ultraviolet light. The researches conducted experiments on nine different water borne bacteria (*Klebsiella Terrigena, vibrio cholerae, Salmonella typhi, Escherichia coli 0157:H7, Shigella dysenteriae, Yersinia enterocolitica, Campylobacter jejuni, Aeromonas hydrophila, and Legionella pneumophila*) and three different water borne viruses (rotavirus SA-11, poliovirus type 1 and hepatitis A virus) in addition to coliphage MS-2. The researches used collimated ultraviolet light test apparatus, laboratory-cultured microorganisms and phosphate-buffered distilled water. The individual microorganisms suspension was placed in a petri dish and exposed to collimated ultraviolet light beam. The test results of Wilson et al. 1993 are presented in **Exhibit 2-10** and **Exhibit 2-11**. Exhibit 2-10 shows that under similar conditions, all tested pathogenic bacteria will suffer a minimum of 5 log reduction at an ultraviolet dose of approximately 16 mWs/cm^2. Exhibit 2-11 shows that under similar conditions, all tested pathogenic viruses will suffer a minimum of 6 log reduction at a dose of about 60 mWs/cm^2. It is important to note that naturally occurring microorganisms are typically more resistant to disinfection than laboratory-cultured microorganisms. In addition the phosphate-buffered distilled water may have lower ultraviolet demand than fresh water.

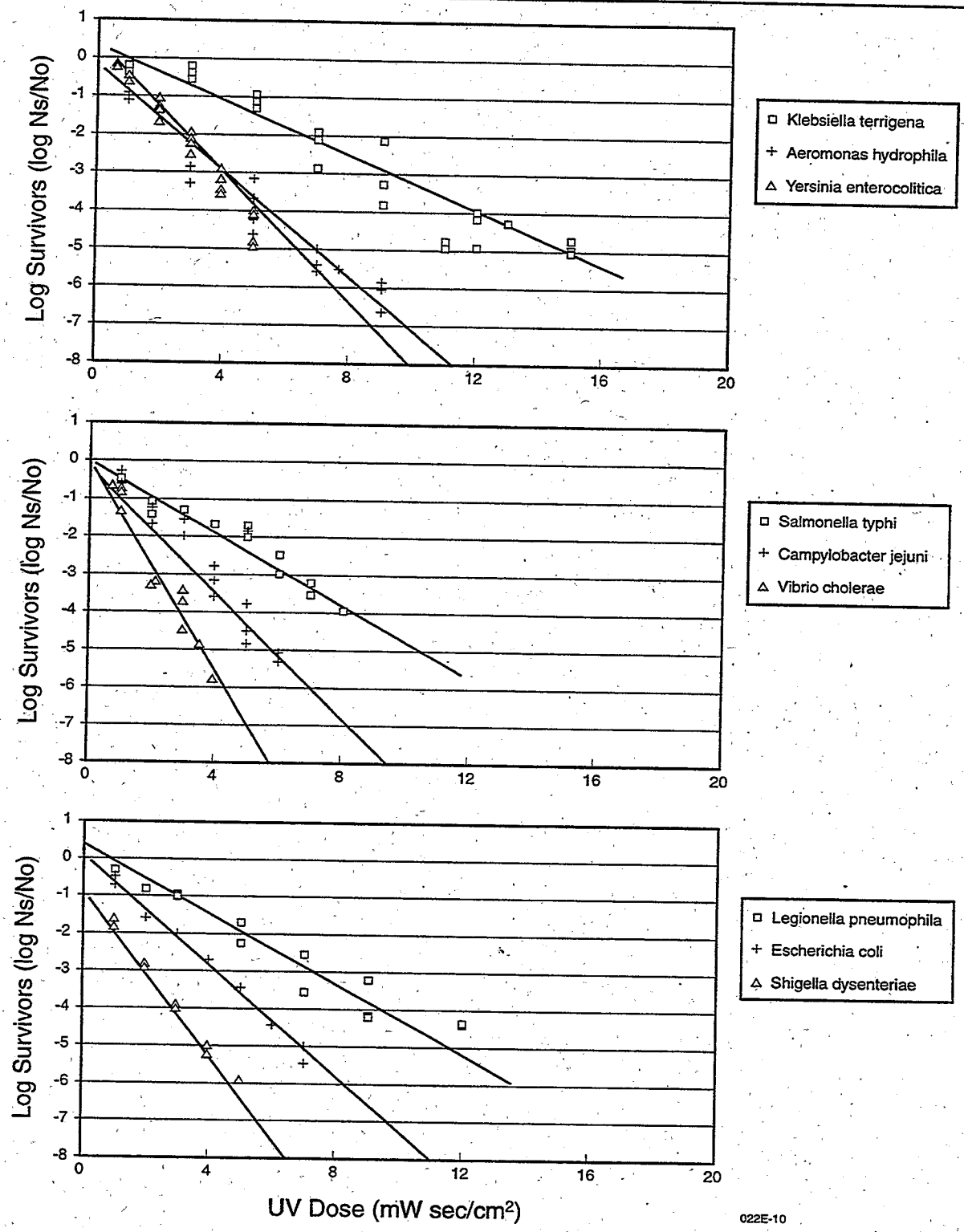
Wilson et al. 1993 using the coliphage MS-2 inactivation data conducted a linear regression analysis to estimate ultraviolet dose with 95 percent confidence intervals.

Wilson et al. 1993 reported ultraviolet dose predictions are presented in **Exhibit 2-12**.

Considering the lower end of the 95 percent confidence interval and based on Wilson et al. 1993 work (see exhibits 2-10 and 2-11), an ultraviolet light dose of 60 mWs/cm^2 will result in more than 4 log reduction for the viruses tested and more than 6 log reduction in all the tested pathogenic bacteria.

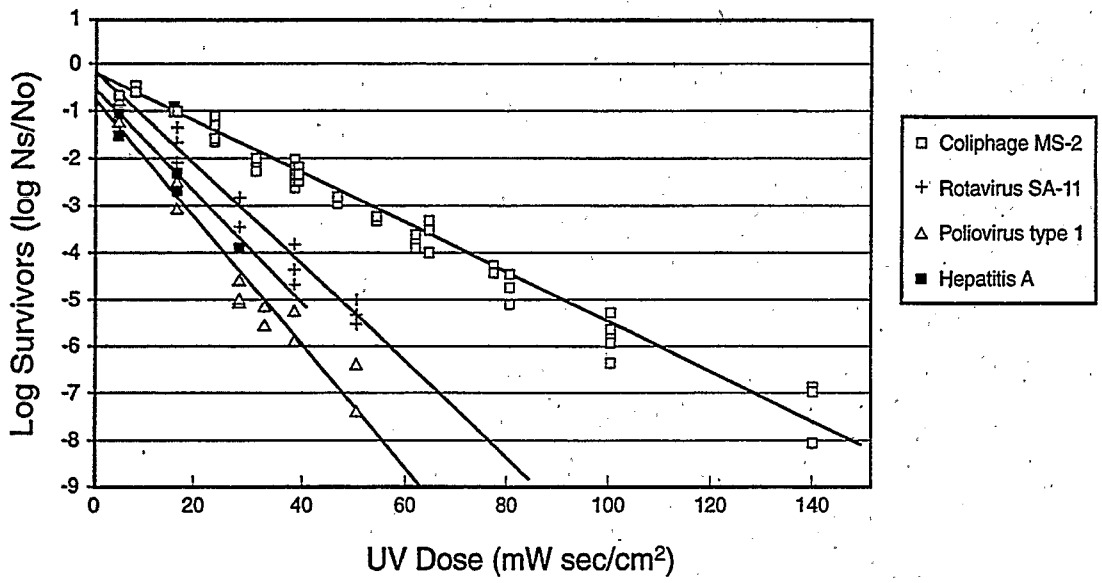
The results and statistical inferences of Wilson et al., 1993 are supported by a more recent research sponsored by the American Water Works Association Research Foundation (AWWARF). In their AWWARF- supported research, Snicer et al., 1996, concluded that 4-log inactivation of MS-2 can be achieved by an ultraviolet light dose of 64 mWs/cm^2 to 93 mWs/cm^2. Snicer et. al., 1996 also concluded that 4 log inactivation of rotavirus, poliovirus and Hepatitis A virus can be achieved by an ultraviolet light

Exhibit 2-10. Survival Curves of Ultraviolet Irradiated Bacteria (Wilson et al., 1993)



* All tests were done in phosphate-buffered distilled water using laboratory cultured microorganisms.

Exhibit 2-11. Survival Curves of Ultraviolet Irradiated Viruses and Test Surrogate Coliphage MS-2 (Wilson et al., 1993)



* All tests were done in phosphate-buffered distilled water using laboratory cultured micro-organisms.

Exhibit 2-12. Ultraviolet Estimation From Linear Regression Model of Coliphage MS-2 (Wilson et al., 1993)

Ultraviolet Dose mWs/cm²	Relative Standard Deviation	95% Confidence Interval mWs/cm²
38	21%	29.9-46.1
46.5	17.3%	38.5-54.6
60	13.4%	51.9-68.1
120	6.74%	112-128

*one tailed *t* test.

dose of 50 mWs/cm², 23 mWs/cm² to 29 mWs/cm², and 6 mWs/cm² to 15 mWs/cm² respectively. Snicer et al., 1996, conducted pilot scale and bench scale studies and pipe loop studies on waters from different groundwater sources. The two pilot plants constructed for the experiments operated for one full year. One pilot plant simulated intermittent water use while the other operated continuously. The bench scale laboratory studies were designed to compare MS-2 sensitivity to ultraviolet light to that of poliovirus, rotavirus and Hepatitis A virus (HAV). The bench scale laboratory studies also were designed to compare

the effects of varying groundwater quality on ultraviolet light dose requirements to achieve a 4-log reduction in the tested microorganisms.

The pilot scale studies demonstrated that 4-log reduction in MS-2 can be achieved through ultraviolet light disinfection. An ultraviolet light dose of 87.4 mWs/cm^2 was sufficient to achieve 4 log reduction in ground water containing up to 0.65 ppm iron (the USEPA has set the secondary MCL of iron at 0.3 ppm). It was also found that performance and maintenance is a function of water quality especially when water chemistry lends itself to deposition or scaling. In addition, pilot studies found that electronic ultraviolet light sensors should be calibrated at the time of installation to guarantee reliable and accurate results.

Pipe loop studies showed that the use of Assimilable Organic Carbon (AOC) as an indicator was not sensitive enough to detect differences in regrowth potential in low TOC groundwaters, and that ultraviolet light did not significantly increase or decrease regrowth. Snicer et al., (1996), did not infer any detailed conclusions from the loop study because of the cursory nature of the study. Laboratory studies demonstrated that groundwater quality is directly related to required ultraviolet light dose for viral inactivation. Ultraviolet light doses ranging from 64 to 93 mWs/cm^2 are required for 4-log inactivation of MS-2 bacteriophage in the groundwaters studied.

Ultraviolet light disinfection systems operating cost estimates ranged between $0.059 and $0.106 per thousand gallons assuming an ultraviolet light dose of 60 mWs/cm^2 and a power cost of $0.15/kWhr and excluding maintenance and lamp replacement costs (Snicer, et al., 1996).

Karanis et al. (1992) examined the sensitivity of different protozoan parasites and bacteria to ultraviolet light. Karanis et al. (1992) research shows that ultraviolet light can kill protozoan parasites, cysts, and trophozoites, but these organisms require a higher dose than that needed to kill the less complex and smaller bacteria. The results of Karanis et al. (1992) experiments are presented in **Exhibit 2-13.** As can be seen from Exhibit 2-13, commercially available ultraviolet light systems are effective against *Escherichia coli* bacteria, with 3 log reduction at 152 mWs/cm^2, but less effective against bacterial spores with 3 log reduction of *B. subtilis* spores at 50 mWs/cm^2.

Abbaszadegan et al. (1993) conducted experiments on POU systems that combined a carbon block filter with an ultraviolet light system. The carbon block filter was designed to remove *Giardia lamblia* cysts and *Cryptosporidium* oocysts. The ultraviolet light dose, as reported in the published study, was greater

Exhibit 2-13. Comparison of Protozoan and Bacterial Sensitivity to Ultraviolet Light (Karanis et al., 1992)

Microorganism	Reduction (log N/N_0)	Dose (mWs/cm^2)	Medium
Parasites			
Trichomonas vaginalis			
secondary	< 3	402	0.9% NaCl
culture	NG[b]	160-240	
secondary	> 2.3	241	water from medicinal spring
culture	NG	80	
Acanthamoeba rysodes[a]			
cysts	1.8	72	dist. H_2O
trophozoites	1.6	60	tap water
Acanthamoeba quina/lugdunensis[a]			
cysts	< 2	72	dist. H_2O
trophozoites	2.7	72	tap water
Giardia lamblia			
human cysts	2	180	dist. H_2O
gerbil cysts	2	180	dist. H_2O
Bacteria			
Escherichia coli (ATCC 11229)	3	15	buffered water
Salmonella typhimurium (ATCC 13311)	< 3	10	buffered water
Yersinia enterocolitica (ATCC 23715)	3	10	buffered water
B. subtilis spores (ATCC 6051)	3	50	buffered water

[a]*Acanthamoeba* cysts and trophozoites were 7 days old.
[b]NG = No growth.

than 128 mWs/cm^2. Abbaszadegan et al. (1993) reported approximately 4 log reduction in HAV, *Giardia lamblia*, and *Cryptosporidium parvum*. Other inactivation rates reported in the study of Abbaszadegan et al. (1993) are presented in **Exhibit 2-14**.

It must be noted that the reductions in microorganisms presented in Exhibit 2-14 are the function of the combined carbon block filter and ultraviolet light system. The published study did not provide any details on the reductions achieved by the carbon block alone and those achieved by ultraviolet light. However, the study shows a consistent pattern of sensitivity to ultraviolet light, with cysts being more resistant to inactivation by ultraviolet light than viruses and viruses being more resistant than bacteria.

Exhibit 2-14. Average Log Reduction of Microorganisms Using Combined Carbon Block Filter with Ultraviolet Disinfection Unit (>128 mWs/cm^2) (Abbaszadegan et al., 1993)

Microorganisms	Log Reduction
Poliovirus	4.28
Rotavirus	4.29
HAV	3.92
MS-2	6
Giardia lamblia cysts	3.99
Cryptosporidium parvum	4.3
Vibrio cholerae	5.96
Shigella dysenteriae	6.7
Escherichia coli	6.3
Salmonella typhi	6.52

ANSI/NSF Standard 55-1991 for POU Class A systems, which requires a minimum 38 mWs/cm^2 dose to disinfect clear drinking water, was based on the work of Chang (1985) and Harris (1986). Chang's work (1985) as cited in ANSI/NSF (1991) shows 3 to 4 log reduction in both poliovirus and rotavirus and a projected 6 log reduction of *Escherichia coli* at an ultraviolet light dose of 30 mWs/cm^2.

Harris' work (1986) as cited in ANSI/NSF (1991) shows a 5 log reduction of poliovirus at a dose of 40 mWs/cm^2. NSF concluded that a 4 log reduction of poliovirus will be achieved at a dose of 38 mWs/cm^2.

Exhibits 2-2 through 2-14 and the above discussion illustrate that inactivation rates of specific microorganisms vary among investigators. It is hypothesized that the previously cited characteristics of microbes tested and/or test conditions contribute to such differences. Generally speaking, however, the data show clearly and with few exceptions that algae, fungi, protozoa, and bacterial spores are more resistant (in that order) to ultraviolet light than bacteria and viruses. Also, gram-positive bacteria are more resistant to ultraviolet light than gram-negative bacteria. Generally, gram-positive bacteria have thicker walls than gram-negative bacteria; therefore, they provide the cell's DNA with better protection from ultraviolet light exposure (Ellis, 1991).

2.2.3 *Cryptosporidium parvum* Oocysts and *Giardia muris* Cysts Inactivation Rates Using Ultraviolet Light

Under normal conditions, ground water sources are not expected to contain *Cryptosporidium* species or *Giardia* species. However, primary sources of ground water contamination are leaks from septic tanks, cesspools, drainage fields, municipal sewer systems, and treatment lagoons (Wolfe, 1990). Also, in cases of floods, natural disasters, or failure of a well casing, ground water might come under direct influence of *Cryptosporidium*- and *Giardia*-containing surface water.

This section and the following section are intended to provide available information about ultraviolet light doses needed to disinfect water that deteriorated in quality and that might contain pathogenic protozoa. Operators in such emergency situations have been known to increase ultraviolet dose by increasing the electric potential difference (voltage) and/or by reducing the flow rate to increase the residence time as deemed necessary.

In 1985, the USEPA (Carlson et al., 1985) funded a project to study the use of ultraviolet light to disinfect drinking water for small water supply systems. *Giardia muris* cysts, *Yerisinia enterocolitica*, and *Escherichia coli* were spiked into an ultraviolet light treatment unit influent. The researchers found that *Giardia muris* cysts are more resistant to ultraviolet light than *Yerisinia enterocolitica* and *Escherichia coli*. The researchers also found that the presence of relatively small inorganic or organic particulates (5 µm diameter or less) had no discernible effect on the ultraviolet light disinfection of cysts. In contrast, turbidity in the form of particulates (> 5 µm) may provide shielding and protection to the organisms present in the treated water. To achieve less than 1 percent survival rate of *Giardia muris* cysts, a minimum ultraviolet light dose of above 121 mWs/cm^2 is needed (reported intensity 0.0914 mW/cm^2, exposure time 22 minutes). **Exhibit 2-15** is a graphical presentation of *Giardia muris* cyst survival rates as reported by Carlson et al. (1985).

Karanis et al. (1992) examined the disinfection capabilities of ultraviolet light against protozoan parasites. The researchers used *Giardia lamblia* cysts extracted from both animals and humans. Both groups of cysts suffered a 2 log reduction when irradiated by ultraviolet light at 180 mWs/cm^2 dose (see Exhibits 2-13 and 2-16). Karanis et al. (1992) also used lab-cultured protozoa and protozoa in dormant and vegetative states from human and animal sources along with different types of bacteria to test their sensitivity to ultraviolet light (most of the experiments were conducted using distilled or buffered water).

Exhibit 2-15. *Giardia muris* Cyst Survival Percent Versus Ultraviolet Light Exposure (Carlson, 1985)

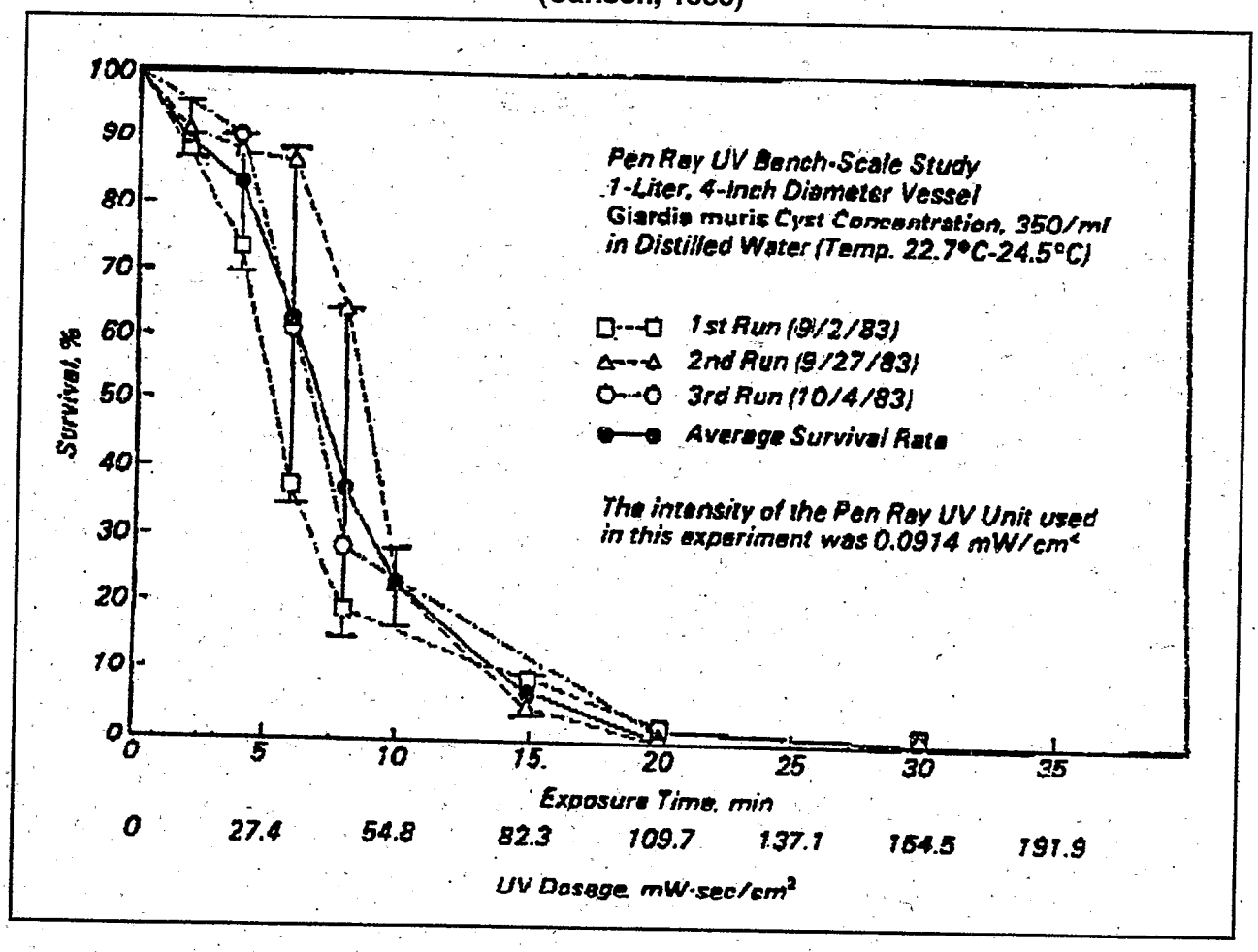
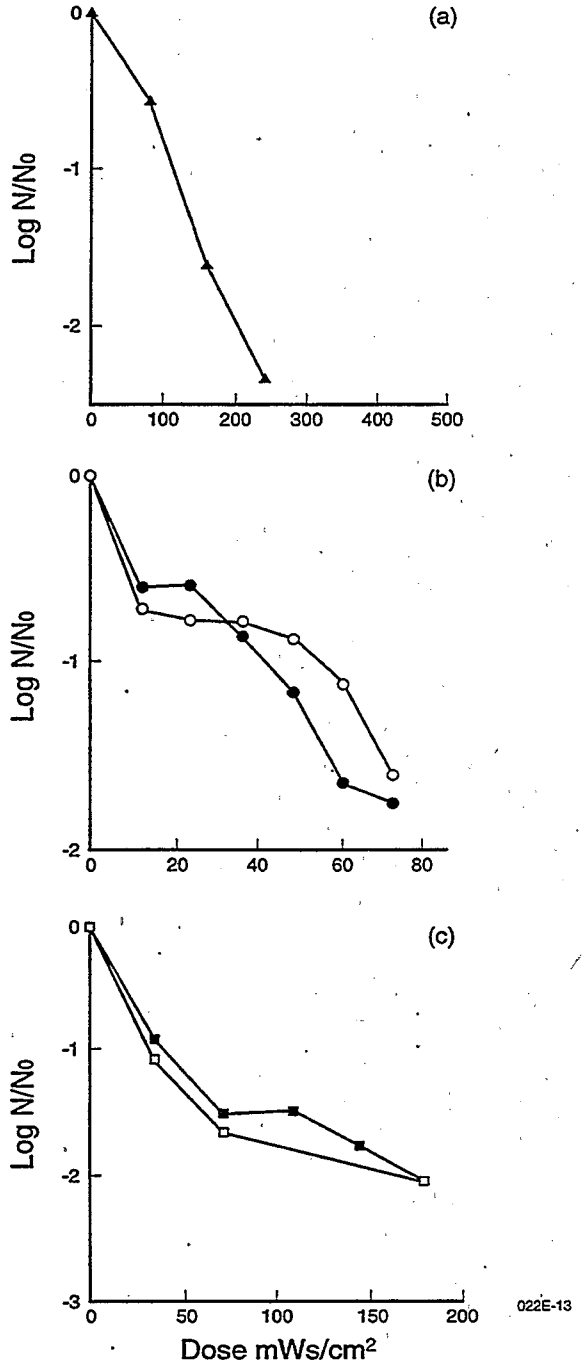


Exhibit 2-16 clearly shows that the source of parasites is important in determining dose requirements and that the growth stage of the microorganism is another important factor. As can be seen from Exhibit 2-16, *Acanthamoeba rhysodes* trophozoites are more sensitive to ultraviolet light than *Acanthamoeba* cysts at a dose of about 38 mWs/cm^2 but more resistant to inactivation at a dose above 40 mWs/cm^2.

Campbell et al. (1995) used a low-pressure ultraviolet light system of a theoretical minimum intensity of 14.58 mWs/cm^2 at the germicidal wavelength of 253.7 nm for 10 minutes (ultraviolet dose 8,748 mWs/cm^2) for the purpose of inactivating *Cryptosporidium parvum* oocysts. The preliminary results from Campbell et al. (1995) show a potential for inactivating *Cryptosporidium parvum* oocysts in clean water, using an ultraviolet light disinfection system. Campbell et al. (1995) indicated that the 2 to 3 log reduction in the viability of oocysts of *Cryptosporidium parvum* is a conservative estimate of the actual inactivation because the viable oocysts count is restricted by the limitations of the standard enumeration technique developed by Campbell et al. (1992) (vital dye assays that rely on morphology and inclusion/

Exhibit 2-16. Ultraviolet Irradiation Curves for Protozoan Type Organisms (Karanis et al., 1992)



Ultraviolet irradiation curves (a) 48-h-old *Trichomonas vaginalis* from a medicinal spring (5×10^4 trichomonads/ml; *n*=10 trials). (b) *Acanthamoeba rhysodes* from tap water (1×10^3amoebas/ml:) (o) 7 day-old-trophozoites (*n*=2 trials). (●) 28-day-old cysts (n=3 trails). (c) *Giardia lamblia* from distilled water: (□) 2×10^3 4-9-day-old group : cysts/ml from humans (1 trail); (■) $9\text{-}27 \times 10^3$ 3-9-day-old group II cysts/ml from gerbils (*n*=4 trials).

exclusion of two vital dyes). To adequately determine ultraviolet light disinfection potential against *Cryptosporidium parvum* using the same system and dose, Campbell et al. (1995) recommended the use of an automated counting system such as flow cystometer and suggested that the use of such technique might reveal an actual log reduction in viability that is higher than the morphological enumeration technique used by the researchers. The best defense against *Cryptosporidium parvum* is filtration, with slow sand filtration providing the possibility of 5 to 6 log reduction in oocysts (Jeffrey, 1991).

A recent report (SWS, 1996) by Clancy Environmental Consultants (CEC), with the support of the University of Arizona, agrees generally with the above-cited findings of Campbell et al. regarding the efficacy of ultraviolet irradiation of *Cryptosporidium parvum* in water. The device, composed of filters (2 µm nominal) that capture *Giardia* and *Cryptosporidium* oocysts and ultraviolet irradiation at a maximum dosage of greater than 8,000 mWs/cm^2, was tested and found to produce a greater than 3 log reduction in oocyst viability. Tests were conducted on cold (4°C) treated surface water. In addition, an accompanying animal infectivity study was conducted that led investigators to believe that reductions may have been much greater, because no animals were found to be infected. Some cautions were expressed by the investigators, mainly in the area of examination of oocysts microscopically for physical characteristics, damage, and/or viability. Evidently the animal infectivity part of this study provided greater confidence in the cyst-reduction results. The investigators also point to the need for additional study of the ultraviolet treatment unit used in the experiment under differing water quality, including ground waters and finished surface waters. Mineral content, natural organics, and inorganic debris (silica, clay) could affect treatment (SWS, 1996).

Recent research studies conducted by Bank et al. (1990) and Dunn, Ott, and Clark (1995) on the use of new ultraviolet light manipulation techniques to inactivate *Cryptosporidium parvum* are discussed in Appendix B of this report.

2.2.4 Doses and Inactivation Rates Achieved in Wastewater Treatment as Compiled from the Scientific Literature

The National Water Research Institute (NWRI, 1993) proposed guidelines for wastewater reclamation in California that call for a minimum dose of 140 mWs/cm^2 to disinfect filtered secondary effluent. This dose is based on pilot studies in which 4 logs of inactivation of poliovirus were accomplished at an ultraviolet dose between 100 and 120 mWs/cm^2. The works of Chen and Kuo (1992) and CH2M HILL (1992) were cited as a base for the above recommendation (NWRI, 1993).

In a Canadian pilot plant study, Zukovs et al. (1986) applied ultraviolet light to disinfect effluent combined sewer overflows (CSOs). Log reductions ranging from 1.5 to 3.5 for *Pseudomonas aeruginosa* were achieved at ultraviolet light doses of 100 mWs/cm^2 to 500 mWs/cm^2. *Pseudomonas aeruginosa* can cause illness, especially in immunodepressed patients. In water it can be found even in the absence of coliform bacteria and can cause enteric, eye, ear, and upper respiratory tract infections (USEPA, 1984).

Dizer et al. (1993) conducted a detailed study on the use of ultraviolet light for inactivation of bacteria and coliphage in a mix of 70 percent domestic wastewater secondary effluent and 30 percent surface water. Dizer et al. (1993) also used cultured bacteria that were artificially added to the ultraviolet reactor. The results of his study are presented in **Exhibit 2-17**. The reduction in inactivation rates in coliphage adsorbed to colloidal material from 94 percent (1.22 log reduction) to 54 percent (0.34 log reduction) indicates the limits of ultraviolet use for disinfection of turbid or unfiltered drinking water sources at the dose used in this experiment.

Exhibit 2-17. Inactivation of Microorganisms in a Mix of 70% Domestic Wastewater, Secondary Effluent, and 30% Surface Water as Reported in Dizer et al. (1993)

Microorganism	Range of Log Inactivation[a]			
	1	2	3	4
Natural				
Total Coliform	<**********>			
E. Coli	<**********>			
Fecal streptococci	*			
Coliphage f2	<**********>			
Artificial Titer				
Coliphage f2	<**********>			
Adsorbed Coliphage f2[b]	0.33			
Free Coliphage f2[c]	1.22			
Salmonella enteritidis				*
Streptococcus faecalis	<**********>			

[a]Reported ultraviolet light dose in the study is 47 mWs/cm^2. Residence time 3.54 seconds.
[b]Introduced to the reactor adsorbed to colloids in a slurry containing fine sand soil sediment of 0.1 g/ml concentration.
[c]Introduced to the reactor in a slurry medium containing fine sand soil sediment of concentration of 0.1 g/ml.

Dizer et al. (1993) results show lower inactivation rates when compared to experiments using laboratory-cultured microorganisms. Reports of the high sensitivity of various laboratory-cultured microorganisms to ultraviolet disinfection as compared with naturally occurring microorganisms confirm the findings of Dizer et al. (1993) (Martiny, Wlodavezzyk, and Rüden 1988; Martiny et al., 1988; Martiny, Seidel, and Rüden, 1989; and Sommer et al., 1989).

Naranjo et al. (1993) evaluated the removal of coliphage MS-2, rotavirus SA-11, and poliovirus 1 from wastewater by ultrafiltration and ultraviolet disinfection. The study did not report the intensity, time, or dose of ultraviolet light applied. The study reported an average removal of MS-2 of more than 4 log in all tests after ultrafiltration achieved log reduction between 2.3 and 3 in four experiments. Because of the high levels of viruses used in the study, Naranjo et al. (1993) concluded that using this system to treat drinking water would result in no detectable enteric viruses in the final product water.

In recent research, Oppenheimer et al. (1993) conducted a study on microbial inactivation rates and by-products formation in reclaimed water in California. Oppenheimer et al. analyzed samples collected from tertiary effluent at the Elsinore Valley Municipal Water District (EVMWD) Regional Plant. The bacteriological analysis included heterotrophic plate count, fecal streptococci, fecal coliform, total coliform, ΦX174 virus, MS-2 bacteriophage, and enterococci. The inactivation rates test results of Oppenheimer et al. are presented in **Exhibit 2-18**. The tertiary effluent quality parameters include a total dissolved solids level of 664 mg/L, a turbidity level of 0.6 NTU, a nitrate level of 13 mg/L as N, and a TOC level of 5.6 mg/L. Exhibit 2-18 shows that the bacteriophage MS-2 is more resistant to ultraviolet light treatment than all the other microorganisms tested in the experiment.

Exhibit 2-18. Ultraviolet Light and Chlorine Doses to Achieve 99.9% Inactivation of Microorganisms in Reclaimed Water (Oppenheimer et al., 1993)

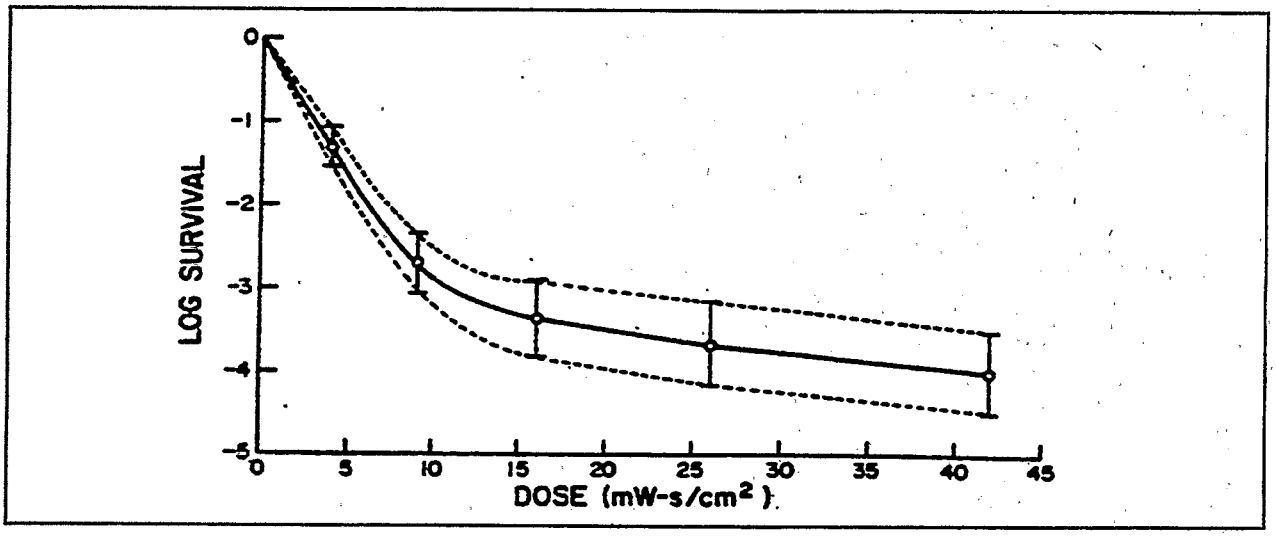
Organisms	Ultraviolet Light Dose (mWs/cm^2)	Chlorine Dose* (mg/l)
Bacteria		
Heterotrophic Plat Count	70	3.0
Total Coliform	35	2.5
Fecal Coliform	30	1.5
Fecal Streptococci	30	2.5
Enterococci	30	3.0
Virus		
MS-2	85	1.0
ΦX174	20	0.5

*2 hours contact time.

Ultraviolet light treatment pilot studies have been plagued by varying sensitivity of bacteria and the differences in applied intensities or the lack of reporting for such information. Qualls et al. (1985), using a simplified system where various water quality parameters could be accurately measured, conducted an average of 33 to 35 observations of irradiated unfiltered effluent samples and concluded that ultraviolet light sensitivity of a single cell and small aggregates of coliforms are relatively uniform from plant to

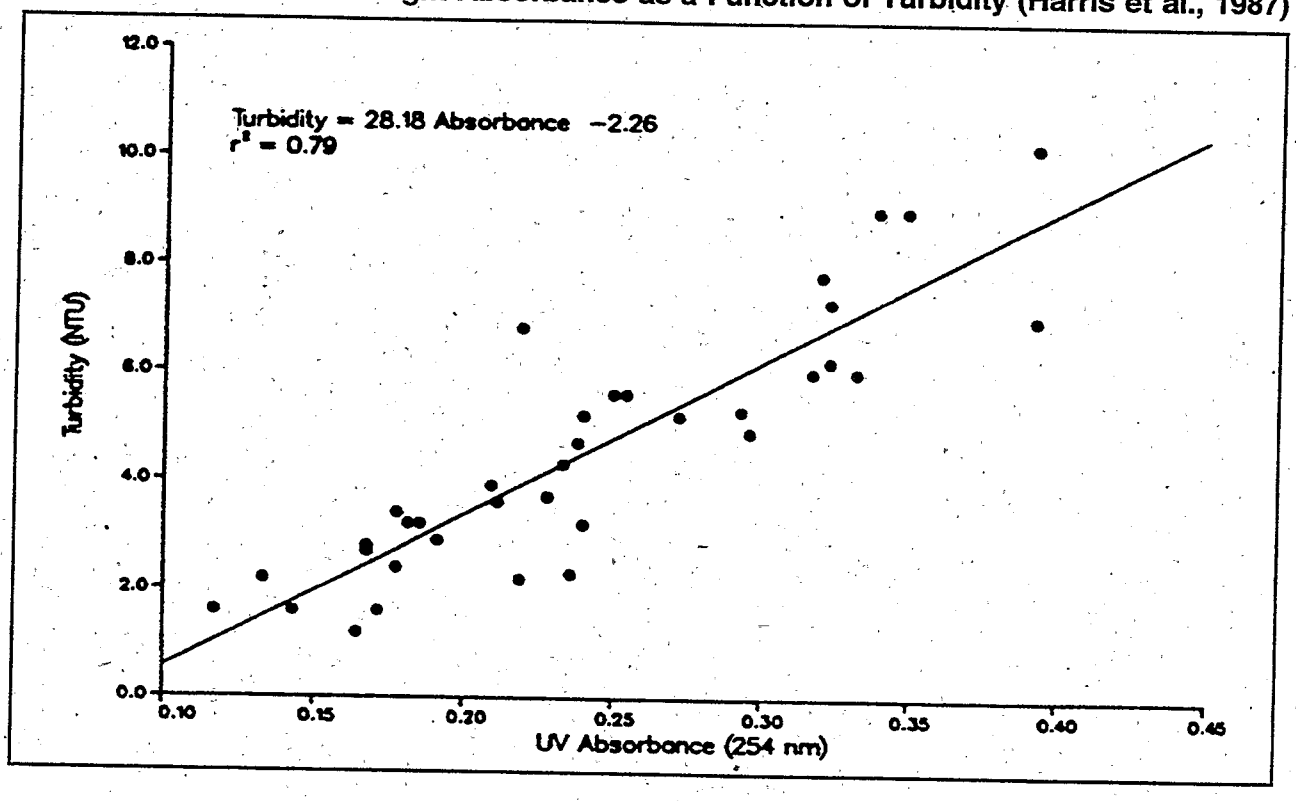
plant. However, the wide variation in survival curves is caused by the varying degree of protection afforded by different particle sizes and by the varying proportion of coliforms that are aggregates or attached to colloids particles. **Exhibit 2-19**, provided by Qualls et al. (1985), is useful as a generalized range of coliforms survival data for planning equipment needs where accurate dose-survival data do not exist and pilot studies are deemed expensive. The upper and lower graph boundaries represent samples ± standard deviation bars.

Exhibit 2-19. Average 33 to 35 Observations of Log Survival of Coliform Bacteria in Unfiltered Effluent Samples (Qualls et al., 1985)



Harris et al. (1987) studied the effects of turbidity on ultraviolet disinfection of secondary municipal wastewater effluents and photoreactivation potentials using two different ultraviolet light reactors. Harris et al. observed up to 2 log survival in total coliform photoreactivation and little evidence of photoreactivation of fecal streptococci. **Exhibit 2-20** is a graphical presentation of the relationship between ultraviolet absorbance at 254 nm and turbidity as reported by Harris et al. 1987. The study showed highly significant correlations between suspended solids, fecal coliforms survival at 5 mWs/cm^2, and ultraviolet light absorbance at 254 nm. The researchers concluded that wastewater turbidity can be used as a good surrogate measure of disinfection efficiency and ultraviolet light absorbance. The graph shows that at a turbidity level close to 5 NTU, about 25 percent of ultraviolet light transmittance is absorbed by turbidity-causing wastewater constituents. It should be recognized that other factors (iron, organics, etc.) may play an additional role in absorbing ultraviolet light in practical drinking water use. However, for drinking water applications and in the absence of similar experiments in turbid drinking water, the Harris et al. work can be used as a base to account for turbidity absorbance of ultraviolet light.

Exhibit 2-20. Ultraviolet Light Absorbance as a Function of Turbidity (Harris et al., 1987)



2.3 ULTRAVIOLET LIGHT OPERATIONAL FACTORS

In this section, factors such as operating procedures and requirements, maintenance requirements, installation features, and design elements are analyzed to determine the viability of ultraviolet light in a ground water treatment setting. This section is organized as follows: section 2.3.1 presents a general description of ultraviolet light equipment operational factors; section 2.3.2 discusses water quality considerations. Hydraulic design considerations are presented in section 2.3.3; and design considerations specific to small systems are presented in section 2.3.4.

2.3.1 Equipment Operational Factors

Ultraviolet light bulb efficiencies decline over time. Therefore, it is important when adopting a standard for ultraviolet light treatment that the standard reflect the efficiency of the light bulb at its lowest point according to the manufacturer's suggested effective use time. The current effective life of ultraviolet light bulbs ranges from 7,000 to 14,000 hours (Aquafine, 1995). Industry brochures show about 30 percent reduction in light transmission efficiency over a period of 10,000 hours. Operators and maintenance crews need to be adequately trained to service the equipment as recommended by the manufacturer.

The operational factors that affect adequate performance of an ultraviolet light system are lamp output, lamp aging, and fouling of unit surfaces.

2.3.1.1 Lamp Output

Ultraviolet lamp output is directly dependent on the optimum conditions of the mercury vapor discharge requirements. These requirements include a steady electric potential that does not fluctuate and drop below a certain level set by the designer. For example, a drop of 5 volts in the electric potential difference acting on a 5-amp lamp means a drop of 25 watts in energy available to the lamp.

Another factor that affects the output of a standard ultraviolet lamp is temperature. The optimum temperature for maximum ultraviolet lamp efficiency is generally between 35°C (95°F) and 50°C (122°F). Maintaining optimum temperature and pressure in an ultraviolet lamp is important to maintain maximum light emission at the desired wavelength. This concern is less important in new ultraviolet lamp models that have devices to regulate temperatures and in those that can operate at temperatures higher than 50°C (122°F).

2.3.1.2 Lamp Aging

Several factors affect the performance of an ultraviolet lamp as it advances in hours of use: solarization (i.e., the effect of ultraviolet light on the lamp and the sleeve that causes lamps to become opaque over time), electrodes failure, and plating of the mercury to the interior lamp wall. If combined, these factors might reduce the efficiency of an ultraviolet light lamp by as much as 30 percent after 7,000 hours of use. The electrodes in an ultraviolet lamp will deteriorate progressively with an increase in the number of times the lamp is started. According to various industry sources, the maximum allowed number of starts per lamp per day is four. In a typical potable water application, ultraviolet lamps are expected to run 24 hours per day. According to various industry sources, the current effective life span of an ultraviolet lamp ranges from a minimum of 7,000 hours to a maximum of 14,000 hours.

2.3.1.3 Fouling and Plating of Lamps and Sleeves

Fouling of the unit's quartz sleeves surface reduces the light energy reaching the volume of water. Typically, high quality fused quartz sleeves have a transmissibility of more than 90 percent when new and clean. With time, the surfaces of the quartz sleeves that are in contact with the body of water start collecting organic and inorganic debris—such as calcium scale, silt, or iron fouling—causing a reduction

in transmissibility. Therefore, it is very important to maintain the surfaces of the sleeves to ensure that they are clean and free of deposits.

To maintain clean ultraviolet units, mechanical wipers can be used. However, like all other mechanical devices, they must be checked periodically to ensure that they are sufficiently cleaning the lamps. To combat fouling, ultrasonics are highly recommended in hard water situations and in ground water that contains iron. The alternative to ultrasonics is the periodic use of detergents such as sulfuric acid or hydrochloric acid. To combat plating (forming a thin coating on surfaces), high water pressure also is used effectively to routinely clean the inside surfaces of the ultraviolet unit. High water pressure cleaning techniques are recommended in situations where ground water contains very fine silt materials, sulfites, or manganese.

Kreft, Scheible, and Venosa (1986), based on hydraulic studies conducted on three wastewater ultraviolet treatment units, recommended both chemical and physical cleaning of ultraviolet units. They also suggested the use of high-pressure nozzles to scour fouled surfaces and a recirculation system for chemical cleaning. The researchers found that wipers and ultrasonics have a great potential for keeping clean units, but neither negates the necessity for occasional chemical treatment or swabbing of the ultraviolet tubes.

2.3.2 Water Quality Considerations

The performance of an ultraviolet disinfection system is directly related to ultraviolet light absorbance by the treated water. When ultraviolet light travels through the water body, the light intensity decreases as the distance from the light source increases. This is caused by energy dilution as light dissipates in a larger volume of water. Another factor that causes ultraviolet light to be absorbed is water quality. Ultraviolet absorbance by water is analogous to chlorine demand in chemical disinfection processes. However, with respect to ultraviolet applications, Weber (1989) suggested that pure water also exerts an ultraviolet demand. Weber (1989) reported that even distilled water absorbs about 8 percent of the applied ultraviolet energy at a depth of 3 cm.

The transmittance of water commonly is used to describe the ultraviolet demand. This can be determined from the absorbance measurement expressed in percent:

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

Where:
a.u. = absorbance units
d = distance in centimeter

The percent absorbed is 100 percent minus transmission. The parameter most often used for design purposes is the Coefficient of Absorbance (C of A) or α expressed as

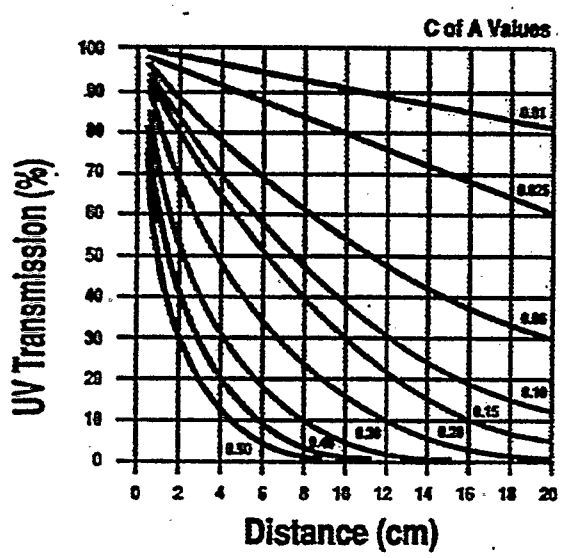
$$\alpha = 2.3 \text{ (a.u./cm)}.$$

The unit of ultraviolet absorbance coefficient is cm^{-1}.

In general, ultraviolet absorbance coefficients decrease with an increase in water quality.

Exhibit 2-21 (courtesy of Aquafine Corporation) presents absorbance coefficient curves as a function of ultraviolet light transmission and distance. For ground water systems using ultraviolet light for disinfection, it is important to determine the absorbance coefficient by sampling at different periods during the year to account for seasonal and temporal water quality fluctuations. In the absence of field data, Exhibit 2-21 or similarly constructed graphs can be used to select an appropriate absorbance coefficient. From Exhibit 2-21, an absorbance coefficient of 0.1 may be a reasonable conservative assumption "α" value for ground water.

Exhibit 2-21. Ultraviolet Transmission and Absorbance Coefficient (Source: Aquafine Corporation, 1995)



High purity water: $\alpha = 0.01$

Municipal drinking water: $\alpha = 0.06$ to $\alpha = 0.15$

% Transmission at "d": $= 100 \times 10^{-(a.u./cm).d}$
$= 100 \times e^{-\alpha.d}$

As with other disinfection technologies, better disinfection results are achieved with ultraviolet light if the water is free of turbidity. Ultraviolet industry representatives recommend that ground water with a turbidity level of 5 Nephelometric Turbidity Units (NTUs) or more should be treated for turbidity removal

before it is run through the ultraviolet light reactor (Atlantic Ultraviolet Corporation, 1995a; Voitle, 1994; Wagenett and Lemley, 1994). Similarly, ground water with suspended solids levels of more than 10 mg/L (10 mg/L was the U.S. Department of Health drinking water standard for turbidity [Steel, 1960]) should be monitored to determine whether the high levels are of a permanent, seasonal, or ephemeral nature. Knowing the upper range of suspended solids in water is important in order to determine which type of ultraviolet light unit will be required.

In wastewater applications, ultraviolet systems are designed to accommodate liquids with suspended solids levels as high as 30 mg/L for any consecutive 30-day period (WPCF, 1986). Therefore, ultraviolet systems for ground water disinfection could be designed to allow for high suspended solids situations although such levels are not expected to occur in drinking water situations. To compensate for ultraviolet light absorbed by high levels of suspended solids, higher ultraviolet light doses need to be applied in order to achieve desired levels of disinfection.

The two major water quality factors that affect the performance of an ultraviolet unit in (clear) ground water are microbial factors and chemical factors.

Severin, Suidan, and Engelbrecht (1983) studied the effects of temperature on ultraviolet light disinfection and found that ultraviolet disinfection is relatively insensitive to temperature changes. The disinfection tests were conducted at 5°C, 20°C, and 35°C. However, earlier *in vitro* studies showed that more disinfection may occur at lower temperatures than at higher temperatures because at lower temperatures (below 25°C), single-stranded polynucleotides and DNA strands are in a stacked configuration. Stacked DNA and stacked single-stranded polynucleotides are more subject to dimerization than unstacked DNA (Rahn, 1970). Malley, Shaw and Ropp, 1996 (as cited in Snicer et al., 1996) concluded that pH levels might have an effect on ultraviolet light disinfection efficiency. The researchers attributed the detected effect to morphological changes in the nature of the protein coat that caused clumping of microorganisms. Montgomery (1985) and USEPA (1986) reported that disinfection by ultraviolet light is pH independent. As mentioned earlier, AWWA (1992) reported that research studies conducted at the University of New Hampshire show that ultraviolet light disinfection processes are independent of water pH. Therefore, unlike chemical disinfection processes, water quality parameters such as temperature and pH have an insignificant effect on ultraviolet light disinfection capabilities. In chemical disinfection processes, an increase in temperature results in an increase in the killing rate of the disinfectant. This could be explained in the context of increased chemical reaction rate and in the decrease of surface tension between

microorganisms, microorganisms and colloidal particles, and the decrease in the viscosity of the medium (Gaudy and Gaudy, 1980). In chemical disinfection processes, pH influence on disinfection rate varies from one chemical to the other. For example, an increase in pH will decrease the disinfection efficiency of chlorine gas and slightly increase the disinfection efficiency of chlorine dioxide (Montgomery, 1985).

Important microbial water quality parameters to be taken into account when selecting an ultraviolet unit for disinfecting ground water are the microbial water quality and the densities of the microbial population. High densities of the microbial population may cause a decrease in the inactivation efficiency of ultraviolet light by shielding and hosting. For an adequate evaluation of the microbial parameters and the potential for microbial contamination, it is recommended that water samples be taken during the warm season after a rainy period to test for Heterotrophic Plate Count (HPC). HPC, also known as the standard plate count, is a procedure for estimating the number of live heterotrophic bacteria in water and measuring changes during water treatment and distribution. In an HPC procedure, colonies may arise from pairs, chains, clusters, or single cells, all of which are included in the term "colony-forming units" (CFU). A high HPC of more than 500/ml may cause a decrease in inactivation rate of viruses (by shielding and hosting). Therefore, it is important to have the microbial data available before purchasing and installing an ultraviolet unit.

The effect of the ultraviolet light on microorganisms is a function of the energy absorbed by the microorganism. The energy absorbed is defined as the product of the rate at which the energy is delivered and the length of time the microorganism is exposed to that intensity.

The ideal ultraviolet disinfection model follows Chick's law (Chick, 1908) whereby:

$$N = N_o e^{-kit}$$

Where N_o = initial bacterial population

N = surviving bacterial population after exposure to ultraviolet light

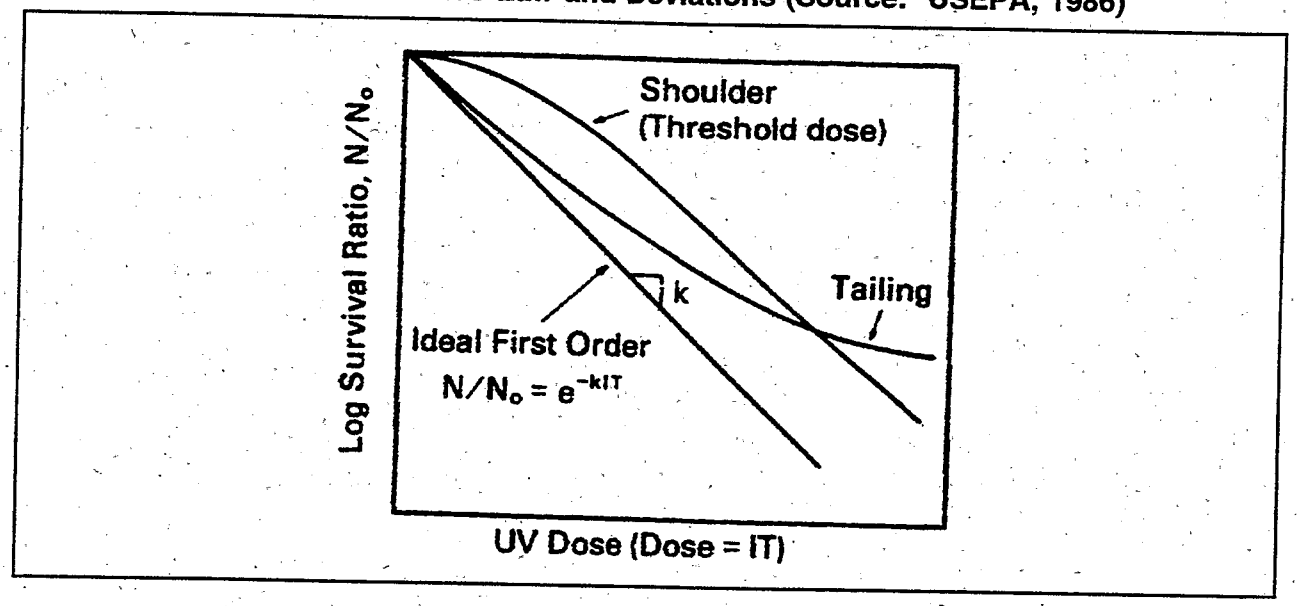
k = rate constant

i = intensity of ultraviolet light

t = time of exposure.

Exhibit 2-22 is a graphical presentation of Chick's law and deviations from it. Chick's law assumes a uniform susceptibility of all organisms within the strain or species. Deviations from this ideal first order representation are manifested by tailing effects and shouldering. In general, the presence of "shoulders"

Exhibit 2-22. Chick's Law and Deviations (Source: USEPA, 1986)



indicates a time lag between the application of ultraviolet light and the onset of disinfection. The presence of "tailing" indicates a decrease in the rate of inactivating surviving microorganisms at higher ultraviolet energy doses.

The presence of a "shoulder" or "tailing off" or both may be explained by the following:

- The presence of protective extracellular layers
- The presence of colloids that absorb ultraviolet light
- The presence of organic and inorganic substances that absorb ultraviolet light
- The presence of organic and inorganic substances that induce microbial resistance to ultraviolet light.
- Inherent differences in sensitivities of the microbial population.

Although avoiding "shouldering" and "tailing off" in disinfection processes is difficult, knowing water quality parameters and designing an ultraviolet system accordingly may result in a lesser manifestation of such phenomena.

Like chemical disinfectants, there are chemical and water quality factors that affect the performance of an ultraviolet light disinfection unit. These factors are presented in **Exhibit 2-23** and include hardness, nitrites, sulfites, manganese, and aromatic organics levels. These water quality factors are known to cause

Exhibit 2-23. Factors Affecting Ultraviolet Light Disinfection Performance*

Factor		Effect
Hardness	≥ 100 mg/l	Plating**
Iron	≥ 0.2 mg/l	Fouling***
Nitrites		Plating
Sulfites		Plating
Manganese		Plating
HPC	> 500	Decrease inactivation of viruses
Aromatic organics		Plating
Turbidity	> 10 NTU	Plating
Ultraviolet transmission	< 75%	Inadequate destruction
Inorganic suspended solids	> 5 µm	Shielding
Color	> 15 NTU	Reduce disinfection efficiency
Short circuiting in contact chamber		Inadequate inactivation
High flow rate		Reduce disinfection efficiency
Low line voltage supply		Low light transmission
Improper lamps arrangement		Low light efficiency decrease inactivation efficiency

*USEPA, 1992. Draft Ground Water Disinfection Rule FR.; Negron, 1994.
**Forming a thin coating on surfaces.
***Incrustation.

plating (the coverage of inner surfaces with a layer of minerals) and fouling (the formation of a crust on sleeve and inner sides of the unit) in ultraviolet units that are not equipped with mechanical wipers and ultrasonic cleaners. Plating and fouling cause inadequate ultraviolet light transmittance and a decrease in inactivation efficiency. Modern ultraviolet units are equipped with automatic wipers and ultrasonic cleaners. The continuous action of the mechanical wipers along with periodic ultrasonic cleaning greatly reduces plating and fouling. It is recommended, as a good process tracking tool, that a log be maintained to record all water quality parameters to recognize any change in ground water quality. For example, levels of nitrites in particular are required to be kept at less than 1 mg/L. Nitrites are regulated under the National Primary Drinking Water Regulations, and their presence in ground water sources may indicate, in the absence of any other explanation, a fresh contamination that requires immediate response.

Other secondary contaminants need to be removed for other reasons. For example, although iron is not a primary drinking water contaminant, iron removal from drinking water sources is highly desirable and is more economical at the treatment plant than at the tap. Ground waters with dissolved iron content above 0.3 ppm will cause brown-red stains on sinks, porcelain, and bathroom fixtures. Upon heating, the clear water color will turn brown-red and will cause cloth discoloration and brown-red stains on cooking pots. At above 3 ppm of iron content, the water will have an offensive metallic taste and the water will be colored. In some cases, precipitation will occur; in other cases, a brownish cast that does not

precipitate will persist. Some iron-containing waters have iron in colloidal form, thus making drinking water very offensive to look at and to use for drinking, cooking, or washing (USEPA, 1991a). Although there are no known health risks associated with high iron levels in drinking water, aesthetic qualities are very important to assure users of the safety of their drinking water.

2.3.3 Hydraulic Design Considerations

The major elements that must be considered in the hydraulic design and operation of an ultraviolet reactor include the following:

- Dispersion
- Turbulence
- Effective volume
- Residence Time Distribution (RTD)
- Flow rate.

2.3.3.1 Dispersion

Dispersion is the characteristic of water elements to scatter spatially in two or three dimensions. The ideal ultraviolet light disinfection reactor is a Plug-Flow Reactor (PFR). In a PFR, water particles are assumed to enter into the reactor and discharge from the reactor in the same sequence they entered. Therefore, in a PFR, each element of the water passing through the reactor resides in the reactor for the same period of time. Hence, an ideal PFR has no flow dispersion. In reactor design, this type of flow is approximated in a long tank with high length-to-width ratio in which longitudinal dispersion is absent or minimal.

2.3.3.2 Turbulence

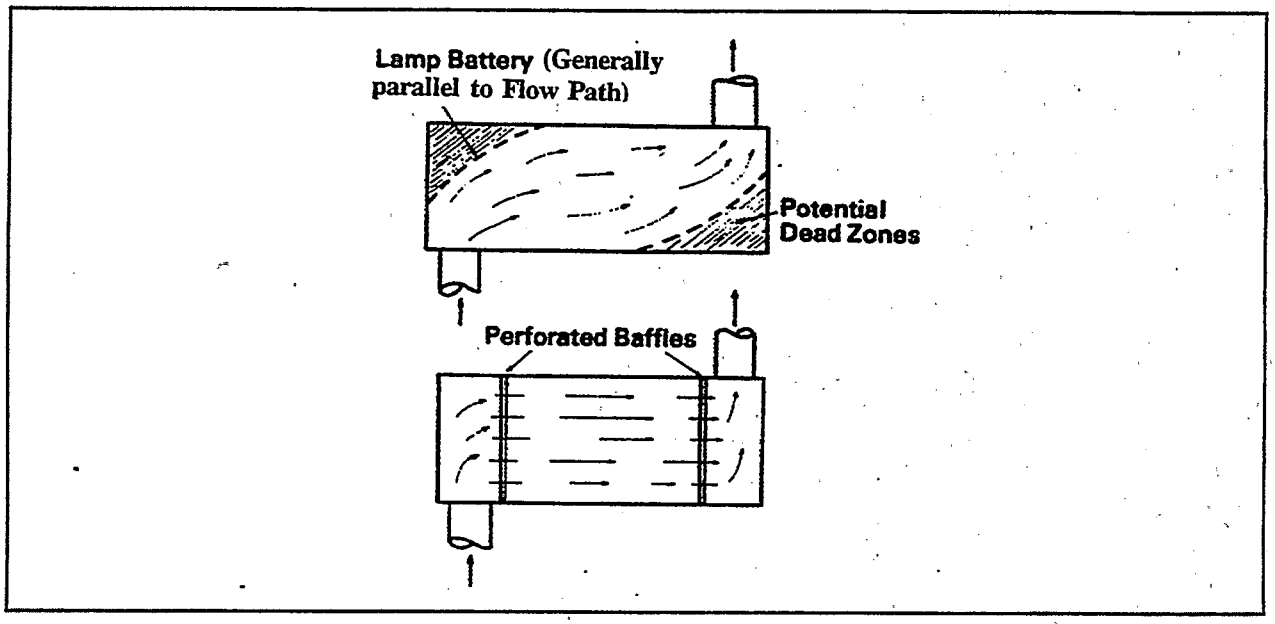
In addition to the desired PFR characteristics, an ideal ultraviolet light reactor is a reactor with a flow that is turbulent radially from the direction of flow with no dead zones. The radially turbulent flow pattern promotes more uniform application of ultraviolet light. However, having a radially turbulent flow results in some axial dispersion, thus disrupting the ideal plug flow sought in a disinfection reactor. By not aligning inlets and outlets of units and using perforated baffle plates, designers accommodate the contradicting plug flow and turbulence requirements.

2.3.3.3 Effective Volume

Avoiding dead zones (i.e., areas of no or reduced flow) results in maximum use of the volume of the reactor. It also results in an effective volume as close as possible to the actual volume available. **Exhibit**

2-24 presents a configuration (top figure) of a closed ultraviolet light reactor where dead zones are induced by a specific inlet and outlet configuration. The exhibit shows how the introduction of perforated baffle plates can help distribute the flow over the entire cross-sectional plane of the reactor, thereby eliminating dead zones.

Exhibit 2-24. Closed Ultraviolet Light Reactor (USEPA, 1986)

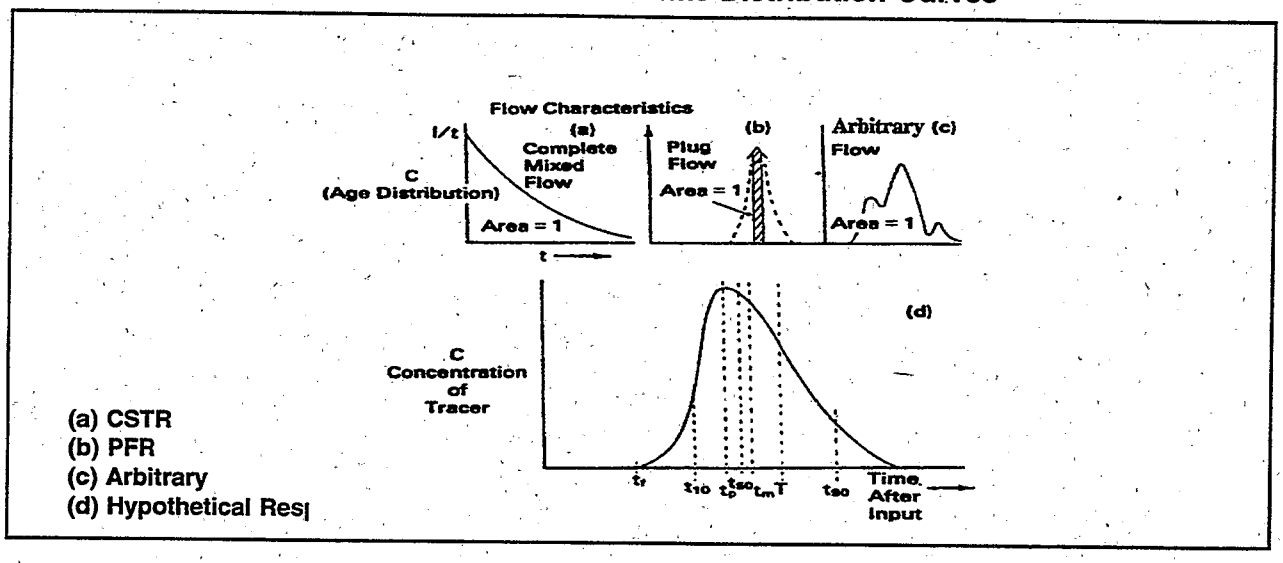


2.3.3.4 Residence Time Distribution (RTD)

RTD is used as a design and diagnostic tool to determine the effects of hydraulics on the ultraviolet system performance. The shape of the curve and the distribution of the area under the curve indicate the hydraulic characteristics of a system and also indicate whether it is close to an adequate disinfection design. **Exhibit 2-25** presents RTD curves for various flow characteristics.

An RTD curve closer to a Continuous-Flow Stirred Tank Reactor (CSTR) or to an arbitrary flow curve than to a PFR curve indicates inadequate performance and poor design. An RTD curve is generated by sampling water at successive intervals of time to measure for concentrations of a non-reactive (conservative) tracer that is pulse-injected into the reactor and then plotting the concentration values versus time. Detailed discussions on RTD and dispersion models in plug-flow reactors are found in Metcalf and Eddy, 1991; USEPA, 1986; and WERF, 1995.

Exhibit 2-25. Residence Time Distribution Curves



2.3.3.5 *Flow Rate*

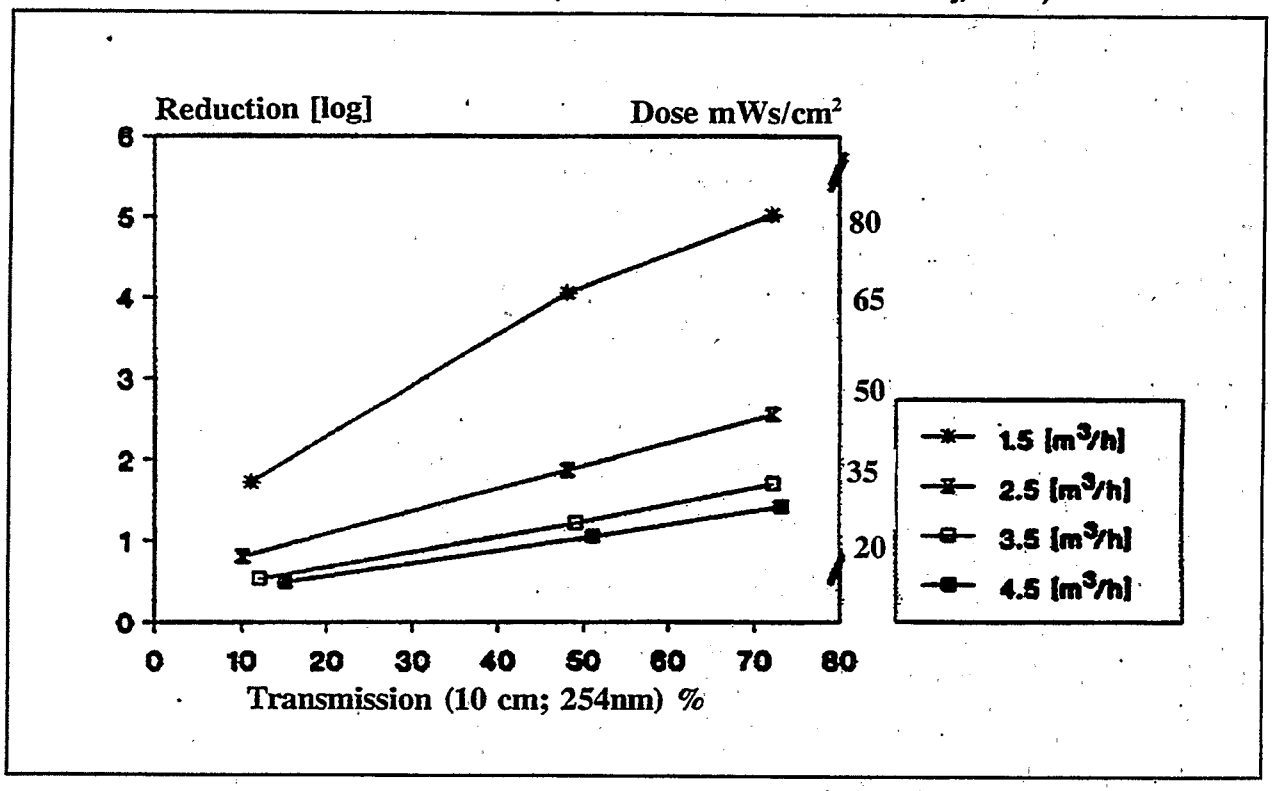
The flow rate is usually set by design based on projections of water consumption. Because multiple parallel ultraviolet units may be used in a water treatment plant, balanced flow split between modules is important for two reasons: first, the balance will avoid overloading a single unit or group of units, hydraulically and with deposits, and second, the inactivation rate increases as flow rate decreases (Sommer and Cabaj, 1993).

Sommer and Cabaj (1993) conducted experiments on *Bacillus subtilis* spores using various flow rates of potable water and ultraviolet doses. The researchers showed that a decrease in ultraviolet transmission results in a decrease in *Bacillus subtilis* spore inactivation. The spore reduction could be read directly as a function of dose and transmission, for different flows treated in the same reactor. The work of Sommer and Cabaj as presented in **Exhibit 2-26** is important because it provides a view of the range of practical application of ultraviolet light in water disinfection under various flow conditions. In any case, it is important that actual flow through an ultraviolet unit does not exceed the manufacturer's recommended flow rate.

2.3.4 Small System Design Considerations

Ultraviolet equipment varies in design. Minor design details may have significant effects on operation and disinfection capabilities of the ultraviolet light unit. Therefore, onsite testing of the equipment may be recommended to determine whether the unit is properly designed for a specific quality of water. It is

Exhibit 2-26. Practical Application of Ultraviolet Light in Water Disinfection, Surrogate Used *Bacillus subtilis* (Source: Sommer and Cabaj, 1993)



recommended also that an engineer design the disinfection system or that an independent third party test the efficacy and reliability of the equipment under various raw water conditions. Testing an ultraviolet unit should include efficiency tests under low flow conditions, high flow conditions, low quality water, and for multiple lamp units, simulation of a situation where one or more lamps are not functioning. (Efficiency tests involve injecting a bacterium stock [challenge microorganism] at a steady rate into the reactor and assaying the effluent to determine surviving population.)

For small ground water applications, ultraviolet systems should consist of multiple units rather than one unit, even if one is capable of carrying the entire design flow. Backup or dual units serve the purpose of maintaining a continuous disinfection process while a unit is being serviced. Also, a system with multiple units can shut down a unit during low flow. Therefore, at a minimum, two ultraviolet units should be provided per system with each unit capable of carrying peak hourly flows.

For a small public water system, it is recommended that all electric fittings be of the modular type in order to make installation, replacement, and maintenance quick and easy. It is also important that the manufacturer provide information on the unit's theoretical and mean residence time at specific flows, as

well as information on peak design flow, ultraviolet transmission assumptions, and minimum dose at the end of the lamp's life. Operation manuals should include a description of control systems, alarm functions, records, and reports.

The manufacturer should provide an equipment operation plan that includes procedures and intervals for cleaning sleeves, frequency of lamp replacement, and frequency of calibration of monitoring equipment. The operator of the ultraviolet unit should be well informed about the location, access, and quantity of a backup supply of lamps, ballasts, and other critical components. Contingency plans for emergencies that necessitate a complete shutdown of the ultraviolet system should be drafted before the system is up and running.

For small ground water systems installing an ultraviolet unit, the operators should consider the following:

- The ultraviolet system should be installed in a place that would permit free movement around the unit and ample space for service (lamp and sleeve removal, periodic cleanup).
- An ultraviolet unit should be equipped with before-and-after shutoff valves, and the housing should have a drain close to the ultraviolet unit to minimize the amount of water the service personnel will encounter upon opening the unit for service.
- Cleanliness of an ultraviolet reactor is an important operation and maintenance issue; therefore, continuous intensity monitoring is recommended to detect fouling of the system.

Operators of small public water systems should at a minimum do the following:

- Check fail-safe devices for proper operation.
- Calibrate the ultraviolet intensity measuring periodically for proper sensitivity.
- Disconnect the unit and clean the lamps by wiping with a soft cloth moistened with ethanol (APHA, 1989) or any other solvent recommended by the manufacturer.
- Inspect and/or clean the interior of the ultraviolet chamber every 6 months.
- Examine seals annually (and then calibrate the intensity meter). Replace the lamps if they emit less than 70 percent of initial output.
- Monitor water turbidity and color since they are natural barriers to the transmission of ultraviolet light. Also, some dissolved minerals have a tremendous effect on ultraviolet absorbance. For example, iron as low as 1 ppm may increase absorbance of ultraviolet light by more than 80 percent (Weber, 1989).

Operators of very small ground water systems are not typically in the treatment plant on a daily basis and are not expected to be on duty 24 hours a day. Therefore, it is recommended that the operator be equipped with a remote system (telemetering) that at a minimum can provide alarm signals for major ultraviolet light system failure.

Major or high priority alarm systems are alarm systems that are initiated by a unit failure or a component failure that might result in an unacceptable level of disinfection. Major alarms, as opposed to minor alarms, are those alarms that would sound or flash in case of ultraviolet lamp failure, power failure, unit failure, or ballast failure. Minor alarms are those alarms that would indicate the failure of equipment that does not affect the disinfection process directly such as a light-emitting diode failure. Many ultraviolet light systems are equipped with automatic treatment plant shutdown in case of a major equipment failure.

In its comment on the Draft EPA GWDR, AWWA suggested that ultraviolet light systems be required to have the following minimum operational controls and procedures:

- A central display showing indicators and alarms for power failure, lamp failure, hours of lamp operation, low ultraviolet dosage, high lamp temperature, high ballast temperature, and high system flows.
- Systems that monitor lamp temperature, ballast temperature, and system water flows.
- A photodiode sensor to monitor ultraviolet dosage at 254 nm. A minimum of two sensors per unit is recommended. These sensors must be calibrated using approved standards each time the lamps are cleaned or replaced or the ultraviolet chamber is serviced.
- Automatic ultraviolet system by-pass or shutoff to be activated whenever peak design flow rates are exceeded, when ultraviolet dosage is low, or when lamp or ballast temperatures are high.
- System redundancy should be provided for the average flow when the largest unit is out of service.

To assess ultraviolet disinfection viability for small drinking water treatment systems, an evaluation should be made of system flexibility, reliability, complexity, and effectiveness. Ultraviolet systems in modular units are easy to upgrade, accommodate flow expansion plans in phases, and are easy to maintain and service. For ground water situations where water quality does not fluctuate as much as surface water quality, ultraviolet systems are reliable and can perform well if properly maintained.

Modern ultraviolet light systems are less complex than early ultraviolet models. They are easier to install, requiring only one electrical connection and two plumbing connections. Changing lamps in modern models is no more difficult than changing a fluorescent light bulb.

For small ground water systems, particularly TNC and NTNC water supply systems, ultraviolet disinfection systems may be more appropriate than chlorination and ozonation, when the ground water is high in THM precursors, for the following reasons:

- Ultraviolet light does not generate THMs.
- For disinfection, ultraviolet light is pH and temperature independent.
- Ultraviolet light is effective in inactivating many pathogenic bacteria and viruses and at higher doses is effective against protozoa.
- There is no danger of overdosing.
- There are no safety precautions to be taken for transporting, storing, or applying chemicals.
- Environmental impacts from ultraviolet systems are lower than impacts related to the use of chlorine or ozone.
- The equipment is reliable and easy to maintain. Many manufacturers provide equipment warranties and transmission performance warranties.
- Process control is flexible and simple.
- Overall, operation and maintenance costs are low.
- There is no need for daily measurement of chemical dose.
- There is no need to prepare fresh stocks of disinfectants (as is the case when using sodium or calcium hypochlorite).

Following are additional factors that should be considered in the design and operation of an ultraviolet facility.

2.3.4.1 Inspections and Shutdown

For small water systems using ultraviolet light for disinfection, it is important to maintain a clean ultraviolet unit and conduct periodic inspections of all monitoring devices. Adequate training of the ultraviolet unit operator is essential, and emergency plans should be in place in case of a ultraviolet system

shutoff. If a shutdown occurs, emergency plans must ensure that positive pressure is maintained in the water supply network to prevent infiltration and cross-contamination and to provide for fire protection.

2.3.4.2 Distribution System

For small ground water systems installing ultraviolet units for disinfection, it is important to exercise good sanitary practices, particularly if ground water contains dissolved organic compounds (DOCs) and natural organic matter (NOM). It is recommended that these systems flush the distribution network, particularly dead ends, before installing ultraviolet units and at least once or twice in spring through summer when temperatures rise. Flushing and cleaning the system is recommended to remove accumulated sediments and reduce biofilm accumulation in the pipe network, reservoirs, and storage tanks. Both sediments and biofilm contain essential substrates that will increase the likelihood of microbial reactivation (as discussed in section 2.4.2).

2.3.4.3 Monitoring Devices

Regular calibration of monitoring devices and checking key components for proper functioning are important steps to avoid any sudden shutdown or malfunction. For example, in some cases the Light-Emitting Diode (LED) may not give a true indication of whether the ultraviolet lamp is actually operating. Therefore, checking for a faulty LED, burned out LED, or malfunctioning ballasts should be done regularly.

2.3.4.4 Manuals and Instructions

Instructions for installation, operation, maintenance, and initiation of service should be provided with each system and component. Compliance with Federal, State, and local engineering, manufacturing, and safety laws and regulations must be ensured. For example, power should be automatically switched off whenever a unit is opened for service to protect maintenance workers' eyes. Manuals provided by the manufacturer typically include drawings and lists of parts for ease of identification and for ordering replacement parts. Because ballasts of ultraviolet lamps may provide a different electrical potential difference (voltage) than those available for fluorescent lamps, operators of ultraviolet units used in water disinfection should not use ballasts other than those specified for use with ultraviolet lamps.

2.3.4.5 Spare Parts and Disposal

Many small systems, particularly in remote areas, should have at a minimum a set of spare parts that includes ballast, lamps, and sleeves. All ultraviolet systems operators, particularly small system operators in remote areas, should follow the manufacturers' disposal and recycling guidelines for ultraviolet mercury-containing lamps, ballasts, and sleeves.

General operation and maintenance practices are well documented in Chapter VI of *Microorganism Removal for Small Water Systems*, USEPA, 1983. In addition, ultraviolet system operators should follow the specific operation and maintenance practices for ultraviolet units that are documented in Chapter VII of *Design Manual: Municipal Wastewater Disinfection*, USEPA, 1986.

2.4 OTHER CONSIDERATIONS RELATED TO THE USE OF ULTRAVIOLET LIGHT FOR DRINKING WATER DISINFECTION

This section discusses issues related to ultraviolet treatment in drinking water. It presents scientific findings on by-products formation and removal of organic contaminants from ultraviolet-treated drinking water. It discusses the issues of microbial reactivation, residual disinfection, and availability of a challenge surrogate microorganism. Finally, this section presents efficiency comparisons between ultraviolet light and chemical disinfectants.

2.4.1 By-Products Formation and Removal of Organic Contaminants by Ultraviolet Light Treatment

This section discusses the potential for by-products formation and removal of organic contaminants during the ultraviolet light disinfection process. The effect of ultraviolet light on organic compounds is the result of two mechanisms. The first mechanism is the direct action of ultraviolet light on the chemical bonds of the targeted organic compounds. The second mechanism is the action of ultraviolet light on water molecules and dissolved oxygen that results in the formation of powerful oxidizing agents, such as ozone and hydrogen peroxide, which in turn react with the targeted organic compounds and destroy them.

Disinfection processes that result in chemical by-products that are harmful or that might contribute to microbial growth should be controlled to minimize the presence of adverse chemical by-products in drinking water. More details on organics removal are presented in Appendix A. Section 2.4.1.1 provides information on the removal of known organic contaminants in drinking water by ultraviolet light. Sections 2.4.1.2, 2.4.1.3, and 2.4.1.4 provide information available on by-products formation.

2.4.1.1 Removal of MX and Other Contaminants from Drinking Water

In a study conducted in Japan, Fukui et al. (1991) used an 18-watt, 30-cm long low-pressure ultraviolet lamp to treat an aqueous solution containing a high potency Ames mutagen 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone (MX). MX is a known by-product of the drinking water chlorination process. One milliliter of the solution was placed in a petri dish 30 cm below the lamp and irradiated for 60 minutes. The removal rate of MX was 76 percent, and its mutagenic potency was reduced by 79 percent. The researchers found that the hydroxyl radicals[1] formed as by-products of the ultraviolet irradiation were not responsible for the removal of MX. When ultraviolet irradiation effects on MX removal were compared to those of oxidative treatments, including H_2O_2 and ozone in the presence of iron ions and thermal treatment, ultraviolet light treatment proved more effective than thermal treatment (59 percent removal) and reductive treatments. However, the researchers noted that thermal treatment is useful for drinking water application if boiled water is kept in a thermos jar more than 60 minutes, which is a practice shared by many Japanese in the work force.

Beltrán, Garcia-Araya, and Acedo, 1994, conducted experiments on atrazine removal by ultraviolet irradiation. The researchers concluded that mainly hydroxyl radicals are responsible for the oxidation of atrazine. Therefore, atrazine-containing drinking water will be oxidized by ultraviolet light-generated hydroxyl radicals during the disinfection process. However, quantification of atrazine oxidation by ultraviolet light needs further investigation to determine the dose-degradation relationship and the effects of chemical and physical water quality parameters on the process.

Nick et al. (1992) noticed that many herbicides do not absorb ultraviolet light above 240 nm and that only those herbicides that contain an aromatic ring or similar chromophore may degrade at wavelengths above 240 nm. Nick et al. (1992) showed that a conversion of more than 10 percent of atrazine, simazine, promazine, and terbuthylazine by photodegradation did not result in mutagenicity (using the Ames test), even when the irradiated material was applied in high concentrations. Therefore, ultraviolet photolysis of triazine herbicides did not give rise to new equally or more hazardous compounds.

At a low ultraviolet light dose of 25 mWs/cm^2, four triazine herbicides in drinking water degrade by up to 5 percent (Nick et al., 1993). Adding hydrogen peroxide and/or ozone to the water to be treated for organics control (before applying ultraviolet light) increases the reduction rate of contaminants (Frances,

[1]Hydroxyl radicals are formed by the portion of ultraviolet light emitted by mercury-containing lamps at 185 nm.

1989; Berglind, Gjessing, and Johansen, 1979). A high pH of approximately 10.3 to 10.5 also improves total organic carbon (TOC) reduction rates (Xu et al., 1989).

Li et al., 1996, studied the effects of ultraviolet light (30-watt low-pressure lamp) on a 2 percent humic acid (a major organic compound in natural water) solution. The test results of Li et al., 1996, show a decrease in humic acid TOC (15 to 5 mg/L in about 375 minutes) and almost a complete loss of the yellowish-brown color of the solution.

Awad, Gerba, and Magnuson (1993) conducted a demonstration-scale study to determine the effectiveness of ultraviolet light in disinfecting reclaimed water. During the pilot testing doses of 45 and 147 mWs/cm^2 were evaluated. Samples from the influent and effluent of the pilot unit were collected and analyzed for by-products, as presented in **Exhibit 2-27**.

Exhibit 2-27. Results of Disinfection By-Products of Ultraviolet Light (Awad, Gerba, and Magnuson, 1993)

Parameter	Influent	Effluent (45 mWs/cm^2)	Effluent (147 mWs/cm^2)
Trihalomethanes, µg/l			
$CHCl_3$	0.88	0.61	0.78
$CHBrCl_2$	0.13	0.11	0.12
$CHBr_2Cl$	0.11	ND	0.10
$CHBr_3$	0.19	0.18	0.15
Total	1.3	0.9	1.2
Aldehydes, µg/l			
Formaldehyde	3.54	5.90	9.62
Acetaldehyde	5.94	7.29	8.34
Heptaldehyde	ND	ND	ND
Benzaldehyde	ND	ND	ND
Glyoxal	2.55	2.73	3.44
Methyl glyoxal	1.25	1.26	1.56
TOC, mg/l	8.27	8.60	8.61
UV absorbance @254 nm, a.u./cm	0.173	0.165	0.165
Bromide mg/l	0.11	0.11	0.10
Bromate, mg/l	<0.005	<0.005	<0.005
8- to 16-carbon hydrocarbons	2 log reduction was observed due to ultraviolet light treatment		

Detection limits are 0.1 µg/l for trihalomethanes and 1 µg/l for aldehydes

As can be seen from the exhibit, some increase in formaldehyde, glyoxal, and acetyldehyde compounds occurred, with formaldehyde concentration almost tripling at a dose of 147 mWs/cm^2. Another

observation is that some trihalomethanes removal occurred at 45 mWs/cm^2 and at 147 mWs/cm^2. Formaldehyde is a B1 carcinogen i.e. probable human carcinogen with limited evidence in epidemiological carcinogenicity studies (based on inhalation exposure). The health advisory for the contaminant formaldehyde is 1 mg/L for a lifetime exposure for a 75 kg adult, and 20 mg/L for long-term exposure. For a 10-kg child, the longer-term health advisory for formaldehyde is 5 mg/L (USEPA, 1996). Therefore, the increases are insignificant and do not pose any known health risks. Moreover, it is unlikely to find formaldehyde in drinking water sources. (USEPA, 1996). There are no health advisories for acetyldehyde and glyoxal (USEPA, 1996).

In a comparative study of highly concentrated effluents from nine wastewater treatment plants, Jolley et al. (1982) determined that the chemical effects of ultraviolet irradiation at 60 mWs/cm^2 were relatively slight, with the elimination of mutagenic constituents in one effluent.

As stated earlier, Oppenheimer et al. (1993) conducted a study on by-products formation in reclaimed water in California. Compared to chlorination, ultraviolet light has minimal by-products formation and some contaminants removal effect. **Exhibit 2-28** shows that ultraviolet light either reduced or slightly increased the concentrations of some trihalomethane compounds.

Exhibit 2-28. Disinfection By-Products Found in Chlorinated and UV-Irradiated EVMWD Tertiary Effluent (Oppenheimer et al., 1993)

Compounds Detected	Before Disinfection (µg/l)	Chlorine[a] (µg/l)	UV[b] (µg/l)
4-methyl-2-pentanone	5.4	5.9	4.5
Chloroform	2.7	21	2.9
Dichlorobromomethane	0.9	22	1.0
Dibromochloromethane	1.1	<1.0	0.8
Methyl Bromide	2.8	<1.0	<1.0
Bromoform	<0.5	3.1	<0.5

[a] Chlorine = 9.8 mg/l dose and 2-hour contact time
[b] UV = 300 mWs/cm^2

2.4.1.2 Effects of Ultraviolet Light Treatment on Assimilable Organic Carbon

Assimilable Organic Carbon (AOC)[2] compounds are best described as ready-to-eat substrate for microorganisms. Therefore, the presence of AOC in drinking water may result in rapid increases in the microorganism population in the distribution system. The relationship between the growth of coliform bacteria and AOC in finished water is well documented (USEPA, 1992a). The effects of AOC in treated drinking water can be seen in biofilm growth in distribution systems and in episodes of high levels of coliform and nuisance bacteria in distribution systems. The following paragraph presents a preliminary literature review of the findings on the issue of AOC formation in ultraviolet-disinfected water.

The effects of ultraviolet light on the AOC of *Pseudomonas fluorescens* strain P 17 (AOC P 17) have been reported in an American Water Works Association Research Foundation (AWWARF) publication. At low intensities of ultraviolet light sufficient to cause 1 to 2 log reduction of colony counts on a nutrient-poor nonselective medium, small increases of the AOC P 17 concentrations were observed (AWWARF, 1988) as shown in **Exhibit 2-29**. The literature search did not find any more recent studies on the effects of ultraviolet light at higher doses on AOC formation. Evidently, extrapolation from these limited data may not be reliable. However, these data remain significant for assessing any future research needs in the area of ultraviolet light effect on drinking water quality.

Exhibit 2-29. Effects of Ultraviolet Radiation on AOC Concentration (AWWARF, 1988)

Log Reduction[a] of Colony Count	AOC (P 17)[b] µgr ac-C[c] eq/l	
	Before UV	After UV
1.2	2.0	2.8
2.0	2.0	2.8
1.9	4.4	7.0
0.0	1.7	1.9
1.2	1.6	1.6
0.76	3.7	4.5
0.71	3.6	3.9
1.25	4.3	4.4
0.77	4.4	5.4

[a]Colony counts (CFU/ml) streak plate method on diluted peptone meat extract agar incubated at 25°C for 10 days.
[b]Average values of duplicate measurements.
[c]ac-C—acetate carbon.

[2]AOC = Assimilable Organic Carbon. Carbon in organic compounds that are easily biodegradable by a specified microorganism. These compounds include proteins, peptides, amino acids, carbohydrates, carboxylic acids, and other compounds that are components of the living biomass.

2.4.1.3 Effects on Nitrite Formation

Groocock (1984) of the Derwent Division of the Severn-Trent Water Authority in the United Kingdom reported an average of about 1 percent conversion of nitrate to nitrite (as N) occurring with two ultraviolet light units used in the Derwent Division of the Severn-Trent Water Authority. The early experiences with ultraviolet light use in drinking water suggest that there can be some conversion of organic nitrogen and nitrate to nitrite due to the effect of radiation of below 240 nm. Groocock (1984) suggested the use of lamp envelopes made from materials that absorb wavelengths below 240 nm (such as Vycor from Corning) in cases of high nitrite production. However, these envelopes have a higher rate of solarization (thus preventing light from passing through) than the common envelopes and therefore a shorter effective lamp life.

In a more recent research, von Sonntag and Schuchmann (1992) concluded that by-product formation is of minor importance and significance. The researchers discussed as an example the formation of nitrites from nitrates caused by ultraviolet application at doses used to disinfect water. However, the researchers did not provide any data or citations to support the given example.

2.4.1.4 Effects on Mutagenicity Before and After Ultraviolet Light Application to River Water

Zoeteman et al. (1982) studied the mutagenic activity associated with by-products formed by drinking water from the Rhine River disinfection with chlorine, chlorine dioxide, ozone, and ultraviolet light at a dose of 120 mWs/cm^2. The study showed that ultraviolet light application does not affect the mutagenicity level of Rhine River water. Prior to 1982, most of The Netherlands' drinking water was not chlorinated. Even part of the drinking water derived from polluted surface waters was distributed without chlorination when bank filtration was applied (Zoeteman et al., 1982). The study by Zoeteman et al. (1982) shows that few compounds are formed and that some destruction of compounds occurs by ultraviolet irradiation. The study showed that some unidentified compounds were formed by ultraviolet irradiation and that a known carcinogen, benzene, was detected at a level of 1 µg/l. There were no more recent studies that confirmed the Zoeteman et al. finding of benzene formation in ultraviolet treated drinking water.

2.4.2 The Phenomena of Photoreactivation, Dark Reactivation, and Chemical Reactivation

Ultraviolet radiation causes damage to nucleic acids. This damage is not always permanent. Exposure of some damaged microorganisms to visible light (400 to 750 nm) reverses the damage, provided that the exposure to the visible light occurs shortly after the exposure to ultraviolet light (Gaudy and Gaudy, 1980; Salle, 1973). This is known as photoreactivation. Also, exposure to visible light before exposure to ultraviolet light for inactivation reduces the damage in some microorganisms. Environmental factors such as temperature and pH are also important in the process of reactivation. The reactivation phenomena associated with the use of ultraviolet light for wastewater disinfection may imply, to some extent, that the inactivation is temporary and hence not an appropriate technology for drinking water disinfection. Therefore, it is important to present the issues surrounding microorganism reactivation mechanisms and the research conducted to investigate this phenomena.

The key to the reactivation process in irradiated microorganisms is the presence of repair enzymes in the cell. The speed at which a microorganism can recover depends on the growth mechanisms. Spores and slow-growing microorganisms are less affected by ultraviolet light than fast-growing microorganisms. In a fast-growing microorganism, the original DNA in a rapidly replicating active cell is lost to the changes caused by ultraviolet light before any repair activity could start. When the cell is no longer exposed to ultraviolet radiation (at 254 nm wavelength), excited $Pi.(\pi)$ electrons in not fully damaged DNA strands in slow-growing microorganisms will return to a lower energy state. Under favorable conditions, the microorganism will repair the damaged sections using the cell's enzymes and resume replication activities. A detailed explanation of the physical action of ultraviolet light on chemical bonds is presented in Appendix B.

Viruses do not have repair enzymes, and thus, theoretically, their inactivation is easier than the inactivation of bacteria or protozoa. However, if a virus is living as a parasite in a bacteria or protozoa, then the viability of the virus is subject to the reactivation of the host cell. In other words, if the host cell reactivates, then viruses protected by the host cell will resume their activities as soon as the host cell reactivates. The same principle applies to infectious bacteria inside a protozoa, such as *Acanthamoebae spp.* or *Cryptosporidium spp.*, where, upon photo or chemical reactivation, the parasites may become a source of bacterial contamination (King et al., 1988).

The problems associated with photo reactivation and dark repair mechanisms have been studied since 1948 (Witherell, Solomon, and Stone, 1979). It has been shown that microorganisms that are not fully destroyed by ultraviolet light could be revived by exposure to long wavelength light (visible light of wavelength between 400 nm and 750 nm). The degree of reactivation in visible light is a function of temperature, pH, and time and intensity of the exposure to visible light (Lamanna and Mallette, 1965). The longer the irradiated cells are kept in the dark, the fewer the number of cells reactivated in visible light. The degree of recovery possible is dependent on ultraviolet light dose. The greater the dose, the smaller the population of the cells that reactivate. Temperature effect was observed in the photoreactivation process. The warmer the cells during exposure to visible light, the greater the proportion of reactivated cells [up to a temperature of 45°C to 50°C (113°F to 122°F)] (Salle, 1973). **Exhibit 2-30** shows the difference in the surviving fraction in four microbial species. As can be seen from Exhibit 2-30, the difference in the surviving fraction (in this experiment of Kelner, 1949) of dark-kept and light-kept irradiated cells ranges from 2 logs to 5 logs.

Exhibit 2-30. Surviving Fraction in Four Microbial Species After Ultraviolet Irradiation

	S. griseus	*E.coli*	*P. notatum*	*S. cerevisiae*
Dark survival[a]	2.1×10^{-6}	4.5×10^{-6}	5.5×10^{-4}	1.0×10^{-5}
Light survival[b]	6.6×10^{-1}	1.2×10^{-1}	2.5×10^{-1}	1.0×10^{-3}

[a]Surviving cells kept in dark after exposure to ultraviolet light.
[b]Surviving cells after illumination with long wavelength light following exposure to ultraviolet light.
Source: Kelner, 1949, as cited in Lamanna and Mallette, 1965.

Cells irradiated by ultraviolet light may be reactivated by chemical means. The chemical reactivation phenomenon and the importance of the type of culture and media in which the microorganisms are irradiated have been observed since 1927. Bedford (1927) (as reported in Salle, 1973) irradiated growth media and discovered the formation of hydrogen peroxide. This discovery is important because it means that the ultraviolet light dose inactivation rate relationship in a growth medium that produces hydrogen peroxide as a by-product cannot be used for design purposes in drinking water application. Wyss et al. (1948) (as reported in Salle [1973]) found that the addition of enzyme catalase would negate the effects of hydrogen peroxide formed by irradiation. Addition of compounds such as nicotinamide-adenine dinucleotide (NAD) and coenzyme A as well as pH adjustment can counter the effect of ultraviolet light irradiation. For example, reducing the pH from 8 to 5 within 2 hours after irradiation increased the number of survivors producing colonies of *Escherichia coli* by as much as 1×10^3 (Weatherwax, 1956, as cited in Salle, 1973).

Groocock (1984) discussed the issue of reactivation and repair mechanisms of microorganisms treated with ultraviolet irradiation. One of these repair mechanisms (photorepair) is encouraged by exposure within 2 to 3 hours of ultraviolet treatment to higher wavelength radiation, notably above 300 nm, i.e., in the ultraviolet long wavelength band/visible bands. This would appear to be largely due to reversal of the dimerization of pyrimidines (chiefly thymidine) caused by irradiation. "Dark repair" mechanisms, however, exist—particularly where only one strand of the double link has been affected. Enzyme action snips out the damaged length and then uses the remaining undamaged strand as a template in the reconstruction. Groocock (1984) argued that it would seem likely that the nucleic acids need to be damaged in more than one place (i.e., more than one photon strike) to ensure permanent inactivation. Therefore, a dose threshold will probably be reached before this happens to any great extent. Ellis (1991) cited Angehrn and Träger in their disbelief that reactivation and repair mechanisms are possible under operational drinking water conditions. Ellis (1991) cited Angehrn and Träger in reporting that no cases of reinfection resulting from photorepair mechanisms have been proved in effectively treated drinking water.

The experience gained from using ultraviolet light to disinfect wastewater shows that photoreactivation is seasonally influenced. During the summer season (because of less cloud cover, because the northern hemisphere is directly facing the sun, and because of longer daylight time and higher cell temperature), a maximum repair of 1 to 2.5 log increase in total coliforms, fecal coliforms, and *Escherichia coli* has been observed in ultraviolet-treated wastewater (USEPA, 1992b). Whitby and Palmateer (1993) conducted experiments to test the significance of photoreactivation in ultraviolet-treated wastewater. The researchers used labeled *Escherichia coli* in their experiment. After ultraviolet treatment, the photoreactivated labeled *Escherichia coli* were detected in glass bottles but not in the receiving stream. The researchers concluded that in the natural environment, photoreactivation is not an important issue. Under operational wastewater conditions, microorganisms receiving insufficient ultraviolet dose (because of shielding as well as other wastewater quality factors) may reactivate. The insufficiently ultraviolet-hit cells exhibit the state known as *biostatic* activity. As stated earlier, *biostatic* activity is a term that indicates inhibited metabolism. Some of these cells do reactivate as they come in contact with visible light as soon as they leave the ultraviolet realtor, and as stated earlier, the faster the cells are put in a favorable environment the more likely that they will recover. Under operational ground drinking water conditions, with sufficient ultraviolet dose, it is very doubtful that many cells will be in the *biostatic* state. It is very doubtful that cells in the *biostatic* state will be able to reactivate as soon as water is drawn from use from the faucets because there is some residence time spent in the dark closed distribution system.

The reactivation of microorganisms that have been subject to disinfection is not unique to the process of ultraviolet light disinfection. Because disinfection as a process is not sterilization, microorganisms injured by chemical disinfection and not completely destroyed can revive (as microorganisms disinfected with ultraviolet light do) under favorable conditions. At insufficient-to-kill chemical disinfectant concentrations, the disinfectant may cause the microorganisms to go into a state known as *biostatic* activity. In a *biostatic* state, metabolism is inhibited and that sets the microorganisms on a course that with time leads to death. The effect of the insufficient-to-kill chemical concentration could be reversed if the microorganisms were placed in a more favorable environment. At concentrations lower than the concentrations sufficient to trigger the *biostatic* state in microorganisms, no inactivation effect of any kind may be exhibited, and with various disinfectants or microbial poisons a very small concentration may stimulate growth (Gaudy and Gaudy, 1981). The problems associated with reactivated microorganisms range from biofilm growth in drinking water distribution systems (USEPA, 1992a) to sicknesses that often go unreported as water-related (USEPA, 1984).

To minimize photoreactivation of microorganisms in ultraviolet treated drinking water, if proved to happen under operational conditions, four possible approaches that need further investigation may be followed:

1. Provide ample disinfection and attenuation time (residence time in the ultraviolet reactor by reducing the flow rate, adding another in-series ultraviolet unit, or providing a closed reservoir immediately after the ultraviolet unit). This additional attenuation time might not exceed few to tens of seconds, but is crucial for inflicting greater damage on the genetic material of slow-growing microorganisms.
2. Increase the intensity and/or use a shorter wavelength emitting lamp (185 nm) along with the standard 254 nm emitting lamp (combine a low-pressure mercury lamp with a medium-pressure mercury lamp) to provide a broader range of germicidal wavelengths that include ozone, peroxides, and free radicals producing wavelengths.
3. In extreme cases use ozone or hydrogen peroxide or both for disinfection prior to ultraviolet to increase the disinfection power of the reactor, particularly when high levels of organic compounds or assimilable organic compounds are present, and follow that by a GAC filter to eliminate any residual by-products.
4. Find the most appropriate disinfection wavelength for specific recalcitrant microorganisms and use the custom manufactured lamp that emits it, in addition to the low-pressure mercury lamp.

2.4.3 Ultraviolet Light and Residual Disinfection

Groocock (1984) noted, from the experience of the Severn-Trent Water Authority in the United Kingdom, that a small amount of ozone is produced by radiation at wavelengths below 200 nm, thus giving a slight

enhancement and prolongment of the germicidal action. In a 20-month pilot plant study, Lund and Ormerod, 1995, found that ultraviolet treatment had an inhibitory effect on biofilm formation. The inhibition effect of ultraviolet light is thought to be the result of hydrogen peroxide and/or other oxygen-containing free radicals produced by irradiation. Gjessing and Källqvist (1991), as cited in Lund and Hongve, 1994, reported the inhibition of *Selenastrum capricornutum* alga growth in ultraviolet irradiated water that lasted for several weeks. It is known that free radicals and oxygen species formed during ultraviolet are very reactive and short lived, but H_2O_2, one of the known ultraviolet irradiation by-products, has a half-life in water ranging from 1 to 8 hours in natural water and more than 80 hours under sterile conditions i.e. H_2O_2 half-life is water quality dependant. (Cooper and Zepp, 1990 as cited in Lund and Hongve, 1994).

Lund and Ormerod, 1995, investigated the effects of chlorination, ultraviolet light treatment and ozonation on biofilm formation in water distribution systems. The ozonated test water received an ozone dose of 1.8 ± 0.4 mg/L. The ultraviolet irradiated water received a 42 mWs/cm^2 dose. The chlorinated water maintained a free residual chlorine level of at least 0.05 mg/L after a 30 minutes contact time. The control test water did not receive any treatment other than straining. The average values of the physicochemical properties of tested water at the Bærum water treatment plant near Oslo, Norway are presented in **Exhibit 2-31**. Exhibit 2-31 includes the number of samples taken during the 20-month pilot study.

Exhibit 2-31. Bærum Average Water Quality Parameters (Lund and Ormerod, 1995)

Parameter	Number of Samples	Mean Value	Standard Deviation
Turbidity (NTU)	146	0.4	0.06
pH	95	6.4	0.16
Color (mg Pt/L)	94	35	5.2
DOC[a] (mg C/L	24	4.6	0.76
Fe[b] (µg/L)	40	128	23.5
Mn (µg/L)	36	36	7.6
Total N (mg N/L)	15	0.34	0.05
Total P (µg P/L)	14	4	0.8

[a]No pronounced seasonal variation
[b]Maximum values in August 1988 and August 1989

All raw water used in the experiments of Lund and Ormerod, 1995 was strained with a 35 µm mesh size. The raw water pipe was forked into four laterals, one for control and one for each of the three disinfection treatments. After the application of treatment at the head of each lateral pipe, the waters were pumped

at a flow rate of 0.20 to 0.25 l/s into 2.6m pipes of 20.4 mm inner diameter. The lateral pipes used in the experiment were high density polyethylene (HDPE) pipes. Each of the four lateral pipes had pieces of mica held inside the HDPE pipe by a fitted-in polyvinyl chloride (PVC) pipe. The pieces of mica were held in a position parallel to the flow of the tested water. Water samples were withdrawn on a monthly basis for measuring Biochemical Oxygen Demand (BOD), ultraviolet absorbance, and Dissolved Organic Carbon (DOC) content.

For qualitative characterization of the biofilms formed, Lund and Ormerod, 1995 examined the mica pieces using an electron microscope. The microscopic inspection of the mica pieces showed that mica from chlorinated water was colonized by rod-shaped bacteria assembled in star-shaped colonies. The mica from the other three systems (control, ultraviolet treatment and ozone treatment) were colonized by rod-shaped and budding bacteria. Extracellular polymer substances were not evident in the chlorinated system but were evident in the other three systems (forming networks on the mica surface) most in the ozonated system and least in the ultraviolet irradiated system.

The BOD test results showed that ozonated water had the highest BOD level (10% higher than the control BOD level) which indicated an increase in the content assimilable organic carbon. Ultraviolet irradiated water showed 70 percent less BOD than the control.

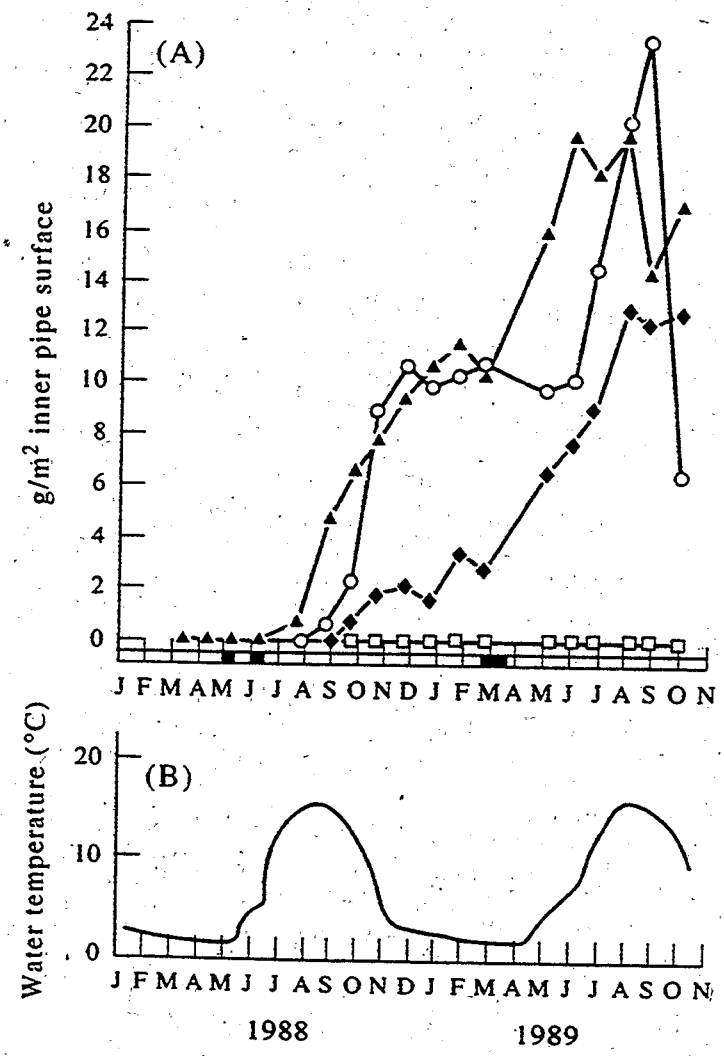
Lund and Ormerod, 1995, noted that biofilm formation started early in the experiment, but amounts of sludge, measured as dry weight, were not produced until the water temperature started to rise above 5°C in May.

Exhibit 2-32 presents seasonal accumulation of biofilm measured as dry weight. The biofilm formed in ultraviolet irradiated water was similar, but not identical, to the biofilm found in the control system.

Lund and Ormerod, 1995, concluded that prevention of biofilm formation in distribution systems is best done by removing as much as possible for the organic material (mean value of DOC in the treated water was 4.6 mg/L) from the source water and maintaining a low free chlorine residual in the distribution system.

To summarize, the test results of the 20-month pilot study by Lund and Ormerod showed that no biofilm formed in the pipes carrying chlorinated water. It also showed that the highest biofilm formation occurred

Exhibit 2-32. Seasonal Accumulation of Biofilm, Measured as Dry Weight, in the Different Pipe Systems and Seasonal Variations in Raw Water Temperature (Lund and Ormerod, 1995)



▲ Microstrained system
○ Onzonated system
◆ Ultraviolet irradiated system
□ Chlorinated system
■ Periods with stagnant water in pipe systems

in the pipes carrying ozonated water followed by control water. The pilot study also showed that ultraviolet-treated water formed considerably less biofilm production than the control water.

Lund and Hongve (1994) investigated the phenomena of bactericidal effect of ultraviolet-irradiated water. To confirm that ultraviolet treatment yield a durable bacterial growth inhibitory effect, Lund and Hongve, 1994, conducted a series of experiments aimed at determining the duration of that inhibitory effect and aimed at determining the residual bactericidal effect of ultraviolet treatment. The researchers used water

from Bærum waterworks near Oslo (**Exhibit 2-33**) and irradiated separate volumes with 42 mWs/cm^2 and 96 mWs/cm^2. Heterotrophic bacteria inoculum was added to the ultraviolet treated water. Water samples were drawn after one minute and 60 minutes of inoculation for enumeration of surviving bacteria. The test results show that 7 days after ultraviolet irradiation, heterotrophic bacterial growth was inhibited. **Exhibit 2-34** presents the test results as reported in Lund and Hongve (1994). The researchers found that approximately 60 percent of the heterotrophic bacteria inoculum in the water samples from the pilot plant near Oslo, Norway, were inactivated within 1 hour of contact time with ultraviolet disinfected drinking water.

Exhibit 2-33. Bærum Water Quality Parameters (Lund and Hongve, 1994)

Parameter	Level
DOC (mg/l)	3.9
UV_{254} absorbance (per cm)	0.17
Color (mg Pt/l)	30
pH	6.4
Fe (mg/l)	0.01
Ca (mg/l)	3
Mn (mg/l)	0.35
Alkalinity (mmol/l)	0.05
Conductivity @25°C (mS/m)	2.7

Exhibit 2-34. Demonstration of Long-Term Inhibitory Effect in U.V.-Irradiated Water Compared to Raw Water, After Addition to Heterotrophic Bacteria (Lund and Hongve, 1994)

Storage Time of U.V. Irradiated Test Water at 4°C (days)	Contact Time Between Bacteria and Test Water (min)	Bacterial Counts (CFU/ml) 95% Conf. Intervals*		Reduction in Bacterial Concentration	
		Normal U.V. Dose	High U.V. Dose	Normal U.V. Dose 42 mWs/cm^2	High U.V. Dose 96 mWs/cm^2
0	1	430 ± 87[a]	440 ±67	66%	65%
0	60	540 ± 85[a]	463 ± 79	57%	63%
7	1	4,056 ± 232[b]	4,920 ± 314	22%	5%
7	60	2,570 ± 185[b]	4,035 ± 284	51%	22%
14	1	overgrown	overgrown	0%	0%
14	60	overgrown	overgrown	0%	0%

* Poisson distribution model.
[a] Initial conc. was 1,250 ± 105 CFU/ml.
[b] Initial conc. was 5,200 ± 100 CFU/ml.

Over a period of 7 days, the growth curves for heterotrophic bacteria in inoculated control raw water and irradiated water samples, show an exponential growth after the first day of inoculation. The growth rate for control samples is significantly higher than the growth rate in irradiated water. The growth rate in control samples are double the rates of treated water samples. The water samples were stored in the dark at 4°C. The difference in results between the 42 mWs/cm^2 irradiated water and the 96 mWs/cm^2 irradiated water is statistically insignificant (Lund and Hongve, 1994).

Also Lund and Hongve, 1994, conducted tracer studies to measure metabolic inhibition and replication inhibition of microorganisms in ultraviolet irradiated humic water. The researchers used ^{3}H-labelled thymidine and leucine as a tool to quantify cell growth and replication in ultraviolet-irradiated water. Leucine is known to be incorporated in the DNA of active bacteria during protein synthesis and thymidine is known to be incorporated in the DNA when the cell is multiplying. The uptake of leucine and thymidine by a microorganism is dependent on the presence of biodegradable organic substances. The physico-chemical properties of the humic water used in the tracer studies are presented in **Exhibit 2-35**.

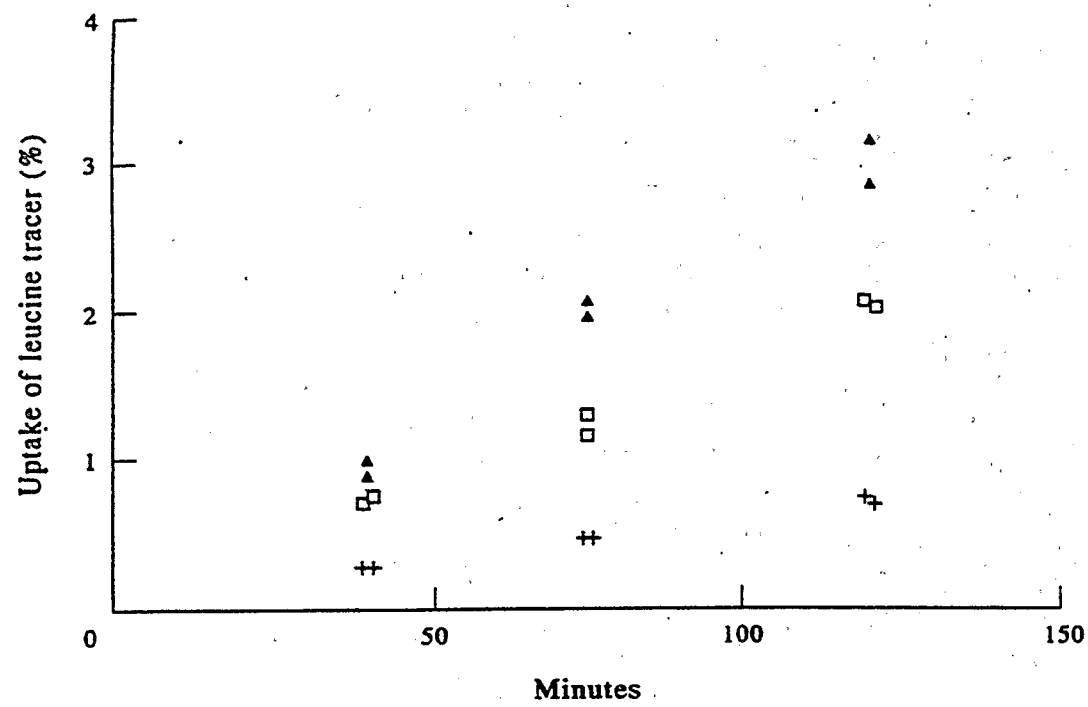
Exhibit 2-35. Water Quality Parameters of the Bærum water used in Tracer Experiments (Lund and Hongve, 1994)

Parameter	Level
DOC (mg/l)	7.8
UV_{254} absorbance (per cm)	0.30
Color (mg Pt/l)	60
pH	7.4
Fe (mg/l)	0.5
Ca (mg/l)	7
Mn (mg/l)	0.08
Alkalinity (mmol/l)	0.3
Conductivity @25°C (mS/m)	2.7

The tracer experiments were conducted on 0.2μm filtered control water. In addition to the control samples, the water samples were either preheated to 70°C or irradiated with an ultraviolet dose of 240 mWs/cm^2. **Exhibit 2-36** shows bacterial uptake of ^{3}H-labeled leucine in treated and control water samples. The uptake rates of Leucine in irradiated water compared to the uptake rates in control water show that ultraviolet light has an inhibitory effect on bacterial growth.

Experiments on microorganisms uptake of ^{3}H-labelled thymidine in ultraviolet irradiated water and control of water samples during 24 hours were conducted with various volumes of added inoculum. **Exhibit 2-37**

Exhibit 2-36. Bacterial Uptake of ^{3}H-Labelled Leucine in Water Samples with Identical Inoculation Volumes (Lund and Hongve, 1994)*

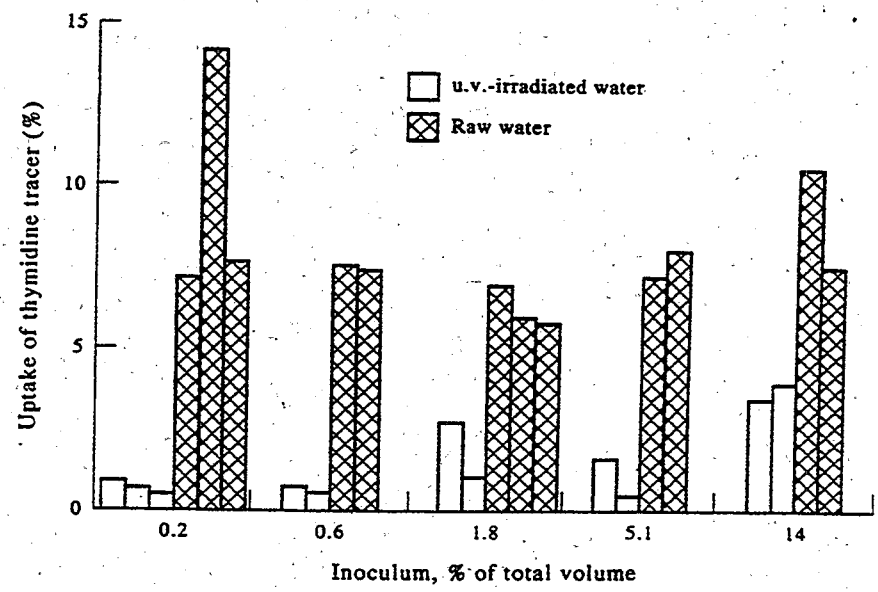


+ Ultraviolet irradiated water samples (240 mWs/cm^2)
▲ Heated water samples (70°C)
□ Sterile filtered water samples (0.2 µm)
* Inoculants were prepared using 100 times the concentration of a chemically treated sewage effluent.

presents thymidine uptake test results. As can be seen from Exhibit 2-37, a near constant ^{3}H-labelled thymidine uptake levels for the control samples are attained. Lund and Hongve, 1994, attributed this uptake inhibition, i.e., cell reproduction inhibition, to a micronutrient limitation. Exhibit 2-37 shows that ^{3}H-labelled thymidine uptake levels in ultraviolet irradiated water samples are consistently lower than the uptake levels in all the control water samples.

Lund and Hongve noted that ultraviolet irradiation alone may inhibit biofilm formation in new and clean distribution systems and may prevent adherence of organic matter on the walls of pipes in short distribution systems. However, Lund and Hongve 1994 cautioned that the inhibitory effect of ultraviolet irradiated water may be very limited in distribution systems with well established biofilm or water high in biodegradable organic substances.

Exhibit 2-37. Bacterial Uptake of ^{3}H-Labelled Thymidine During 24 Hours in Ultraviolet-Irradiated and Untreated Control Samples for Various Volumes of Inocular Added (Lund and Hongve, 1994)*



* The inoculated suspension was prepared using 100 times the concentration of particulate organic matter extracted from the same water.

As stated earlier, ultraviolet radiation produces hydrogen peroxide in irradiated water. Lund and Hongve, 1994, believe that the residual disinfectant effect in ultraviolet-irradiated waters is due to hydroxyl radicals produced as a by-product of hydrogen peroxide reaction with reduced compounds such as ferrous iron in humic compounds. Lund and Hongve, 1994, allude to the fact that oxygen species radicals produced in some disinfection processes such as ozonation, can give rise to more biodegradable substances and hence surmised that ultraviolet irradiation may to some degree enhance bacterial growth in humic water.

2.4.4 The Search for a Surrogate

Because traditional surrogate microorganisms (e.g., total coliform) are sensitive to ultraviolet light, and because it is not economically feasible to test every target pathogenic microorganism, an appropriate surrogate microorganism is needed to quantify the correlation of its inactivation rates to that of microorganisms of interest, such as reovirus, rotavirus, or Hepatitis A virus (HAV). Therefore, the viability of ultraviolet technology depends to a certain extent on the identification of a surrogate microorganism that is suitable and reliable in quantifying ultraviolet efficacy against pathogenic microorganisms commonly found in ground water sources.

Wilson et al. (1993) proposed the use of coliphage MS-2 as a challenge surrogate microorganism to test the efficacy of ultraviolet light. The main reason for his proposal is the similar reaction to chemical and ultraviolet treatment exhibited by MS-2 and members of the genus enteroviruses that includes polioviruses, Norwalk, and Coxsackie virus. Wilson et al. (1993) compared the ultraviolet inactivation results of MS-2 to those of a variety of waterborne pathogens (see Exhibits 2-10 and 2-11). The work of Wilson et al. (1993) shows that a 99.5 percent inactivation (2.3 log reduction) at 39.4 mWs/cm^2 of MS-2 using ultraviolet light is equivalent or greater than 6 log reduction of *Klebsiella Terrigena, vibrio cholerae, Salmonella typhi, Escherichia coli* 0157:H7, *Shigella dysenteriae, Yersinia enterocolitica, Campylobacter jejuni, Aeromonas hydrophila,* and *Legionella pneumophila.* For the same (2.3 log) reduction in MS-2, using ultraviolet light, a 4 log reduction was obtained in HAV, rotavirus SA-11, and poliovirus type 1. In this study, Wilson et al. (1993) concluded that a minimum of 6 log reduction in all of the above-mentioned pathogenic bacteria could be achieved using an ultraviolet light dose of 15.6 mWs/cm^2 and that a 39.4 mWs/cm^2 minimum ultraviolet dose was necessary to achieve a minimum of 4 log reduction in the tested viruses.

Exhibit 2-38 presents the bar graph inactivation rates. The work of Wilson et al. (1993) may be considered in the Agency's technical review for a ground water disinfection requirement using ultraviolet light. However, it is worthwhile to consider that

Surrogates: An EPA Perspective

Many problems are associated with trying to detect specific pathogens. Because of these problems, bacteria that are not themselves pathogenic are measured as surrogates for the more harmful bacteria. The ideal indicator for drinking water contamination is:

- Suitable for all types of drinking water
- Present in polluted water at higher concentrations than harmful bacteria
- Able to survive in water at least as long as pathogens and is at least as resistant to disinfection
- Easy and inexpensive to measure in drinking water samples
- Generally not present unless harmful contamination is also present.

(USEPA, 1992a)

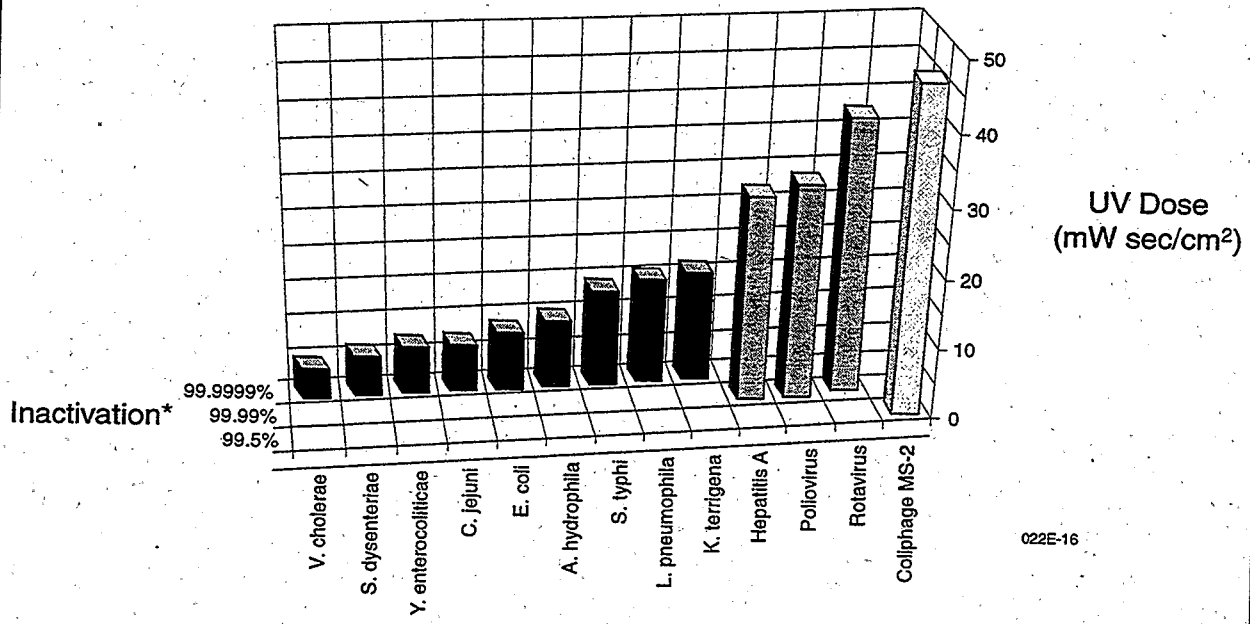
Surrogates: A German Perspective

In Germany, drinking water is assumed to be microbiologically acceptable when coliform bacteria or *E. coli* are not detected in water samples. Carlson (1991) suggested specific requirements for microorganisms to be acceptable as surrogate indicators for microbial contamination:

- The microorganisms must be present in large numbers.
- They must be easily and reliably detected with routine methods.
- Their survival period should correspond at least to that of the pathogenic organism in question.

The last requirement presents a problem because some pathogens, like certain viruses, remain infectious in the environment for longer periods than bacteria. As presented by Carlson (1991), the German view for selecting a surrogate indicator microorganism is very close to the USEPA perspective on the subject, but not as specific as the USEPA point of view.

Exhibit 2-38. Extrapolated Inactivation Rates for Bacteria, Viruses, and Test Surrogate Coliphage MS-2 (Wilson et al., 1993)



* Inactivation rates extrapolated using linear regression model

the above-cited 6 log and 4 log reductions presented in the bar graph in Exhibit 2-38 were concluded by extrapolation. To extrapolate and estimate ultraviolet doses, Wilson et al. (1993) used a linear regression analysis software (Statgraphics® Version 5.1, 1991) to develop an MS-2 linear regression model (no tailing factor is considered) based on the data presented in Exhibits 2-10 and 2-11. From the linear regression model, ultraviolet light dose estimates with 95-percent confidence intervals were calculated using a one-tailed *t* test. It is important also to note that all challenge microorganisms and the proposed surrogate microorganism were tested in phosphate-buffered distilled water. Phosphate-buffered distilled water media may have lower ultraviolet demand than does naturally occurring water. In addition, naturally occurring microorganisms are typically more resistant to disinfection than laboratory-cultured microorganisms.

Wilson et al. (1993) argued in favor of adopting coliphage MS-2 as a surrogate microorganism because (1) it is more resistant to ultraviolet light than all the tested pathogenic bacteria and viruses; (2) it has highly reproducible ultraviolet light inactivation results; (3) the cost is low; (4) high titers are easily attainable; (5) it shows results within 6 hours; and (6) it is not pathogenic to humans. Moreover, coliphage MS-2 requires 18 to 24 hours to culture.

Sommer and Cabaj (1993), realizing that lab-cultured microorganisms are more sensitive to disinfection, proposed criteria for selecting a suitable surrogate microorganism. The microorganism that satisfies these criteria would then be used to test the efficiency of ultraviolet light disinfection in drinking water. The proposed criteria call for a microorganism with the following characteristics:

- A steady inactivation over a wide dose
- A simple and sufficient culturability
- Nonpathogenic
- A temporal stability with regard to ultraviolet susceptibility.

Sommer and Cabaj (1993) proposed a specific cultural procedure (method C) for *Bacillus subtilis* spores (ATCC6633) that satisfies the above criteria. The proposed cultural procedure (presented previously in Exhibit 2-11) is not the same cultural procedure required under ANSI/NSF Standard 55-1991 for the same challenge microorganism *Bacillus subtilis* spores and was selected after two other cultural procedures failed to satisfy the proposed criteria (refer to Exhibit 2-11 for more details). *Bacillus subtilis* spores require 3 days to culture (method C). The test results of its susceptibility to ultraviolet light are highly reproducible.

2.4.4.1 ORP, a Non-Microbial Surrogate

Carlson (1991) addressed the issue of microbiological water examination in Germany. According to the provisions of the Bundes-Seuchengesetz (Federal Communicable Disease Act), proving the existence of bacterial pathogens requires special permission from the authorities. Moreover, it is a time-consuming process, and it is impractical if not impossible for a public water system to get sampling test results before the water is pumped into the distribution network or consumed. The fact that various pathogenic bacteria actually lead to an outbreak after a long incubation period further complicates the issue of microbiological examination of water. For example, the incubation period of HAV infection is 15 to 50 days depending on dose, with an average of 28-30 days. A 1- to 3-week incubation is needed to have typhoid fever symptoms (APHA, 1981). If an operational error or system failure allowed the pathogens causing HAV infection or typhoid fever to be waterborne through the distribution system to the consumer, it would take at least 15 days before the first case of HAV infection would be reported and a minimum of 1 week before the first case of typhoid fever would be reported. Thus, if water is examined for the pathogen causing the typhoid fever, it is more than likely that the microorganism will not be found because it would have been flushed out of the system during the incubation period. Because of the impracticality of testing

all pathogens that might exist in drinking water, surrogate challenge and indicator microorganisms are used to test disinfection efficiency. Still, testing for these surrogate microorganisms is time consuming, requiring skills that might not be available in operators of small and remote water systems.

Because the Oxidation Reduction Potential (ORP)[3] of the medium plays an important part in the physiology and ecology of microorganisms, the metabolism of a microorganism and, consequently, its ability to survive and propagate are influenced by the ORP of the medium in which it lives. The range of the ORP at which bacteria can live is limited, with anaerobes propagating in medium to low levels and aerobes in the low to high ORP levels. The inability of anaerobes and aerobes to survive at high ORP levels can be explained by the fact that the SH groups (these are highly oxidizable groups that play an important role in electron transfer mechanisms in microorganisms) or radicals-containing enzymes within the microorganism will be inactivated at high levels of ORP. For microorganisms, like all life forms including humans, placing them in direct contact with an extreme environment will be detrimental. Therefore, the elimination of microorganisms in drinking water can be achieved by high ORP, so that the vital enzymes are blocked. Appendix B of this report describes how ultraviolet light is used to achieve high levels of ORP in polluted drinking water sources. Carlson (1991) argued in favor of using ORP as an indicator of disinfection efficiency. The researcher presented studies that correlate the killing rates of pathogenic organisms to ORP levels. The studies conducted by Carlson (1991) to determine ORP levels at which chlorination would result in a satisfactory disinfection show that ORP levels above 700 mV versus a saturated calomel electrode at pH 7 should be maintained for at least 10 to 30 seconds. If this proves to be reliable, it will be easier to train water works operators on how to place an ORP probe in finished water and take a continuous reading than to take a water sample and to test for microbial presence on an occasional basis.

2.4.5 Comparison of Ultraviolet Light to Chemical Disinfection

Because it is not economically feasible to require public water supply systems to test for every pathogenic microorganism that might be present in drinking water, surrogate microorganisms are tested for and used as indicators of microbial water quality and disinfection. Traditional indicator surrogate microorganisms

[3]Oxidation is defined as the addition of oxygen to a compound, the removal of a hydrogen, or the loss of a pair of electrons (Gaudy & Gaudy, 1980). Reduction is the removal of oxygen from a compound, the addition of hydrogen, or the addition of a pair of electrons. In an oxidation-reduction reaction, a potential is formed at a submersed platinum electrode by supplying and accepting electrons. This potential is measured by using an electronic voltmeter without drawing current against a reference electrode (saturated calomel electrode or silver-silverchloride electrode). The difference in potential between the reference electrode and the metal at which the oxidation and reduction reaction takes place is referred to as the ORP.

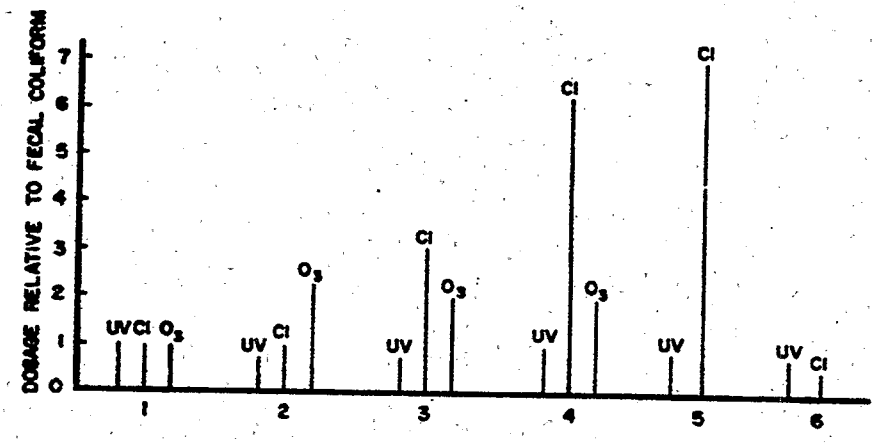
(e.g., total coliform, *Escherichia coli* microorganisms) are sensitive to ultraviolet light. Therefore, it would be inappropriate to compare the inactivation rate of ultraviolet light and those of traditional chemical disinfectants for those indicator surrogate microorganisms. Moreover, quantified comparison of chemical doses (in mg/L) and ultraviolet light doses (in mWs/cm^2) for specific microorganism inactivation rates cannot be established at this point. However, when comparing chemical disinfection with ultraviolet light disinfection, a few issues stand out:

- *Cryptosporidium spp.* is resistant to chemical disinfection and cannot be inactivated using chlorine or ozone at doses normally used for drinking water disinfection (USEPA, 1993). Therefore, for ground water contaminated with *Cryptosporidium spp.*, chemical disinfection has no advantage over ultraviolet light.
- The 1991 Article 80 of the Uniform Fire Code (UFC) requires treatment systems to handle the accidental release of chlorine gas, chlorine dioxide, or sodium chlorite, as well as provide emergency power sufficient to operate chemical scrubbing equipment (WERF, 1995). These new requirements may well double the costs of chlorination (gas type) systems in States that require compliance with the UFC.
- For small systems where space is not available, or where capital and construction experience is not available, ultraviolet systems are useful in upgrading and retrofitting with minimal construction work. An ultraviolet unit can disinfect 0.5 MGD in a 40 ft^2 space (USEPA, 1983) while a chlorination unit requires more than 1,000 ft^2 space, assuming a 30-minute contact time and a flow velocity of 0.1 ft/sec.
- Unlike chemical disinfection, there are no known risks associated with oversizing the unit and there is no limit on the dose that could be applied. These qualities give ultraviolet light an edge over chemical disinfection in water applications where disinfection by-products pose health risks, and their production is sensitive to chemical dose.
- At proper dose applications, ultraviolet light systems are effective in destroying bacterial and viral pathogens.

Exhibit 2-39 compares the germicidal effects of ultraviolet light with chemical disinfectants (Yip and Konasewich, 1972). Using fecal coliform log reduction as a yardstick to measure the number of yardstick units required by chlorine, ozone, and ultraviolet light to achieve the same log reduction for a number of pathogenic microorganisms, Yip and Konasewich (1972) showed that ultraviolet light is comparatively more effective than chlorination and ozonation with about the same relative dose requirement for five different pathogens other than *Escherichia coli*. However, another study by Chang et al. (1985) showed that ultraviolet light is less effective.

Chang et al. (1985) address the issue of using coliforms as a valid indicator for disinfection efficiency using ultraviolet light. Based on the relative dose required to disinfect pathogenic organisms (see **Exhibit 2-40**), they concluded that the survival rate of coliform bacteria in ultraviolet irradiated effluents does not

Exhibit 2-39. Germicidal Effects of Ultraviolet Light Versus Chemical Disinfectants in Drinking Water Applications (Yip and Konasewich, 1972)



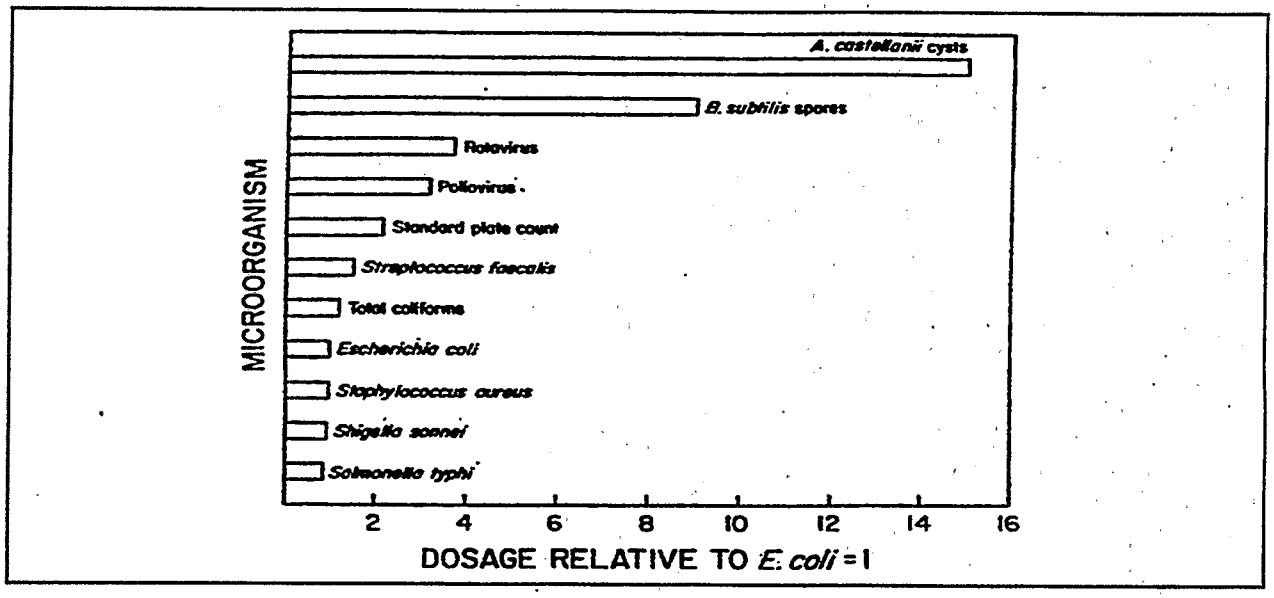
(1) Escherichia coli B (2) Salmonella typhosa
(3) Staphylococcus aureus (4) Polio type 1 virus
(5) Coxsackie AZ virus (6) Adenovirus Type 3.

directly reflect the level of disinfection needed to disinfect the more resistant organisms. The ultraviolet light resistances of viruses and *Escherichia coli* as reported by Chang et al. (1985) are not as comparable, as implied by Yip and Konasewich (1972) (see Exhibit 2-39). The Yip and Konasewich 1972 study showed a comparatively uniform ultraviolet light disinfection capability against a variety of pathogenic microorganisms, while Chang et al. showed a nonuniform ultraviolet light disinfection capability. For example, Kip and Konasewich (1972) found that *Escherichia coli* and poliovirus require the same ultraviolet dose to achieve the same log reduction. Chang et al. (1985) found that the poliovirus requires more than three times the ultraviolet light dose applied to *Escherichia coli* to achieve the same log reduction. To compare ultraviolet resistance by various microorganisms, Chang et al. (1985) proposed the use of standardized growth conditions of the tested microorganisms.

The advantages of using ultraviolet light rather than chemical disinfection are the following:

- No known toxic or significant nontoxic by-products.
- No danger of overdosing.
- Some removal of organic contaminants.
- If used for volatile organic compound (VOC) destruction, no VOC emissions or toxic air emissions result (WWEMA, 1990).
- No onsite smell and no final water product smell.

Exhibit 2-40. Relative Ultraviolet Light Dose for Some Microorganisms (Chang et al., 1985)



- Very little residence time (seconds versus minutes for chemical disinfection).
- No storage of hazardous material required.
- Minimal space required for equipment and contact chamber.
- Taste is not negatively altered, only improved, with the destruction of some organic contaminants and nuisance microorganisms.
- Minerals in water are not affected.
- No mutagenicity effect using the Ames test.
- No or little (disposal of spent lamps or obsolete equipment) impact on the environment.

The main disadvantage of using ultraviolet light for disinfection is that no long-term residual disinfection is provided. **Exhibit 2-41** presents a quick comparison between ultraviolet light and common chemical processes.

2.5 FINDINGS

Ultraviolet light of sufficient intensity and exposure is an excellent disinfecting agent for drinking water. However, because of its limited penetration power at 254 nm, microorganisms that are covered with protective membranes or are parasites in other microorganisms are less affected by the ultraviolet light intensity and time of exposure needed to kill exposed microorganisms. Ultraviolet light is suitable to disinfect clear water at intensities and times of exposure that are feasible to accomplish disinfection rates

Exhibit 2-41. Ultraviolet Light Versus Chlorination and Ozonation in Drinking Water

Parameter	Chlorine	Ozone	UV	Remarks
Tannins, Humus, Dissolved Organics, and Colloidal Material	Increased Demand	Increased Demand	Increased Demand	Increased harmful by-products for both chlorine and ozone. Some contaminants removal by ultraviolet light.
Iron and Magnesium	Increased Demand	Increased Demand	Increased Demand	Could require pretreatment for efficient use of ultraviolet light.
Suspended Solids (Turbidity)	Increased Demand	Increased Demand	Increased Demand	Significant suspended solids levels are not likely in most ground water.
pH Effect	Varies	Little	None	Some chlorine compounds are sensitive to pH. pH is a factor in organics destruction efficiency by ultraviolet light.
Temperature Effect	Yes	Yes	No	Recent research suggests better inactivation rates at lower temperatures using ultraviolet light.
Mutagenicity	Yes	Unknown	No	
Time Required to Inactivate Microorganisms	Minutes	Minutes	Seconds	Ultraviolet light systems have the smallest space requirement.
Limits of Solubility at Normal Temperatures	Varies	Yes	N/A	
Microorganism Inactivation	Effective	Effective	Effective	
By-Product Formation	Yes	Yes	No	
Hazardous Material Storage Requirement	Yes	No	No	

comparable to chemical disinfectants. The successful use of ultraviolet light for disinfection in the food industry is a testimony to its feasibility and viability. In the food industry, ultraviolet light is used to sterilize equipment, control surface growth on bakery products, inhibit mold growth and bacterial growth in meat-processing plants, and treat water used for the depuration of shellfish and the production of cell protein.

The data reviewed to date clearly show that:

- The required inactivation dose for bacteria using ultraviolet light varies from one organism to another and within the same species. Many factors could contribute to this variance:
  - Source of microorganism
  - Age of microorganism
  - Method of ultraviolet dose measurement
  - Medium used
  - Organic and inorganic media quality parameters
  - Physical parameters
  - Initial microorganisms density
  - Ultraviolet intensity used
  - Residence time
  - Flow rate.

- The order of disinfection resistance with few exceptions is as follows: bacteria < viruses < bacterial spores < protozoan cysts and oocysts, with Gram-positive bacteria being more resistant to ultraviolet light than Gram-negative bacteria.

- Naturally occurring microorganisms are more resistant to inactivation by ultraviolet light than microorganisms cultured in laboratories.

- Current indicator surrogate microorganisms are more sensitive to ultraviolet light than many identified microorganisms (including viruses) that are of concern in drinking water.

- In the meantime, two challenge surrogate microorganism candidates appear to be the best to test ultraviolet light disinfection efficiency: *Bacillus subtilis* spores and bacteriophage MS-2.

Disinfectants, including ultraviolet light, have limitations, such as undesirable interaction with other water constituents, lack of residual effect, or O&M costs and problems. In many applications, it might be useful to consider the use of multiple disinfectants and water treatment processes. An example of the practical applicability of multiple use of disinfection treatment can be found aboard cruise ships that use ultraviolet light for disinfection (the DHEW guideline dose is 16 mWs/cm^2) followed by chlorine as a secondary disinfectant for residual effect as per shipboard regulations (USEPA, 1983). In England, multiple disinfection systems have been in use for more than 10 years; small systems of up to 2 MGD use ultraviolet light for primary disinfection followed by hypochlorite for distribution system residual effects (McCarty, 1986). The new studies from Norway concluded that ultraviolet light has some residual disinfection effect although this is believed to be of very limited effect. For a large number of small NTNC and TNC ground water systems, a secondary disinfectant may not be necessary, as these systems have no or a small distribution network.

As a tool to disinfect drinking water, ultraviolet light is effective against microorganisms. Ultraviolet light is not, however, a panacea. For example, if a ground water source is iron-rich, it can cause fouling to the ultraviolet light system and, hence, reduce light transmissibility. Therefore, the water needs to be treated before reaching the ultraviolet disinfection unit. Located at the end of the treatment process where proper pretreatment is needed or required, water entering an ultraviolet unit may be assumed to be clear and contain little or no suspended matter or colloids.

To summarize the data reviewed, the effectiveness of ultraviolet light depends on the proper wavelength, the intensity of the radiation, the exposure time, the distance from the light source to the organism to be disinfected, and the water quality. Therefore, any guidelines to be developed for the use of ultraviolet light for ground water disinfection need to consider the above-mentioned factors. However, based on the

work of Sommer and Cabaj (1993), a 60 mWs/cm^2 ultraviolet dose is sufficient to achieve a 4 log reduction in *Bacillus subtilis* spores. Based on Harris et al. (1987), a dose of 45 mWs/cm^2 is sufficient to achieve a 3 log reduction in Reovirus 1 in buffered distilled water. A dose of 40 mWs/cm^2 is sufficient to cause a 5 log reduction in poliovirus (Harris, 1986). The scientific literature review revealed that a greater than 2 log reduction of *Giardia muris* cysts can be achieved using ultraviolet light at a dose of 121 mWs/cm^2. A minimum of 2 to 3 log reduction in *Cryptosporidium parvum* oocysts can be achieved using an ultraviolet light dose of about 8,750 mWs/cm^2.

Some by-products formation is associated with the use of ultraviolet light to disinfect effluent waters. However, by-products formation is insignificant in effluent treatment and extremely insignificant in drinking water applications. Moreover, by-products formation in ultraviolet disinfection processes in water and wastewater application is far less than that produced with the use of chlorination or ozonation. Guidance on use of ultraviolet disinfection technology should identify a minimum specific intensity and residence time and specify lamp arrangement and spacing based upon principal water quality parameters.

A breakdown in etiological agents of waterborne disease in outbreaks in the United States between 1971 and 1977 shows that in ground water systems bacteria accounts for 33 percent (main agents: *Shigella*, 30 percent; *S. typhi*, 2 percent; and Salmonella, 1 percent). HAV comes in second place as a microbial agent of waterborne diseases with 3 percent. Finally, *Giardia* comes in third place with less than 1 percent. Other agents of waterborne disease include chemical agents (6 percent) and unknown agents (58 percent) (USEPA, 1993b). The non chemical-related waterborne disease outbreaks in all water systems resulted in about 130,000 cases of illness between 1971 and 1988 (USEPA, 1993b). The information provided in USEPA, 1993, shows that 35 percent of outbreaks of waterborne diseases in the United States occurred in non-community water supply systems. This figure is very conservative because of long incubation periods and because symptoms of illness often occur in geographical areas far from where the exposure occurred. A study by Moore et al., 1993 shows that 68 percent of outbreaks (for the 1991-1992 period) of waterborne disease associated with drinking water occurred in non-community systems with well water being the source in 77 percent of the cases. Therefore, any form of disinfection in TNC and NTNC water systems will greatly reduce the number of outbreaks. The reviewed data clearly show that many pathogenic bacteria (such as *Vibrio cholerae*) and viruses (such as poliovirus and HAV) associated with high morbidity and mortality around the world and that might be found in ground water sources, are susceptible to ultraviolet disinfection. TNC ground water systems and NTNC ground water systems that are not under direct influence of surface water (protozoa free) and that have little or no distribution systems may benefit the most from ultraviolet light application.

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CHAPTER 3. EVALUATION OF ULTRAVIOLET LIGHT TECHNOLOGY COSTS AND COMPARISON TO OTHER DISINFECTION PROCESSES

3.1 INTRODUCTION

Presented in this chapter are findings to date on costs associated with using ultraviolet light to disinfect ground water sources of public drinking water. Cost factors relevant to ultraviolet light disinfection include capital costs (i.e., equipment and construction costs) and operation and maintenance costs (i.e., parts replacement, power, and labor costs). Ultraviolet light costs derived from available information are presented in section 3.2. Section 3.3 compares these costs with ultraviolet system cost estimates developed previously by USEPA. Ultraviolet light costs are compared to costs associated with other disinfection technologies such as chlorination and ozonation in section 3.4, while the costs of providing secondary disinfection (i.e., a residual to protect distribution systems) are addressed in section 3.5. Section 3.6 presents costs from some foreign ultraviolet light systems.

The ultraviolet light system cost estimates and costing methodology in this report were based on previous USEPA cost estimate reports, cost information collected from ultraviolet light equipment manufacturers, other USEPA drinking water reports, and articles published in the scientific literature. Cost information collected from ultraviolet light equipment manufacturers was used to compare current market prices with previously reported cost estimates and to compare current ultraviolet costs with the cost of other well-established disinfection technologies such as chlorination and ozonation. The costs presented in this report are estimates and subject to some variance. Site-specific considerations, such as influent water quality, are a major variable in cost estimation and would impact the overall cost of the ultraviolet disinfection system. *In addition, USEPA considers these to be preliminary estimates of cost which will be subject to change as cost methodologies, and groundwater disinfection requirements develop.*

The cost estimates in this report are for USEPA flow categories 1 through 5. This includes all USEPA flow categories for small water systems, one medium-flow, and one large-flow USEPA category. The average flow, design flow, and population served for those flow categories are presented in **Exhibit 3-1**.

Capital and operation and maintenance costs were studied for two doses: 40 mWs/cm^2 and 140 mWs/cm^2 at 253.7 nm for USEPA flow categories 1 through 5. The 40 mWs/cm^2 dose was selected based on the work of Harris (1986) that showed a 5 log reduction of poliovirus. Harris' work was adopted as the base

Exhibit 3-1. USEPA Flow Categories and Population Served

USEPA Flow Category	Average Flow (MGD)	Peak Factor	Design Flow (MGD)	Population Range
1	0.0056	4.3	0.024	25-100
2	0.024	3.6	0.087	101-500
3	0.086	3.1	0.270	501-1,000
4	0.23	2.8	0.650	1,001-3,300
5	0.7	2.6	1.80	3,301-10,000

for ANSI/NSF (1991) standard 55-1991 for Class A POU drinking water disinfection treatment systems. The 140 mWs/cm^2 dose is the minimum dose required under the National Water Research Institute (NWRI, 1993) guidelines for water reclamation (e.g., for agricultural end users) in California. The NWRI (1993) guidelines are based on the works of Chen and Kuo (1992) and CH2M HILL (1992) that showed a 4 log reduction of poliovirus in treated domestic wastewater.

Costs can be expressed as annual costs or costs per thousand gallons of treated water. Costs per thousand gallons are helpful in estimating the impact on the consumer's water bill. Both methods of cost expression are used in this chapter to facilitate the use of the generated cost figures to assess the impact on the consumer's water bill and to assess the national economic impact of using ultraviolet light for disinfecting ground water for drinking.

Costs in this report are based on the use of modular vessels (closed systems) that require one electrical connection and two plumbing connections. The capacity of modular units is assumed to follow the following criteria:

- There is a minimum of two units per treatment plant.
- When one unit is not in service, the other unit(s) have the capacity to carry peak design flow (daily or hourly). The determination of whether the remaining units should be capable of carrying hourly or daily peak flow capacity must be based on the system's water storage capacity to account for peak hourly demand.

These criteria are based on USEPA's suggested recommendations for the use of ultraviolet systems under the Draft Ground Water Disinfection Rule (GWDR).

3.2 ULTRAVIOLET DISINFECTION COSTS

The total cost estimate for an ultraviolet system is the sum of two major costs: capital, including equipment cost, and operation and maintenance cost.

Due to the fact that costs rise and fall in accordance with the economic market, costs need to be adjusted to current value. Capital costs are adjusted through the use of the Engineering News Record Construction Cost (ENRCC) Index (ENR, 1995). Operation and maintenance costs are adjusted using the Producer Price Index, which is found in the publication *Producer Prices and Price Indexes* (PPPI, 1995). All capital costs obtained from earlier reports and used in this study were adjusted to the August 1995 20-city average ENRCC Index value of 5506.33. This average value is not as accurate as a value for a specific city or region of the United States and may overestimate or underestimate costs due to varying construction costs in different parts of the country. If a specific city or region is known to be the future site of an ultraviolet treatment system, the ENRCC index for that city or region should be used. This method of cost adjustment is more applicable to chlorination systems than to ultraviolet systems, because ultraviolet systems require very little construction work.

Cost data in other literature were updated for comparison with current costs using the following standard equation (WERF, 1995):

$$\text{Construction Cost} = \frac{5506.33}{\text{Reported ENRCC Index}} \times \text{Reported Cost}$$

Costs contained in this report can be adjusted for comparison to future costs in a similar manner (WERF, 1995):

$$\text{Future Cost} = \frac{\text{Future ENRCC Index}}{5506.33} \times \text{Cost Cited Within This Report}$$

In order to present capital costs in cents per thousand gallons or in dollars per year, an amortization factor must be used. For the purposes of this report, an amortization factor of 0.11746 is used to represent the cost of the treatment system at 10 percent interest over a period of 20 years (USEPA, 1983). By multiplying the capital cost in dollars by the amortization factor, it is easy to find the annualized cost. To find the cost in cents per thousand gallons, the following formula can be used:

Capital Cost (c/kgal) =

$$\frac{\text{Capital Cost (\$)} \times \text{Amortization factor} \times \frac{100\text{c}}{\$1} \times \frac{1\text{ Year}}{365\text{ days}} \times \frac{1\text{ MG}}{1000\text{ Kgal}}}{\text{Flow (MGD)}}$$

3.2.1 Capital Costs

The capital cost for an ultraviolet system is mainly the equipment cost. Capital costs for this quasi "turn-key" system involve the purchase of equipment and construction (if any) of a protection structure (room or shed) and installation of the system. These costs depend on several factors, such as flow rate, degree of treatment, and influent water quality. As flow rate increases, more lamps will be needed to provide adequate light energy. The equipment becomes larger and more complex, and the cost rises accordingly. The degree of treatment also affects the cost of equipment. An ultraviolet treatment for drinking water that is closer to sterilization requires doses that are far higher than the doses required for disinfection. Therefore, a high degree of treatment could be far more expensive than current disinfection requirements. By the same token, a "poor" quality water that is high in microorganism densities or in plating and fouling agents requires more ultraviolet energy to achieve the desired treatment levels.

The degree of treatment considered in this analysis is based on the use of ultraviolet systems capable of delivering 40 mWs/cm^2 and 140 Mws/cm^2 doses to achieve the 5 log reduction of poliovirus in "good," i.e., filtered water sources that are low in plating and fouling agents, and a 4 log reduction of poliovirus in "poor" water quality sources comparable to a filtered secondary wastewater effluent, respectively.

3.2.1.1 Equipment Costs

The cost estimates presented here are quotes from three manufacturers that have considerable market share and experience in ultraviolet technology. The equipment considered for use in small water systems includes closed chamber ultraviolet modules with lamps and quartz sleeves, module support racks, instrumentation and control panels, power supply distribution and ballasts, automatic cleaners, pipes and valves, and other equipment to control and monitor the system. Through the use of modular systems, the equipment cost can be calculated easily by estimating the number of modules required. The cost of shipping and installation is included in the estimates. It is assumed in this study that all units include self-cleaning mechanisms. Prefilter cost, if any, is not included in this analysis. The equipment costs and the number of modular units and lamps required for different systems are summarized in **Exhibit 3-2**. As

Exhibit 3-2. Equipment Costs*

Dose 40 mWs/cm^2

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C		
		Units Required	Total # of Lamps per Unit	Equipment Cost ($)	Units Required	Total # of Lamps per Unit	Equipment Cost ($)	Units Required	Total # of Lamps per Unit	Equipment Cost ($)
1	0.024	2	4 @30"	8,000	2	2 @58"	11,600	2	2 @36"	8,000
2	0.087	2	8 @30"	10,600	2	4 @58"	14,800	2	4 @58"	10,000
3	0.270	2	12 @60"	26,000	2	8 @58"	29,600	2	10 @58"	22,000
4	0.650	2	24 @60"	73,100	2	18 @58"	44,400	2	24 @58"	46,000
5	1.80	3	36 @60"	142,610	4	24 @58"	133,300	2	40 @58"	76,000

Dose 140 mWs/cm^2

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C		
		Units Required	Total # of Lamps per Unit	Equipment Cost ($)	Units Required	Total # of Lamps per Unit	Equipment Cost ($)	Units Required	Total # of Lamps per Unit	Equipment Cost ($)
1	0.024	2	8 @30"	10,600	2	4 @58"	14,800	2	4 @58"	10,000
2	0.087	2	16 @60"	31,200	2	10 @58"	24,000	2	10 @58"	22,000
3	0.27	2	36 @60"	95,100	3	16 @58"	56,000	2	32 @58"	62,000
4	0.650	4	24 @60"	146,200	5	16 @58"	128,000	2	40 @58"	76,000
5	1.80	8	36 @60"	380,400	10	20 @58"	288,000	6	40 @58"	226,000

*August 1995 dollars.

shown in Exhibit 3-2, the cost range for equipment delivering 40 mWs/cm^2 is $8,000 to $143,000 and $11,000 to $381,000 for equipment delivering 140 mWs/cm^2 for flow categories 1 through 5.

3.2.1.2 Construction Costs

Because ultraviolet modules are typically small in size, no major construction costs are assumed in this cost analysis. However, a 20-percent markup of the equipment cost is included in total capital cost to account for engineering (10%); legal, fiscal, and administrative services (3%); sitework and interconnecting piping (6%); and contingencies (1%), including any minor construction work that may be necessary, such as a small shed to protect the ultraviolet equipment and its spare parts from the elements. This is shown in **Exhibit 3-3**. According to USEPA (1993a), factors such as contractor's overhead and profit, electrical connections, and standby power should be added to equipment costs to calculate capital costs for all types of systems. However, these cost factors are not included here because closed ultraviolet systems resemble a turnkey job more than an engineering design, construction, and supervision job. Also, USEPA (1993a) states that electrical work would cost $1,300 per installed horsepower or approximately $1,740 per installed kilowatt. This is not applicable to ultraviolet systems, because there is little electrical work involved beyond plugging the system in. In addition, such costs account for comparatively insignificant amounts.

Exhibit 3-3. Added Engineering and Installation Costs

Item	Cost*
Engineering	10 percent of equipment cost
Legal, Fiscal, and Administrative	3 percent of equipment cost
Sitework and Interconnecting Piping	6 percent of equipment cost
Contingencies	1 percent of equipment cost

*Modified from USEPA (1993a).

3.2.1.3 Total Capital Costs

Equipment costs are the major source of capital costs. Therefore, total capital cost is equipment cost plus 20 percent, as detailed earlier. Although sheds, piping, electrical connections, engineering, legal services, and construction in general do not account for a fixed percentage, the 20-percent markup in equipment costs allows for variations in prices from one region to another and among different industries. For large systems, the 20-percent markup might be an over-estimation, thus providing a more conservative cost assessment of ultraviolet systems. This is illustrated in **Exhibit 3-4**, which gives a straightforward total

Exhibit 3-4. Total Capital Costs*

Dose 40 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C			Average Capital Costs (k$)	Average Capital Costs** (c/kgal)
		Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)	Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)	Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)		
1	0.024	8.00	9.60	12.87	11.60	13.92	18.66	8.00	9.60	12.87	11.04	14.80
2	0.087	10.60	12.72	4.71	14.80	17.76	6.57	10.00	12.00	4.44	14.16	5.24
3	0.27	26.00	31.20	3.72	29.60	35.52	4.23	22.00	26.40	3.15	31.04	3.70
4	0.65	73.10	87.72	4.34	44.40	53.28	2.64	46.00	55.20	2.73	65.40	3.24
5	1.80	142.61	171.13	3.06	133.20	159.84	2.86	76.00	91.20	1.63	140.72	2.52

Dose 140 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C			Average Capital Costs (k$)	Average Capital Costs** (c/kgal)
		Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)	Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)	Equipment Costs (k$)	Total Capital Costs (k$)	Total Capital Costs** (c/kgal)		
1	0.024	10.60	12.72	17.06	14.80	17.76	23.81	10.00	12.00	16.09	14.16	18.99
2	0.087	31.20	37.44	13.85	24.00	28.80	10.65	22.00	26.40	9.77	30.88	11.42
3	0.27	95.10	114.12	13.60	56.00	67.20	8.01	62.00	74.40	8.87	85.24	10.16
4	0.65	146.20	175.44	8.69	128.00	153.60	7.60	76.00	91.20	4.52	140.08	6.94
5	1.80	380.40	456.48	8.16	288.00	345.60	6.18	226.00	271.20	4.85	357.76	6.40

* August 1995 dollars.
** Costs amortized at 10% for 20 years.

of capital costs in dollars and capital costs estimates in cents per thousand gallons for ultraviolet systems delivering the two set doses of 40 mWs/cm^2 and 140 mWs/cm^2 for USEPA flow categories 1 through 5.

3.2.2 Operation and Maintenance Costs

Once a treatment system is in place, costs are incurred in the everyday operation of the facility. Continuous 24-hour per day operation for the treatment system is assumed. However, during periodic maintenance, a unit can be shut down while another unit or units carry the design flow. Operation and maintenance costs include parts replacement, electric power consumption, and labor. The subsequent operation and maintenance cost estimates are based on the following assumptions:

- The size of the system is based on design flow with redundancy in equipment, i.e., a minimum of two module units with each unit capable of carrying design flow; if more than two module units are used, then the total number of units minus one unit should be capable of carrying the set design flow.
- Power consumption of lamp and ballast is calculated according to manufacturer's estimates (the range is 70 - 85 watts for low-pressure lamp units).
- Lamp replacement is calculated according to manufacturer's estimates of lamp life at 70 percent of its initial efficiency (as measured after 100 hours of service, the range is 8,000 – 14,000 hours).
- Ballast replacement is done every ten years (worst case assumption).
- Quartz sleeves are replaced every five years (worst case assumption).
- Labor is estimated at 0.5 hours per lamp per year for cleaning and repairs. (The range is 0.25 hours per year to two hours per year).
- Chemicals (0.1 gallon per lamp per year) for cleaning once every 6 months (range 6 to 12 months).
- Miscellaneous equipment repair costs are accounted for at 0.1% of capital costs with a minimum of $15 per year [for repairs such as replacement of a malfunctioning LED].

It is assumed that ultraviolet equipment is disposed of in a safe manner consistent with the disposal of any electrically driven equipment, such as high-efficiency mercury-containing lamps and fluorescent lamps and ballasts, and therefore present no significant additional costs. It should be noted that some manufacturers willingly take back ultraviolet lamps and ballasts for recycling of materials, presumably at no cost to the water system user.

3.2.2.1 Parts Replacement

Regular maintenance of equipment is necessary to keep the system operating properly. Materials in need of regular replacement in an ultraviolet treatment system include ultraviolet lamps, ballasts, and sleeves. Based on industry quotes, lamps cost between $40 and $100 each and should be replaced every 8,000 to 14,000 hours. Ballasts and LEDs may need to be replaced every 10 years. Quartz sleeves and miscellaneous switches, valves, and rings may need to be changed every 5 years.

Exhibit 3-5 presents part replacement costs for equipment used to provide for the doses considered in this report. These costs were provided by ultraviolet equipment manufacturers. Exhibit 3-5 shows that the difference in maintenance costs could be significant. The calculated maintenance costs for manufacturer "A" are almost twice those of manufacturer "B" for all ultraviolet systems delivering 40 mWs/cm^2 and more than thrice the calculated maintenance costs of manufacturer "B" for systems delivering 140 mWs/cm^2.

3.2.2.2 Power Costs

Power costs are estimated assuming a unit rate of $0.086 per kilowatt-hour (USEPA, 1993b). This rate is highly variable based on the geographic location of the facility in the country and the source of electric power. Power costs are based on the power requirements for each type of lamp and unit as provided by the manufacturers assuming 24-hour per day operation.

Exhibit 3-6 presents calculated power costs in cents per thousand gallons of treated water for the doses considered in this report and for USEPA flow categories 1 through 5.

3.2.2.3 Labor Costs

The facility's labor requirements are for the replacement of parts, general maintenance (cleaning of lamps, sleeves, and the unit body), and monitoring. Cleaning requirements are highly site-specific in frequency, level of effort, and time requirements. For high-quality water, an annual cleaning could be accomplished by flushing the unit with a liquid detergent (approved synthetic organic detergent, ethanol, dilute phosphoric acid, or dilute hydrochloric acid) after recycling it under pressure for a specific time, according to manufacturer's recommendations. For low-quality water with fouling and plating problems, a monthly cleaning might be necessary. The labor rate is assumed to be $15.50 per hour. This rate is in August 1995 dollars and is based on estimates cited by DPRA (1993) for a 10-city average for non-union scale

Exhibit 3-5. Parts Replacement Costs*

Dose 40 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Part Replacement Cost							
		Manufacturer A		Manufacturer B		Manufacturer C		Average $/year	Average c/kgal
		$/year	c/kgal	$/year	c/kgal	$/year	c/kgal		
1	0.024	320	3.65	80	.91	130	1.48	177	2.01
2	0.087	640	2.02	160	0.50	360	1.13	387	1.22
3	0.27	1,300	1.32	320	0.32	900	0.91	840	0.85
4	0.65	2,630	1.11	720	0.30	2,160	0.91	1,837	0.77
5	1.8	7,880	1.20	2,880	0.44	3,600	0.55	4,787	0.73

Dose 140 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Part Replacement Cost							
		Manufacturer A		Manufacturer B		Manufacturer C		Average $/year	Average c/kgal
		$/year	c/kgal	$/year	c/kgal	$/year	c/kgal		
1	0.024	640	7.31	160	1.83	360	4.11	387	4.42
2	0.087	1,750	5.51	400	1.26	900	2.83	1,017	3.20
3	0.27	3,940	4.00	1,280	1.30	2,880	2.92	2,700	2.74
4	0.65	7,880	3.32	2,560	1.08	3,600	1.52	4,680	1.97
5	1.8	27,600	4.20	7,200	1.10	18,000	2.74	17,600	2.68

*August 1995 dollars.

Exhibit 3-6. Power Costs*

Dose 40 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C			Average Power Cost ($/year)	Average Power Cost (c/kgal)
		kW Required	Power Cost ($/year)	Power Cost (c/kgal)	kW Required	Power Cost ($/year)	Power Cost (c/kgal)	kW Required	Power Cost ($/year)	Power Cost (c/kgal)		
1	0.024	0.26	196	2.24	0.17	128	1.46	0.16	121	1.38	148	1.69
2	0.087	0.50	377	1.19	0.34	256	0.81	0.39	294	0.93	309	0.97
3	0.27	1.14	859	0.87	0.68	512	0.52	0.9	678	0.69	683	0.69
4	0.65	2.28	1,718	0.72	1.53	1,153	0.49	2.2	1,657	0.70	1,509	0.64
5	1.8	6.84	5,153	0.78	6.12	4,611	0.70	3.6	2,712	0.41	4,159	0.63

Dose 140 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A			Manufacturer B			Manufacturer C			Average Power Cost ($/year)	Average Power Cost (c/kgal)
		kW Required	Power Cost ($/year)	Power Cost (c/kgal)	kW Required	Power Cost ($/year)	Power Cost (c/kgal)	kW Required	Power Cost ($/year)	Power Cost (c/kgal)		
1	0.024	0.50	377	4.3	0.34	256	2.92	0.38	286	3.26	306	3.49
2	0.087	1.56	1,175	3.7	0.85	640	2.02	0.90	678	2.14	831	2.62
3	0.27	3.42	2,577	2.62	2.72	2,049	2.08	3.0	2,260	2.29	2,295	2.33
4	0.65	6.84	5,153	2.17	5.44	4,098	1.73	3.6	2,712	1.14	3,988	1.68
5	1.8	23.99	18,073	2.75	15.3	11,526	1.75	18.0	13,560	2.06	14,386	2.19

* August 1995 dollars.

laborers. The hourly rate of $15.50 includes an average salary of $9.15 per hour plus a 12.2 percent fringe benefit and a 50 percent labor overhead cost. Average salaries ranged from $7.65 to $10.75 per hour in the south central and western United States, respectively. Fringe benefit rates ranged from approximately 8 to 15 percent, depending on the region of the country (DPRA, 1993).

Based on these assumptions, **Exhibit 3-7** presents labor requirements in hours per lamp per year, total hours per year, labor costs per year, and labor costs in cents per thousand gallons. As can be seen from Exhibit 3-7, the labor costs for ultraviolet systems of 140 mWs/cm^2 dose capacity are about double those required for ultraviolet systems of 40 mWs/cm^2 dose capacity for the same treated flows. Labor costs are directly tied to the total number of lamps used in an ultraviolet light system. The increase in labor costs between flow categories 4 and 5 could be traced back to the number of lamps used (see Exhibit 3-2).

3.2.2.4 Summary of Operation and Maintenance Costs

Major operation and maintenance costs can be found simply by adding part replacement cost, power cost, and labor cost. It may be most appropriate to put major operation and maintenance costs in cents per thousand gallons, as this allows for simple estimation of cost based on a plant's flow. Exhibits 3-5 (parts replacement costs), 3-6 (power costs), and 3-7 (labor costs) are summarized in **Exhibit 3-8**.

Exhibit 3-9 presents an itemized account for total operation and maintenance costs per year and in cents per thousand gallons. All the components of major operation and maintenance costs are included plus miscellaneous and chemicals costs. The figures in Exhibit 3-9 are average figures calculated from Exhibits 3-5, 3-6, and 3-7 according to the assumptions detailed in section 3.2.2. Where possible, unit prices are listed, or a range is specified or a calculation method is provided. As can be seen for Exhibit 3-9, for every flow category, parts replacement costs constitute the highest operation and maintenance costs followed by power consumption costs. Labor costs come in third place constituting less than 10 percent of the total operation and maintenance costs for ultraviolet systems of 140 mWs/cm^2 and 40 mWs/cm^2 for USEPA flow categories 1 through 5.

Exhibit 3-7. Labor Costs*

Dose 40 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A				Manufacturer B				Manufacturer C				Average Labor Cost ($/year)	Average Labor Cost (c/kgal)
		Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)	Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)	Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)		
1	0.024	0.5	4	62	0.71	0.5	2	31	0.35	0.25	1	15.5	0.18	36.17	0.41
2	0.087	0.5	8	124	0.39	0.5	4	62	0.20	0.25	2	31	0.10	72.33	0.23
3	0.27	0.5	12	186	0.19	0.5	8	124	0.13	0.25	5	77.5	0.08	129.17	0.13
4	0.65	0.5	24	372	0.16	0.5	18	279	0.12	0.25	12	186	0.08	279.00	0.12
5	1.8	0.5	54	837	0.13	0.5	48	744	0.11	0.25	20	310	0.05	630.33	0.10

Dose 140 mWs/cm²

USEPA Flow Category	Design Flow (MGD)	Manufacturer A				Manufacturer B				Manufacturer C				Average Labor Cost ($/year)	Average Labor Cost (c/kgal)
		Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)	Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)	Attention Required (hrs/lamp/yr)	Attention Required (hrs/yr)	Labor Cost ($/year)	Labor Cost (c/kgal)		
1	0.024	0.5	8	124	1.41	0.5	4	62	0.70	0.25	2	31	0.35	72.33	0.83
2	0.087	0.5	16	248	0.78	0.5	10	155	0.49	0.25	5	77.5	0.24	160.17	0.50
3	0.27	0.5	36	558	0.57	0.5	24	372	0.38	0.25	16	248	0.25	392.67	0.40
4	0.65	0.5	48	744	0.31	0.5	40	620	0.26	0.25	20	310	0.13	558.00	0.23
5	1.8	0.5	144	2,232	0.34	0.5	100	1,550	0.24	0.25	60	930	0.14	1,570.67	0.24

*August 1995 dollars.

Exhibit 3-8. Major Operation and Maintenance Costs (Excluding Miscellaneous and Chemical Costs)

Dose 40 mWs/cm^2

USEPA Flow Category	Average Flow (Kgpd)	Design Flow (MGD)	Cost (c/kgal)			Average Cost c/kgal
			Manufacturer A	Manufacturer B	Manufacturer C	
1	5.6	0.024	6.60	2.72	3.04	4.12
2	24	0.087	3.60	1.51	2.16	2.42
3	86	0.27	2.38	0.97	1.68	1.68
4	230	0.65	1.99	0.91	1.69	1.53
5	700	1.8	2.11	1.25	1.01	1.46

Dose 140 mWs/cm^2

USEPA Flow Category	Average Flow (Kgpd)	Design Flow (MGD)	Cost (c/kgal)			Average Cost c/kgal
			Manufacturer A	Manufacturer B	Manufacturer C	
1	5.6	0.024	13.03	5.46	7.72	8.74
2	24	0.087	9.99	3.77	5.21	6.32
3	86	0.27	7.18	3.76	5.46	5.47
4	230	0.65	5.80	3.07	2.79	3.89
5	700	1.8	7.29	3.09	4.94	5.11

Exhibit 3-9. Unit and Total Operations and Maintenance Costs for Ultraviolet Light Disinfection System*

Dose 40 mWs/cm²

Item	Unit	Unit Cost $	Cost per Year ($)					Cost per 1,000 Gallons (c/kgal)				
Flow Category			1	2	3	4	5	1	2	3	4	5
Electrical Power	kWhr	0.086	148	309	683	1,509	4,159	1.69	0.97	0.69	0.64	0.63
Lamp Replacement	Each	40-100	113	275	664	1,485	3,943	1.29	0.87	0.67	0.63	0.60
Sleeve	Each	60	48	96	160	336	816	0.55	0.30	0.16	0.14	0.12
Ballast	Each	80	16	16	16	16	28	0.18	0.05	0.02	0.01	0.00
Misc.**	pr yr	**	15	15	26	55	117	0.17	0.05	0.03	0.02	0.02
Labor	per hour	15.50	36	72	129	279	630	0.41	0.23	0.13	0.12	0.10
Chemicals	gallons/yr	5	3	6	10	21	51	0.03	0.02	0.01	0.01	0.01
Total			**379**	**789**	**1,688**	**3,701**	**9,744**	**4.32**	**2.49**	**1.71**	**1.57**	**1.48**

Dose 140 mWs/cm²

Item	Unit	Unit Cost $	Cost per Year ($)					Cost per 1,000 Gallons (c/kgal)				
Flow Category			1	2	3	4	5	1	2	3	4	5
Electrical Power	kWhr	0.086	306	831	2,295	3,988	14,386	3.49	2.62	2.33	1.68	2.19
Lamp Replacement	Each	40-100	275	793	2,200	3,940	15,576	3.14	2.50	2.23	1.66	2.37
Sleeve	Each	60	96	208	480	704	1,952	1.10	0.66	0.49	0.30	0.30
Ballast	Each	80	16	16	20	36	72	0.18	0.05	0.02	0.02	0.01
Misc.**	per yr	**	15	26	71	117	300	0.17	0.08	0.07	0.05	0.05
Labor	per hour	15.50	72	160	393	558	1,571	0.82	0.50	0.40	0.23	0.24
Chemicals	gallons/yr	5	6	13	30	44	122	0.07	0.04	0.03	0.02	0.02
Total			**786**	**2,047**	**5,489**	**9,387**	**33,979**	**8.97**	**6.45**	**5.57**	**3.96**	**5.18**

*August 1995 dollars
**Misc. cost = $15 or 1% of average equipment cost, whichever is greater.

3.2.3 Total Costs of Ultraviolet Disinfection (Capital Costs and Operation and Maintenance Costs)

Total production cost is the capital cost, amortized at 10 percent interest over a period of 20 years, plus the operation and maintenance cost. The total cost estimates of ultraviolet systems as per quotes available from ultraviolet equipment manufacturers are presented in **Exhibit 3-10**. Exhibit 3-10 was constructed by combining the annualized cost estimates presented in Exhibit 3-4 (capital costs) and Exhibit 3-9 (operation and maintenance costs). Analysis of total production costs and operation and maintenance costs indicate a linear relationship with flow capacity above 0.087 MGD.

Exhibit 3-10. Total Current Costs

Dose 40 mWs/cm^2

USEPA Flow Category	Design Flow (MGD)	Cost per Year (k$)			Cost (c/kgal)		
		Total Capital**	Total O&M	Total Production Costs	Total Capital**	Total O&M	Total Production Costs
1	0.024	1.30	0.38	1.7	14.80	4.32	19
2	0.087	1.66	0.79	2.5	5.24	2.49	8
3	0.27	3.65	1.69	5.3	3.70	1.71	5
4	0.65	7.68	3.70	11.4	3.24	1.57	5
5	1.8	16.56	9.74	26.3	2.52	1.48	4

Dose 140 mWs/cm^2

USEPA Flow Category	Design Flow (MGD)	Cost per Year (k$)			Cost (c/kgal)		
		Total Capital**	Total O&M	Total Production Costs	Total Capital**	Total O&M	Total Production Costs
1	0.024	1.66	0.79	2.5	18.99	8.97	28
2	0.087	3.63	2.05	5.7	11.42	6.45	18
3	0.27	10.01	5.49	15.5	10.16	5.57	16
4	0.65	16.45	9.39	25.8	6.94	3.96	11
5	1.8	42.05	33.98	76.0	6.40	5.18	12

*August 1995 dollars.
**Costs amortized at 10% for 20 years.

3.3 COMPARISON OF CURRENT ULTRAVIOLET SYSTEMS COST ESTIMATES TO ULTRAVIOLET COSTS REPORTED IN A 1993 USEPA DOCUMENT

For comparison, the document titled *Very Small Systems Best Available Technology Cost Document* (USEPA, 1993a) provides a recent estimate of costs of using ultraviolet technology in drinking water treatment.

As stated earlier, cost estimates calculated in section 3.2 are based on two ultraviolet light doses 40 mWs/cm^2 and 140 mWs/cm^2. *Very Small Systems Best Available Technology Cost Document* (USEPA, 1993a) presents models for the calculation of ultraviolet light system capital and operation and maintenance costs. These models were not used in the development of cost estimates for this report because they were based on the 1984 WATER model, which assumes an ultraviolet light dose of 16 to 30 mWs/cm^2. Also, when equipment and costs are being considered, it is reasonable to assume that the ultraviolet technology of 1984 does not include all the components of 1995, such as better control systems and greater lifespan. Moreover, the 1984 WATER model is an old model that might not reflect all the cost variables encountered in 1995 ultraviolet systems (such as ultrasonic cleaners and automatic wipers). The cost estimates generated using the USEPA 1993a cost analysis are presented here to show similarities and differences among cost estimates.

For flows less than or equal to 270 kgpd, the governing equation used in USEPA (1993a) to calculate capital costs is:

$$CAP = 0.099[FLOW] + 3.45$$

WHERE: CAP = Total capital costs (k$)
FLOW = Design flow (kgpd)

The governing equation:

$$CAP = 0.125\ [FLOW] + 4.16$$

is used to calculate capital costs for flows greater than 270 kgpd. The capital costs according to this equation, adjusted to 1995 dollars, are presented in **Exhibit 3-11** for the five EPA flow categories.

Exhibit 3-11. Ultraviolet Capital Cost Estimates (Source: USEPA, 1993a)

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	Capital Cost (k$)	Annualized Capital Cost* (c/kgal)
1	5.6	24	5.83	7.82
2	24	87	12.06	4.46
3	86	270	30.18	3.60
4	230	650	85.41	4.23
5	700	1,800	229.16	4.10

*Costs are annualized at 10% interest for 20 years.

The WATER model for operation and maintenance costs for ultraviolet light disinfection systems assumes a maximum 30 mWs/cm^2 dose and 0.12 hours per week for labor requirements. The model does not explicitly indicate whether equipment redundancy is considered in the cost estimates.

For flows less than or equal to 86 kgpd, the governing equation used in USEPA, 1993a to calculate operation and maintenance is:

$$OM = 17.8\ [AVG]^{-0.427} + 209.4\ [LAB]\ [AVG]^{-1}$$

WHERE: OM = Operation and maintenance costs (c/kgal)
AVG = Average daily flow (kgpd)
LAB = Labor required (hours/week).

For flows greater than 86 kgpd, the equation used to calculate operation and maintenance cost is:

$$OM = 17.8[AVG]^{-0.427} + 398.9\ [LAB]\ [AVG]^{-1}$$

The operation and maintenance costs calculated using this model are presented in **Exhibit 3-12**.

Exhibit 3-12. Ultraviolet Operation and Maintenance Cost Estimates (Source: USEPA, 1993a)

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	O&M (c/kgal)
1	5.6	24	13.02
2	24	87	5.63
3	86	270	2.95
4	230	650	1.95
5	700	1,800	1.15

*August 1995 dollars.

To account for varying labor estimates for different flow categories, the USEPA (1993a) O&M estimates are adjusted in **Exhibit 3-13** using average labor requirements from three manufacturer quotes based on an ultraviolet light dose of 40 mWs/cm^2. A graphical comparison of total production costs based on USEPA (1993a) labor requirement estimates (see Exhibit 3-12) and based on manufacturer's labor requirement estimates (see Exhibit 3-13) is presented in **Exhibit 3-14**. Exhibit 3-14 is constructed by adding the USEPA, 1993a annualized capital costs (see Exhibit 3-11) to USEPA, 1993a operation and maintenance costs (see Exhibit 3-12), and to the adjusted operation and maintenance costs (see Exhibit 3-13). Exhibit 3-14 shows that adjusted labor costs have the greatest impact on the total production costs of flow category one.

Exhibit 3-13. Adjusted (USEPA, 1993a) Operation and Maintenance Costs as per Manufacturers' Estimates of Labor Requirements

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	Labor Required* (hours per week)	Adjusted O&M Costs (c/kgal)
1	5.6	24	0.045	10.21
2	24	87	0.090	5.37
3	86	270	0.160	3.05
4	230	650	0.346	2.35
5	700	1,800	0.782	1.53

*Based on average labor requirements as recommended in three manufacturer quotes.

Exhibit 3-15 summarizes the total cost estimates of ultraviolet systems calculated based on labor requirements as reported in *Very Small Systems Best Available Technology Cost Document* (USEPA, 1993a), and based on adjusted operation and maintenance costs.

For cost verification purposes, graphical comparisons of the costs developed by SAIC under this task for ultraviolet systems delivering a 40 mWs/cm^2 dose and a 140 40 mWs/cm^2 dose and costs calculated based on the methodology provided in USEPA (1993a). Graphical presentation for capital costs are presented in **Exhibit 3-16**. As can be seen from Exhibit 3-16, for flow category 1 (design flow 24 Kgpd), capital costs for ultraviolet systems delivering doses ranging from 16-30 mWs/cm^2 to 140 mWs/cm^2 are very close.

For flow categories 2 and 3, capital costs for ultraviolet systems delivering an ultraviolet light dose of less than 40 mWs/cm^2 are almost identical. The capital costs of 140 mWs/cm^2 ultraviolet treatment system

Exhibit 3-14. Comparison of Total Production Costs with Varying Labor Requirements

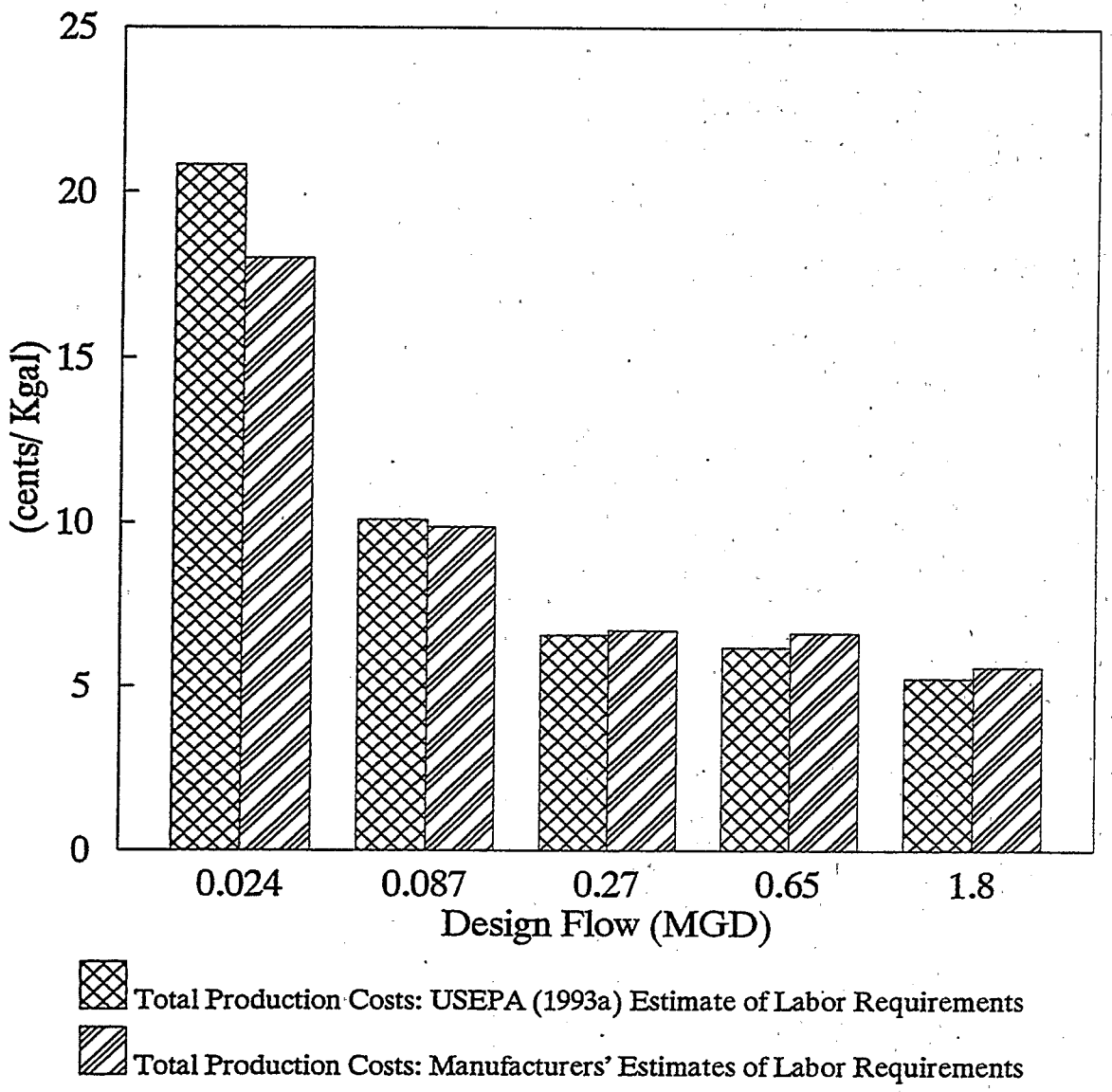


Exhibit 3-15. Ultraviolet Cost Estimates (Source: USEPA, 1993a)

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	Capital Cost (k$)	Annualized Capital Cost* (c/kgal)	O&M** (c/kgal)	Total Production Costs (c/kgal)	Total Production Costs with Adjusted O&M Costs (c/kgal)
1	5.6	24	5.83	7.82	13.02	21	18
2	24	87	12.06	4.46	5.63	10	10
3	86	270	30.18	3.60	2.95	7	7
4	230	650	85.41	4.23	1.95	6	7
5	700	1,800	229.16	4.10	1.15	5	6

*Capital cost amortized at 10% interest over 20 years.
**Based on USEPA (1993a) labor requirements of 0.12 hours per week, for all flow categories.

is the highest for flow categories 2 through 5. For flow categories 4 and 5, current capital cost estimates for 40 mWs/cm^2 ultraviolet systems are lower than capital cost estimates calculated based on the USEPA, 1993a water cost model for a 16-30 mWs/cm^2 ultraviolet treatment system. Graphical presentations of operation and maintenance costs for 16-30 mWs/cm^2, 40 mWs/cm^2, and 140 mWs/cm^2 ultraviolet treatment systems are presented in **Exhibit 3-17**. As can be seen from Exhibit 3-17, operation and maintenance cost estimates for a 140 mWs/cm^2 ultraviolet treatment system are higher than the operation and maintenance cost estimates for a 40 mWs/cm^2 ultraviolet treatment system for flow categories 1 through 5. Operation and maintenance cost estimates for a 140 mWs/cm^2 ultraviolet treatment system are higher than the operation and maintenance costs estimates developed using USEPA, 1993c methodology for flow categories 2 through 5.

Graphical comparisons of total production cost estimates developed by SAIC under this task for 40 mWs/cm^2 and 140 mWs/cm^2 ultraviolet treatment systems and total production cost estimates for 16-30 mWs/cm^2 ultraviolet treatment systems developed using USEPA, 1993a methodology are presented in **Exhibit 3-18**.

As can be seen from Exhibit 3-18, the costs estimated by USEPA (1993a) are close to those estimated using manufacturer's quotes for the 40 mWs/cm^2 dosage. Overall, however, costs for ultraviolet systems delivering 40 mWs/cm^2 dosage are consistently approximately two cents per thousand gallons less expensive than the USEPA (1993a) estimates for total production costs for ultraviolet systems delivering 16 to 30 mWs/cm^2 dosage.

Exhibit 3-16. Comparison of Capital Costs of Ultraviolet Treatment

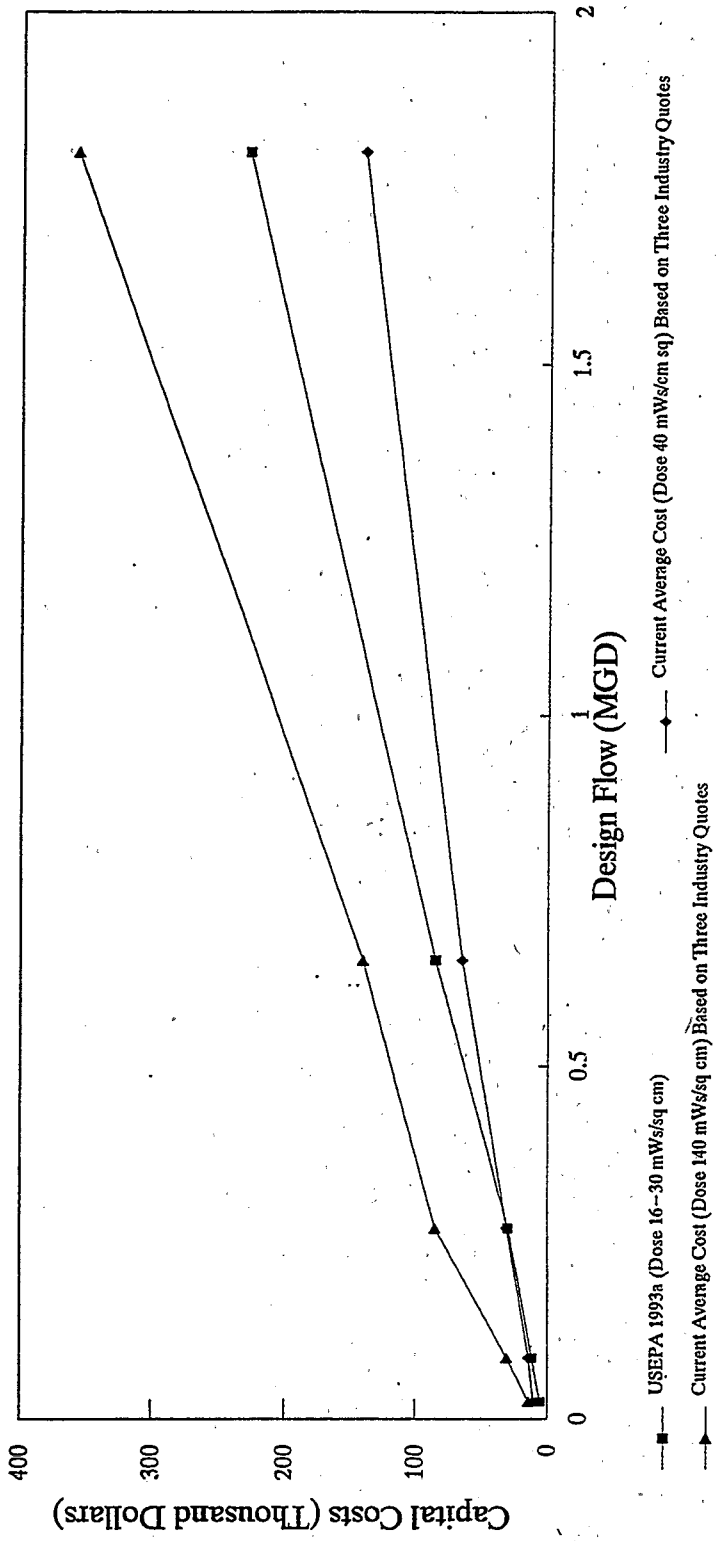


Exhibit 3-17. Comparison of Operation and Maintenance Costs of Ultraviolet Treatment

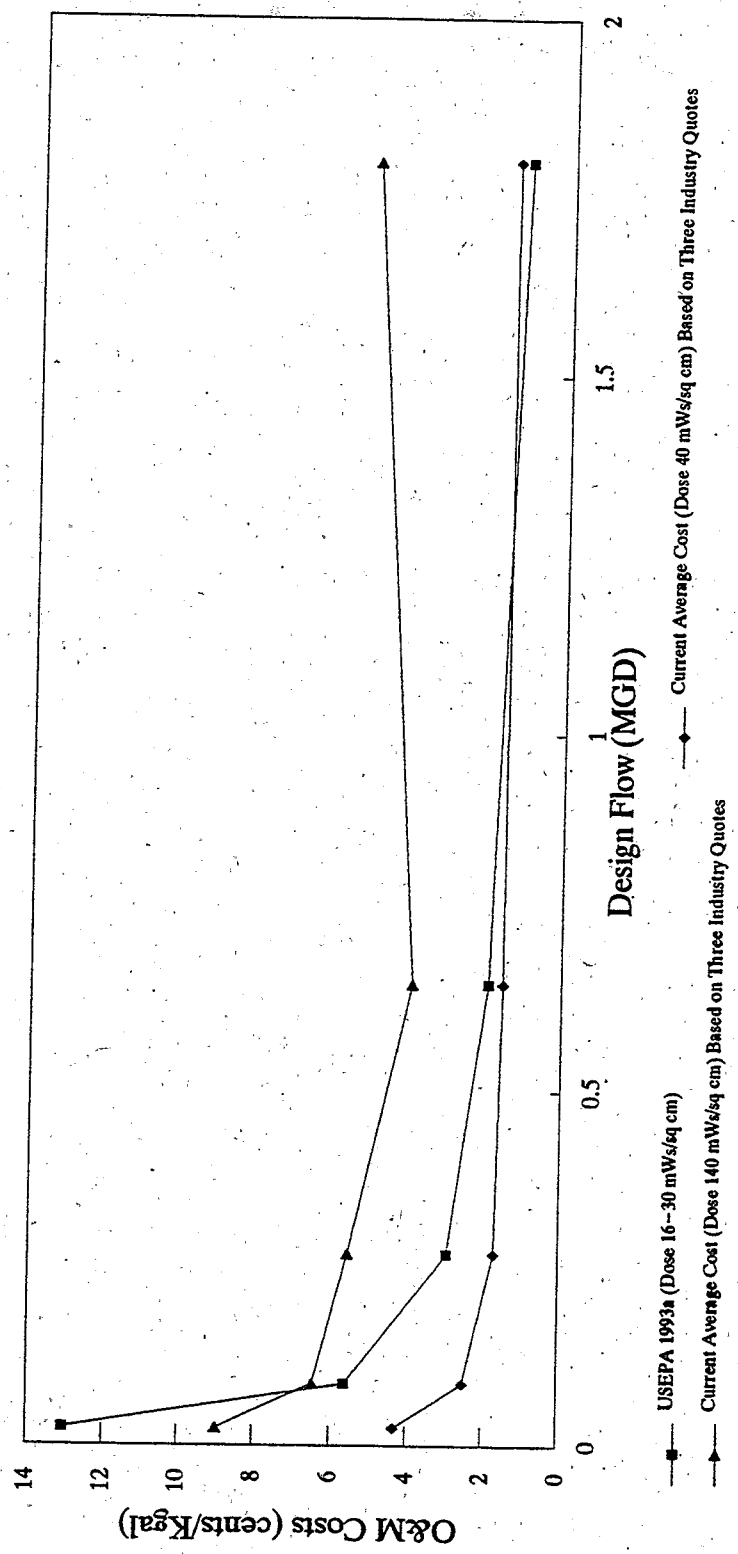
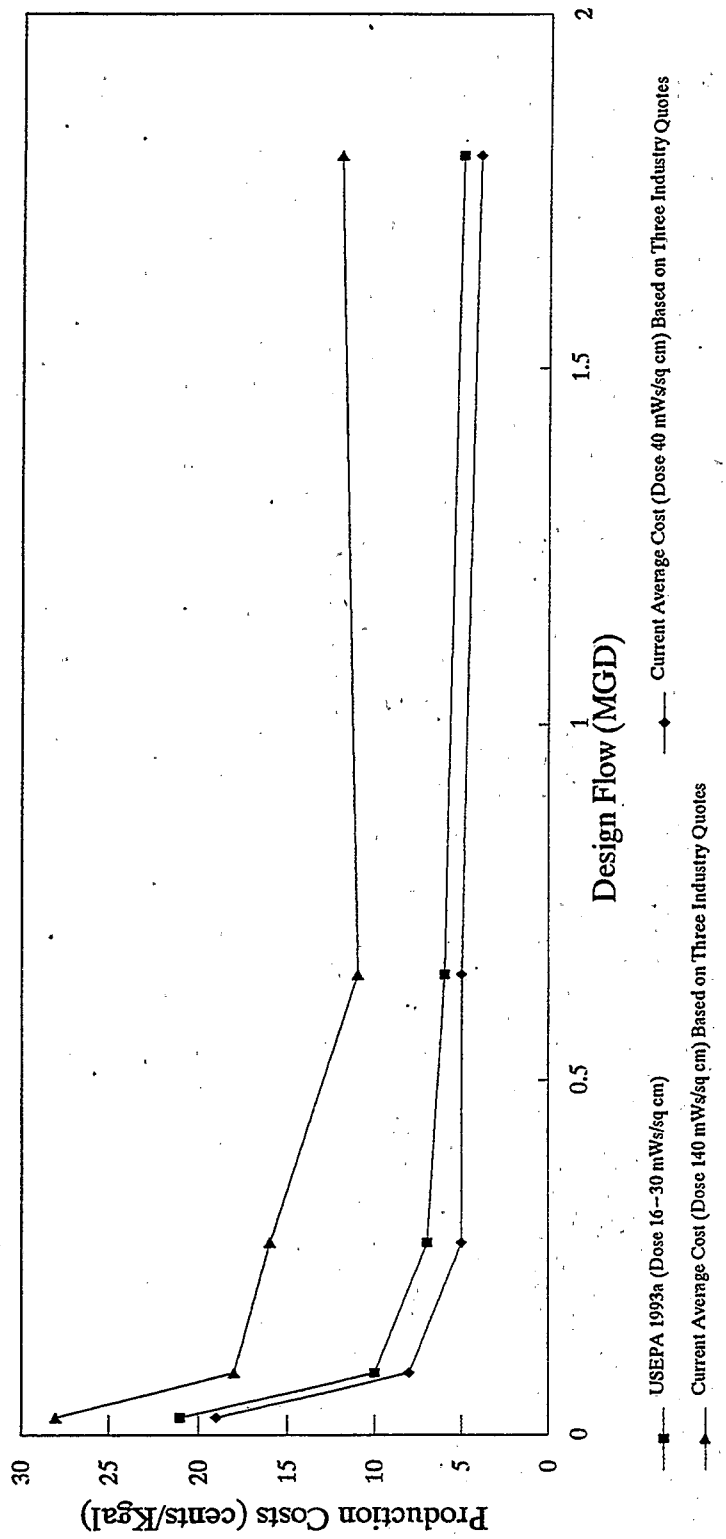


Exhibit 3-18. Comparison of Total Production Costs of Ultraviolet Treatment



3.4 ULTRAVIOLET LIGHT SYSTEM COSTS COMPARED TO CHLORINATION AND OZONATION DISINFECTION TECHNOLOGIES

In this section, the current total cost for ultraviolet treatment is compared to that of chlorination and ozonation. Chlorination and ozonation costs reported here are obtained from USEPA (1993a), calculated in August 1995 dollars.

3.4.1 Ozonation Costs

The following formulas apply to small and large decentralized systems employing primary treatment through ozonation (USEPA, 1993a):

CAPITAL COSTS:

For flows less than or equal to 270 kgpd, the equation used to calculate capital costs for an ozonation system that can deliver an ozone dose of 1 mg/L is:

$$CAP1 = 24.2[DES]^{0.272}$$

WHERE: CAP1 = Total capital cost, 1 mg/L ozone dose (k$)
DES = Total design flow (kgpd)

For flows greater than 270 kgpd, the equation used to calculate capital costs for an ozonation system that can deliver an ozone dose of 1 mg/L is:

$$CAP1 = 28.0[DES]^{0.269}$$

WHERE: CAP1 = Total capital cost, 1 mg/L ozone dose (k$)
DES = Total design flow (kgpd)

These ozonation costs are based on a dose of 1 mg/L and an assumed contact time of 10 minutes. This dose is a "low demand" dose with an assumed residual of 0.1 mg/L. Ozone treatment at this dose provides the lowest cost estimate for an ozone drinking water disinfection system.

O&M COSTS:

For flows less than or equal to 86 kgpd, the equation used to calculate operation and maintenance costs of an ozone system delivering 1 mg/L is:

$$OM1 = 24.8[AVG]^{-0.486} + 209.8[LAB][AVG]^{-1}$$

WHERE: OM1 = O&M costs, 1 mg/L ozone dose, (c/kgal)
AVG = Average daily flow (kgpd)
LAB = Available labor for O&M (hrs/week)

For flows greater than 86 kgpd, the equation used to calculate operation and maintenance costs is:

$$OM1 = 24.8[AVG]^{-0.486} + 398.9[LAB][AVG]^{-1}$$

WHERE: OM1 = O&M costs, 1 mg/L ozone dose, (c/kgal)
AVG = Average daily flow (kgpd)
LAB = Available labor for O&M (hrs/week)

According to USEPA (1993a), labor requirements are assumed to be 7 hours per week. The cost estimates for the installation of such an ozone facility include an off-gas destruction unit, ozone gas detector and alarm, and building with ventilation to house the system (USEPA, 1993a).

Exhibit 3-19 is a tabular representation of the calculated costs of ozone treatment from USEPA (1993a).

Exhibit 3-19. Small System Ozonation Costs (Source: USEPA, 1993a)

USEPA Flow Category	Average Flow (kgpd)	Total Capital (k$)	Total Capital (¢/kgal)	Total O&M (c/kgal)	Total Production Cost (c/kgal)
1	5.6	57.44	77.02	273.99	351
2	24	81.54	30.16	66.48	97
3	86	110.95	13.22	19.92	33
4	230	159.39	7.92	13.90	22
5	700	210.29	3.76	5.02	9

*August 1995 dollars.
**Cost amortized at 10% for 20 years.

3.4.2 Chlorination Costs

Chlorination cost estimates are based on a 5 mg/L dose with an assumed residual concentration of at least 0.5 mg/L and a labor requirement of seven to ten hours per week. This extrapolates (linear extrapolation) to 7, 7.1, 7.4, 8.1, and 10 hours per week for flow categories 1 through 5, respectively. While chlorine treatment dose could range from 1 to 10 mg/L, the 5 mg/L dose also reflects a "medium demand" dose and provides a reasonable cost estimate for a chlorination process (sodium hypochlorite feed system). The cost estimates based on the USEPA (1993a) document for the installation of a chlorination facility include a metering pump, a mixer and storage tank, and various pipes and valves.

CAPITAL COSTS

For flows less than or equal to 270 kgpd, the capital costs are assumed to be:

CAP = 4.7

For flows greater than 270 kgpd, the capital costs are assumed to be:

CAP = 6.9

WHERE: CAP = Total capital cost (k$)

It is important to note that the capital costs do not vary with flow due to the wide range of pumping rates achievable by similarly priced pumps (USEPA, 1993a)

O&M COSTS:

For flows less than or equal to 86 kgpd, the governing equation for operation and maintenance costs is:

$OM = 66.0[AVG]^{-1} + 0.67[Cl] + 209.4[LAB][AVG]^{-1}$

WHERE: OM = O&M costs (c/kgal)
AVG = Average daily flow (kgpd)
Cl = Chlorine dosage (mg/L)
LAB = Available labor for O&M (hrs/week)

For flows greater than 86 kgpd, the governing equation for operation and maintenance costs is:

$OM = 66.0[AVG]^{-1} + 0.67[Cl] + 398.9[LAB][AVG]^{-1}$

WHERE: OM = O&M costs (c/kgal)
AVG = Average daily flow (kgpd)
Cl = Chlorine dosage (mg/L)
LAB = Available labor for O&M (hrs/week)

Exhibit 3-20 presents the calculated costs for chlorination based on the equations provided in the USEPA (1993a) document.

Exhibit 3-21 is a tabular presentation of current ultraviolet light system costs developed for ultraviolet light doses of 40 mWs/cm^2 and 140 mWs/cm^2 compared to ozonation and chlorination. **Exhibit 3-22** is a graphical presentation of current ultraviolet light costs for an ultraviolet dose of 40 mWs/cm^2 developed under this work assignment compared to costs of ozonation and chlorination. **Exhibit 3-23** is a graphical presentation of current ultraviolet light system costs for an ultraviolet light dose of 140 mWs/cm^2 developed under this task compared to costs of ozonation and chlorination.

Exhibit 3-20. Small System Chlorination Costs (Source: USEPA, 1993a)

USEPA Flow Category	Average Flow (kgpd)	Total Capital (k$)	Total Capital (c/kgal)	Labor Requirements (hours/week)	Total O&M (c/kgal)	Total Production Cost (c/kgal)
1	5.6	4.70	6.30	7	276.89	283
2	24	4.70	1.74	7.1	68.05	70
3	86	4.70	0.56	7.4	22.14	23
4	230	6.90	0.34	8.1	17.68	18
5	700	6.90	0.12	10	9.14	9

*Costs amortized at 10% interest for 20 years.
*August 1995 dollars.

Exhibit 3-21. Ultraviolet Light System Costs for USEPA Flow Categories 1-5 Compared to Chlorination and Ozonation in Cents per Thousand Gallons*

USEPA Flow Category	Design Flow MGD	Ultraviolet Dose 40 mWs/cm^2	Chlorination Dose 5 mg/L	Ozonation Dose 1 mg/L	Ultraviolet Dose 140 mWs/cm^2
1	0.024	19	283	351	28
2	0.087	8	70	97	18
3	0.27	5	23	33	16
4	0.65	5	18	22	11
5	1.8	4	9	9	12

*August 1995 dollars.

Based on the above, it is clear that ultraviolet light technology is an economically viable and feasible technology, particularly for small water systems that lack highly paid qualified operators. Moreover, it is anticipated that, as more ultraviolet light technology is developed, the capital and operation and maintenance costs associated with ultraviolet treatment will decrease, making this technology more competitive.

Exhibit 3-22. Ultraviolet [40 mWs/cm^2], Chlorination, and Ozonation Total Costs: USEPA Flow Categories 1-5

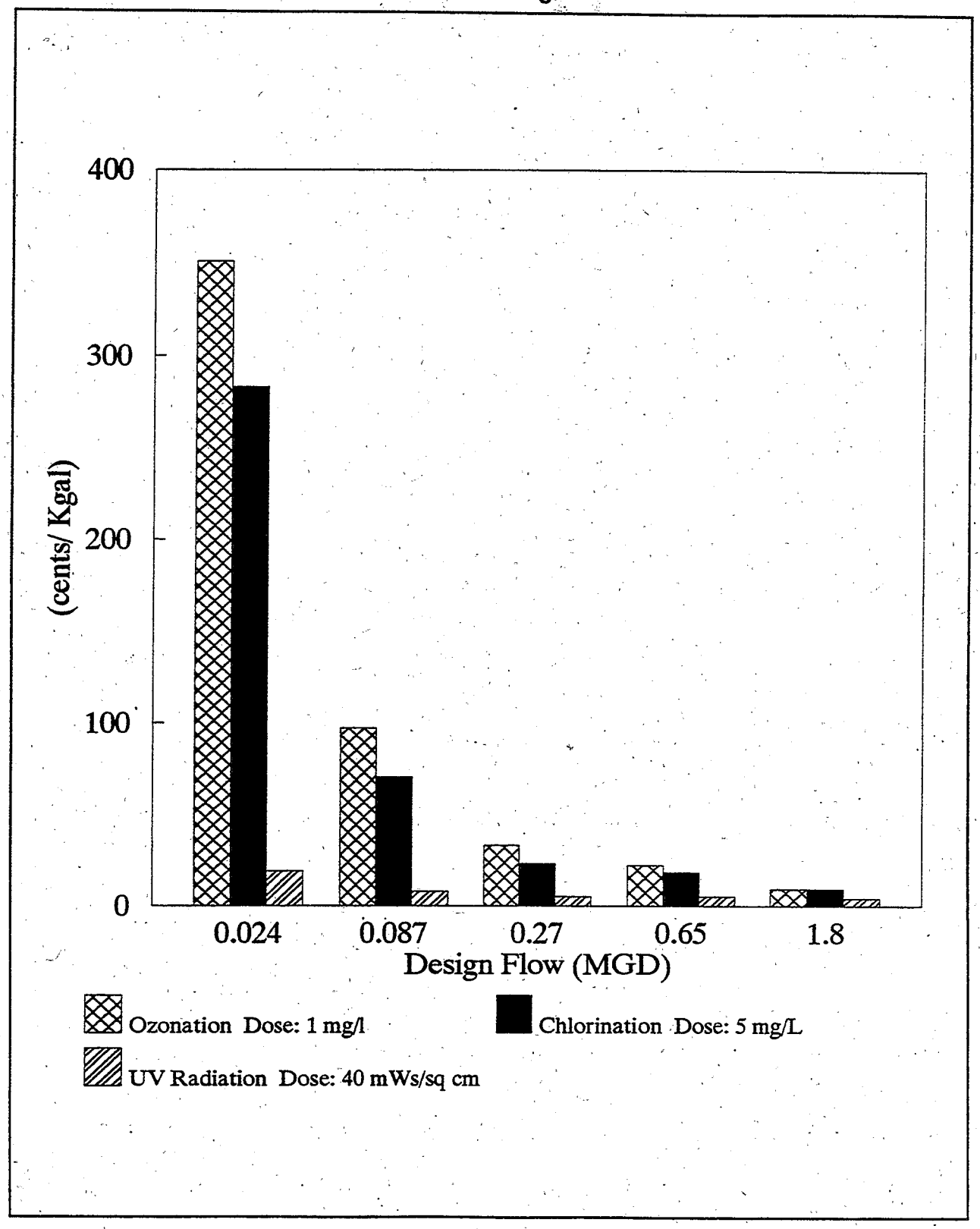
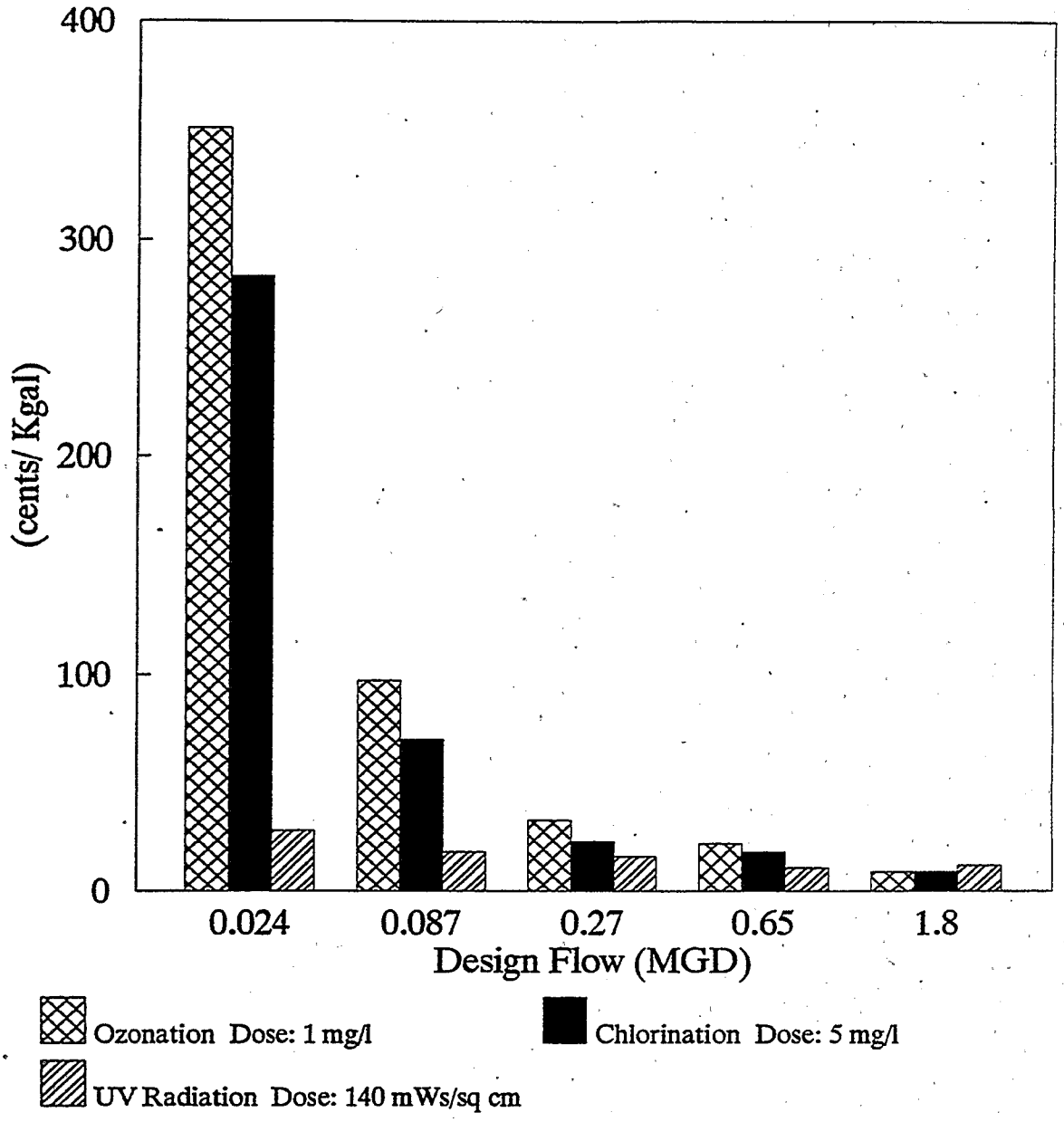


Exhibit 3-23. Ultraviolet [140 mWs/cm^2], Chlorination, and Ozonation Total Costs: USEPA Flow Categories 1-5



3.5 COST OF ULTRAVIOLET DISINFECTION WITH SECONDARY TREATMENT THROUGH CHLORINATION

Because a residual may be desired in the distribution system, ultraviolet disinfection may be supplemented by chlorination as a secondary treatment process. This typically involves the use of sodium hypochlorite or calcium hypochlorite. A chlorine concentration of 1 mg/L can be assumed. Such a concentration is sufficient to control microbial growth in the distribution system.

3.5.1 Cost of Secondary Treatment

For our purposes, sodium hypochlorite will be used, which, according to USEPA (1993a), costs approximately $190 per ton of chemical. The amount of chemical to be used per day can be calculated by dividing the amount of chlorine required per day by the percentage of available chlorine in the chemical to be purchased. One can assume that sodium hypochlorite (NaOCl) or calcium hypochlorite [$Ca(ClO)_2$] is at least 65 percent available chlorine (practical grade; theoretical available chlorine in NaOCl is 95.4% and in $Ca(ClO)_2$ is 99.2%). The use of the dose-dependent equation for chlorine disinfection costs presented in USEPA (1993a) as shown in section 3.4.2 is appropriate here, assuming a chlorine dose of 1 mg/L. This dosage is high enough to leave a residual and ensure thorough disinfection while low enough to minimize costs.

Although it is not necessary to determine the amount of chlorine required to satisfy a 1 mg/L dosage requirement, doing so may shed some light on the size of storage tank needed and the amount of labor required to mix the chemicals and fill the storage tank. The following equations may be used to determine chlorine and stock solution requirements:

- Pounds per day chlorine required =

$$\text{Average Flow}\left(\frac{\text{gal}}{\text{day}}\right) \times \text{dose}\left(\frac{\text{mg}}{\text{l}}\right) \times \frac{1\ \text{kg}}{1000000\ \text{mg}} \times \frac{\text{lb}}{0.45\ \text{kg}} \times \frac{3.78\ \text{l}}{\text{gal}}$$

- Assume 65% available chlorine in sodium hypochlorite and a 5% stock solution
- Gallons per day of stock solution requires =

$$\frac{(\text{lbs/day chlorine})}{(5\%\ \text{Hypochlorite Strength}) \times 8.3\ \frac{\text{lbs}}{\text{gal}}}$$

The resulting stock solution requirements are presented in **Exhibit 3-24.**

Exhibit 3-24. Amount of Chlorine Stock Solution Required Per Day (1 mg/L Dose)

USEPA Flow Category	Average Daily Flow (kgpd)	Gallons/Day Stock Solution Required
1	5.6	0.12
2	2.4	0.48
3	86.0	1.71
4	230.0	4.60
5	700.0	14.00

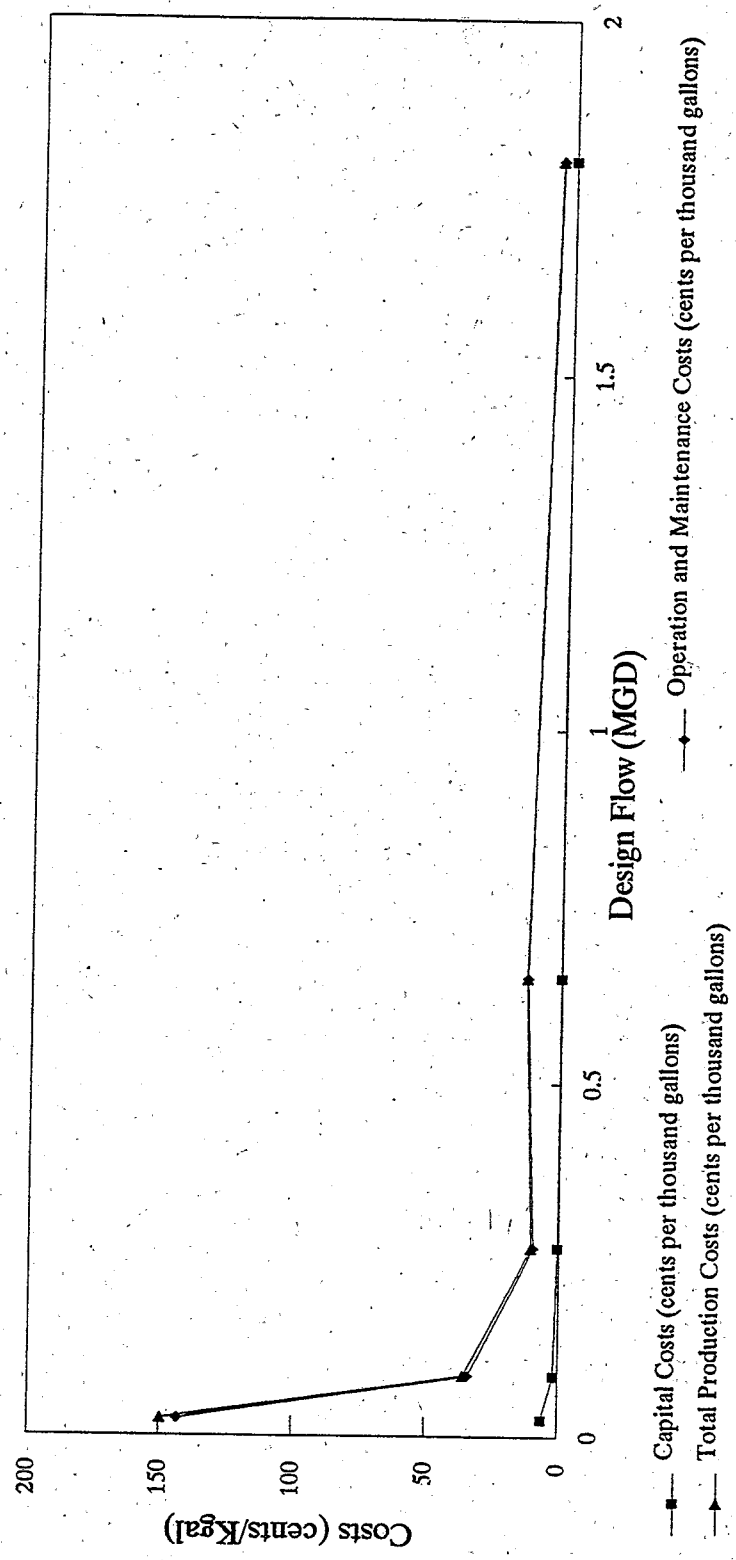
Because these are relatively small amounts of required stock solution, a standard 150-gallon tank would be too large. If a 150-gallon stock is prepared for use, the chlorine would evaporate out of the solution before the solution is completely used. A smaller storage tank that would necessitate refilling with stock solution would be more suitable. To prepare fresh stocks, a 2-hour labor requirements is assumed every 4 days for flow categories one, two, and three (35 hrs/week). A 2-hour labor requirement is assumed for flow categories four and five with chlorine stock solution prepared every other day (7 hrs/week).

The costs associated with secondary treatment are presented in tabular form in **Exhibit 3-25** and graphically in **Exhibit 3-26**. Some non-community water systems may find the 1 mg/L dosage of chlorine suitable for complete water treatment, in which case these costs could be adapted to estimate primary disinfection through chlorination. In a 20-month pilot study, 0.05 mg/L of free chlorine after ultraviolet treatment was found to be sufficient to suppress biofilm formation (Lund and Ormerod, 1995). In small systems, a residual free chlorine levels of 0.2 mg/L are considered to be sufficient to protect water supplies (Huck, 1989). It is of interest to note that the overall cost of treatment with 1 mg/L chlorine differs from treatment with 5 mg/L chlorine by only a few cents per thousand gallons.

Exhibit 3-25. Total Production Costs of Secondary Treatment Through 1 mg/L Chlorine

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	Capital Cost (k$)	Amortized Capital Cost (c/kgal)	Labor Requirement (hrs/week)	O&M Costs (c/kgal)	Total Production Costs (c/kgal)
1	5.6	24	4.70	6.30	3.5	143.33	150
2	24	87	4.70	1.74	3.5	33.96	36
3	86	270	4.70	0.56	3.5	9.96	11
4	230	650	6.90	0.34	7.0	13.10	13
5	700	1800	6.90	0.12	7.0	4.75	5

Exhibit 3-26. Costs of Disinfection Through Chlorination (1 mg/L Dose)



3.5.2 Total Production Costs for Ultraviolet Disinfection with Chlorination

Total production costs of primary disinfection through ultraviolet treatment and secondary disinfection through chlorination are presented in **Exhibit 3-27**. These costs were found by simply adding the costs of ultraviolet treatment at dosages of 40 and 140 mWs/cm^2 to the costs of chlorination at a dosage of 1 mg/L. Total production costs for ultraviolet treatment and secondary disinfection through chlorination are presented graphically in **Exhibit 3-28**.

Exhibit 3-27. Total Production Costs of Ultraviolet Treatment with Secondary Disinfection

USEPA Flow Category	Average Flow (kgpd)	Design Flow (kgpd)	Total Production Costs (c/kgal)			
			40 mWs/cm^2 UV Treatment	140 mWs/cm^2 UV Treatment	40 mWs/cm^2 UV Treatment with 1 mg/L Chorine	140 mWs/cm^2 UV Treatment with 1 mg/L Chorine
1	5.5	24	19	28	169	178
2	24	87	8	18	44	54
3	86	270	5	16	16	27
4	230	650	5	11	18	24
5	700	1800	4	12	9	17

3.5.3 Comparison to Other Treatment Techniques

Exhibits 3-29 and **3-30** are graphical presentations of the total costs of ozonation, chlorination, and ultraviolet disinfection with 1 mg/L chlorine secondary treatment, at ultraviolet doses of 40 mWs/cm^2 and 140 mWs/cm^2, respectively. **Exhibit 3-31** is a tabular presentation of the costs of ultraviolet light system with chlorination compared to ozonation and chlorination.

3.6 ULTRAVIOLET LIGHT SYSTEM COST ESTIMATES FROM OTHER SOURCES

The Canadian pilot plant study cited earlier (Zukovs et al., 1986) compared the costs of ultraviolet light application in combined sewer overflows (CSOs) to those of chlorination/dechlorination systems required to achieve similar bacterial kill. The estimated capital costs for ultraviolet light systems used on low-quality CSOs were consistently higher than those for chlorination/dechlorination systems for flow rates between 5,000 and 500,000 m^3/d (1.3 MGD - 132 MGD). However, the operation and maintenance costs for both systems were within the same order of magnitude (**Exhibit 3-32**).

Exhibit 3-28. Total Production Costs for Ultraviolet Disinfection with Chlorination

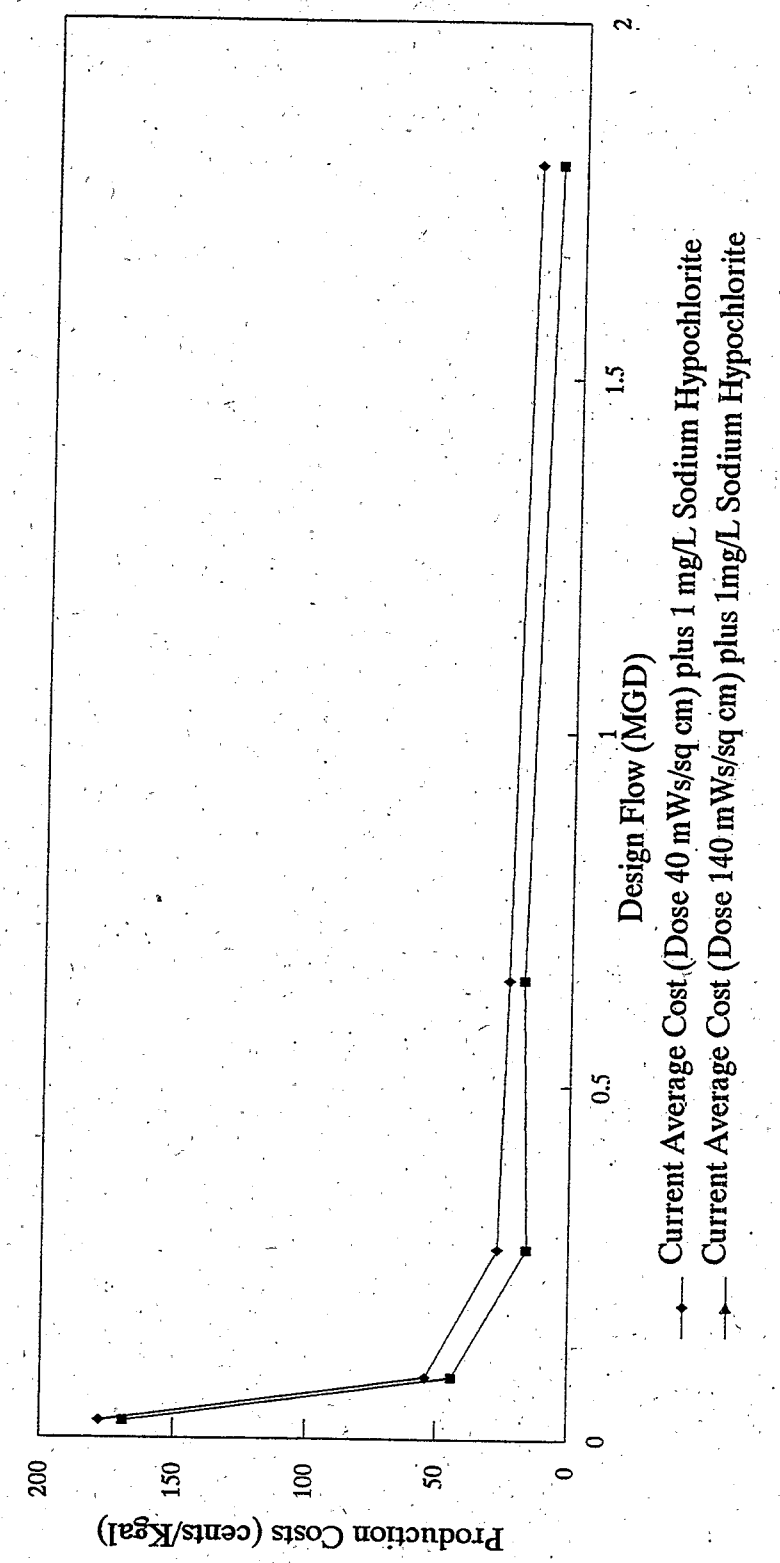


Exhibit 3-29. Total Costs: Ozonation, Chlorination, and Ultraviolet Radiation (40 mWs/cm^2) with Secondary Treatment

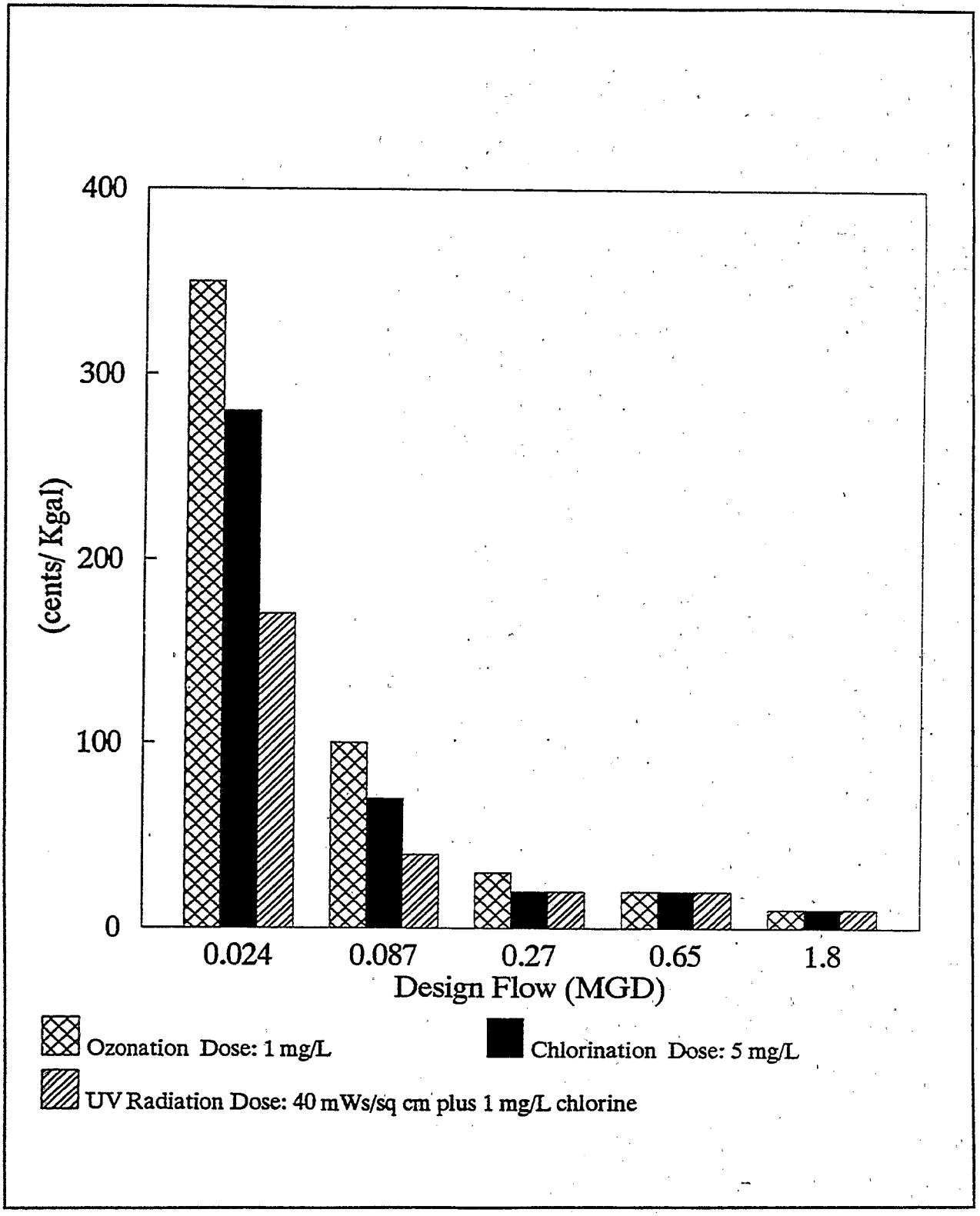


Exhibit 3-30. Total Costs: Ozonation, Chlorination, and Ultraviolet Radiation (140 mWs/cm^2) with Secondary Treatment

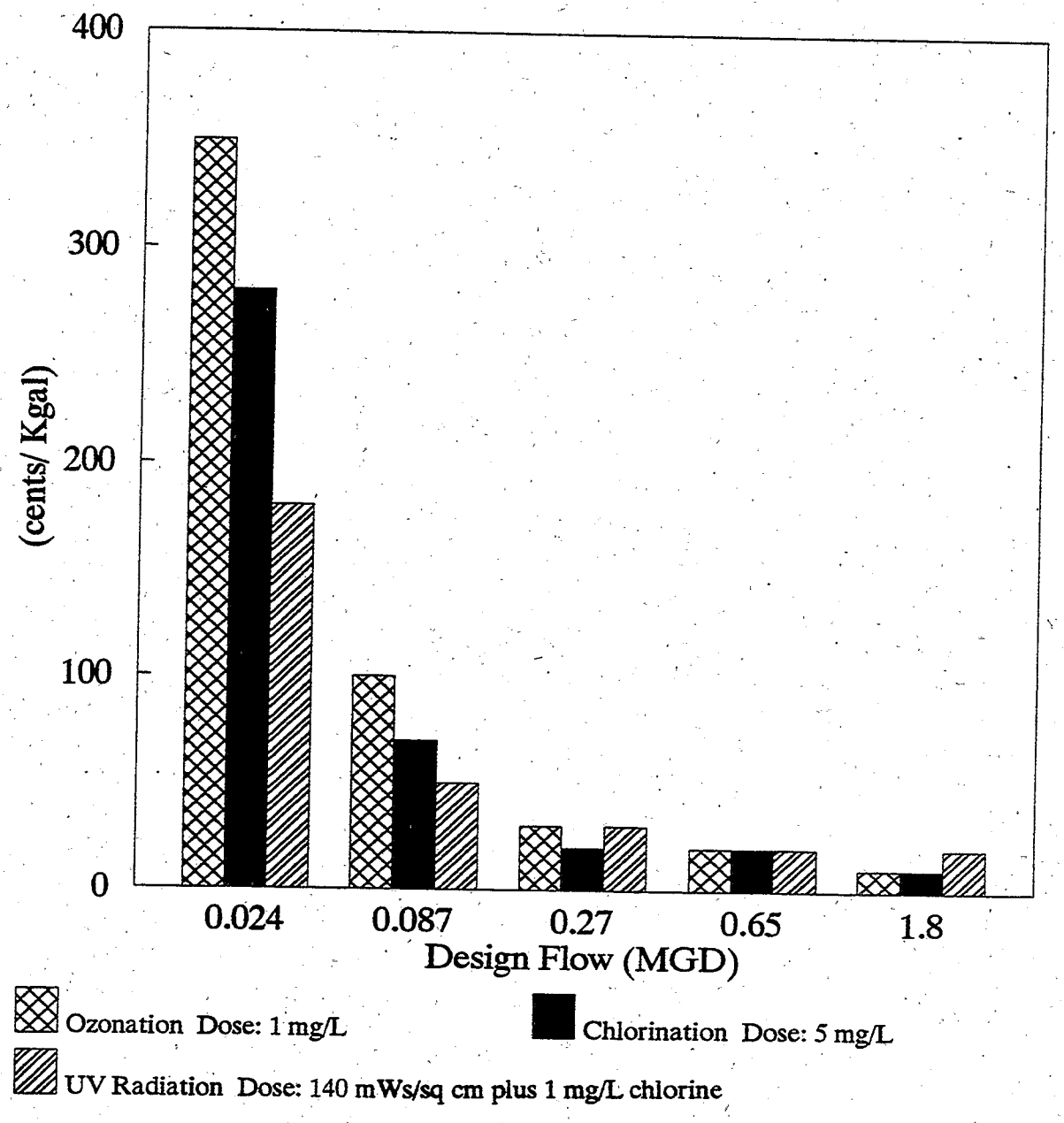


Exhibit 3-31. Total Production Costs of Ultraviolet Treatment with Secondary Treatment Compared to Chlorination and Ozonation

USEPA Flow Category	Design Flow (MGD)	Average Flow (kgpd)	Total Production Costs (Cents per Thousand Gallons)[1]			
			Chlorination Dose 5 mg/L	Ultraviolet Dose 40 mWs/cm² with 1 mg/L Chlorination	Ozonation Dose 1 mg/L	Ultraviolet Dose 140 mWs/cm² with 1 mg/L Chlorination
1	0.024	5.6	280	170	350	180
2	0.087	24	70	40	100	50
3	0.27	86	20	20	30	30
4	0.65	230	20	20	20	20
5	1.8	700	10	10	10	20

[1]Figures are rounded to nearest ten.

Exhibit 3-32. Estimated Capital and Operating Costs for Ultraviolet Irradiation and Chlorination/Dechlorination (Zukovs et al., 1986)

Flowrate MGD	UV Irradiation		Chlorination/Dechlorination	
	Capital Cost ($1985 Canadian)	O&M Cost ($1985 Canadian/Year)	Capital Cost ($1985 Canadian)	O&M Cost ($1985 Canadian/Year)
1.3	245,200	18,110	50,560	16,790
13.2	2,208,180	78,925	84,120	60,700
132	21,801,000	672,700	380,305	496,000

In an actual case study of costs associated with ultraviolet disinfection in the Zevenbergen drinking water treatment plant (the Netherlands), the annual costs associated with a design flow of 450 m^3/hr (1,981 gpm) with an actual production of 2.5×10^6 m^3/yr (1.8 MGD) using two different ultraviolet light disinfection devices were \$0.0054/m^3 and \$0.0057/m^3 (2.04 c/kgal and 2.16 c/kgal) (see **Exhibit 3-33**). The annualized cost of ultraviolet light disinfection reported in the text of the article by Kruithof et al. (1992) at \$1/2,000 m^3 (0.1893 c/kgal) is one order of magnitude less than the figures shown in Exhibit 3-33. Evidently, this low cost figure of 0.1893 c/kgal is the result of a mathematical error on the part of the authors.

As can be seen from Exhibit 3-33, the high cost estimates of ultraviolet light water disinfection systems in the United States (see Exhibits 3-4, 3-9, and 3-10) compared to the costs of ultraviolet disinfection systems in the Netherlands as reported in Kruithof et al. (1992) has to do primarily with capital costs (\$73,000 to \$80,000 per system in the Netherlands compared to \$91,200 to \$171,100 per system for the same flow category as a 40 mWs/cm^2 ultraviolet dose in the United States) and energy costs (5.2 to 5.5

Exhibit 3-33. Ultraviolet Light Treatment System

Model Berson 3X 2 HGS-200		Model Katadyn 2X GR-16	
Depreciation $73,000; annuity 15 years, 7%	$8,000	Depreciation $80,000; annuity 15 years, 7%	$8,700
Energy Consumption 61,325 kWhr for UV radiation 7,700 kWhr for headloss	$3,200 $420	Energy Consumption 10,946 kWhr for UV radiation 20,989 kWhr for headloss	$600 $1,1500
Replacements 6 UV-burners 2 Quartz tubes	$1,350 $270	Replacements 20 UV-burners 4 Quartz tubes	$2,900 $1,000
Total Costs	**$13,240**	**Total Costs**	**$14,350**
Costs: per m^3	$0.0054	Costs: per m^3	$0.0057
per kgal	$0.0204	per kgal	$0.0216

cents per kWhr in the Netherlands compared to 8.6 cents per kWhr in the United States). The average annualized cost of ultraviolet disinfection systems in the Netherlands is about 2 c/Kgal for a flow of 1.8 MGD. The average annualized cost estimated for comparable systems in the United States is 4.4 c/Kgal.

3.7 SMALL NON-COMMUNITY WATER SYSTEMS FLOW REQUIREMENTS AND COST IMPLICATIONS

Ultraviolet disinfection cost estimates for USEPA flow category 1 are estimated at $1,700 per year for an ultraviolet light system delivering 40 mWs/cm^2, and at $2,500 per year for an ultraviolet light system delivering 140 mWs/cm^2. As stated earlier, USEPA flow category 1 has a design flow of 24,000 gallons per day and an average flow production of 5,600 gallons per day. Such design and average flow assumptions are believed to be sufficient to satisfy the drinking water requirements of a population of 25 to 100 persons served by a Community Water Supply (CWS) system. These flows and population assumptions imply a minimum average water production of 56 gallons per person per day (based on a population of 100).

While such assumptions are useful to USEPA in its evaluation of costs projected for community water supply systems, it is unlikely that they will apply to many Non-Community Water (NCW) systems according to some sources. The drinking water requirements for water use in many NCW systems are expected to be much lower than those required in small CWS systems. The information obtained from USEPA's Safe Drinking Water Information System (SDWIS) shows that approximately 91,000 ground water NCW systems service a population of about 12 million. **Exhibit 3-34** presents SDWIS data on ground water NCW systems facility type for two population ranges.

Exhibit 3-34. Ground Water NCW Systems Serving Two Population Ranges

Facility (SDWIS Description)	Number of Systems Serving a Population of 25 to 50 Persons	Number of Systems Serving a Population Greater Than 3,300 Persons
Day Care Center	280	-
Dispenser	-	-
Homeowners Association	-	-
Hotel/Motel	1864	2
Highway Rest Area	293	37
Industrial/Agricultural	2059	19
Interstate Carrier	11	2
Institution	437	3
Medical Facility	122	4
Mobile Home Park	346	-
Mobile Home Park, Principal Residence	-	-
Municipality	-	-
Other Area	4,840	18
Other Non-Transient Area	946	8
Other Residential Area	314	-
Other Transient Area	10,450	22
Recreation Area	7,609	68
Residential Area	716	6
Retail Employees	-	-
Restaurant	7,649	10
School	921	14
Sanitary Improvement District	-	-
Summer Camp	895	3
Secondary Residences	-	-
Service Station	1,376	1
Subdivision	-	-
Water Bottler	-	-
Wholesaler (Sells Water)	42	-
TOTAL	**41,170**	**217**

* Based on 9/25/96 SDWIS data for ground water NCW systems with treatment equipment

Exhibit 3-35 provides a list of average water use per person at typical NCW facilities. If the USEPA flow rate for category 1 (i.e., 5,600 gpd) were used in this context (for small NCW systems), then NCW systems servicing carry-out restaurants or airports, could conceivably be providing enough water for 1,865 persons and 1,600 persons, respectively, which is far greater than the number of people served by that flow category (25 - 100).

Exhibit 3-35. Typical Rates of Water Use in Non-Community Water Systems*

Facility	Average Water Use gal/person/day
Airport	3.5
Amusement Parks:	
With water entertainment, food facilities, flush toilets, and shower facilities	40
Without water entertainment, but with food facilities and flush toilets	10
Car Service Station	10
Camps:	
Construction	50
Day with no meal served	15
Luxury	100
Resorts	50
Tourist with central bath and toilet facilities	35
Cottages	50
Country Club	40
Day Care Center	4
Department Store	10
Factory	25
Highway Rest Area	10
Highway Rest Area with Minimarket	5
Hospital	100
Lodging House/Tourist House	40
Medical Facility	10
Motel	40
Office	15
Parks:	
Overnight with Flush Toilets	25
Trailers	40
Picnic Areas	10
Restaurant:	
Conventional	9
Carry-Out	3
Bar and Cocktail Lounge	15
Schools:	
With cafeteria, gymnasium, and showers	25
With cafeteria, but no gymnasium or showers	20
Without cafeteria, gymnasium, or showers	15
Side Road Store	5
Shopping Center	2
Theater	4
Worship Places:	
With day care facility, and no permanent residents	2
With abolition facilities, day care facility, and no permanent residents	5
With less than 25 permanent residents and day care facility	12
With less than 25 permanent residents and no day care facility	10

*Based in part on best professional judgment, Metcalf and Eddy, 1991 and Corbitt, 1990.

Water use rates shown in Exhibit 3-35 were compiled in part from Metcalf and Eddy, 1991, and Corbitt, 1990, and based in part on best professional judgment. Exhibit 3-35 suggests a need for developing new flow methodologies for USEPA treatment cost analyses addressing various types of NCW systems.

3.8 CONCLUSIONS

Based on the cost estimates presented in this chapter, ultraviolet light technology is an economically viable and feasible technology, particularly for small water systems. The costs of using ultraviolet light alone (at a dose of 140 mWs/cm^2 or less) to disinfect ground water are far lower than using ozone and more economical than chlorination for flow categories 1 through 4 (design flow 0.024 to 0.65 MGD). The costs of using ultraviolet light alone at a dose of 40 mWs/cm^2 are far lower than using ozone or chlorine (hypochlorites) for primary disinfection for flow categories 1 through 5 (design flow 0.024 to 1.8 MGD).

The costs of chlorination, used in this chapter for comparison purposes, do not include the additional costs incurred to cover the new requirements under Article 80 of the Uniform Fire Code (UFC) of 1991. These new requirements include additional equipment to handle accidental release of chlorine gas or chlorine dioxide and its onsite production components (where used) and emergency power sufficient to operate chemical scrubbing equipment. The costs associated with these requirements can represent as much as 25 percent of the total capital costs for small systems using chlorine gas or chlorine dioxide for disinfection (WERF, 1995).

The costs of using ultraviolet light (at a dose of 140 mWs/cm^2 or less) for primary disinfection in combination with chlorination for secondary disinfection to disinfect ground water are lower than the costs of ozonation and chlorination for flow categories 1 and 2. Ultraviolet disinfection costs, at a dose of 140 mWs/cm^2, plus the costs of chlorination for residual disinfection, are comparable to ozonation costs for USEPA flow categories 3 and 4 and higher than the costs of ozonation and chlorination alone for USEPA flow category 5. Ultraviolet light disinfection costs at 40 mWs/cm^2 plus the costs of chlorination for residual disinfection are comparable to the costs of chlorination for USEPA flow categories 3 through 5 and are comparable to the costs of ozonation for USEPA flow categories 4 and 5 and lower than the costs of ozonation for USEPA flow category 3. Also, it is concluded that rationale are available to justify use of an alternate flow regime and, therefore, alternate cost estimates that would better fit in the analysis of non-community type water systems.

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CHAPTER 4. OPERATIONAL CASE STUDIES

4.1 INTRODUCTION

In this chapter, ultraviolet light operational case studies are presented. The purpose of this chapter is to provide brief summaries of available information from public water systems (PWS) that have installed ultraviolet (UV) treatment for ground water disinfection. The availability of information from operators of PWS systems or the lack of it provides insight into the practicality of using ultraviolet treatment. Operators' information provides an opportunity to assess actual field experiences. Such assessment helps in determining the degree and level of operation and maintenance this technology requires and provides a realistic estimate of the expenses incurred by various communities to obtain and maintain an ultraviolet system.

In general, case studies indicate actual performance evaluation of the technology investigated, and indicate realistic operation and maintenance problems for specific site conditions. Ultraviolet light technology application case studies also serve as an indicator for the acceptance or rejection of technologies that are not well established (or accepted by the scientific community or by the USEPA as a reliable technology) to disinfect drinking water.

The case studies also may serve as indicators of the price small and often rural and isolated communities are willing to pay in the absence of State mandates for ground water disinfection. Another aspect of these case studies is reported water use and production capacities in Transient Non-Community (TNC) and Non-Transient Non-Community (NTNC) water systems. The information reported by the operators of very small TNC and NTNC systems shows that average water production appears to be much less than the water consumption generally assumed in calculating treatment costs for Community Water Systems (CWS) with similar population sizes. In addition to the ultraviolet light application in drinking water case studies, this chapter also presents information collected from two ultraviolet light equipment service contractors and a general discussion of ultraviolet units costs as demonstrated from the case studies and the design flows of the investigated systems. Finally, this chapter presents suggested criteria for the use of ultraviolet light units based on the interviews conducted to develop the case studies.

The case studies presented from the State of New Jersey are for TNC and NTNC ground water. The case study presented from the State of Oregon is a ground water CWS case study. A surface water case study from the State of Montana and a brief case study from the State of Maryland where ultraviolet light is used in a wastewater reclamation facility are presented. Moreover, one case history from the Netherlands is presented.

To obtain information about drinking water systems that have installed ultraviolet light technology for disinfection, the USEPA contacted drinking water program supervisors in four states (New Jersey, Montana, Oregon, and California). The State of New Jersey provided the name, address, and contact person telephone number for twenty drinking water facilities that use ultraviolet light for primary disinfection (Monaco, 1996). The State of Oregon provided information on the single public water system that uses ultraviolet light for primary disinfection and chlorine as a secondary disinfectant. The State of California informed the USEPA that they are not aware of any PWS systems that have installed an ultraviolet light unit to disinfect drinking water. The State of Montana provided the telephone number of the contact person in a PWS that uses ultraviolet light for primary disinfection.

Apparently there are many private non-community water systems that use ultraviolet light for disinfection in the State of Oregon[1] and in the State of New Jersey[2]. These private water systems include private homes and small shops. Interviews, conducted with two water treatment units service contractors, presented in this report, show the extent to which very small communities, families and individuals are willing to go to have safe disinfected drinking water available on demand.

Most of the information presented in this chapter was collected through telephone interviews with systems' managers or operators. The information provided here on the CWS that uses ultraviolet light for disinfection in the State of Oregon was collected by the State. The information collected via telephone interviews with system operators or through field visits by State representatives were based on a questionnaire that covers basic information on operation and maintenance, system costs and water quality parameters and compliance. The questionnaire is presented in Appendix C.

[1]Personal communication with Mr. Gary Burnett and Ms. Kari Salis of the Oregon Drinking Water Program (5/20/96).

[2]Personal communication with Mr. Pete Cicalese an ultraviolet light equipment service contractor (5/27/96).

Newly proposed ultraviolet light use regulations developed by the State of New Jersey are included in Appendix D. Also, Appendix D includes drinking water regulations from the State of Utah, and the U.S. Department of Health, Education, and Welfare (DHEW) [now the Department of Health and Human Services (HHS)] 1966 Policy Statement on the use of ultraviolet light for drinking water disinfection. While the proposed regulations for the use of ultraviolet light in the State of New Jersey require the same minimum dose (16 mWs/cm^2) mandated under current State regulations, the new regulations specify some construction and light monitoring requirements (New Jersey, 1995). The ultraviolet light disinfection application regulations in the State of Utah appear to be modeled on the DHEW regulations.

4.2 CASE STUDIES FROM THE STATE OF NEW JERSEY

The case studies presented from the State of New Jersey cover mainly TNC and NTNC systems and reflect satisfaction with ultraviolet use for disinfection. The systems in these case studies draw their water from ground water sources. All ultraviolet light units were reported to operate 24 hours per day and the majority had one unit in operation without a backup unit onsite. These case studies include a TNC system that has been in operation for more than 10 years. Another case study presents a TNC system that switched from chemical disinfection to ultraviolet disinfection.

Examining the information collected from the case studies conducted in the State of New Jersey revealed that *ultraviolet units receive little attention and require very little supervision.* On the other hand operators of the PWS do not know much about the technology or the units that were purchased and installed. Basic water quality parameter information is typically not kept onsite and certain parameters that could affect the disinfection efficiency of an ultraviolet unit such as iron or turbidity had never been tested. Very few operators know the minimum ultraviolet dose their unit could provide. Not a single PWS operator or contact person complained about operation and maintenance costs. All contacted persons praised the minimum service time ultraviolet units require and how practical it is to use such a technology. All the persons who had experience with chemical disinfection equipment complained about equipment monitoring and service time and costs in contrast to ultraviolet treatment operational requirements. In addition, it appears that in most of these systems installation costs were very minimal, as were engineering requirements and site modification.

4.2.1 PWS in Phillipsburg, New Jersey

The public water supply system in Phillipsburg, New Jersey, serving about 30 persons, installed its ultraviolet light disinfection unit in October 1995. The age of the majority of the population served is

above 47 years (range 47 years to 98 years). The disinfection capacity of the unit, at 30 mWs/cm^2 is 20 gpm (29,000 gpd). The system has no backup unit and no storage capacity. The reason given for favoring ultraviolet disinfection over chlorination is the dislike of chlorine taste and that in ultraviolet treatment, chlorine and chemicals do not have to be added to drinking water. The unit is equipped with a 5 micron filter, a light emitting diode, a sound alarm and a manual wiper. The ultraviolet light unit is a closed ultraviolet light unit, made in Vermont and came with a 1-year warranty on parts. According the manager of the system the ground water source is of "good quality". There are no turbidity measurements, but according to the contact person, the ground water is clear and the turbidity may be assumed to be "very low". There have been no coliform outbreaks from the time the system was installed. Once a week, in a few seconds, the system manager would manually clean the bulbs by pulling and pushing the arm of the manual wiper a few times. No detergents or chemical agents are used in the weekly cleaning. During the annual service, the ultraviolet light bulb is changed (i.e., once every 9,000 hours) and the unit is thoroughly cleaned. The capital cost of the system was $2,100 including engineering, installation and instruction. The operation and maintenance cost is estimated at $90 to $100 per year.

4.2.2 TNC in Lebanon, New Jersey

The ultraviolet light disinfection equipment at this TNC in Lebanon, New Jersey was installed near the end of the year 1994. Before installing the present unit the facility had an old ultraviolet light unit that could not be maintained any longer. The present unit serves an average of 50 persons per day. The owners of the facility estimate water consumption at 200 gpd. The unit's design flow is 15 gpm (21,600 gpd). Part of the facility that uses the unit is a restaurant. The negative effect of chlorination on water taste and the operation and maintenance requirements for chlorinators favored the use of ultraviolet light technology over traditional chemical disinfection technology. The system has a storage capacity of 80 gallons. The unit delivers a minimum dose of 17 mWs/cm^2 assuming water with an absorbance coefficient of 0.1 (a level between an absorbance coefficient of 0.06 for municipal drinking water and an absorbance coefficient of 0.15 for sea water).

The unit, manufactured in Pennsylvania, is equipped with a mechanical wiper, a sound alarm system, and one ultraviolet lamp, and is made out of stainless steel. It came with a 1-year warranty. Water tests have shown no presence of total coliform in the finished water. The person who services the system said that he has not noticed any biofilming in the storage tank or the pipes connected to the ultraviolet light unit. The unit is cleaned with synthetic detergents and alcohol. The owners of the facility say that once a year the bulb is changed and the full service cleanup takes about 1/2 an hour. The capital cost was estimated

at $2,000 to $3,000 (including engineering and installation). The operation and maintenance is contracted out. The operation and maintenance costs for the system are estimated at $500 per year including all quarterly water sampling, analysis, testing and reporting requirements.

4.2.3 TNC in Branchville, New Jersey

The ultraviolet light system was installed in 1990-1991. It serves an average population of 40 per day. Ultraviolet light was considered because of its effectiveness against nuisance microorganisms and because it does not add any taste to the water. Before installing the ultraviolet light unit, disinfection was available through an iodinator. The use of chemical disinfection was not satisfactory because of its effects on the taste of the beverages served at the facility such as tap soda. In addition, some operation and maintenance problems associated with the chemical disinfection unit, such as measuring and applying the right chemical dose, brought the owner to the decision of installing an ultraviolet unit with the promise that it requires little attention. The unit was manufactured in the United States and is equipped with one light bulb and a sound alarm system. The system has a storage capacity of 40 gallons.

Turbidity levels and iron levels are unknown. However, for some time the system was equipped with a softener which at the time of the interview had not been used for over a year and a half. There were no coliform or other microbiological outbreaks.

Service of the ultraviolet light unit is contracted out to the firm that installed it. The unit is serviced once per year. The service includes cleaning the unit and replacing the light bulb. The annual service of the unit takes about 20 minutes. As stated earlier the unit was put in service 5 to 6 years ago, nevertheless, no diodes, ballasts, or sleeves have been replaced. Moreover, the owners of the facility have not noticed any biofilm accumulation in the pipes or the storage tank. The cost of the system including engineering and installation was $1,500. The operation and maintenance cost is estimated at $125 to $150 per year.

4.2.4 NTNC in Harmony Township, New Jersey

The ultraviolet light unit at this system was installed in the winter of 1994. The unit is a closed-type unit. The treated water is used by 20 employees for showering and washing only. The owners of the facility provide bottled water for drinking. The average water consumption is about 10,000 gallons per day. The ultraviolet light unit has the capacity of treating 24 gallons per minute (34,560 gallons per day). Water treatment includes an activated carbon filter installed before the ultraviolet unit. The facility where the ultraviolet unit is installed is a chemical manufacturing facility. The ultraviolet light unit was

manufactured in New Jersey and came with a 1-year warranty on parts. The unit is equipped with two ultraviolet light bulbs, a sound alarm system and mechanical wipers. The quarterly tests for coliform bacteria in treated waters show an absence of coliforms.

The unit is serviced once every 6 months. It takes about one person-hour to clean and service the unit. Iron deposits are removed using dilute acids. The installer did not provide any special training for the employee who services the unit. Bulbs are replaced when ultraviolet light emission is at 50 percent of the maximum power. The caretaker of the unit could not provide any information on the intensity of the unit or its dose. Installation and capital costs are not known, however, the operation and maintenance costs are estimated at $1,000 per year.

4.2.5 TNC in Ringoes, New Jersey

This TNC system in Ringoes, New Jersey, is a deli store with 12 regular employees. It serves about 300 persons per day. The ultraviolet unit was installed in 1985. The reason for selecting ultraviolet light treatment over chemical treatment is unknown to the current owners. The unit is a closed-type unit equipped with one ultraviolet light bulb and a water meter. The unit is not equipped with a light or a sound alarm system or any other accessories. The current owners do not know where the unit was manufactured and could not tell whether it was covered by any form of a warranty. The system has a storage capacity of 50 gallons. The water is pre-treated by means of a "paper-like" filter of unknown pore size. This filter removes some silt and sediments. The operators could not provide any information on the ultraviolet light intensity the unit is capable of delivering.

The unit is cleaned once a year. The cleaning is done manually and the unit is flushed with a chlorine solution. During the past 10 years there has been one positive coliform test, in 1992. The owners attribute the positive coliform test to the fact that the ultraviolet light bulb was not changed in a year and half.

The owners could not provide any information on capital, installation and operational and maintenance costs. However, the owners expressed satisfaction with the performance of the unit as it requires very little attention on their part and its service is contracted out to a plumbing company.

4.2.6 NTNC in Ringoes, New Jersey

According to the contact person at this PWS, this system provides water to about 30 residents in an apartment building, and a store with 3 employees which serves about 50 to 100 customers per day. The system was installed 7 years ago. The new owner does not know why ultraviolet light was selected by the previous owner. According to the store manager where the ultraviolet light unit is located, the ultraviolet light system is an open-type unit. The unit is installed in a storage room. The contact person knows that the unit is working by looking at the blue light coming from the unit (ultraviolet light units do emit some gray-blue visible light). Microbiological tests are conducted by the county health department. The new owner did not know that the unit needs periodic service such as changing the ultraviolet light bulbs or occasional service such as cleaning. According to the contact person there is no sign at the door where the ultraviolet light unit is located to warn the users of that room that looking directly at the light emitted from the ultraviolet lamps is hazardous and could cause temporary and permanent eye injury. Store employees, where the unit is located, did not appear to be warned in any manner against gazing at the unit with its serene blue light.

4.2.7 NTNC in Stewartsville, New Jersey

This NTNC system is located in a metal work manufacturing facility. The population served is 50 persons per day. The capacity of the ultraviolet unit is 20 gallons per minute (29,000 gpd). The intensity and dose of the unit are not known. The unit was installed, in 1991, when for the first time the ground water source tested positive for coliform bacteria. Because the water source is contaminated with high levels of nitrates and nitrites, the treated water is used only for washing, sanitation and toilets flushing. According to the contact person at the facility, the source of ground water contamination is a 1.5 million-chicken farm located about 2 miles away from the facility. According to the contact person, the well water is tested by the county department of health for microbial contamination once every 6 months and possibly for nitrates/nitrites. The ultraviolet unit installed 5 years ago was manufactured in the United States, it contains two ultraviolet light bulbs and came with a 2-year warranty on parts. The system does not have any storage capacity. There has been no positive coliform test after the installation of the unit. Twice a year, the unit is fully serviced. This service includes replacing the bulbs and cleaning the unit with detergents. The full service is done by one person and it takes several hours to complete. The unit cost including engineering and installation was about $1,000. The operation and maintenance costs are estimated at $200 per year.

4.2.8 TNC Ground Water System in Washington, New Jersey

Merrill Creek Visitors Center in Washington, New Jersey, is a transient non-community water supply system. The system has three sites where ultraviolet light is used for ground water disinfection. The sites include a visitors center, a rental property (guest houses), and a pump house.

The Center has four closed ultraviolet light units—three units each with one bulb and one unit with four bulbs (guest houses site). The operator could not provide information on the dose or intensity used. The population served is estimated by the operator to be between 5,000 to 10,000 per year. The system is not equipped with an alarm or telemetry system. The system is a U.S.-made system, manufactured in California. It was installed 8 years ago. There is no distribution system and the system has no storage capacity. Also, chlorination is not used as a secondary disinfection.

There are no turbidity measurements taken. There have been no coliform outbreaks and no biofilm formation in the pipes within the buildings. The system uses a pH adjuster on only one site and applies hardness and iron removal treatment prior to ultraviolet treatment. Microbiological samples are taken on a monthly basis. Cleaning of the units is performed once HPC reaches 100 CFU/ml. If the HPC count remains high, the light bulbs are replaced. Also, light bulbs are changed annually; during the past 8 years, only one faulty ballast was changed; and no diodes have been changed. The system is not equipped with wipers or ultrasonics. Cleaning of units occurs once every 6 months and it takes 2 hours to finish the cleaning process. The operator mentioned that over the last 8 years only two quartz sleeves were broken during maintenance.

The estimated O&M costs are $100 to $200 per year, and the capital costs for one of the units, including pH adjuster and softener, were approximately $4,000 to $5,000 (personal communication with the supervisor, 1996).

4.3 CASE STUDIES FROM THE STATES OF OREGON, MONTANA, AND MARYLAND

The case study presented from the State of Oregon covers a ground water CWS. The case study reflects satisfaction with ultraviolet use for primary disinfection. The four ultraviolet units installed in this CWS operate 24 hours per day. A close look at the information presented in this case study shows that the theoretical flow capacity of this CWS system is 100,800 gallons per day or 70 gpm. The theoretical disinfection capacity of the installed ultraviolet units is even greater at 115,200 gallons per day. The

USEPA assumed design flow category for a CWS population of less than 100 persons is 24,000 gallons per day or 16.67 gpm. The USEPA average flow category for a CWS population of less than 100 persons is 5600 gallons per day or 3.89 gpm. The ratio of USEPA design flow category to the USEPA average flow is 4.3. Some authorities use a factor of three for instantaneous peak factor (i.e., maximum water demand/average water demand per day) (Masschelein, 1992). Using the USEPA peak factor figure to determine average water demand would yield 245 gallons per capita per day (population served 96). An average water demand of 52 gpd is normally considered to calculate water demand in very high-standard residential areas (Masschelein, 1992). The case study from Montana is a Ranney-filtered drinking water application. The case study from Montana reflects satisfaction with ultraviolet application for primary disinfection. The case study from Maryland covers a water reclamation facility that uses an open channel ultraviolet system. The case study from Maryland reflects satisfaction with ultraviolet application for treated wastewater disinfection.

4.3.1 Villadom Mobile Home Park CWS In Umatilla County, Oregon

Only one public water system in Oregon has installed ultraviolet light for primary disinfection, with chlorination providing secondary disinfection. This community water system, Villadom Mobile Home Park is located just north of Milton-Freewater, in Umatilla County. The system has a well with a capacity of 70 gpm, and serves a population of 96.

Ultraviolet light was first considered at Villadom in 1990, but was not chosen as a disinfectant until June of 1994 when a series of samples (May and June) tested positive for total coliform. With no existing disinfectant capabilities, the owner decided to install both an ultraviolet light system, and a liquid sodium hypochlorinator to provide the required residual. Household bleach (5.25%) is used and diluted 1:5. The owner chose not to use chlorine as the main disinfectant due to the undesirable taste and high maintenance needs.

The ultraviolet light system installed, Water Soft model UV-20F, is a stainless steel cylinder with a space requirement of 13 x 7 x 36 inches per unit. The system uses four units in parallel, each preceded by a 120-mesh screen filter, to provide a maximum capacity of 80 gpm (note: this capacity exceeds well capacity). The shipping weight of each unit is 23 pounds. The dose provided by each unit is 30 mWs/cm^2. Each unit has a capacity of 20 gpm, and is equipped with an automatic shut-off valve ("Failsafe" brand) in case of a malfunction or a weak bulb. The shut-off valve is also hooked up to an alarm. The manufacturer location is unknown, as Water Soft purchased the product and marketed it as

a Water Soft product. Pump and Drilling Supply, located in Wilsonville, OR, was the distributor for these units, but the line has been discontinued. The distributor offered a 1-year warranty, but overall the CWS system operators have not found any major problems with the product.

Villadom Mobile Home Park has a storage capacity of 75 gallons, from three pressure tanks. The feed pump for chlorination is a 28 gpd capacity Mec-a-Matic, with a theoretical dosage of 1.6 ppm. However, at the time of the field visit, a chlorine residual was barely detected (<0.2 ppm). The owner was not available for further questioning.

Turbidity levels for this system are not known. The source is a 48 foot deep well, and sand entering the treatment system has been an occasional problem in the past. No problems other than complaints about the aesthetic water quality were experienced. There is no noticeable iron in the source water, although there is no record of any lab analysis results. All monthly tests for coliform bacteria after June 1994 have been negative. The chlorine residual is not routinely measured at the time of sample collection, so the level of protection provided by chlorine is unknown. No increase in biofilm formation has been noticed in the PVC distribution pipe. No other microbiological problems are known.

The pre-filters would be cleaned only when sediment builds up, and this has not been necessary in the 2 years the system has been in operation. The ultraviolet units are cleaned with alcohol whenever the bulb is changed. With the Failsafe feature, the unit ceases operation if the ultraviolet light bulb is out or weaker than the set dosage. The local supplier is on call for any operation or maintenance needs. The supplier attended a 4-day "Water Soft" seminar covering all aspects of the ultraviolet light units in order to be able to sell and service them. He changes the light bulb at least every year, and cleans the glass sleeve at that time. It takes one person about an hour and a half to accomplish both of these tasks on all four units. He has never broken a sleeve or bulb during cleaning or changing, though he says it is common with inexperienced private homeowners. The sleeves, diodes, and ballasts have not yet needed to be replaced, and the safety valve would shut the unit off should anything go wrong. As far as calibration, the only adjustable parameter the service person knew of was the capacity, which is designed for 20 gpm per unit but could be lowered using the flow control valve.

The cost of the ultraviolet light system was about $20,000. Each 20 gpm unit costs $5,000, including engineering and installation. Operation and maintenance costs are as little as $550 per year, which includes materials and labor (about an hour and a half to change the bulbs and clean the sleeves).

4.3.2 Fort Benton, Montana

The city of Fort Benton, Montana, obtains drinking water from the Missouri River. The filtration plant, which is more than 20 years old, was in need of upgrading due to coliform bacteria outbreaks. Rather than building a new filtration plant, the city built a new 0.088 m^3/sec (2 MGD) treatment plant in 1987. Water is drawn through Ranney collectors installed 6 to 7.5 m (20 to 25 ft) below the river bed, a system that allows the river bed to naturally filter the raw water. Turbidities of water entering the treatment plant average 0.08 NTU. No *Giardia* cysts have been found in the flow from the Ranney collectors.

The water is treated with ultraviolet radiation for primary disinfection, then chlorinated for secondary disinfection. An applied chlorine dosage of about 1 mg/L is used. The entire water treatment system is housed in a 2.97-m^2 (32 sq ft) building.

The ultraviolet disinfection system consists of six irradiation chambers, two control cabinets with alarms, chart recorders, relays, hour-run meters, lamp and power on-lights, six thermostats, electrical door interlocks, mimic diagrams, and six ultraviolet intensity monitors measuring total ultraviolet output. Each irradiation chamber contains one 2.5 kW mercury vapor, medium-pressure arc tube, generating ultraviolet radiation including radiation at 253.7 nm.

The initial ultraviolet dosage is 41 mWs/cm^2 at maximum water flow of 104 L/S (1,650 gal/min) through each irradiation unit. Expected arc tube life is 4,500 operating hours, providing a minimum ultraviolet dosage of 25 mWs/cm^2 at 253.7 nm. These conditions were assumed to reduce concentrations of *Escherichia coli* organisms by a minimum of 5 logs (10^5 reduction) (USEPA, 1989).

The system (made in England) is equipped with a telemetry control system and fully automated backup system. Each bank of three irradiation chambers has two units on-line at all times, with the third unit serving as backup. In the event that the ultraviolet intensity drops below acceptable limits (20 mWs/cm^2 in any of the chambers), the automatic butterfly valve on the standby unit will open. The alarm system also is activated if ultraviolet intensity drops below acceptable limits in any of the chambers. The ultraviolet alarm system is interfaced with an automatic dialer and alarm system.

In 1987, total equipment costs for the six-unit ultraviolet irradiation system with butterfly valves were $74,587 (USEPA, 1989). The current population served by the system is about 1,700. No outbreaks of

coliform bacteria have occurred since the installation of the ultraviolet unit in 1987, and the system is cleaned once a year (personal communication with superintendent, 1996).

4.3.3 Mayo Water Reclamation Facility, Maryland

In the Greater Washington, D.C. area, the Mayo Water Reclamation Facility (that treats gray water before discharging it into a river) uses ultraviolet light for disinfection. The Mayo Water Reclamation Facility is located in Anne Arundel County on the Eastern Shore of Maryland, near the town of Edgewater. The ultraviolet disinfection system is an open-channel system that has been in operation for 7 years. The system was designed and built by Trojan and disinfects a peak flow of about 0.5 MGD. The BOD levels are about 90 mg/l, and the suspended solids levels are about 60 mg/l. The effluent from the ultraviolet disinfection system is discharged directly to Rhode River. The dose applied at the Mayo water reclamation facility could not be verified by the current operator.

An early problem in operating the system was rapid algae growth in the ultraviolet unit. The problem was corrected by covering the open channel and preventing the sunlight from reaching the water. The operation and maintenance crew clean the ultraviolet lamps weekly with diluted HCl solution. The unit is equipped with an intensity meter to indicate when the lamps must be cleaned and an alarm system to indicate a lamp failure. Although the manufacturer recommended that lamps be replaced once a year, according to the operator, some lamps that were put in operation a few years ago are still functioning satisfactorily (personal communication with operator, 1995).

4.4 CASE HISTORY, LANDEUS WATER TREATMENT PLANT IN THE NETHERLANDS

Kruithof et al. (1992) presented a ground water treatment plant case history from the Netherlands. The case history shows that ultraviolet light was used at the Landeus water treatment plant following an outbreak of coliforms and *Escherichia coli* bacteria in 1980. In the 5-year period (1981-1985) following the installation of an ultraviolet light disinfection system, *Escherichia coli* tested positive in the finished water five times of 200 measurements. Simultaneously, the source water total coliforms were detected 116 times and *Escherichia coli* were detected 65 times. The reason for *Escherichia coli* presence in the finished water (five times out of 65 *Escherichia coli* detection in source water) was low ultraviolet radiation dose. In three cases, the cause of the low dose was a malfunctioning ultraviolet light intensity monitor showing a higher dose than the actual. In the other two cases, the dose was experimentally reduced to 23 mWs/cm^2, a level that did not eliminate all coliform bacteria. In the 6 years that followed

the year 1985, no *Escherichia coli* outbreaks occurred. The no-outbreak period came following more accurate monitoring and routine lamp replacement at 60 percent (24 mW/cm^2) of the original intensity (40 mW/cm^2). No capital or operation and maintenance costs were reported by Kruithof et al. (1992). However, Kruithof et al. (1992) reported costs associated with the use of ultraviolet light for drinking water disinfection for other treatment plants in the Netherlands. The costs reported by Kruithof et al. (1992) are presented in chapter 3.

4.5 PERSPECTIVE OF TWO WATER TREATMENT UNITS SERVICE CONTRACTORS

As the case studies have revealed, many ultraviolet units operation and maintenance services are contracted out to professional contractors or plumbing firms, and these are typically the same firms that market and install the units. This indicates that some ultraviolet units are sophisticated enough to warrant professional assistance particularly when thorough cleaning is required. Two contractors were interviewed to provide information that the contact persons could not provide about their systems' ultraviolet light unit. Moreover, the contractors were asked two specific questions that raised some concerns about possible environmental impacts of spent ultraviolet light bulbs, and about actual operation and maintenance costs. The first question was about the fate of the spent bulbs. The second question was about how often bulbs and sleeves get broken when being installed or replaced. The fact that ultraviolet light bulbs contain some mercury, and that at least in one State (California) wastewater treatment plants utilizing ultraviolet technology for disinfection are required to recycle spent bulbs, prompted the first question. The second question was in response to claims that the expensive ultraviolet light bulbs and sleeves often break during cleaning and replacement.

The interviewed contractors, in New Jersey and the other in Umatilla county, Oregon, said that ever since they started servicing ultraviolet units, they have not broken any ultraviolet light bulbs. The contractor in New Jersey said that his firm services well over 150 ultraviolet units per year. The contractor admitted to breaking one sleeve 3 years ago. Both contractors indicated that bulbs and sleeves do break if an inexperienced person like a homeowner tries to do the job himself or herself. Usually people try to do the replacement themselves in the first or second year of installing the unit. Then when the expensive bulb breaks they ask for help.

The contractor in New Jersey said that spent ultraviolet light bulbs are disposed of along with regular trash. The contractor in Oregon said that spent bulbs are disposed of along with other toxic substances

in a toxic wastes landfill. When asked if spent bulbs break in the shop or before being disposed of during transportation or storage, the contractor in Oregon said that never happens because the bulbs come in well padded corrugated cardboard boxes. When asked if he thinks that spent ultraviolet light bulbs constitute an environmental hazard his response was that the amount of mercury in the bulbs is less than the amount one would find in the old electric heating and air conditioning switches installed in homes, therefore the pollution risk in his view is small.

The contractor in New Jersey estimates his service charge at an average of $175 per unit with one light bulb per year. This includes changing the bulb and the "O" rings, and cleaning the unit. The contractor in Oregon charges $46 per service call plus parts.

The contractor in Oregon services chlorinators also, including that used for secondary disinfection at the Villadom Mobile Home Park CWS. Servicing a chlorinator is time consuming and requires close attention. The service includes checking and cleaning the valves once every 2 months and testing the chlorine level once per week. It also entails filling the chlorine tank and preparing the solution once every 3 days. His fees for these services are the same as those for servicing an ultraviolet unit (i.e., $46 per service call plus materials with each service call lasting for about an hour). The contractor in New Jersey also services chlorinators at private homes and very small private water systems. The contractors' remarks on chlorinators were similar to those expressed by the service contractor in Oregon adding that the service requirements are cumbersome to private home owners and time consuming to the service worker.

Both service contractors indicated that they have not noticed any biofilm accumulation in pipes or storage tanks and did not need to change diodes. According to the contractor in New Jersey, ballasts are changed once every 4 years, mostly because of improper use or lightening. The contractors experience with the industry indicates that the ultraviolet industry stands behind the quality of its products and the parts it supplies.

4.6 COSTS OF ULTRAVIOLET LIGHT UNITS AND DESIGN FLOWS OF TNC AND NTNC SYSTEMS AS REVEALED FROM THE CASE STUDIES

The costs of the ultraviolet light treatment units reported in these case studies reflect actual costs incurred by these systems. The installed equipment costs for treating flows less than 100,000 gpd ($1,000 to $5,000), vary greatly although the units provide similar disinfection power to almost similar flows. The reported capital costs reflect the variance in price quotes obtained directly from ultraviolet light unit

manufacturers and reported in Chapter 3 of this report. The same observation can be made when looking into the reported operation and maintenance costs ($90 per year per unit to $200 per year per unit). The operation and maintenance costs reported in Chapter 3 of this report are comparable to those reported in these case studies (the operation and maintenance costs reported in chapter 3 of this report are higher because they include power costs and other miscellaneous costs for ultraviolet units with higher dose capabilities). None of the investigated PWS systems were equipped with telemetry equipment. The benefit of equipping water systems troubled with microbiological and monitoring violations is reported in a case study from California (USEPA, 1995). In this case study installing telemetry equipment reduced operation and maintenance costs by about 33 percent. This was in a rural California system that was plagued with bacteriological and monitoring violations. Installing telemetry equipment reduced the required daily inspection visits to weekly visits, thus reducing the time required to operate and maintain the system to 13 hours per month including travel time.

The flows reported in the case studies above show that many small systems have some storage capacity. Having some storage capacity helps in reducing the peak demand on the treatment plant. This reduction in peak demand at the treatment plant also translates into installing equipment with smaller capacity and hence lower capital and operation costs. The case studies also show that in small systems, using chemicals to maintain residual disinfection in the network might not be necessary. As stated earlier the flow requirements for TNC and NTNC systems might not be the same as those of CWS with similar population. This area warrants further investigation as it bears heavily on treatment options and cost estimates.

4.7 SUMMARY OF FINDINGS

The presented case studies revealed important commonalities in general systems' features and in specific operation and maintenance procedures. Examination of the information collected from the case studies shows the following:

- All the investigated systems have ultraviolet units with disinfection capabilities for flows that exceed actual water demand. The summary table presented below clearly shows that the per capita water consumption availability at these systems exceeds, by far, normal residential water consumption demand. The reported estimate of average water consumption at the TNC PWS in Lebanon, NJ is 4 gallons per capita per day while the system's conservative available average demand capacity is at 100 gallons per capita per day. Installing equipment with appropriate capacity and having some storage capacity would certainly result in lower capital costs and operation costs.

- All ultraviolet units operate 24 hours per day.
- There are no backup units available onsite.
- Maintenance is contracted out.
- Operation and maintenance costs were not specifically raised as a concern.
- Installation costs are part of the equipment costs and site modification are either minimal or not necessary. Space requirements are very small and the weight of a single unit is less than 25 pounds.
- Chemical and physical water quality parameters are often not known.
- No coliform violation occurred with ultraviolet treatment.
- No biofilming in networks pipes or reservoirs occurred.
- Operators and users expressed satisfaction with the performance of the installed ultraviolet units, and the simplicity of its operation and maintenance requirements.
- Sleeves and bulbs breakage was not specifically reported as a concern.

Exhibit 4-1 presents a summary table of ultraviolet light disinfection applications in drinking water based on case studies.

Exhibit 4-1. Ultraviolet Light Technology in Drinking Water Applications-Case Studies Summary Table

System	Lebanon, NJ	Washington, NJ	Branchville, NJ	Ringoes, NJ	Phillipsburg, NJ	Harmony, NJ	Ringoes, NJ	Stewartsville, NJ	Villadom, OR	Fort Benton, MT
Type	TNC	TNC	TNC	TNC	CWS (?) NTNC	NTNC	NTNC?	NTNC	CWS	CWS
Source of Water	Ground	Ground	Ground	Ground	Ground	Ground	Ground	Ground	Ground	Surface
Population Served	50	5000-10000 per year	40	312	30	20	85	50	96	1700
Type of Installed Unit	Closed	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Open
Year of Installation	1994	1988	1990-1991	1985	1995	1994	Unknown	1991	1990	1987
Made in	Pennsylvania	California	U.S.	Unknown	Vermont	Unknown	Unknown	U.S.	Unknown	England
Minimum UV Dose	17 mWs/cm^2	Unknown	Unknown	Unknown	30 mWs/cm^2	Unknown	Unknown	Unknown	30 mWs/cm^2	25 mWs/cm^2
Type of Alarm	Sound	None	Sound	None	Sound & Light	Sound	Unknown	Unknown	Sound	Sound & Light & Telemetry
Cleaning Equipment	Mechanical Wiper	None	Unknown	None	Manual Wiper	Mechanical Wiper	Unknown	Unknown	Unknown	None
Other Treatment	—	pH adjuster, and hardness removal	—	Paper-Like Filter	5 µ filter	GAC Filter	None	None	120 mesh Filter & Chlorination	Chlorination
Design Flow	21,600 gpd	Unknown	Unknown	Unknown	29,000 gpd	34,600 gpd	Unknown	29,000 gpd	101,000 gpd	2.3 MGD
Reported Water Consumption	200 gpd	Unknown	Unknown	Unknown	Unknown	10,000 gpd	Unknown	Unknown	Unknown	Unknown
Average per Capita per Day Water Consumption Availability assuming a peak factor of 4.3 (design flow/average flow)	100 gallons	Undetermined	Undetermined	Undetermined	225 gallons	400 gallons	Unknown	134 gallons	245 gallons	324 gallons
Storage Capacity	80 gallons	None	40 gallons	50 gallons	None	None	None	None	75 gallons	Unknown
Turbidity and Iron Levels	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown but Iron is present	Unknown	Unknown	Unknown	0.08 NTU
Coliform Violations	None	None	None	Once in 1992**	None	None	Unknown	None	None	None
Frequency of Service and Time	Annual - ½ hour	6 months 2 hours	Annual - 20 minutes	Annual ?	Weekly (minor service) Annual - 1 hour	6-month - 1 hour	None	6-month several hours	Annual 25 minutes	Annual
Capital Cost per Unit	$2,500	$4500	$1,500	?	$2,100	?	Unknown	$1,000	$5,000	$74,587
Annual O&M Cost per Unit	$500*	$150	$135	?	$100	$1,000*	?	$200	$140	?

*Includes costs of other treatments and water analysis for compliance purposes.
**Ultraviolet light bulb was left in operation half a year beyond its service life.

4.8 SUGGESTED CRITERIA FOR THE USE OF ULTRAVIOLET LIGHT UNITS BASED ON THE PRESENTED CASE STUDIES

Based on the interviews conducted with operators of public water systems using ultraviolet light to disinfect drinking water or water for human consumption, the following requirements are suggested for the use of ultraviolet units in small public water systems:

- All units must be of the closed-type.
- Mechanical wipers and ultrasonic cleaners should be mandatory if water fouling agents such as iron are present in the water entering the unit.
- Annual cleaning of the unit, at a minimum.
- Minimum set dose at any wavelength(s) within the 250nm to 270nm spectrum (this needs to be decided by the work group).
- Automatic shutoff valve, flow control valves with shutoff triggered when light intensity falls below the minimum set level.
- Sound and light alarm and telemetry equipment if users or operators are not close by.
- The unit body needs to be made of material that would not permeate or degrade under the effect of ultraviolet light, such as high quality stainless steel.
- Testing the disinfection efficiency of the unit as a whole by means of bioassay or actinometry before installation. Research might be necessary to determine whether recalibration of the installed unit is necessary after years of service. Testing the unit's ballasts and diodes after years of service also requires some research to determine the time span when such testing might be necessary.
- Microbiological tests for ultraviolet treated finished water should include HPC tests. HPC microorganisms may provide a better assessment of disinfection than the ultraviolet sensitive coliforms.
- Education of the users and the servicepersons about the hazardous compounds contained in the components of the ultraviolet light unit and proper ways of disposing spent parts.
- When possible a backup unit should be available or at least one set of spare parts stored onsite.

4.9 REFERENCES

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Masschelein, W. J. (1992). *Unit Processes in Drinking Water Treatment*. Marcel Dekker Inc. New York.

Monaco Vince, (1996). Memoranda to Dr. Faysal Bekdash Sr. Environmental Engineer dated 4/18/1996 and 4/30/1996.

New Jersey, (1995). Regulations for Disinfection by Ultraviolet Light. New Jersey Register CITE 27 N.J.R 4112. November 6, 1995.

USEPA, (1995). *Restructuring Small Drinking Water Systems. Options and Case Studies.* Office of Water. Washington D.C. EPA 810-R-95-002.

CHAPTER 5. SUMMARY OF FINDINGS

This chapter summarizes the findings presented in the previous chapters. Sections 5.1, 5.2, and 5.3 present the main findings of chapters 2 and 3. Section 5.4 presents the main findings of chapter 4.

5.1 EFFICACY AND APPLICABILITY

The initial summary of findings presented below is based on the reviewed literature and information provided by non-governmental organizations and ultraviolet light manufacturers. These findings are presented in more detail in section 2.5.

- Ultraviolet light (at a 253.7 nm wavelength) is effective against a wide range of pathogenic and nuisance microorganisms commonly found in ground water.
- The required inactivation dose of bacteria using ultraviolet light varies from one organism to another and within the same species.
- Generally, the order of disinfection resistance is as follows: bacteria (least resistant) < viruses < bacterial spores < protozoan cysts and oocysts (most resistant).
- Naturally occurring microorganisms are more resistant to inactivation than microorganisms cultured in laboratories.
- Current contamination indicator surrogate microorganisms (total coliform bacteria, fecal coliforms, *Escherichia coli*) are more sensitive to disinfection by ultraviolet light than many identified pathogenic microorganisms (including viruses) that are of concern in drinking water.
- Bacteriophage MS-2 inactivation data show that in a pilot study setting a 4 log reduction can be achieved by an ultraviolet light dose of 93 mWs/cm^2. *Bacillus subtilis* spores inactivation data show that in a laboratory setting a 4 log reduction can be achieved using an ultraviolet light dose of 60 mWs/cm^2. A 60 mWs/cm^2 dose is sufficient to cause more than a 5 log reduction in poliovirus. A 50 mWs/cm^2 dose is sufficient to achieve 4 log reduction in rotavirus, which is more resistant to ultraviolet light than poliovirus and Hepatitis A virus.
- Two log reduction of *Giardia lamblia* is achieved at a dose of 180 mWs/cm^2. A minimum of 3 log reduction of *Cryptosporidium* is achieved at a dose of about 8,750 mWs/cm^2.
- For water with a turbidity level of 5 NTU, 25 percent of the ultraviolet light is absorbed by turbidity-causing water constituents.

Additional advantages of using ultraviolet light for disinfection are:

- Based on the current literature research, the use of ultraviolet light for water disinfection is not associated with the formation of known toxic or non-toxic conventional treatment by-products. If used for VOC destruction, no VOC emissions result.
- Unlike chemical disinfectants, there are no known risks associated with over-sizing the disinfection chamber and there is no limit to the dose that could be applied in the disinfection process. Overdesign of ultraviolet systems may be advantageous to cover transient periods during which surface water may contaminate a source.
- Ultraviolet light is successfully being applied in the field to mitigate contaminated ground water at Superfund sites. The literature search conducted for this report shows that even at low doses of ultraviolet light (doses that are normally applied in POU commercially available devices) certain commonly used organic pesticides are slightly reduced.
- Ultraviolet light disinfection systems are very practical tools for upgrading and retrofitting small systems requiring small space with minimal or no construction work.
- Ultraviolet light disinfection systems require no storage of hazardous material.
- No onsite smell and no final water product smell.
- Very little residence time.
- Taste is not altered (only improved) with the destruction of some organic contaminants and nuisance microorganisms.
- Minerals in water are not affected.
- No or little (disposal of spent lamps or obsolete equipment) impact on the environment (some States require recycling of ultraviolet lamps).

The Dutch waterworks guidance on the use of ultraviolet shows that if both the number of microorganisms and AOC concentrations are low (no definite figure given), then post-disinfection can be omitted completely (ultraviolet light application fits here as an additional safety measure). In a typical Dutch waterworks, this occurs when multiple filtration steps (rapid filtration, GAC filtration, and slow sand filter) are the final treatment steps. If the high concentrations of AOC are present in the water, then regardless of the number of microorganisms, post-disinfection with a residual disinfectant is necessary. If high numbers of microorganisms and low concentrations of AOC are present in the water (this may happen when GAC filtration is the final step in the treatment train), then disinfection to decrease the number of microorganisms is needed. It is in this last situation where ultraviolet light technology fits best for ground water application (Kruithof et al., 1992).

Therefore (according to the Dutch experience), the main parameter used to determine the applicability of ultraviolet light as a disinfectant instead of chemical disinfectants is the AOC level in the water before the disinfection stage.

Disadvantages of using ultraviolet light for disinfection are:

- Lack of measurable disinfection residual.
- Lack of an in-place standardized mechanism to measure and calibrate equipment efficiency before and after installation.
- Lack of a firm technical database on system efficacy in various water quality conditions.
- Need for a secondary disinfectant for distribution network.

5.2 OPERATIONAL FACTORS

Closed ultraviolet light systems are recommended for drinking water applications rather than the open ultraviolet systems used in wastewater treatment. The practical advantages of closed ultraviolet light systems, which are commonly used for drinking-water disinfection, are:

- Minimal or no exposure hazards to workers as compared to open systems
- Very small space requirement; therefore, minimal or no construction costs
- Simplicity of installation due to modular design with two plumbing connections and one electrical hook-up
- Simplicity of dismantling and replacing small units with larger units as population increases without the need for extensive construction
- Lower maintenance requirements as compared to open systems, which are exposed to depositions from the air.

Ultraviolet light systems designed for small drinking water systems should consist of several modular units to allow for a continuous operation while one or two units are maintained. For small ground water systems, it is recommended that all electric fittings be of the modular type to facilitate installation, replacement, and maintenance. All ultraviolet light systems should be equipped with monitoring devices and before-and-after shut off valves.

5.3 EVALUATION AND COMPARISON OF ULTRAVIOLET LIGHT TECHNOLOGY COSTS TO OTHER DISINFECTION PROCESSES

Capital costs for two ultraviolet light systems (one provides a dose of 40 mWs/cm^2 and the other provides 140 mWs/cm^2) were compiled from three ultraviolet light equipment manufacturers. The average total costs are presented in **Exhibit 5-1**. **Exhibit 5-2** compares the costs of the ultraviolet systems at the two set doses to ozonation at 1 mg/l and chlorination at 5 mg/l. **Exhibit 5-3** compares the costs of ultraviolet systems that included chlorination as a secondary disinfectant at a dose of 1 mg/l to ozonation at a dose of 1 mg/l and chlorination at a dose of 5 mg/l.

Exhibit 5-1. Average Total Costs for Ultraviolet Light Disinfection Systems*

Dose 40 mWs/cm^2

EPA Flow Category	Design Flow (MGD)	Cost per Year (k$)			Cost per Year (c/kgal)		
		Total Capital	Total O&M	Total Production Cost	Total Capital	Total O&M	Total Production Cost
1	0.024	1.3	0.4	1.7	14.8	4.3	19
2	0.087	1.7	0.8	2.5	5.2	2.5	8
3	0.27	3.7	1.7	5.3	3.7	1.7	5
4	0.65	7.7	3.7	11.4	3.2	1.6	5
5	1.8	16.6	9.7	26.3	2.5	1.5	4

Dose 140 mWs/cm^2

EPA Flow Category	Design Flow (MGD)	Cost per Year (k$)			Cost per Year (c/kgal)		
		Total Capital	Total O&M	Total Production Cost	Total Capital	Total O&M	Total Production Cost
1	0.024	1.7	0.8	2.5	19.0	9.0	28
2	0.087	3.6	2.1	5.7	11.4	6.5	18
3	0.27	10.0	5.5	15.5	10.2	5.6	16
4	0.65	16.5	9.4	25.8	6.9	4.0	11
5	1.8	42.1	34.0	76.0	6.4	5.2	12

*August 1995 dollars

Exhibit 5-2. Comparison of Ultraviolet Light Disinfection Process Costs to Chlorination and Ozonation Process Costs in Cents per Thousand Gallons

USEPA Flow Category	Design Flow MGD	Ultraviolet Dose 40 mWs/cm^2	Chlorination Dose 5 mg/l	Ozonation Dose 1 mg/l	Ultraviolet Dose 140 mWs/cm^2
1	0.024	19	280	350	30
2	0.087	8	70	100	20
3	0.27	5	20	30	20
4	0.65	5	20	20	10
5	1.8	4	10	10	10

Exhibit 5-3. Comparison of Total Production Costs of Ultraviolet Treatment with Secondary Disinfection to Chlorination and Ozonation Process

Costs* in Cents Per Thousand Gallons

USEPA Flow Category	Design Flow (MGD)	40 mWs/cm^2 Ultraviolet Dose with 1 mg/l chlorine	Chlorination Dose 5 mg/l	Ozonation Dose 1 mg/l	140 mWs/cm^2 Ultraviolet Dose with 1 mg/l chlorine
1	0.024	170	280	350	180
2	0.087	40	70	100	50
3	0.27	20	20	30	30
4	0.65	20	20	20	20
5	1.8	10	10	10	20

*Costs are rounded to the nearest ten.

As can be seen from Exhibit 5-2, ultraviolet light disinfection at the selected doses (without chlorination as a secondary disinfectant) is more economically feasible than ozonation and chlorination for treating all USEPA flow categories 1 through 4; and is more feasible than ozonation and chlorination at a 40 mWs/cm^2 dose for the largest flow category. At 140 mWs/cm^2, ultraviolet light treatment cost for flow category 5 is more expensive but comparable to ozonation and chlorination costs. As can be seen from Exhibit 5-3, at the selected doses ultraviolet light technology plus chlorination is still economically as feasible or more feasible than ozonation for flow categories 1 through 4, less feasible at 140 mWs/cm^2 than ozonation for flow category 5, but has the same cost estimate as ozonation at 40 mWs/cm^2 for flow category 5. Ultraviolet light disinfection at 40 mWs/cm^2 plus chlorination is more feasible than

chlorination alone for USEPA flow categories 1 and 2 and as feasible as chlorination for USEPA flow categories 3 through 5. At a 140 mWs/cm^2 dose plus chlorination, ultraviolet light is economically more feasible than chlorination for USEPA flow categories 1 and 2, less feasible for flow categories 3 and 5, and as feasible as chlorination as flow category 4.

5.4 CASE STUDIES

Satisfaction with ultraviolet treatment in water and wastewater applications has been expressed by the operators and systems managers contacted for this report. Ease and low cost of operation and maintenance were stated to be the major factors in selecting ultraviolet technology over chlorination.

APPENDIX A. OTHER ULTRAVIOLET-RELATED DRINKING WATER DISINFECTION TECHNIQUES

This appendix provides a brief description of nonconventional ultraviolet disinfection technologies. These technologies include photoassisted heterogenous catalytic oxidation (PHCO), and pulsed or modulated ultraviolet irradiation.

The new ultraviolet manipulation techniques are either at experimental stage or have limited field applications. Both techniques seem to be very promising and warrant further investigation and investment in terms of research and development. At this point, both techniques lack a firm technical database for system design and feasibility (technical and economical). One technique manipulates the amplitude of ultraviolet light (pulsed ultraviolet light technique). The other one uses ultraviolet light on a catalyst (TiO_2), the water to be treated (PHCO).

A.1 PHOTOASSISTED HETEROGENOUS CATALYTIC OXIDATION (PHCO)

Purifics®, an ultraviolet light firm in Canada, uses a new ultraviolet light manipulation technique known as Photoassisted Heterogeneous Catalytic Oxidation (PHCO) to inactivate microorganisms and to destroy organic contaminants. This technique is being used successfully at many contaminated ground water sites (Purifics, 1995). PHCO is a process where photoactivated titanium dioxide (TiO_2) is illuminated with near visible ultraviolet light in an oxygenated suspension. The energy absorbed by titanium dioxide would produce a redox environment sufficient to mineralize organic compounds. The high oxidation reduction potential (ORP) levels achieved through this technique are also sufficient to inactivate microorganisms in water and wastewater. The source of ultraviolet light could be either artificial or natural. TiO_2 could be used in the form of TiO_2-coated mesh or in the form of powder suspended in an aqueous solution. The PHCO process has been reported to be effective in degrading disinfection by-products precursors compounds (Hand, Perram, and Crittenden, 1995). Also, the PHCO process has been shown to successfully degrade a wide variety of organic contaminants, including drinking water regulated contaminants, such as polychlorinated biphenyls (PCBs) and polyaromatic hydrocarbons (PAHs), into simple mineral acids, carbon dioxide, and water. As mentioned above, the PHCO process has been reported to inactivate microorganisms. However, one of the known drawbacks of the process is the lack of a residual disinfectant after treatment. Richardson et al. 1996 (unpublished study) investigated the effects of using chlorination for residual disinfection on water treated with ultraviolet-activated TiO_2. The

research investigated the presence of by-products before and after chlorine treatment. As a result of the PHCO alone, the research identified one disinfection by-product (tentatively identified as 3-methyl-2,4-hexanedione). When chlorine was used as a secondary disinfectant following the PHCO treatment, several chlorinated and brominated DBPs were formed. Most of these DBPs (although less in number and lower in concentration than DBPs resulting from chlorination only) were the same as those DBPs identified when chlorine was used alone for disinfection (Richardson et al., 1996).

Wei et al., 1994, and Ireland et al., 1993, investigated the inactivation of *Escherichia coli* by TiO_2 photocatalytic oxidation. The researchers concluded that the PHCO process is effective against *Escherichia coli* and reported 100 percent destruction at a TiO_2 catalyst dose of 1 g/L and a contact time of 30 minutes. The researchers cautioned that although the results may be exciting, any optimism must be tempered by the fact that *Escherichia coli* and other traditional surrogate microorganisms are rather "easy" targets for disinfection by ultraviolet disinfection techniques. The real challenge would involve demonstration of the efficacy of TiO_2 in inactivating recalcitrant pathogenic microorganisms such as *Giardia lamblia* and *Cryptosporidium parvum* (Wei et al., 1994).

Hand, Perram, and Crittenden, 1995, demonstrated in a laboratory setting that PHCO degrades DBP precursors using an artificial ultraviolet light source or sunlight. A minimum of 66 percent of the Total THM Formation Potential (TTHMFP) were destroyed (contact time 30 minutes). Hand et al., 1995, provided information on PHCO process cost estimates using artificial light and sunlight as a source for TiO_2 illumination. The Hand et al. cost estimates for treating 1 MGD are presented in **Exhibit A-1.**

Exhibit A-1. Cost Estimates for the Removal of DBP Precursors from 1 MGD Using the PHCO Process (Hand et al., 1995)

Contact Time (min)	Capital Costs (K$)	Annualized Capital Cost (K$)	Annual Operation and Maintenance (K$)	Total Production Cost (¢/Kgal)
Artificial Light				
15	75.3	8.844	109	32
30	117	13.750	193	57
45	143	16.800	267	75
60	176.7	20.800	346	100
Sunlight	1,082	127	49	48

Exhibit A-1 shows that the operation and maintenance cost of sunlight-activated PHCO process is about 56 percent of the total annual cost of treatment; the operation and maintenance cost of artificial light is about 97 percent of the total annual cost of treatment. Hand et al., 1995, reported that electricity costs alone account for 80 percent of the total annual cost of treatment in systems using artificial ultraviolet lights.

Hand et al. (1991), as reported in USEPA (1992) at 4-41, gave the following advantages:

- Removal of non-purgeable organic carbon (NPOC) and disinfection by-products (DBP) precursors
- Reduction in biodegradable fraction of NPOC
- Lower disinfection dosage, compared to the use of direct ultraviolet light
- Mineralization of trace organics such as pesticides, hydrocarbons, chlorinated hydrocarbons, and taste and color compounds
- Inactivation of pathogenic microbes
- Sunlight or near-ultraviolet light will activate the catalyst.

Disadvantages:

- Uncertainties in cost (no information is available at this point)
- Lack of a firm technical database for system design.

A.2 INACTIVATION RATES ACHIEVED WITH THE USE OF MODULATED ULTRAVIOLET LIGHT

Bank et al. (1990) studied the effectiveness of computer-controlled modulated ultraviolet-C (200 nm to 280 nm) in a series of in vitro experiments. The low-intensity pulsed[1] lamp (< 0.04 mW/cm^2 at 8 cm distance) was used to irradiate 5 strains of bacteria. The exposure time was 60 seconds, which implies an ultraviolet light dose of about 2.5 mWs/cm^2 at 8 cm distance using the pulsed lamp. Bacteria were irradiated with modulated ultraviolet light for 60 seconds at 31 cm, which indicates a dose that is considerably less than 2.5 mWs/cm^2. The bactericidal effect was almost the same for *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 25923, *Pseudomonas aeruginosa* ATCC 27853, *Serratia*

[1]In pulsed energy techniques, power (energy/time) is magnified many times by means of a capacitor. A capacitor stores the electric energy and then releases it rapidly all together. This allows power to be amplified using average power consumption.

marcesceus ATCC 8100, and *Staphylococcus epidermidis* VAS 9, with 6 to 7 log reduction in the number of viable bacteria. When bacteria were irradiated with non-modulated ultraviolet light at the same intensity and distance, the number of colonies surviving the treatment was more than 100 times the number of colonies surviving the modulated treatment. The energy requirements and costs of this new technique are considerably less than those of the traditional ultraviolet systems required to meet same log reduction; however, the capital costs are unknown and the applications are still in the experimental stage.

Dunn, Ott, and Clark (1995) reported a 6 to 7 log reduction of both *Klebsiella terrigena* and *Cryptosporidium parvum* oocysts, using pulsed ultraviolet light at a dose of 1000 mWs/cm^2. The dose is delivered in one flash. The source of *Cryptosporidium parvum* oocysts was infected mouse feces. The same results were achieved by two pulsed-light flashes at a dose of 500 mWs/cm^2 each.

For surface applications (food, equipment, etc., disinfection), Dunn, Ott, and Clark (1995) reported that the cost of a pulsed-ultraviolet light system capable of delivering 4,000 mWs/cm^2 is less than a few tenths of a cent per square foot of treated area. This conservative cost estimate includes equipment amortization, lamp replacement, electricity, and maintenance (Dunn, Ott, and Clark, 1995).

A.3 REFERENCES

Bank, H.L., et al. (1990). "Bactericidal Effectiveness of Modulated UV Light." *Applied and Environmental Microbiology*. Vol. 56, No. 12, pp. 3888-3889.

Dunn, Ott, and Clark (1995). "Pulsed-Light Treatment of Food and Packaging." *Food Technology*. September. pp. 95-98.

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Richardson, et al. (1996). "Identification of TiO_2/UV By-Products in Drinking Water," draft paper of research conducted by the USEPA Ecosystems Research Division, National Exposure Research Laboratory, Athens, Georgia, and the USEPA Drinking Water Research Division, National Risk Management Research Laboratory, Cincinnati, Ohio. 13 pages, 29 references, 5 figures, and 2 tables.

USEPA (1992). *Technologies and Costs for Control of Disinfection By-Products* (Draft). Science and Technology Branch, Criteria and Standards Division, OGWDW. Malcolm Pirnie, Inc.

Wei, et al. (1994). "Bactericidal Activity of TiO_2 Photocatalyst in Aqueous Media: Toward a Solar Assisted Water Disinfection System." *Environmental Science and Technology*. Vol. 28, pp. 934-.

APPENDIX B. ORGANICS DESTRUCTION

B. INTRODUCTION

This appendix provides a brief description of the theoretical scientific foundation that explains the potential destruction capabilities of ultraviolet light against organic compounds. It presents current findings from a literature search and information provided by ultraviolet light equipment manufacturers. Appendix B also describes the analysis of ultraviolet light technology potentials for the destruction of volatile organic compounds and other priority organics that might be found in drinking water sources.

B.1 BACKGROUND

Molecules absorb specific wavelengths (range) of electromagnetic radiation. The most useful region of the ultraviolet spectrum for transferring energy to a molecule is at wavelengths greater than 200 nm. When a molecule absorbs ultraviolet radiation, the energy level in the bonds of that molecule increases. The absorption of ultraviolet radiation also results in an increase in the orbiting level of the excited electron or electrons in higher energy orbitals (Fessenden and Fessenden, 1986). In general, molecules that require more energy for electron promotion absorb photons at shorter wavelengths and molecules that require less energy absorb photons at longer wavelengths.

As a practical electromagnetic energy form, ultraviolet light has been employed in many chemical manufacturing processes. A classical example of the use of ultraviolet light to form chemical compounds is the production process of the widely used solvent, carbon tetrachloride (CCl_4) (Giancoli, 1991). Ultraviolet light energy is used to break the C-H bonds in natural methane gas (CH_4) in the presence of chlorine molecules (Cl_2):

$$CH_4 + 2Cl_2 \xrightarrow{h\nu} CCl_4 + 2H_2$$

At a wavelength of 254 nm, organic compounds with double conjugated bonds like the C=C bond absorb ultraviolet radiation. The presence of pesticides and other organic contaminants in varying amounts in ground water sources raises the issue of the efficacy of ultraviolet light for destroying organic compounds found in ground water and of the possibility of harmful by-product formation.

The scientific literature contains sufficient evidence that ultraviolet light, alone and in combination with O_3 and H_2O_2, is a viable tool in degrading toxic and nuisance organic compounds that occur in ground water. However, the efficacy of ultraviolet light at doses typically applied in household treatment devices to destroy organic compounds has not been studied by many researchers.

B.2 DESTRUCTION POTENTIAL

The effects of ultraviolet light on organic compounds are well known. The formation of ozone and hydrogen peroxide from the action of ultraviolet light on drinking water is one of two mechanisms that lead to the disinfection of microorganisms and destruction of organic compounds. The other mechanism is the direct action of ultraviolet light on the bonds connecting the atoms in organic compounds, thus destroying the fundamental building blocks in an organic compound or microorganism. In contaminated ground water, the use of ozone and hydrogen peroxide in combination with ultraviolet light hastens the oxidation process and, hence, the destruction of both microorganisms and organic contaminants.

The destruction potential of organic compounds using ultraviolet light can be explained through understanding the chemical bonding processes and the effect of electromagnetic energy on the electrons engaged in bonding processes. The figures and illustrations presented within **Exhibit B-1** are intended to be used as theoretical background information and are not intended to be used as exact figures or for interpolation for direct field application.

Ultraviolet light is a viable technology for destroying organic contaminants in drinking water sources, however, cost may be an obstacle. For example, the equipment manufactured to destroy high levels of organic contamination in ground water Superfund sites is designed to produce ultraviolet light at significantly higher doses and intensities than those needed for conventional drinking water treatment purposes. Therefore, the power costs required to operate equipment specifically intended for organic destruction are high.

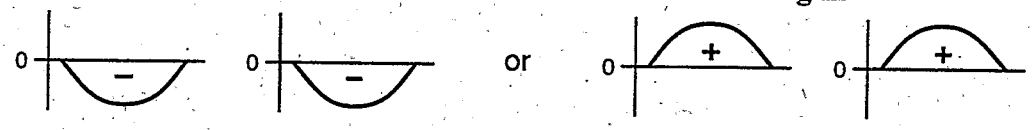
Exhibit B-1. A Précis Description of Chemical Bonding to Explain Organics Destruction Potential Using Ultraviolet Light

A covalent bond results from the sharing of a pair of electrons by two atoms. In a covalent bond, the molecular orbital that is symmetrical about its axis is called a sigma (σ) molecular orbital and the covalent bond is a sigma bond. An example of a σ bond is a C-H bond in a methane molecule.

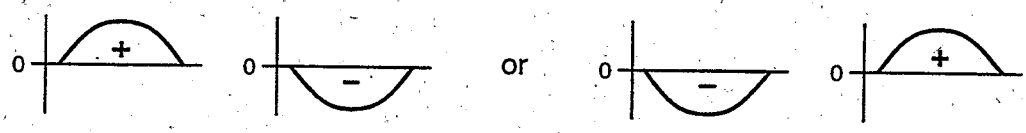
The energy from ultraviolet light pushes the pair of electrons into a higher orbital level, causing the electrons to become out-of-phase (in wave function). This is called an antibonding orbital and is given the symbol σ^*.

The figure below shows a two-dimensional schematic presentation of electrons in orbital motion. Closer to reality representation is far more complex and beyond the scope of this report. The important aspect of this presentation is that it shows that when two electrons are in phase forming a bond, both electrons do move together above and below the axial plane. The positive and negative signs in the figure are used to indicate the presence of electrons above the plane or below the plane and are not an indication of charge or anything else.

Electrons in in Phase and out of Phase Wavelengths



In Phase Electrons



022E-06

Out of Phase

A covalent Pi (π) bond is a molecular orbital bonding joining two atoms and is located above and below the plane of sigma bond. An example of this bond would be the double bond in ethylene $H_2C = CH_2$ where the first C-C bond is the σ bond and the second C-C bond is the π bond. When a π bond is unexcited, the electrons are in phase. When ultraviolet light is absorbed by the molecule, the electrons become out of phase and the antibonding orbital is called π^* (McMurry, 1992).

Because all organic contaminants have σ and π bonds, the transition of π and σ electrons into an antibonding state is a very important step in the destruction of organic contaminants in drinking water. Many of the slow or non-biodegradable organic contaminants found in ground water have ring molecules like benzene, pyridine, and furan compounds. Ultraviolet light is very effective in breaking up rings and making these compounds more prone to undergo mineralization or become more biodegradable.

Also important in the understanding of molecular destruction through ultraviolet light is the role of nonbonded electrons. These are pairs of electrons (called the (η) pair of electrons) that fill a molecular orbital, but were not formed by a bond.

An example of (η) electrons is the electron pairs of an oxygen atom in methyl alcohol $CH_3\ddot{O}H$..

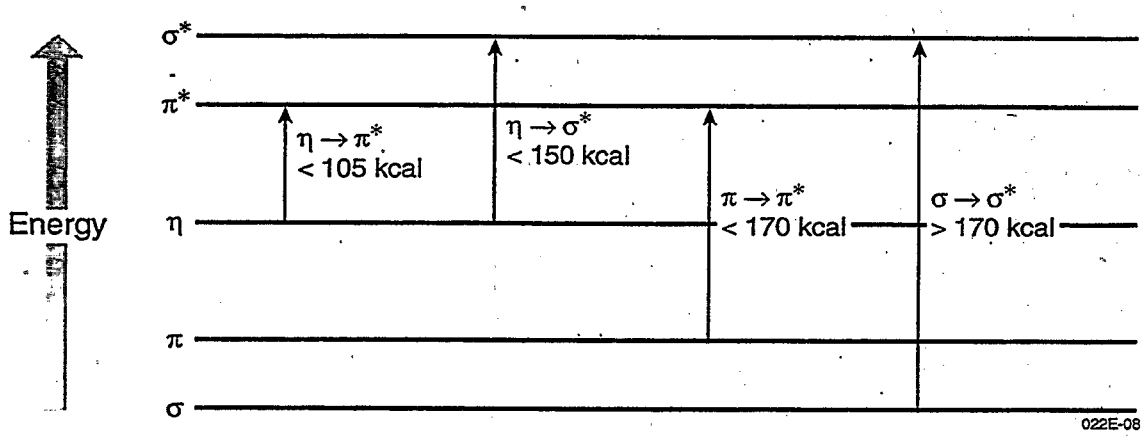
Exhibit B-1. A Précis Description of Chemical Bonding to Explain Organics Destruction Potential Using Ultraviolet Light (Continued)

When ultraviolet light is absorbed by such a molecule, the orbital containing (η) electrons does not have an antibonding orbital like σ and π, because it was not formed by the bonding of two orbitals. So when the molecule is excited by ultraviolet light, (η) electrons can either go to a π^* energy level or to a σ^* energy level. Organic compounds that contain nitrogen, sulfur, phosphorus, or halogen have unshared (η) electrons (Gaudy and Gaudy, 1980), therefore making them amenable to ultraviolet treatment.

Like all electromagnetic radiation, ultraviolet light is transmitted in packets of energy called photons or quanta. The energy of a photon is inversely proportional to the wavelength. What happens when ultraviolet light is intercepted by a molecule is that the molecule absorbs the photons, thus the number of photons decreases and the intensity of ultraviolet light decreases. The intensity of radiation is an important concept in the use of ultraviolet radiation for disinfection and destruction of organic chemicals and is proportional to the number of photons (Fessenden and Fessenden, 1986). As stated earlier, molecules absorb specific wavelengths of ultraviolet radiation. Therefore, a threshold energy level requirement must be met to break up bonds in a molecule.

The transition of electrons described above and presented in the figure below is at the heart of the destruction process of organic compounds.

Energy Requirements for Some Electronic Transmissions

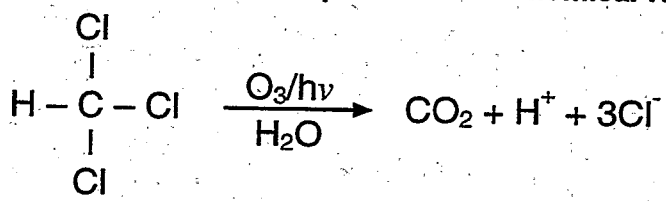


Examples of reactions in an O_3/UV system and other photochemical reactions are compiled from different sources in the following figure.

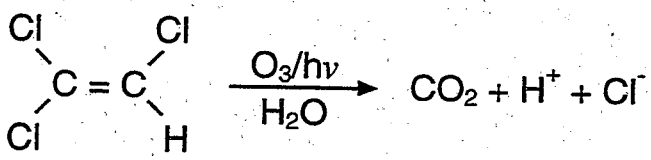
The reactions presented are unbalanced and are intended to show treated contaminants and resulting end products.

Exhibit B-1. A Précis Description of Chemical Bonding to Explain Organics Destruction Potential Using Ultraviolet Light (Continued)

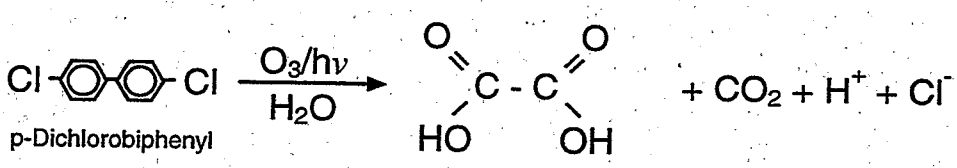
Examples of Photochemical Reactions



Trichloromethane (Chloroform)

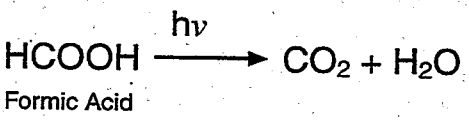


Trichloroethene

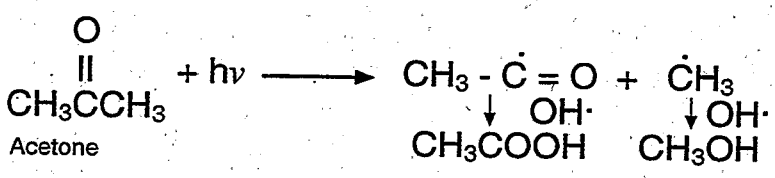


p-Dichlorobiphenyl

Oxalic Acid



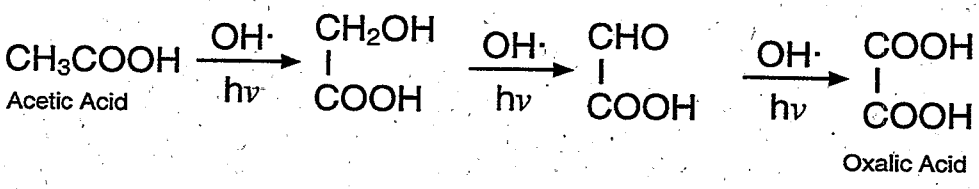
Formic Acid



Acetone

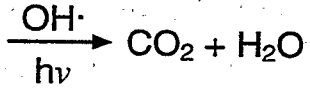
Acetic Acid

Methyl Alcohol (Methanol)



Acetic Acid

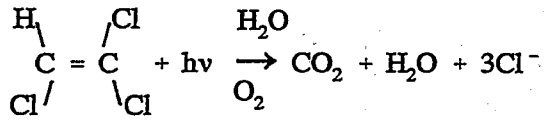
Oxalic Acid



022E-07

The destruction of an organic compound by ultraviolet light is given in the following example:

Trichloroethylene (TCE) is a contaminant found in many ground water sources in the United States.



$$H(Cl)C=C(Cl)Cl + h\nu \xrightarrow[O_2]{H_2O} CO_2 + H_2O + 3Cl^-$$

Ultraviolet light absorbed by dissolved oxygen and water molecules ultimately leads to the formation of unstable radicals such as hydroxyl radicals. These radicals react with excited TCE molecules and break them up, leading to the formation of the innocuous final product of water and carbon dioxide.

To effectively control organic compounds in water and wastewater using ultraviolet light, three approaches can be followed:

1. Determine the optimal absorption wavelength of the target compound, and order the hardware that can deliver ultraviolet light at that wavelength. The absorption spectra of many organic compounds are available in the literature.
2. Use ultraviolet light to produce compounds that can attack the target compound. For example, ultraviolet light at 184.9 nm attacks water molecules to produce $H^{\bullet}$ and $OH^{\bullet}$ radicals that are powerful oxidizing agents.
3. Increase the oxidizing power available by adding oxidizing agents such as ozone and hydrogen peroxide and then irradiate the water. The use of ultraviolet light not only will produce free radicals as in approach number 2 but also will excite the added ozone and hydrogen peroxide, thus increasing their already powerful oxidizing power.

It must also be noted that the oxidation potential of ultraviolet-produced radicals in drinking water compared to those of chlorine gas and ozone (in volts) is in the following order (Jody, Klein, and Judeikis, 1989):

$OH^{\bullet}$	>	$O^{\bullet}$	>	O_3	>	$HO_2^{\bullet}$	>	Cl_2	
2.80		2.42		2.07		1.70		1.36	in volts

The literature search conducted for this report resulted in the following findings regarding the destructive potential of organics using ultraviolet light. Nick et al. (1992) studied the degradation of selected triazine herbicides by ultraviolet light as used in the ultraviolet disinfection of drinking water. Triazine herbicides are a family of herbicides that include simazine and atrazine. Atrazine is a commonly used herbicide in

corn cultivation and is found in many ground water sources. In their research, Nick et al. (1992) addressed two issues:

- The extent to which ultraviolet photolysis of herbicides gives rise to new anthropogenic compounds that are as, or more, dangerous than the original compounds
- The extent to which herbicides degrade during normal ultraviolet application to drinking water.

Nick et al. (1992) noticed that many herbicides do not absorb ultraviolet light above 240 nm and that only those herbicides that contain an aromatic ring or similar chromophore may degrade at wavelengths above 240 nm. Using an ultraviolet lamp of an average dose of 25 mWs/cm^2, Nick et al. (1992) concluded that the degradation of triazine herbicides remains below 5 percent. Nick et al. (1992) also reported that a conversion of more than 10 percent of atrazine, simazine, propazine, and terbuthylazine by photodegradation did not result in mutagenicity (using the Ames test), even when the irradiated material was applied in high concentrations. Therefore, ultraviolet photolysis of triazine herbicides did not give rise to new equally or more hazardous compounds. Ultraviolet photolysis of triazine compounds does eliminate the mutagenicity risks associated with the triazine compounds. Treatment of drinking water for disinfection by commercially available POU ultraviolet lamps, even at doses as low as 25 mWs/cm^2, has a positive side effect. The Nick et al. (1992) research shows a herbicide degradation of less than 5 percent for four triazine compounds.

Exhibit B-2 presents the photodegradation of herbicides of the atrazine family as reported by Nick et al. (1992).

Exhibit B-2. Photodegradation of Herbicides of the Atrazine Family

Herbicide	Fraction Decomposed at 25 mWs/cm^2 (%)	Dose Required to Achieve 90% Decomposition (mWs/cm^2)
Atrazine	2.4	2400
Simazine	3.4	2700
Propazine	4.1	1400
Terbuthylazine	4.4	1300

As can be seen from Exhibit B-2, the dose required to degrade 90 percent of the initial herbicide concentration in the solution is about two orders of magnitude higher than the dose emitted by most commercially available ultraviolet devices used for disinfection purposes.

Francis (1989) studied the physio-chemical parameters of oxidating organic pollutants using ultraviolet light and ozone. Using ethylene glycol as a surrogate and a 2 kw antimony halide medium-pressure lamp, Francis (1989) concluded that using ultraviolet light after saturating the flow with ozone increased the reduction rate of TOC. Francis (1989) made another important observation. He observed that a smaller reactor in series with a larger reactor leads to an increase in TOC reduction. Francis (1989) attributed this increase in TOC reduction to the improved uniformity of the ultraviolet light distribution in the smaller reactor.

Berglind, Gjessing, and Johansen (1979) studied the effects of ultraviolet light in combination with H_2O_2 on aquatic humus and organic compounds. The early results compiled by the researchers showed that, after one minute of irradiating hydrogen peroxide containing water, a 45 percent reduction in color and a 43 percent reduction in organic carbon were achieved. The researchers also reported their own research on water containing humus and 65 µg/l of the contaminant 3,4-benzo(a)pyrene [B(a)P] (a polyaromatic hydrocarbon [PAH] compound, which is a contaminant regulated under the National Primary Drinking Water Regulations [NPDWR]), 1 µg/l 2-methylisoborneol (MIB), 100 µg/l of chloroform, and 100 µg/l of bromodichloromethane (BDCM). The results of the researchers' experiments are presented in **Exhibit B-3.** The ultraviolet radiation unit consisted of six 30-watt ultraviolet lamps; however, the intensity was not reported in the published paper.

As can be seen from **Exhibit B-3**, after 2 hours of irradiation without hydrogen peroxide, 29 percent of B(a)P was destroyed and 91 percent was destroyed in the presence of hydrogen peroxide.

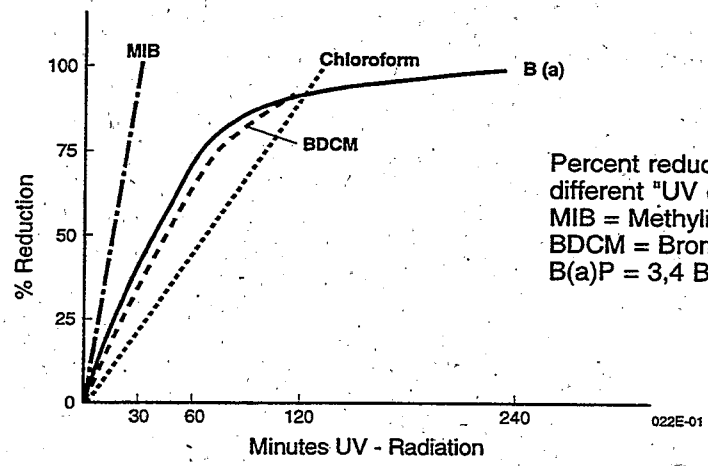
The results for chloroform and BDCM were better, with 58 percent and 91 percent reduction in chloroform and 25 percent and 91 percent reduction in BDCM without and with the addition of 0.1 ml 35-percent hydrogen peroxide in a 0.8 liter reactor.

Xu et al. (1989), using ozone and ultraviolet light, examined TOC reduction in wastewater under different pH conditions. Xu et al. (1989) used the compound pyridine as a surrogate for refractory compounds commonly found in industrial wastewater. The Xu et al. (1989) research shows that at high pH, better TOC reductions could be attained. The research also suggests that the breakup of pyridine molecules occurs in stages where the ozone breaks the ring molecule, leading the way to more oxidative intermediary

Exhibit B-3. Removal of Organic Chemicals from Water with Ultraviolet Radiation and Hydrogen Peroxide

µg/l (percent destruction)							
	Without H_2O_2			With 0.1 ml 35 % H_2O_2/l			
Minutes UV Radiation	B(a)P	Chloroform	BDCM	B(a)P	MIB	Chloroform	BDCM
0	65 (0)	100 (0)	100 (0)	–	1	100 (0)	100 (0)
30	–	–	–	–	0 (100)	75 (25)	58 (42)
60	–	92 (8)	91 (9)	18 (72)	–	68 (32)	44 (56)
120	42 (29)	42 (58)	75 (25)	6 (91)	–	9 (91)	9 (91)
240	–	–	–	1 (98)	–	–	–

B(a)P: 3,4-Benzo(a)pyrene
MIB: Methylisoborneol
BDCM: Bromodichloromethane
( ): Denotes percent-reduction

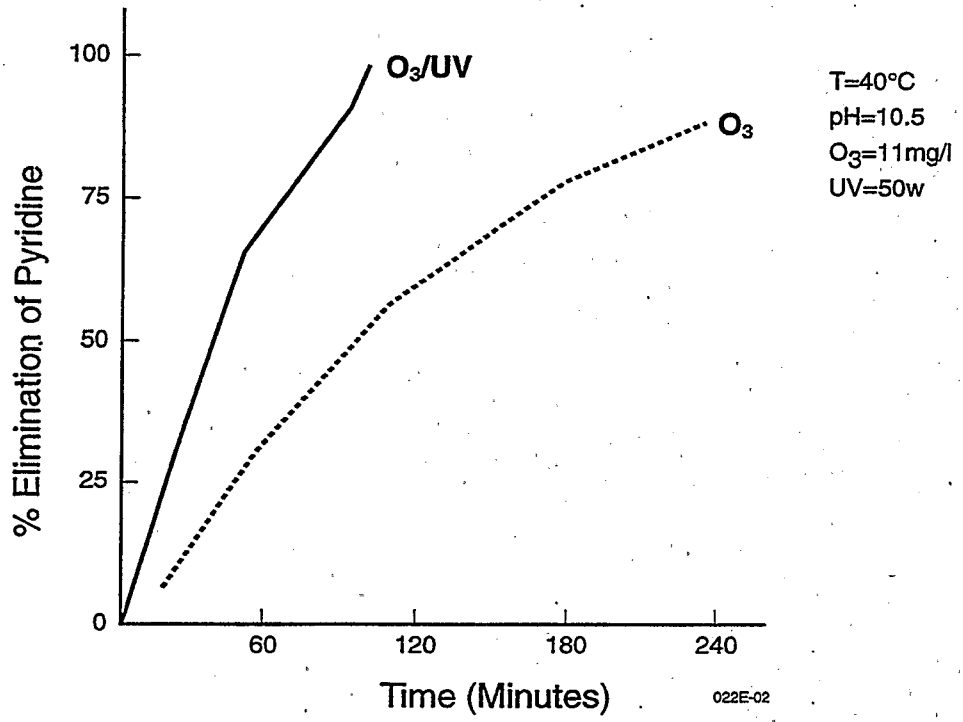


Percent reduction of chemicals in aqueous solutions with different "UV doses"; 0.1 ml 35% H_2O_2/l was added.
MIB = Methylisoborneol
BDCM = Bromodichloromethane
B(a)P = 3,4 Benzo(a)pyrene

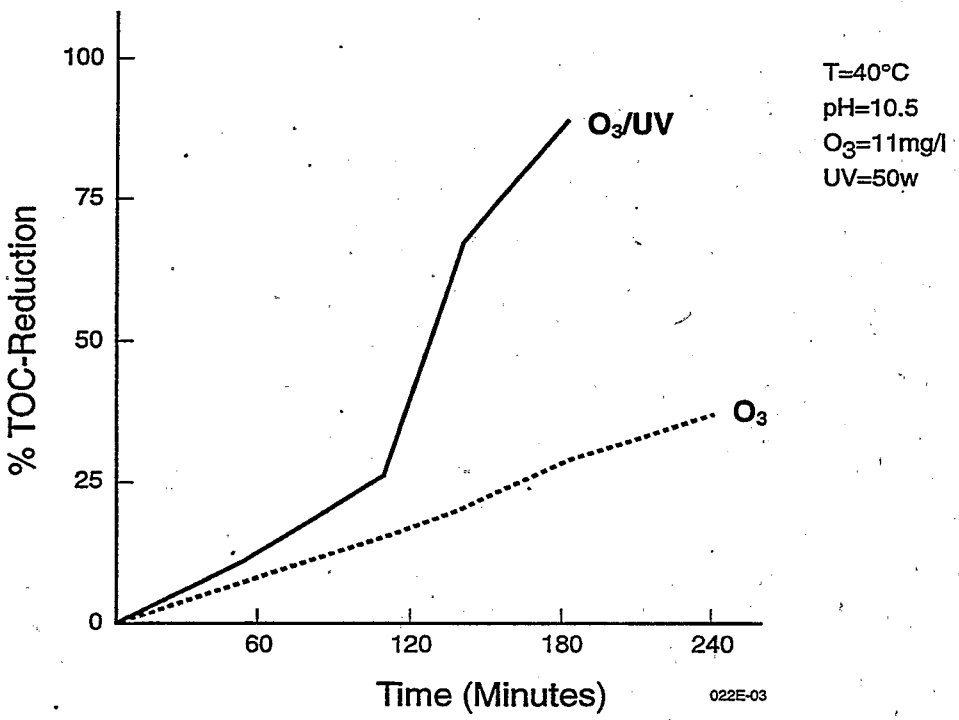
compounds. Once all pyridine molecules are destroyed, a fast degradation of TOC occurs as the newly formed intermediary compounds quickly mineralize (i.e., breaking organic compounds down to inorganic compounds such as CO_2 and H_2O). Xu et al. (1989) found that pH 10.3 to be the optimal pH. The results of the Xu et al. (1989) work are presented in **Exhibits A-4** and **A-5**.

Exhibit B-4 shows that the breakup rate of pyridine in an ozone/ultraviolet system was faster than the TOC reduction rate in the same system and under the same conditions. This implies that complete mineralization of pyridine is not direct and that intermediary organic compounds are formed in the process. Exhibit B-4 also shows that a combined ozone/ultraviolet system is more effective in destroying pyridine and reducing TOC than an ozone system alone.

Exhibit B-4. Elimination of Pyridine and TOC Reduction by O_3/UV and Ozone Alone

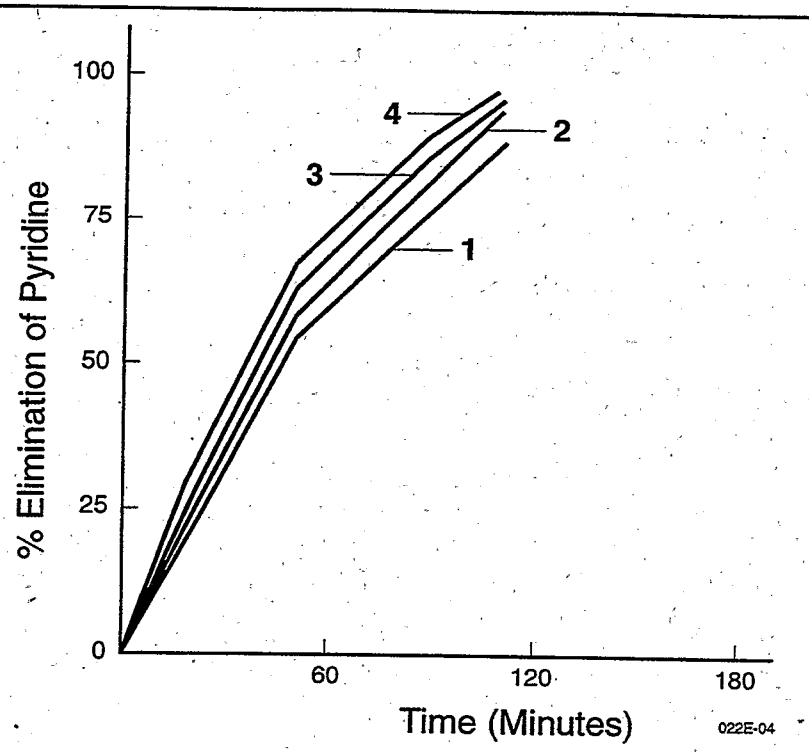


a. Percent elimination of pyridine by O_3/UV and O_3 alone



b. Percent reduction of pyridine TOC by O_3/UV and O_3 alone

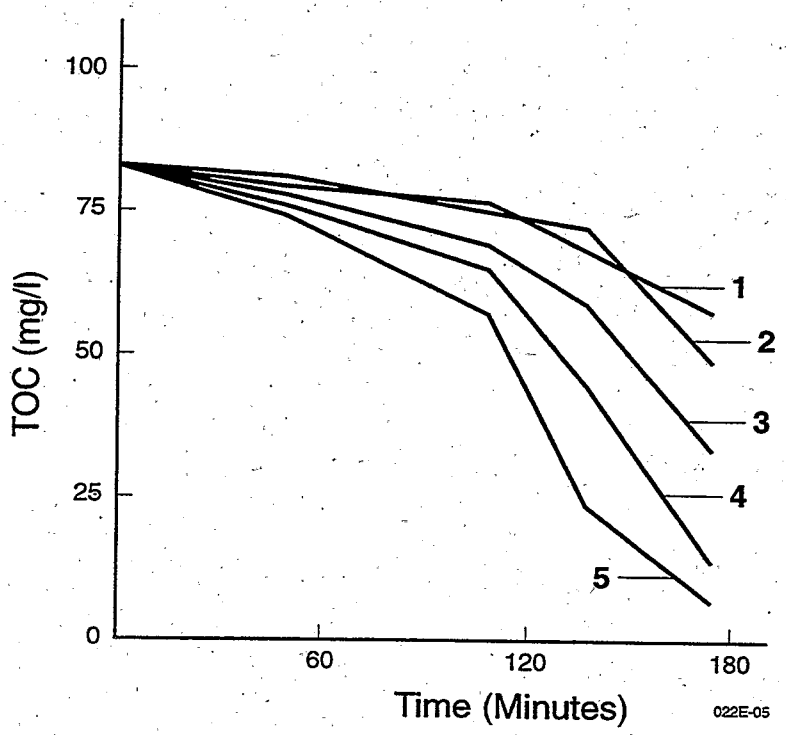
Exhibit B-5. Pyridine Elimination and TOC Reduction at Different pHs



1. pH=2.1
2. pH=12
3. pH=7.8
4. pH=10.5

T=40°C, UV=50W
O_3 at 10.7-10.8 mg/l
initial concentration
of pyridine 194ppm

a. Percent elimination of pyridine at different pHs



1. pH=2.1
2. pH=12
3. pH=3.5
4. pH=7.8
5. pH=10.5

T=40°C, UV=50W
O_3 at 10.7-10.8 mg/l
initial concentration
of pyridine 194ppm

b. TOC reduction at different pHs

Exhibit B-5 shows that at low pH, pyridine destruction rate and TOC reduction rates are the lowest. The highest pyridine destruction rate and TOC reduction rate occurred at a pH of 10.5.

Yu, Wan, and Tsai (1989) compared TOC removal from activated sludge using oxygen/ultraviolet systems versus ozonation as pretreatment. The researchers found that in activated sludge, pretreatment with ozone had a better effect on the biodegradability of phenolic compounds than the O_2/UV system. The researchers did not report any ultraviolet doses in their published paper.

Zeff, Leitis, and Barich (1989) used ultraviolet/ozone and ultraviolet/H_2O_2 systems to control an array of contaminants usually found in ground water at Superfund sites. The researchers reported that tetrachloroethylene or perchloroethylene (PCE) contaminated water treated with these systems resulted in the reduction of VOCs and color to below State action level. They also reported that dibromochloropropane (DBCP) and PCBs were reduced to less than 1 ppb. Both contaminants are regulated under NPDWR with an MCL of 0.002 mg/l for DBCP and an MCL of 0.0005 mg/l for PCBs. The researchers reported direct operation and maintenance costs associated with treating PCE-contaminated drinking ground water of 200 ppb as being $0.20 to $0.30 per 1,000 gallon (1989 prices).

Jody, Klein, and Judeikis (1989), using ozone/ultraviolet systems to treat wastewater containing hydrazine compounds, found that the presence of metal ions such as copper and iron help in the destruction of hydrazine compounds. The researchers also confirmed the findings of Xu et al. (1989) that the destruction of organic compounds is more efficient at high pH. The researchers did not report any ultraviolet doses in their published paper. More research on the effects of metal ions on the destruction of organic contaminants is needed to elucidate the processes involved and determine the kinetics of the destruction process.

In a more recent study of Ultrox®, Zeff (1993) reported the results of using an ozone/hydrogen peroxide/ ultraviolet system to remove PCE from a contaminated ground water well. The results are presented in **Exhibit B-6.** As can be seen from Exhibit B-6, the system tested is capable of reducing PCE levels to below MCL levels and 1,1,2-trichloroethane (TCA) levels in two tests. However, the author did not report any specific ultraviolet doses.

Exhibit B-6. Ultrox® Demonstration at South Gate Ground Water Supply Site

Pilot Test Procedures and Analytical Results* (all tests run at 50 gpm)							
				PCE Analysis		TCA Analysis	
Test No.	O_3 Dose (mg/l)	H_2O_2 Dose (mg/l)	UV Lamp Complement	Infl. H_2O (ppb)	Effl. H_2O (ppb)	Infl. H_2O (ppb)	Effl. H_2O (ppb)
1	13	None	Full	14	4	3	2.4
2	19	None	Full	20	0.2	N/D**	N/D**
3	19	8.3	None	17	0.4	–	–
4	0	13	None	17	14	–	–
5	0	8.3	One Third	17	0.1	–	–
6	0	0	Full	17.5	4	0.4	0.5
7	13	8	None	18	0.2	0.5	0.4
8	0	8.3	One Fourth	16	13	1.3	1.3
9	0	8.3	One Half	16	1.3	1.2	0.3
10	9	4	None	18	2.2	–	–
11	13	0	None	–	0.32	–	–
12	9	0	None	18	4.4	–	–

*Analysis conducted by Ultrox's Analytical Laboratory.
**Non-detectable
TCA = 1,1,2-trichloroethane MCL of 5 ppb
PCE = tetrachloroethylene MCL of 5 ppb

The six tests that produced PCE levels below 2 ppb are:

Test No.	Conditions
2	UV/O_3
3	O_3/H_2O_2
5	$UV//H_2O_2$
7	O_3/H_2O_2
9	UV/H_2O_2
11	O_3

Leitzke (1993) used an ozone/ultraviolet system to treat ground water contaminated with chlorinated organic compounds. The system was manufactured by WEDECO, a German firm. In this system, a small flow of ozone-rich water is mixed with the raw water entering the ultraviolet reactor. The results are presented in **Exhibit B-7**.

Exhibit B-7. Chlorinated Hydrocarbon Elimination with Ozone/Ultraviolet Treatment in Drinking Water Supply of Niederrohrdorf

Parameter	Sample A (µg/l)		Sample B (µg/l)	
	Before	After	Before	After
	Ozone/UV-Treatment		Ozone/UV-Treatment	
1,1-Dichloroethylene	<0.05	0.12	n.a.	n.a.
cis-1,2k-Dichloroethylene	31	0.37	16	0.06
Chloroform	0.12	<0.05	<0.05	0.1
1,1-Dichloropropene	0.12	<0.05	n.a.	n.a.
Trichloroethylene	100	5.9	84	5.3
Perchloroethylene	0.12	<0.05	n.a.	n.a.

Gehringer et al. (1993) investigated the feasibility of using an ozone/ultraviolet system to treat TCE- and PCE-contaminated water in a real situation compared to an ozone/electron beam system. The researchers found that the destruction of organic compounds using an O_3/electron beam system was about one order of magnitude higher than the destruction obtained using the ozone/ultraviolet system. Moreover, the researchers found that the electric power consumption in an ozone/electron beam accelerator system was five times less than that of an ozone/ultraviolet system. The ultraviolet lamp used in the experiment had an output of 7.8 kw and the electron beam output was a 500 keV electron accelerator, or 8×10^{-14} Joules.[1]

In 1994, the *Journal of Hazardous Waste Consultants* compared the use of ultraviolet systems for the destruction of VOCs with other technologies and noted that ultraviolet systems destroy VOCs found in drinking water, while air stripping systems, for example, transfer the VOC contamination from the liquid phase to the gas phase (JHWC, 1994).

B.4 OPERATIONAL FACTORS

Operational factors that should be considered for maximizing the effectiveness of ultraviolet systems for the destruction of organic contaminants are the following:

- Proper selection of an ultraviolet lamp that emits the proper effective wavelength range and that delivers the required dose.
- Age of the lamps.

[1]KeV = 1.6 x 10^{-16} Joules
1 Watt = 1 Joule/sec

- Keeping track of lamp efficiency, particularly when lamps are at the end of their operational life span.
- Cleaning the unit periodically as recommended in the manufacturer's manual, regardless of whether the unit looks clean to the naked eye.
- Waters that contain light-obstructing material, such as colloids or certain minerals such as iron, need to be treated before entering the ultraviolet unit.
- Keeping a record of influent and effluent quality parameters such as pH and ORP (oxidation reduction potential) to monitor any sudden changes that require immediate attention.

The following section discusses factors related to ultraviolet wavelength transmission and presents intensities required to destroy certain chemical bonds normally found in organic contaminants. Other operational factors are discussed in more detail in Chapter 2.

The graphical presentation for the distribution of wavelengths emitted by low- and medium-pressure arcs given in (Exhibit 1-3) was constructed from a paper published by Legan in 1982. As can be seen from Exhibit 1-3 and Exhibit B-8, for that specific low-pressure lamp, about 93 percent of ultraviolet light is transmitted at 254 nm and 6 percent is transmitted at 185 nm.

The distribution of wavelengths emitted by modern low-pressure arcs used in water application varies but is assumed to be at a minimum about 85 percent of the energy at 254 nm (range 85% - 90%), 7-10 percent of the emitted energy in the 180 to 185 nm range, and 5 percent at more than 254 nm (von Sonntag and Schuchman, 1992). This spectrum of ultraviolet light range increases the likelihood of ultraviolet absorption by different molecules. As stated earlier, molecules absorb ultraviolet energy at specific wavelengths and not at all wavelengths. For example, benzene absorbs ultraviolet light at 260 nm. Thus, when a low-pressure ultraviolet light is used for disinfection of drinking water, a contaminant that absorbs a wavelength other than 254 nm wavelength will absorb the specific wavelength that constitutes a small fraction of the light emitted by the ultraviolet lamp.

There are medium-pressure and high-pressure arc lamps that are capable of producing a broader spectrum of the ultraviolet range, and there are high-pressure arc lamps that produce the bulk of their ultraviolet light at a higher energy wavelength (180 to 185 nm). These high-energy (shorter)[2] wavelengths are

[2]Intensity is defined as the power transferred across a unit area, where:
Power = Work/time = Energy transferred/time, where Energy is inversely proportional to wavelength.
For further details, please refer to page vii.

capable of producing unstable radicals that in turn attack other organic compounds found in the water. This is an important mechanism in which contaminants that do not absorb the ultraviolet light emitted energy, or only a small portion of it, get destroyed by intermediaries formed by ultraviolet light action.

Exhibits A-9 and A-10 (presented below) are intended to give an idea of the destruction potential of ultraviolet light against various organic and inorganic compounds. The maximum wavelengths (lowest energy) needed to break a bond (σ or π) varies from one compound to the other. This variation in energy requirements to break an organic compound also can be found in the range of wavelengths that could be absorbed in certain compounds. For example, for aromatic compounds, intense ultraviolet light absorption occurs at 205 nm, while weak ultraviolet light absorption occurs at 260 nm (McMurry, 1992).

The power of various wavelengths emitted by different ultraviolet lamps are presented in **Exhibit B-8**. Exhibit 2-8 shows that the wavelengths emitted by ultraviolet light vary from one pressure lamp to the other. As can be seen from Exhibit B-8, low-pressure arc lamps emit the bulk of their energies at about 254 nm wavelength, while medium- and high-pressure lamps emit their energies at a wider range. The germicidal effects of ultraviolet light at 254 nm are high. Because of that, when ultraviolet light is to be used for disinfection, low-pressure mercury lamps are selected over medium- and high-pressure mercury lamps.

Exhibit B-9 presents the maximum light wavelengths (minimum energies) absorbed by electrons in different chemical bond settings and leading to their dissociation. Exhibit B-9 shows the energy required to break different types of covalent bonds. The values presented in Exhibit B-9 are to be viewed as trend-indicative and not as exact values. Exhibit B-9 shows which wavelengths, and therefore ultraviolet energies, can interfere in the motions of a pair of electrons forming a covalent bond to the level of breaking the bond they form. For example, the H-O bond in water will break under the effect of ultraviolet light at a wavelength of about 185 nm. This H-O bond break will lead to the formation of powerful hydroxyl radicals. In natural waters, these radicals react with organic compounds or microorganisms normally found in water and cause a change in their nature.

Exhibit B-10 presents important photochemical reactions that relate to organics destruction and microorganisms disinfection. The photochemical reactions presented in Exhibit B-10 show the formation of free radicals in water under the effect of ultraviolet light.

Exhibit B-8. Power of Light Emitted by Mercury-Vapor Ultraviolet Lamps

Wavelength, nm	Power, W		
	Low-Pressure (85W)	Medium-Pressure (550W)	High-Pressure (7,500W)
Infrared			
1,367.3	–	4.6	39.3
1,128.7	–	3.8	46.2
1,014.0	–	12.2	165.0
Visible			
578.0 (yellow)	3.04	23.0	297.0
546.1 (green)	0.26	28.2	290.0
435.8 (blue)	0.30	23.3	216.0
404.5 (violet)	0.12	12.7	150.0
Ultraviolet			
366.0	0.16	30.1	44.30
334.1	0.01	2.8	46.6
313.0	0.18	15.0	270.0
302.5	0.02	8.2	117.6
296.7	0.06	5.0	66.9
289.4	0.01	1.8	21.0
280.4	0.01	2.8	63.9
275.3	0.01	0.8	21.6
270.0	–	1.2	22.9
265.2	0.02	4.6	158.0
257.1	–	1.8	31.0
253.7 (germicidal)	30.00	5.0	137.0
248.2	–	2.6	41.8
240.0	–	2.2	31.9
232.0	–	2.4	31.2
184.9	1.80	0.3	8.2
Total ultraviolet power	32.30	95.2	1,619.1

Source: Canrad-Hanovia, Inc., as cited in Legan, 1982.

Exhibit B-9. Dissociation Energies for Chemical Bonds

Bond	Dissociation Energy, kcal/gmol	UV Light Maximum Wavelength to Break Bond, nm	Will UV Light at These Wavelengths Break the Bond?	
			253.7 nm	184.9 nm
Carbon				
C–C	82.6	346.1	yes	yes
C=C	145.8	196.1	no	yes
C≡C	199.6	143.2	no	no
C–Cl	81.0	353.0	yes	yes
C–F	116.0	246.5	no	yes
C–H	98.7	289.7	yes	yes
C–N	72.8	392.7	yes	yes
C=N	147.0	194.5	no	yes
C≡N	212.6	134.5	no	no
C–O	85.5	334.4	yes	yes
C=O (aldehydes)	176.0	162.4	no	no
C=O (ketones)	179.0	159.7	no	no
C–S	65.0	439.9	yes	yes
C=S	166.0	172.2	no	no
Hydrogen				
H–H	104.2	274.4	yes	yes
Nitrogen				
N–N	52.0	549.8	yes	yes
N=N	60.0	476.5	yes	yes
N≡N	226.0	126.6	no	no
N–H (NH)	85.0	336.4	yes	yes
N–H (NH_3)	102.0	280.3	yes	yes
N–O	48.0	595.6	yes	yes
N=O	162.0	176.5	no	no
Oxygen				
O–O (O_2)	119.1	240.1	no	yes
–O–O–	47.0	608.3	yes	yes
O–H (water)	117.5	243.3	no	yes
Sulfur				
S–H	83.0	344.5	yes	yes
S–N	115.0	248.6	no	yes
S–O	119.0	240.3	no	yes

Source: Dean, 1973, as cited in Legan, 1982.

Exhibit B-10. Examples of Photochemical Reactions and Their Effects

Reaction	Effective Wavelength, nm	Result
$H_2O + h\nu = H^{\bullet} + HO^{\bullet}$	184.9	Water broken into free radicals
$H_2O_2 + h\nu = 2\ HO^{\bullet}$	253.7	Hydrogen peroxide broken into hydroxyl radicals
$O_2 + h\nu = O_3$	253.7	Oxygen molecules converted to ozone
$RH + h\nu = H^{\bullet} + R^{\bullet}$	184.9	Organic broken into free radicals
$Fe^{+2} + h\nu = Fe^{+3}$	253.7	Ferrous ion converted to ferric ion
$Fe(CN)_6^{-4} + h\nu = Fe(CN)_6^{-3}$	184.9	Ferrocyanide ion converted to ferricyanide ion
$NO + h\nu = N_2 + O_2$	184.9	Nitric oxide decomposed (smog avoided)
$NO_2 + h\nu = NO + O$	313.0	Nitric oxide formed (part of smog cycle)
$NH_3 + h\nu = NH_2^{\bullet} + H^{\bullet}$	184.9	Ammonia broken into free radicals

Source: Calvert and Pitts, 1966, as cited in Legan, 1982.

B.5 ULTRAVIOLET LIGHT TECHNOLOGY AND CURRENT SAFE DRINKING WATER REGULATIONS

Ultraviolet light is not identified as a Best Available Technology (BAT) for the treatment of any NPDWR contaminant. The current advances in ultraviolet technology and its wide applications alone and in combination with ozone and hydrogen peroxide in treating ground water contamination in many Resource Conservation and Recovery Act (RCRA) Superfund sites strongly suggest its dual beneficial use as a disinfectant and as an organics control technology.

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APPENDIX C. QUESTIONNAIRE USED FOR STATE INQUIRY AND AS GUIDE IN TELEPHONE INQUIRIES

U.S. EPA
SAIC Contract 68-C3-0365
Ultraviolet Light Disinfection Study

C.1 GENERAL SYSTEM QUESTIONS AND EQUIPMENT

1. What is the location of the system?
2. What is the population served and design flow?
3. When was the system installed?
4. Why was UV treatment selected? What was the anticipated advantage over traditional disinfection systems?
5. Is the UV system a closed-type system or an open type system?
6. Is the system equipped with telemetry control system? Is there a fully automated backup system in place?
7. Was the UV system locally manufactured? Did it come with a warranty?
8. Does the public water system have storage capacity? What is the capacity? Open reservoirs or cisterns?
9. Type of treatment applied before and after UV treatment (secondary disinfection)?
10. If chlorination is used as a secondary disinfectant what kind of chlorination (gas, chloramine, calcium or sodium hypochlorites)? What are the assumed and residual doses?
11. How are UV intensity and dose measured?

C.2 WATER DATA

1. What is the maximum turbidity levels before and after UV treatment?
2. What are the maximum iron levels in source water or before UV treatment?
3. Have there been any coliform outbreaks? Any increase in biofilm formation in the network has been noticed?
4. Have there been any microbiological problems?

C.3 OPERATION AND MAINTENANCE

1. How often does the system get cleaned?

2. Is the system equipped with mechanical wipers? Ultrasonic cleaners? Are cleaning agents used to clean the system manually? Is water under high pressure used to clean the units? At what pressure? If any which cleaning agents are used (synthetic detergents, dilute hydrochloric acid, dilute sulfuric acid, dilute phosphoric acid)?

3. Was any special training provided for employees dealing with UV equipment?

4. How much time does it take to clean a unit? How many persons do the cleaning at a time?

5. How often does a sleeve or bulb get broken during cleaning?

6. How often are bulbs, sleeves, diodes, and ballasts replaced?

7. How often and by what method does the system get calibrated?

C.4 COSTS

1. What was the cost of the system?

2. Were engineering, installation, and training included in the price? If not, what was the additional cost?

3. What are the operation and maintenance costs? What are the labor requirements (hours per week) and costs?

4. If the system is equipped with telemetry control, what was the cost?

C.5 ON-SITE CONTACT

1. Contact name, phone number, and address

APPENDIX D. REGULATIONS AND STANDARDS FOR DRINKING WATER DISINFECTION USING ULTRAVIOLET LIGHT

D. INTRODUCTION

This appendix provides available regulations and standards regarding the use of ultraviolet light for drinking water disinfection. This appendix includes the 1966 U.S. Department of Health, Education, and Welfare (DHEW) policy statement on the use of ultraviolet light for water disinfection (copies provided by Ideal Horizons, Inc. and Atlantic Ultraviolet Corporation). Also, this appendix presents ultraviolet light regulations, guidance, and standards used in the States of Utah, Wisconsin, Pennsylvania, and New Jersey. In addition, Sections 1 through 6 and the preface of the ANSI/NSF Standard 55-1991 are presented in this appendix. These excerpts are reprinted with permission from NSF International. All the regulations, guidance, and standards are copied verbatim and seriatim from documents provided by the respective State's drinking water supervision managers.

D.1 DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

[April 1, 1966]

DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
PUBLIC HEALTH SERVICE

Division of Environmental Engineering and Food Protection

Policy Statement on Use of the Ultraviolet Process for Disinfection of Water

The use of the ultraviolet process as a means of disinfecting water to meet the bacteriological requirements of the Public Health Service Drinking Water Standards is acceptable provided the equipment used meets the criteria described herein.

In the design of a water treatment system, care must be exercised to insure that all other requirements of the Drinking Water Standards relating to the Source and Protection, Chemical and Physical Characteristics, and Radioactivity are met. (In the case of an individual water supply, the system should meet the criteria contained in the "Manual of Individual Water Supply Systems", Public Health Service Publication # 24.) The ultraviolet process for disinfecting water will not change the chemical and physical characteristics of the water. Additional treatment, if otherwise dictated, will still be required, including possible need for residual disinfectant, in the distribution system.

Color, turbidity, and organic impurities interfere with the transmission of ultraviolet energy and may decrease the disinfection efficiency below levels required to insure destruction of pathogenic organisms. It may be necessary to pretreat some supplies to remove excess turbidity and color. In general, units of color and turbidity are not adequate measures of the decrease that may occur in ultraviolet energy transmission. The organic nature of materials present in waters can give rise to significant transmission difficulties. As a result, an ultraviolet intensity meter is required to measure the energy levels to which the water is subjected.

Ultraviolet treatment does not provide residual bactericidal action. Therefore, the need for periodic flushing and disinfection of the water distribution system must be recognized. Some supplies may require routine chemical disinfection, including the maintenance of a residual bactericidal agent throughout the distribution system.

D.1 DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE (CONTINUED)

Criteria for the Acceptability of an Ultraviolet Disinfecting Unit

1. Ultraviolet radiation at a level of 2,537 Angstrom units must be applied at a minimum dosage of 16,000 microwatt-seconds per square centimeter at all points throughout the water disinfection chamber.

2. Maximum water depth in the chamber, measured from the tube surface to the chamber wall, shall not exceed three inches.

3. The ultraviolet tubes shall be:

   A. Jacketed so that a proper operating tube temperature of about 105°F is maintained.
   B. The jacket shall be of quartz or high silica glass with similar optical characteristics.

4. A flow or time delay mechanism shall be provided to permit a two minute tube warm-up period before water flows from the unit.

5. The unit shall be designed to permit frequent mechanical cleaning of the water contact surface of the jacket without disassembly of the unit.

6. An automatic flow control valve, accurate within the expected pressure range, shall be installed to restrict flow to the maximum design flow of the treatment unit.

7. An accurately calibrated ultraviolet intensity meter, properly filtered to restrict its sensitivity to the disinfection spectrum shall be installed in the wall of the disinfection chamber at the point of greatest water depth from the tube or tubes.

8. A flow diversion valve or automatic shut-off valve shall be installed which will permit flow into the potable water system only when at least the minimum ultraviolet dosage is applied. When power is not being supplied to the unit, the valve should be in a closed (fail-safe) position which prevents the flow of water into the potable water system.

9. An automatic, audible alarm shall be installed to warn of malfunction or impending shutdown if considered necessary by the Control or Regulatory Agency.

10. The materials of construction shall not impart toxic materials into the water either as a result of the presence of toxic constituents in materials of construction or as a result of physical of [sic] chemical changes resulting from exposure to ultraviolet energy.

11. The unit shall be designed to protect the operator against electrical shock or excessive radiation.

D.1 DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE (CONTINUED)

As with any potable water treatment process, due consideration must be given to the reliability, economics, and competent operation of the disinfection process and related equipment, including:

1. Installation of the unit in a protected enclosure not subject to extremes of temperature which cause malfunctions.

2. Provision of a spare ultraviolet tube and other necessary equipment to effect prompt repair by qualified personnel properly instructed in the operation and maintenance of the equipment.

3. Frequent inspection of the unit and keeping a record of all operations, including maintenance problems.

D.2 UTAH

R309 Drinking Water Regulations
Utah Department of Environmental Quality,
Division of Drinking Water

R309-107-9. Ultraviolet Light.

Proposals for use of ultraviolet disinfection should be discussed with the Division of Drinking Water prior to the preparation of final plans and specifications.

Secondary disinfection and maintenance of the required residual will be necessary where disinfection of the supply is required.

Ultraviolet disinfection will be permitted where the design conforms to the minimum recommendations of the U.S. Public Health Service listed below.

(1) Ultraviolet radiation at a level of 2,537 Angstrom units must be applied at a minimum dosage of 16,000 microwatt-seconds per square centimeter per second (1,600 Finsen Units) at all points throughout the water disinfection chamber.

(2) Maximum water depth in the chamber, measured from the tub surface to the chamber wall, shall not exceed three inches.

(3) The ultraviolet tubes shall be:

(a) Jacketed so that a proper operating tube temperature of about 105 degrees F is maintained.

(b) The jacket shall be of quartz or high silica glass with similar optical characteristics.

(4) A flow or time delay mechanism shall be provided to permit a two minute tube warm-up period before water flows from the unit.

(5) The unit shall be designed to permit frequent mechanical cleaning of the water contact surface of the jacket without disassembly of the unit.

(6) An automatic flow control valve, accurate within the expected pressure range, shall be installed to restrict flow to the maximum design flow of the treatment unit.

(7) An accurately calibrated ultraviolet intensity meter, properly filtered to restrict its sensitivity to the disinfection spectrum, shall be installed in the wall of the disinfection chamber at the point of greatest water depth from the tube or tubes.

D.2 UTAH (CONTINUED)

(8) A flow diversion valve or automatic shut-off valve shall be installed which will permit flow into the potable water system only when at least the minimum ultraviolet dosage is applied. When power is not being supplied to the unit, the valve should be in a closed position which prevents the flow of water into the potable water system.

(9) An automatic, audible alarm shall be installed to warn of malfunction or impending shutdown.

(10) The materials of construction shall not impart toxic materials into the water either as a result of the presence of toxic constituents in materials of construction or as a result of physical or chemical changes resulting from exposure to ultraviolet energy.

(11) The unit shall be designed to protect the operator against electrical shock or excessive radiation.

(12) As with any potable water treatment process, due consideration must be given to the reliability, economics, and component operation of the disinfection process and related equipment, including:

(a) Installation of the unit in a protected enclosure not subject to extremes of temperature which could cause malfunction.

(b) Provision of a spare UV tube and other necessary equipment to effect prompt repair by qualified personnel properly instructed in the operation and maintenance of the equipment.

D.3 WISCONSIN

Department of Natural Resources Criteria for
Ultraviolet (UV) Water Treatment Devices
for Private and Non-Community Public Water Supplies
To Control Microbiological Contamination
November 17, 1995

Introduction

The Department has historically required use of wells that naturally produce bacteriologically safe water. The rational is that microbiologically safe groundwater provides the best long-term public health protection. The potential for providing a naturally safe water source must be fully evaluated and found to be impracticable before a treatment process can be approved by the Department.

This document contains information about UV treatment design criteria for microbiologically contaminated private and non-community public water supplies. It contains general information and guidance, specifies when DNR approval is required, lists information that is to be submitted for DNR approval and lists likely approval conditions. Refer to the well code, Chapter NR 812, Wis. Adm. Code, specifically ss. NR 812.09 and NR 812.37, for specific administrative code requirements.

General

Well owners may install a UV water treatment system on a safe water supply without Department approval. The Department recommends that the owner comply with the design criteria specified in the remainder of this document. Unsafe water supply wells eligible for UV treatment are those that have confirmed positive test results for total coliform or Escherichia coli bacteria more than once, have failed three attempts at batch chlorination to eliminate the problem <u>and</u> which do not appear to be correctable by well reconstruction or replacement.

Wells where treatment is proposed for microbiological contamination shall comply with chapter NR 812, Wis. Adm. Code requirements. The well depth and depth of casing must be determined from the well construction report or an actual measurement. Casing depths shall meet either the special casing requirement for the area or be extended to a greater depth than the present special casing requirement. An exception may be made when the Department agrees that there is a low probability of acquiring safe water at a greater depth. In this case, the required minimum well casing depth shall be determined on a case-by-case basis.

D.3 WISCONSIN (CONTINUED)

Private residential UV water treatment devices serving one or two dwellings must be approved by the Department of Industry, Labor and Human Relations (DILHR) prior to installation or sale. Installation must be made according to manufacturers printed instructions and Chapters ILHR 81 through 86, Wisconsin Administrative Code. An owner may install the treatment device on their residence. A licensed pump installer or plumber is required for installation on rented property that an owner does not occupy and for non-community systems. Contracted work shall be done by a licensed pump installer if the device will be installed before the pressure tank. A licensed plumber must install the equipment after the pressure tank. All work must comply with applicable code requirements.

Water Quality Characteristics

The water supply shall be analyzed for the following water quality parameters and the results shall be included in the UV application. Pretreatment is required for UV installations if the water quality exceeds any of the following maximum limits. When an initial sample exceeds a maximum limit, a check sample shall be taken and analyzed.

Parameter	Maximum	Preferred
Color	15 APHA units	No APHA units
Dissolved Iron	0.3 mg/L	<0.01 mg/L
Dissolved Manganese	0.05 mg/L	<0.0004 mg/L
Hardness	120 mg/L	17.1 mg/L
Hydrogen Sulfide	Non-Detectable	Same
Iron Bacteria	None	Same
pH	6.5 to 9.5	Same
Suspended Solids	10 mg/L	<1 mg/L
Turbidity	5.0 NTU	1.0 NTU
Total Coliform	1,000 Colonies/100 mg/L	
Escherichia coli	100	

Raw water quality shall be evaluated and pretreatment equipment shall be designed to handle water quality changes. Turbidity caused by rainfall events is of special concern.

UV with Microfiltration Approval Process

DNR approval is required prior to installation of a UV water treatment device on a microbiologically unsafe water supply.

D.3 WISCONSIN (CONTINUED)

1. The owner must sign a short statement describing the steps taken to correct the microbiological problem and send it along with the application to:

DNR Private Water Supply WS/2
Box 7921
Madison, WI 53707-7921

2. The DNR will review the application for completeness. Incomplete materials will be returned. Disapproved applications will be returned to the applicant with the reasons for disapproval. There is no fee for reviewing the application.

3. Installation of the DNR approved water treatment system may proceed subject to approval conditions. Most approvals require:

a. Installation according to the submitted plans and approval conditions.

b. Initial sampling of raw water and treated water at startup and a routine sampling program.

c. Routine maintenance requirements.

d. Non-Community public water supply systems will be required to submit periodic reports of sample results and maintenance actions to the Department.

Application

The information that is required for a complete application is found in the attached outline. The Department asks that you take the time to obtain the information specified and be as complete as possible in your application. Information as requested in item #5 on the attached outline about the depth of well casing, casing integrity and the well's total depth must be obtained in order to evaluate the request. In addition, the water quality data specified in item #6 on the attached outline is critical in designing a UV water treatment system. Attached are the UV specifications that must be met in order for the Department to approve the installation of the water treatment device(s) on a microbiologically unsafe water supply.

D.3 WISCONSIN (CONTINUED)

Application Content

1.	Property Owner:	Include the name, mailing address, and telephone number.
2.	Water Treatment Device Operator:	Provide the name, mailing address and telephone number of the water treatment device operator if different from owner above.
3.	Property Location and Legal Description:	Provide the village or city street and number or if rural, the road and fire number and the legal description including the ¼¼ Section, ¼ Section, Section number, Town and Range numbers, and County.
4.	Property Map:	Locate the property on a map. A plat map or topographic map is acceptable.
5.	Well Description:	Provide a copy of the well construction report if available. If not available, provide the following information: a. The approximate date of well construction, b. The total depth of the well and c. The depth of the casing in the well. d. A copy of an inspection report showing compliance of the well and pumping system with Chapter NR812.
6.	Water Quality:	Results of the following well water quality tests collected at the well sampling faucet: a. Total coliform bacteria, b. E-Coli bacteria, c. Iron bacteria, d. Color, e. Dissolved iron, f. Dissolved manganese, g. Hardness, h. Hydrogen sulfide if odor is present, i. pH, j. Suspended solids, k. Turbidity These tests shall be performed by a state Safe Drinking Water Act certified laboratory.
7.	Water Quantity:	Measure or estimate the average daily water usage in gallons. Indicate the pump capacity in gallons per minute.

D.3 WISCONSIN (CONTINUED)

8.	Water Distribution System Sketch:	Provide a sketch of the water distribution system from the well to the final treated water distribution point including the location of any sampling faucets, pressure gauges, shutoff valves, by-pass piping, pressure tanks, any other treatment devices, and the proposed location of the water treatment device or water treatment system.
9.	Water Treatment Device or System Installation Information:	Provide the name of the manufacturer, the product name and model number.
10.	Maintenance Program:	Describe the required maintenance for the UV water treatment device and any pretreatment devices to be installed. Provide a copy of any maintenance and operational agreements. Specify the responsible party for maintaining the water treatment system.

D.3 WISCONSIN (CONTINUED)

DESIGN AND OPERATIONAL CRITERIA

FOR POINT-OF-ENTRY INSTALLATIONS USING ULTRAVIOLET (UV) FOR PRIVATE AND NON-COMMUNITY WATER SUPPLY SYSTEMS.

The following are Wisconsin Department of Natural Resources (WDNR) criteria for installation, monitoring and replacement requirements for consideration of UV treatment of a microbiologically unsafe water for private and non-community public water supplies. The following criteria must be met in order to install a UV water treatment device on a bacteriologically unsafe water supply well.

A. CRITERIA FOR UV WATER TREATMENT DEVICES

1. UV water treatment devices must comply with Class A criteria under the American National Standard Institute (ANSI)/National Sanitation Foundation (NSF) Standard 55 - Ultraviolet Microbiological Water Treatment Systems; Residential UV models shall be approved by the Department of Industry, Labor and Human Relations (DILHR); each UV water treatment device shall meet the following standards;

a. Ultraviolet radiation at an [sic] wavelength of 253.7 nanometers shall be applied at a minimum dose of 38,000 microwatt-seconds per square centimeter (μW-sec/cm^2) at the failsafe set point at the end of lamp life;

b. The UV device shall be fitted with a lamp viewing port to safely visually verify electrical operation of the lamp(s);

c. The UV light assembly shall be insulated form direct contact with the influent water by a lamp jacket and the lamp and lamp jacket shall be replaceable;

d. An automatic fixed flow rate control shall be provided to prevent flow above the manufacturer's maximum rated flow over the manufacturer's recommended operating pressure range;

e. The UV assemblies shall be accessible for visual observation, cleaning and replacement of the lamp jackets and sensor window/lens;

f. The ultraviolet tube(s) shall be 1) jacketed so that a proper operating lamp temperature of about 104 degrees Fahrenheit is maintained and 2) the jacket shall be of quartz or high silica glass with similar optical and strength characteristics;

g. A narrow band UV monitoring device shall be provided. It shall be accurately calibrated to 253.7 nanometers and installed at the point of greatest water depth. The device shall trigger an audible alarm in the event the sensor or lamp fails or if insufficient dosage is detected as defined in item "a" above;

D.3 WISCONSIN (CONTINUED)

h. An automatic shutdown valve shall be installed ahead of the UV treatment system that will be activated whenever the water treatment system loses power or is tripped by a monitoring device when the dosage drops below 38,000 μW-sec/cm^2.

i. The UV housing shall be stainless steel 304 or 316L;

2. A flow delay mechanism shall be provided to permit a sufficient time for tube warm-up per manufacturer recommendations before water flows from the unit upon startup.

3. Identical parallel UV treatment systems shall be provided at public water systems to provide a continuous water supply when one unit is out of service;

4. No bypasses shall be installed;

5. All water from the well shall be treated;

6. The well pump shall have adequate pressure capability to maintain minimum water system pressure after the water treatment devices;

B. PRETREATMENT

1. A 5 micron sediment prefilter shall be installed before the UV device. The filter model shall be approved by DILHR if installed on a residential water supply;

2. A filter rated for cyst reduction shall be installed before the UV device. The filter shall be approved by DILHR if installed on a residential water supply;

3. The prefilter and cyst reduction filter shall be replaced when the pressure loss across an in use filter has increased by 10 psig above a clean new filter at the manufacturers rated service flow rate.

4. Other pretreatment water treatment devices may be necessary depending on source water quality.

C. REQUIRED ONGOING WATER QUALITY MONITORING

Total coliform monitoring will be used to evaluate UV treatment effectiveness. The monitoring frequency will be as follows:

Startup and 2 weeks after start up - one raw and one treated sample - all systems
Monthly thereafter for all public water systems - raw and treated
Private water system owners are encouraged, but not required, to routinely monitor effectiveness of the water treatment system.

Monitoring for additional parameters or total coliform on an increased frequency may be required by the Department on a case-by-case basis.

D.3 WISCONSIN (CONTINUED)

D. OVERSIGHT AND MONITORING

UV light intensity of each installed unit shall be monitored continuously. Treatment units and the water system shall automatically shutdown if the UV dosage falls below the required output of 38,000 μW-sec/cm^2. Water systems that have a large variation in the turbidity of the water source may be required to install a turbidimeter ahead of the UV water treatment device. An automatic shutdown valve shall be installed and operated in conjunction with the turbidimeter. Each owner shall have at least one replacement lamp, quartz sleeve, 5 micron replacement filter and cyst reduction filter available onsite.

E. SEASONAL OPERATIONS

UV water treatment devices that are operated on a seasonal basis shall be inspected and cleaned prior to use at the start of each operating season. All prefilters shall be replaced prior to start up of the water supply system after a shut down of greater than three months. The UV water treatment system including the filters shall be disinfected prior to placing the water treatment system back into operation. A procedure for shutting down and starting up the UV treatment system shall be developed for or by each owner based upon manufacturer recommendations and submitted in writing to the department.

F. APPLICATION, RECORD KEEPING and ACCESS

A record shall be kept of the water quality test data, dates of lamp replacement and cleaning, a record of when the device was shutdown and the reason for shutdown, and the dates of prefilter replacement.

Department representatives shall have access to the UV water treatment system and records.

Non-community water systems will be required to submit operating reports and required sample results on a monthly or quarterly basis as described in the conditions of approval.

D.4 PENNSYLVANIA

Public Water Supply Manual – Part IV
Noncommunity System Design Standards
Pennsylvania Department of Environmental Protection

3.3 Ultraviolet Irradiation (UV)

Ultraviolet light produced by UV lamps has been shown to be effective bactericide for certain pathogenic bacteria. However, the department does not consider the use of UV acceptable for the inactivation of *Giardia lamblia*. Only UV systems approved as Class A units under the National Sanitation Foundation (NSF) Standard 55 - Ultraviolet Water Treatment Systems are acceptable for use in drinking water disinfection.

Ultraviolet light disinfection will be considered only for small nonresidential water supplies and in certain special cases where other methods are not considered feasible. As ultraviolet treatment does not provide a residual disinfectant, post-chlorination may be required to maintain safe water in the system.

UV system or component shall be designed and constructed so that its intended purpose shall be accomplished when installed and operated according to the manufacturer's instructions. Components shall not be adversely affected by the normal environment to which they are subjected. Normal environment shall include usual vibration, shock, climate condition and cleaning procedures as prescribed by the manufacturer.

3.3.1 Materials

The materials in contact with water must not impart undesirable taste, odor, color, and/or toxic materials into the water as a result of the presence of toxic constituents in materials of construction or as a result of physical or chemical changes resulting from exposure from ultraviolet energy. Materials exposed to ultraviolet irradiation shall be formulated to resist deterioration and shall not impart undesirable tastes, odor, color, and/or toxic chemicals to the water upon irradiation.

Systems and/or components shall be constructed of materials suitable to withstand temperatures generated during sustained periods when the unit is not in use.

3.3.2 Design Criteria

The use of UV devices as a means of disinfection of public water supplies in Pennsylvania is acceptable provided the equipment used meets the design criteria described herein:

1. Ultraviolet radiation at a level of 2,537 Angstrom units must be applied at a minimum dosage of 16,000 microwatt-seconds per square centimeter at all points throughout the water disinfection chamber;

2. The UV system or component shall be provided with a visual means to verify electrical operation of lamps;

D.4 PENNSYLVANIA (CONTINUED)

3. UV lamp assemblies shall be designed to be insulated from direct contact with the influent water. If the ultraviolet lamps or assemblies are intended to be replaced, they shall be removable;

4. The unit is to have an automatic flow control device, accurate within the expected range of operating pressures, so that the maximum design flow rate of the unit is not exceeded;

5. The systems and all components subject to line pressure shall be designed for a working pressure of at least 689 kPa (100 psig);

6. The system or component shall be designed to be accessible for cleaning and replacement of the lamp jackets and sensor window/lens which are provided on the systems. The manufacturer's cleaning procedures shall result in thorough cleaning of the system. The treatment chamber shall be designed so that at least one end can be dismounted for cleaning.

7. Maximum water depth in the chamber measured from the tube surface to chamber wall must not exceed three inches;

8. The ultraviolet tubes must be:

   a. Jacketed so that a proper operating tube temperature of about 105° F is maintained,

   b. The jacket shall be of quartz or high silica glass with similar optical characteristics;

9. A flow or time delay mechanism is to be provided to permit a two minute tube warm-up period before water flows from the unit;

10. An accurately calibrated ultraviolet intensity meter, properly filtered to restrict its sensitivity to the disinfection chamber at the point of greatest water depth from the tube(s) shall be provided;

11. A flow diversion valve or automatic shut-off valve is to be installed which permits flow into the potable water system only when at least the minimum ultraviolet dosage is applied. When power is not being supplied to the unit, the valve should be in a closed (fail-safe) position which prevents the flow of water into the potable water system;

12. The unit must incorporate a device for monitoring or sending ultraviolet transmission or intensity through the maximum depth of water in the chamber during operation. The monitoring or sensing device is to be installed that triggers an audible alarm in the event of lamp or sensor failure or if insufficient ultraviolet light reaches the sensor;

13. The unit must protect the operator against electrical shock or excessive ultraviolet energy;

D.4 PENNSYLVANIA (CONTINUED)

14. The operation of the ultraviolet light unit shall be synchronized with the operation of the well pump.

3.3.3 Installation

1. The unit should be installed in a protected enclosure not subject to extremes of temperature which could cause malfunction.

2. Spare UV tubes and other necessary equipment are to be provided to effect prompt repair by qualified personnel properly instructed in the operation and maintenance of the equipment.

3. The unit is to be installed so as to allow ease of access for disassembly, repairs, or replacement.

D.5 NEW JERSEY

NEW JERSEY PROPOSED REGULATIONS FOR DISINFECTION BY ULTRA-VIOLET LIGHT AS APPEARED IN THE NEW JERSEY REGISTER CITE 27 N.J.R.4112 NOVEMBER 6, 1995

(c) Regulations for disinfection by ultra-violet light are as follows:

1. Ultra-violet tubes shall be jacketed so that a temperature of 105 degrees Fahrenheit is maintained.

2. The jacket on the ultra-violet light tubes shall be quartz or high-silica glass with similar optical characteristics.

3. The ultra-violet light disinfection unit shall be designed to permit frequent mechanical cleaning of the water contacts surface of the ultra-violet tube jacket without disassembly of the unit.

4. The maximum water depth in the disinfection chamber, measured from the ultra-violet light tube surface to the outer walls of the chamber, shall not exceed three inches.

5. Ultra-violet radiation at a level of 2,537 Angstrom shall be applied at all points throughout the disinfection chamber at a minimum rate of 16,000 microwatt seconds per square centimeter.

6. An automatic flow control valve, accurate within the expected pressure range, shall be installed to restrict flow to the maximum design flow of the ultra-violet disinfection unit.

7. An accurately calibrated ultra-violet light intensity meter, filtered to confine its sensitivity to the range of disinfection spectrum, shall be installed in the wall of the disinfection chamber at the point of greatest water depth from the light transmitting source.

8. A flow diversion valve or automatic shut-off valve controlled by the ultra-violet light intensity meter shall be installed so as to permit water flow into the water system only when the minimum radiation level specified at (c)5 is applied. When power is not being supplied to the unit, the valve shall be in a closed (fail-safe) position to prevent the flow of water into the water system.

9. The ultra-violet light disinfection unit shall be installed in a manner such that it cannot be bypassed.

D.6 ANSI/NSF STANDARD 55-1991

STANDARD 55
FOR
ULTRAVIOLET MICROBIOLOGICAL WATER TREATMENT SYSTEMS

PREFACE

This standard was developed for the purposes of establishing reliable methods for determining the performance of point-of-entry and point-of-use ultraviolet water treatment systems designed to reduce specific contaminants from public or private water supplies. Systems covered by this standard are in keeping with the *Report of Task Force on Guide Standard and Protocol for Testing Microbiological Water Purifiers*, April 1987.[1]

It is recognized that the federal, state and local objective is to provide a safe water supply without user treatment. However, many users are faced with the presence of contaminants of both aesthetic and health concern in their water supply and need guidance as to the availability of tested and certified point-of-entry and point-of-use ultraviolet water treatment systems. This standard will help to meet this need, but cannot be expected to address claims beyond those covered in this standard.

Since it was not economically feasible to mount a routine testing program using all of the target microorganisms, e.g., bacteria, viruses, and protozoan cysts, an equivalent "disinfection" set of tests and requirements were developed for point-of-use and point-of-entry ultraviolet disinfection systems.

A virus reduction of 4-log against a poliovirus and rotavirus challenge and a bacteriological reduction of 6-logs against a challenge of a coliform bacteria (*Klebsiella terrigena*) has been recommended by Schaub and an expert task force (1987).[2]

The technical and health protection problems (laboratory staff) and the inherent cost of establishing and maintaining a live virus test program precludes its routine application in a multipurpose standards testing laboratory. Consequently, an alternate means of assuring virus efficacy was developed.

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[1] *Guide Standard and Protocol for Testing Microbiological Water Purifiers*, Report of Task Force, submitted by Steven A. Schaub to the USEPA, April 1987.

[2] Ibid., p. 7.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

Survival data for poliovirus and rotavirus (Chang, 1985)[3], show between a 3 to 4-log reduction in both poliovirus and rotavirus may be accomplished by a UV dosage of 30,000 μW-sec/cm^2 while a greater than 6-log reduction of *Escherichia coli* may be projected. Additional data (Harris, 1986)[4] shows a 5 log reduction of poliovirus at 40,000 μW-sec/cm^2. Consequently, a minimum UV dosage of 38,000 μW-sec/cm^2 at the failsafe setpoint is set as an equivalent 4-log virus reduction requirement.

Since ultraviolet light has limited cysticidal ability, information will be required for the use as to the need for a prefilter complying with ANSI/NSF Standard 53: Drinking Water Treatment Units - Health Effects for cyst reduction.

Where drinking water is considered to be free of disease causing pathogenic organisms and has a turbidity level within acceptable drinking water standards, ultraviolet treatment may be useful for the supplemental treatment of this drinking water. It would be suitable for the reduction of normally occurring microbiological flora (non-spore forming heterotrophic bacteria) commonly found in drinking water. Survival data (Chang, 1985)[5] show a greater than 2 log reduction of non-spore forming heterotrophic bacteria may be accomplished by an ultraviolet dosage of 16,000 μW-sec/cm^2. The yeast organism *Saccharomyces cerevisiae* was chosen as the test challenge to allow for a reasonable influent concentration and an easily measured reduction in the effluent. Most vegetative bacteria including coliform species are too susceptible to UV radiation at the dose range of 16,000 μW-sec/cm^2 to allow for measurable testing.

This standard and the accompanying testing program will provide assurance to the use and the regulatory officials that point-of-entry and point-of-use ultraviolet water treatment systems will perform, with proper operation and maintenance, in accordance with the claims made under the standard. However, final acceptance of systems for any application covered under governmental regulation will be subject to the approval of the appropriate federal, state, and/or local regulatory agency having jurisdiction.

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[3] *UV Inactivation of Pathogenic and Indicator Microorganisms*, Chang, J.C., Johnson, J. Donald, et al. Journal of Applied Environmental Microbiology, Vol. 49, pp. 1361-1365, 1985.

[4] *UV Inactivation of Selected Bacteria and Viruses With Photoreactivation of the Bacteria*, Harris, D. George, Adams, Dean, et al., Water Resources, Vol, Vol. 21, pp. 687-692, 1986.

[5] Ibid., p. 1362.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

SECTION 1. GENERAL

1.0 SCOPE: This standard covers ultraviolet (UV) microbiological water treatment systems and components for point-of-use (POU) and point-of-entry (POE) applications. Systems are intended to be used under the following specific conditions.

1.0.1 CLASS A SYSTEMS: Class A point-of-entry and point-of-use systems covered by this standard are designed to disinfect and/or remove microorganisms from contaminated water, including bacteria and viruses, to a safe level. Systems covered by this standard are not intended for the treatment of water that has an obvious contamination source, such as raw sewage; nor are systems intended to convert wastewater to microbiologically safe drinking water. The systems are intended to be installed on visually clear water (not colored, cloudy, or turbid). Systems intended for treatment of surface waters will need to be installed downstream of a prefilter tested for cyst reduction in compliance with ANSI/NSF Standard 53: Drinking Water Treatment Units - Health Effects.

1.0.2 CLASS B SYSTEMS OR COMPONENTS: Class B point-of-use systems covered by this standard are designed for supplemental bactericidal treatment of treated and disinfected public drinking water or other drinking water which has been tested and deemed acceptable for human consumption by the state or local health agency having jurisdiction. The system is designed to reduce normally occurring nonpathogenic or nuisance microorganisms only. The Class B system is not intended for the disinfection of microbiologically unsafe water.

1.1 MINIMUM REQUIREMENTS: Variations from these minimum requirements may be permitted if they make the system or component as resistant to corrosion, wear, and physical damage, or if they improve the general operation or performance of the system or component. Proposed variations shall be accepted by the testing agency prior to use. Systems with components or functions covered under existing NSF standards or criteria shall comply with those applicable requirements.

1.2 ALTERNATE MATERIALS: If specific materials are mentioned, other materials equally satisfactory from the standpoint of performance and sanitation that meet the requirements of the standard shall be acceptable.

1.3 REVIEWS AND REVISIONS: A complete review of the standard shall be conducted at least every five years. These reviews are to be conducted by representatives from the industry, public health, and user groups of the NSF Joint Committee on Drinking Water Treatment Units.

SECTION 2. DEFINITIONS

2.0 ACCESSIBLE: Fabricated to be exposed for cleaning and inspection using simple tools (screwdriver, pliers, open-end wrench).

2.0.1 READILY ACCESSIBLE: Fabricated to be exposed for cleaning and inspection without using tools.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

2.1 CHALLENGE WATER: The stream entering a component, system, or process.

2.2 CLASS A SYSTEMS: Systems capable of producing an ultraviolet dosage at the failsafe setpoint equivalent to a dosage of 38,000 μW-sec/cm^2.

2.3 CLASS B SYSTEMS: Systems capable of producing an ultraviolet dosage equivalent to a dosage of 16,000 μW-sec/cm^2 at 70 percent of the ultraviolet lamp normal output or at the failsafe point.

2.4 CORROSION RESISTANT MATERIAL: Capable of maintaining original surface characteristics under prolonged contact with the use environment.

2.5 DISINFECTION: The action of removing, killing, or inactivating all types of disease-causing microorganisms to render contaminated water safe for drinking.

2.6 DRINKING WATER: Water intended for human consumption.

2.7 EFFLUENT WATER: The stream emerging from a unit, system, or process.

2.8 FAILSAFE SET POINT: The point at which the ultraviolet sensor activates the alarm.

2.9 FLOW CONTROL: An automatic flow control device which limits flow over a pressure range to the specified flow rate for the system or component.

2.10 JOINING MATERIAL: Any substance used to produce a tight joint; e.g., solvent cements, adhesives; or elastomeric seals.

2.11 NORMAL OUTPUT (CLASS B SYSTEMS): The UV dosage provided by the ultraviolet lamp after a 100 hour conditioning period.

2.12 POINT-OF-ENTRY SYSTEMS: A system used to treat all or part of the water for the facility at the point of entry. For Class A systems a facility shall be considered a single family dwelling.

2.13 POINT-OF-USE SYSTEMS: A system used to treat the water at a single tap or multi-taps, but not for the entire facility.

2.14 REMOVABLE: Fabricated to be taken away from the system or component using simple tools (screwdriver, pliers, open-end wrench, etc.).

2.14.1 READILY (OR EASILY) REMOVABLE: Fabricated to be taken away from the main system or component without using tools.

2.15 SENSITIVITY CALIBRATION: A measured level of spore and/or yeast inactivation resulting from the specified ultraviolet dose. (Term is synonymous with UV sensitivity.)

2.16 TOXIC: Having an adverse physiological effect on humans.

2.17 TURBIDITY: A condition caused by the presence of suspended and/or colloidal matter, which results in the scattering and/or absorption of light rays.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

2.18 ULTRAVIOLET SENSOR: The physical sensing system used to measure the intensity of ultraviolet light (225-300 Nanometers [nm]) transmitted.

2.19 ULTRAVIOLET COMPONENT: The ultraviolet treatment lamp of an ultraviolet system.

2.20 WASTEWATER: Blackwaste and greywaste generated from residences, commercial buildings, industrial plants, and institutions, and the water or medium used to transport it.

2.20.1 BLACKWASTE: Human and/or animal body waste, toilet paper, and any other material intended to be deposited in and discharged therefrom a receptacle designed to receive urine and/or feces.

2.20.2 GREYWASTE: Waste materials, exclusive of urine, feces, or industrial waste, deposited in and discharged therefrom plumbing fixtures found in residences, commercial buildings, industrial plants, and institutions.

SECTION 3. MATERIALS

3.0 GENERAL: Materials in contact with water shall not impart undesirable taste, odor, color, and/or toxic substances to the water when tested and evaluated in accordance with Annex A. Materials used in the construction of systems or components shall be capable of withstanding exposure to the intended use environment. Materials exposed to ultraviolet irradiation shall be formulated to resist deterioration and shall not impart undesirable tastes, odor, color, and/or toxic chemicals to the water upon irradiation.

3.1 TEMPERATURE RESISTANCE: Systems and/or components shall be constructed of materials suitable to withstand temperatures generated during sustained periods of no water use.

3.2 CORRODIBLE MATERIALS: Corrodible materials shall be provided with a corrosion resistant protective coating completely covering all wetted surfaces.

3.3 GASKETS, O-RINGS, SHAFT SEALS, AND PACKING MATERIALS: Gaskets, o-rings, shaft seals, and packing materials shall conform to the applicable requirements of Item 3.0.

3.4 DISSIMILAR METALS: Dissimilar metals not normally considered compatible on the electromotive scale shall not be in direct contact.

3.5 INSULATING FITTINGS: Insulating fittings shall be provided when materials are not compatible on the electromotive scale with adjoining fittings or parts.

3.6 PLASTICS: If plastics are exposed to UV light, the manufacturer shall provide data to substantiate that the plastics meet the requirements of Items 3.0 and 3.1.

3.7 SOLDER: Solder and fluxes on water contact surfaces shall be hard solder and shall conform to the requirements of Item 3.0. Lead based solders (0.2% lead or greater) shall not be used.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

3.8 WELDING: Welded seams and deposited weld material shall meet the requirements of Items 3.0 and 3.4.

SECTION 4. DESIGN AND CONSTRUCTION

4.0 GENERAL: A system or component evaluated under this standard shall be designed and constructed so that its intended purpose will be accomplished when installed and operated according to the manufacturer's instructions. Components shall not be adversely affected by the normal environment to which they are subjected. Normal environment shall include usual vibration, shock, climate condition, and cleaning procedures as prescribed by the manufacturer. Systems and components shall be designed to eliminate UV light exposure to humans when operated and serviced according to manufacturer's recommendation.

4.1 LAMP OPERATION INDICATION: The UV system or component shall be provided with a visual means to verify electrical operation of all lamps.

4.2 UV LAMP ASSEMBLIES: UV lamp assemblies shall be designed to be insulated from direct contact with the influent water. If the UV lamps or assemblies are intended to be replaced, they shall be removable.

4.3 FLOW CONTROL: An automatic fixed flow rate control shall be provided to prevent flow above the manufacturer's maximum rated flow over the manufacturer's recommended operating pressure range.

4.4 PERFORMANCE INDICATION: Class A systems shall be equipped with an UV sensor to monitor UV transmission or intensity through the water during operation. A visual and/or auditory alarm shall be used to indicate ineffective operation. A system that terminates discharge when ineffective operation occurs shall be considered as meeting this requirement. Class B systems or components are exempt from these requirements. If an alarm is provided on a Class B system to measure UV transmission the alarm shall comply with Item 4.4.1.

4.4.1 The alarm shall operate for at least 100 on-off cycles when tested in accordance with Annex F.

4.5 ELECTRICAL REQUIREMENTS: Systems and components shall be accepted by a recognized electrical testing laboratory (Underwriters Laboratories [UL] or equivalent) when applicable. Certification of conformance shall be provided by the manufacturer.

4.6 WORKING PRESSURE: The systems, and all components subject to line pressure, shall be designed for a working pressure of at least 689 kPa (100 psig).

4.7 LAMP REPLACEMENT (CLASS B SYSTEMS): The recommended lamp replacement intervals for Class B systems shall be verified by submittal of intensity vs. time curves. The intensity shall be measured at 254 nm at a distance of 1 m (3.3 ft.).

4.8 MAINTENANCE: The system or component shall be designed to be accessible for cleaning and replacement of the lamp jackets and sensor window/lens provided on the systems. The

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

manufacturer's cleaning procedures shall result in thorough cleaning of the system. The treatment chamber shall be designed so that at least one end can be dismounted for cleaning.

SECTION 5. PERFORMANCE

5.0 GENERAL: Systems and components covered under this standard shall be designed to meet the microbiological performance requirements at the manufacturer's recommended operating pressures and flow rates.

5.1 STRUCTURAL INTEGRITY PERFORMANCE: Systems and components shall comply with the following structural integrity performance requirements when tested in accordance with Annex E.

5.1.1 Units with permanent pressure vessels less than 203 mm (8 in.) in diameter subject to line pressure shall conform to the following requirements:

- Complete assemblies shall withstand a hydrostatic test pressure of 2.4 times the working pressure or 1654 kPa (240 psig), whichever is greater, for a period of 15 minutes without leakage of water from the unit.

- Metallic pressure vessels shall withstand a hydrostatic test pressure of 2.4 times the working pressure or 1654 kPa (240 psig), whichever is greater, for a period of 15 minutes without excessive permanent distortion, defined as an increase in vessel circumference more than 0.2 percent of the original circumference, or top or bottom head deflection more than 0.5 percent of the tank diameter.

- Nonmetallic pressure vessels shall have a burst pressure of at least 4.0 times the working pressure or 2756 kPa (400 psig), whichever is greater.

- Nonmetallic pressure vessels shall be watertight at 1034 kpa (150 psig) and after a minimum of 100,000 pressure cycles of 0 to 1034 kPa (0 to 150 psig) at 20 ± 2.5° C (68 ± 5° F).

- Valves and controls subject to line pressure shall be watertight at 1034 kPa (150 psig) and after a minimum of 100,000 pressure cycles of 0 to 1034 kPa (0 to 150 psig) at 20 ± 2.5° C (68 ± 5° F).

5.1.2 Units with permanent pressure vessels 203 mm (8 in.) and greater in diameter subject to line pressure shall conform to the following requirements:

- Complete assemblies shall withstand a hydrostatic test pressure of 1.5 times the working pressure or 1034 kPa (150 psig), whichever is greater, for a period of 15 minutes without leakage of water from the unit.

- Metallic pressure vessels shall withstand a hydrostatic test pressure of 1.5 times the working pressure or 1034 kPa (150 psig), whichever is greater, for a period of 15 minutes without excessive permanent distortion, defined as an increase in tank

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

circumference more than 0.2 percent of the original circumference, or top or bottom head deflection more than 0.5 percent of the vessel diameter.

- Nonmetallic pressure vessels shall have a burst pressure of at least 4.0 times the working pressure or 2756 kPa (400 psig), whichever is greater.

5.1.3 DISPOSABLE PRESSURE VESSELS: Disposable pressure vessels and all replaceable components subject to line pressure shall meet the following requirements:

- Disposal pressure vessels and replaceable components shall withstand a hydrostatic test pressure of 2.4 times the working pressure or 1654 kPa (240 psig), whichever is greater, for a period of 15 minutes without leakage of water from the unit.

- Disposable pressure vessels and replaceable components shall be water-tight and show no evidence of failure after being subjected to 10,000 pressure cycles of 0 to 1034 kPa (0 to 150 psig) at 20 ± 2.5° C (68 ± 5° F).

5.1.4 UNITS DESIGNED FOR OPEN DISCHARGE: All components subject to pressure, including connecting tubing where required, shall meet the following requirements:

- Complete assemblies, with the outlet plugged, shall withstand a hydrostatic test pressure of 1.2 times the working pressure or 867 kPa (120 psig), whichever is greater, for a period of 15 minutes without leakage of water from the unit.

- Complete assemblies, with the outlet plugged, shall be watertight at 344 kPa (50 psig) after a minimum of 10,000 cycles of 0 to 344 kPa (0 to 150 psig) at 20 ± 2.5° C (68 ± 5° F).

5.1.5 PORTABLE UNITS: Portable units, not designed for direct pressurized connection to a water line, shall meet the following hydrostatic requirements:

- Units designed to be pressurized by the user shall withstand a hydrostatic test pressure of 1.5 times the working pressure for a period of 15 minutes without leakage of water from the unit.

- Units designed for only atmospheric (open) pressure or only gravity flow shall be exempted from hydrostatic tests, but shall be water-tight in normal use.

5.2 SENSITIVITY CALIBRATION: Spore and/or yeast sensitivity calibration (UV sensitivity) shall be determined in accordance with Annex B prior to conducting performance testing in accordance with Annex C or D.

5.3 DISINFECTION PERFORMANCE: Disinfection performance for a Class A system shall provide a minimum UV dose equivalent to 38,000 μW-sec/cm^2 at the fail-safe point, as determined by the inactivation of spores whose sensitivity has been determined in Item 5.2.

5.4 MICROBIAL REDUCTION PERFORMANCE: Microbial reduction performance for a Class B system shall provide a minimum UV dose equivalent to 16,000 μW-sec/cm^2 at 70 percent of the

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

UV lamps' normal output or at the fail-safe point as determined by the inactivation of yeast whose sensitivity has been determined in Item 5.2.

SECTION 6. INSTRUCTION AND INFORMATION

6.0 OPERATION, MAINTENANCE, AND INSTALLATION INSTRUCTIONS: Instructions for installation, operation, maintenance, and initiation of service shall be provided with each system or component. Installation instructions shall note the need for compliance with state and local model laws and regulations. Supply sources for expendable components and supplies for the system or component shall be clearly stated. A manual shall be provided which includes drawings and parts lists for easy identification and ordering of replacement parts and shall include:

- Model number and class designation
- Statement of applications:

  This Class A system conforms to NSF Standard 55 for the disinfection of microbiologically contaminated water that meets all other public health standards. The system is not intended for the treatment of water that has an obvious contamination source, such as raw sewage; nor is the system intended to convert wastewater to microbiologically safe drinking water. The system is intended to be installed on visually clear water (not colored, cloudy, or turbid water). If this system is used for the treatment of surface waters a prefilter found to be in compliance for cyst reduction under ANSI/NSF Standard 53: Drinking Water Treatment Units - Health Effects shall be installed upstream of the system.

  NSF Standard 55 defines wastewater to include human and/or animal body waste, toilet paper, and any other material intended to be deposited in a receptacle designed to receive urine and/or feces (blackwaste); and other waste materials deposited in plumbing fixtures (greywaste).

  OR

  This Class B system or component conforms to NSF Standard 55, and contains ultraviolet lamps that require replacement at intervals in accordance with the manufacturer's instructions. The system is designed for the supplemental bactericidal treatment of either treated and disinfected public drinking water or other drinking water which has been tested and deemed acceptable for human consumption by the state or local health agency having jurisdiction. The system is designed to reduce normally occurring non-pathogenic or nuisance microorganisms only. Class B Systems are not intended for treatment of contaminated water.

- Model number of UV lamp
- Use limitations
- Cleaning instructions
- Maximum and minimum flow rates
- Recommended frequency for the replacement of UV lamps (Class B systems)

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

6.1 DATA PLATE: A data plate or plates shall be clearly and permanently affixed to the system or component in a readily accessible location and shall contain:

- Manufacturer's name and address
- Model number and class designation
- Model number of UV lamps
- Maximum operating feed water temperature in degrees C (degrees F)
- Applicable warning signs
- Use limitations statement: "See instruction manual for use conditions."
- Maximum rated operating pressure in kPa (psi)
- Maximum flow rate in L/min (gpm or gpd)
- Operational volts, amperage, and Hertz of system
- Recommended frequency for the replacement of UV lamps (Class B systems)
- The following applicable statement:

CLASS A SYSTEM: Conforms to NSF Standard 55 for the disinfection of microbiologically contaminated waster that meets all other public health standards. The system is not intended for the treatment of water that has an obvious contamination source, such as raw sewage; nor is the system intended to convert wastewater to microbiologically safe drinking water.

OR

CLASS B SYSTEM: The system or component conforms to NSF Standard 55, and contains ultraviolet lamp(s) that require replacement at intervals in accordance with the manufacturer's instructions. The system is intended for the supplemental bactericidal treatment of either treated and disinfected public drinking water or other drinking water that has been tested and deemed acceptable for human consumption by the state or local health agency having jurisdiction. The system is designed to reduce normally occurring non-pathogenic or nuisance microorganisms only. Class B Systems are not intended for the disinfection of contaminated water.

6.2 SALES FACTS SHEET: A sales fact sheet shall be available to the purchasers and shall include the following information:

- Model number and class designation

- Statement of applications:

This Class A system conforms to NSF Standard 55 for the disinfection of microbiologically contaminated waster that meets all other public health standards. The system is not intended for the treatment of water that has an obvious contamination source, such as raw sewage; nor is the system intended to convert wastewater to microbiologically safe drinking water. The system is intended to be installed on visually clear water (not colored, cloudy, or turbid water). If this system is used for the treatment of surface waters a prefilter found to be in compliance for cyst reduction under ANSI/NSF Standard 53: Drinking Water Treatment Units - Health Effects shall be installed upstream of the system.

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

NSF Standard 55 defines wastewater to include human and/or animal body waste, toilet paper, and any other material intended to be deposited in a receptacle designed to receive urine and/or feces (blackwaste); and other waste materials deposited in plumbing fixtures (greywaste).

OR

This Class B system or component conforms to NSF Standard 55, and contains ultraviolet lamps that require replacement at intervals in accordance with the manufacturer's instructions. The system is designed for the supplemental bactericidal treatment of either treated and disinfected public drinking water or other drinking water which has been tested and deemed acceptable for human consumption by the state or local health agency having jurisdiction. The system is designed to reduce normally occurring non-pathogenic or nuisance microorganisms only. Class B Systems are not intended for treatment of contaminated water.

- Manufacturer's name and address
- Rated service flow rate in L/min (gpm or gpd)
- Pressure drop of unit in kPa (psig) at rated flow.
- Electrical characteristics, volts, amperage, and Hertz. Recommended service life of UV lamps
- Maximum and minimum operating pressure in kPa (psig).
- Maximum operating feed water temperature in degrees C (degrees F).
- Use limitations
- Recommended frequency for the replacement of UV lamps (Class B systems)

D.6 ANSI/NSF STANDARD 55-1991 (CONTINUED)

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