Drinking Water Operator Certification Training

Module 26:
UV Disinfection

This course includes content developed by the Pennsylvania Department of Environmental Protection (Pa. DEP) in cooperation with the following contractors, subcontractors, or grantees:

The Pennsylvania State Association of Township Supervisors (PSATS)
Gannett Fleming, Inc.
Dering Consulting Group
Penn State Harrisburg Environmental Training Center

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Unit 1 – Introduction to Ultraviolet Disinfection

Learning Objectives

- Explain what ultraviolet disinfection is and how it works.
- Indicate the removal or inactivation levels of *Cryptosporidium*, *Giardia*, and viruses during treatment of surface water or ground water under the direct influence of surface water for current disinfection regulations.
- State the relative effectiveness of UV in disinfecting for *Cryptosporidium*, *Giardia*, and viruses.
- Explain advantages/disadvantages of UV disinfection compared to other disinfectants.
- Indicate how UV is used with other disinfectants.
- List the four categories of UV light.
- Explain how UV light is generated.
- Describe the four ways UV interacts with its surroundings.
- Perform absorbance and transmittance calculations.

Definitions

Adsorption— is the attraction and bonding of a molecule of gas, liquid or dissolved solid on a surface.

Disinfection— is a treatment that destroys or prevents the growth of harmful microorganisms.

Ultraviolet (UV) Light— is electromagnetic energy with a wavelength between 100 and 400 nanometers (nm).

UV Disinfection— is the use of ultraviolet light for disinfection. Ultraviolet light disinfects by damaging deoxyribonucleic acid (DNA) or ribonucleic acid (RNA).

UV Transmittance— is the measurement (in percent) of the water's ability to convey ultraviolet light/energy.

How UV Disinfection Works

- DNA and RNA are made up of small pieces, called nucleotides, bonded together in a long chain. The chain has a sugar-phosphate backbone with branches of nitrogenous bases.
- The genetic material of bacteria and protozoans is made up of double-stranded DNA—two chains of DNA bonded together at the nitrogenous bases. Viral genetic material can be either single or double-stranded DNA or RNA.

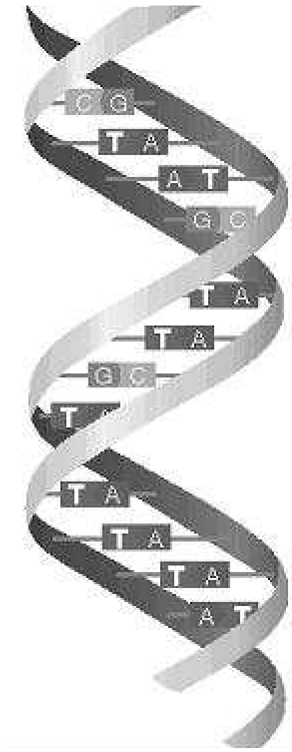

Figure 1.1 – DNA[1]

- UV light, especially at wavelengths of 300 nm or less, will break the existing bond between the bases and form a stronger bond.
- The stronger bond formed by UV light prevents separation of the two chains, disrupting replication of the DNA or RNA.
- To infect a person, a microorganism must be able to reproduce. When the DNA cannot undergo replication, the microorganism cannot reproduce and becomes harmless.
- The UV dose normally used for water treatment does not usually kill the microorganism, so there is some chance that the damage to the DNA can be repaired. Viruses do not appear to be able to repair the damage to the DNA or RNA, but some bacteria can.

Microbial and Disinfection By-Products Rules

Target Microorganisms for Disinfection

Current and near-future regulations target three types of microorganisms for disinfection:

- *Cryptosporidium* - a protozoan
- *Giardia* - a protozoan
- Viruses

Regulatory Requirements

- Current disinfection regulations under the Surface Water Treatment Rule (SWTR), Interim Enhanced Surface Water Treatment Rule (IESWTR), and Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) require the following removal or inactivation levels during treatment of surface water or ground water under the direct influence of surface water (GUDI):
  - *Cryptosporidium* - 2-log (99%)
  - *Giardia* - 3-log (99.9%)
  - Viruses - 4-log (99.99%)

The (proposed) Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) would potentially require systems with a surface water or GUDI source to increase their removal/inactivation of *Cryptosporidium*, depending on the concentration of *Cryptosporidium* in the source water.

- Log inactivation/removal is calculated by the following formula:

  Log inactivation/removal = $\log_{10}(N_0/N)$

  where:

  N_0 = Concentration of infectious microorganism before treatment

  N = Concentration of infectious microorganism after treatment

  Example

  If the *Cryptosporidium* concentration is 1.0 oocysts/L before filtration and 0.001 oocysts/L after filtration, what is the log inactivation/removal?

  Log inactivation/removal = $\log_{10}(N_0/N)$

  = $\log_{10}(1.0/0.001)$

  = $\log_{10}(1000)$

  = 3.0-log

Calculation

If you need to achieve 2.0- log inactivation of *Giardia* through UV disinfection and the active *Giardia* concentration before disinfection is 0.05 cysts/L, what is the maximum allowable concentration of active cysts remaining after the UV disinfection process?

- The (proposed) Ground Water Rule would require systems with ground water sources that are found to have indicators of fecal contamination in their source water or found to have significant deficiencies in one or more of eight categories to do one of the following:
  - Improve the system to eliminate deficiencies
  - Change sources to eliminate the fecal contamination in the source water
  - Treat for 4-log virus inactivation
- The Stage-1 Disinfection Byproduct Rule decreased the maximum contaminant limit (MCL) for two categories of disinfection byproducts (DBPs) known as halogenated organics and introduced MCLs for two new DBPs. Maximum residual disinfectant limits (MRDL) were introduced for chlorine, chloramines, and chlorine dioxide.

- The (proposed) Stage-2 Disinfection Byproduct Rule would change the method in which compliance with the DBP MCLs is calculated, changing from a running annual average of all sampling points to a running annual average for each individual sampling point.

UV Disinfection Effectiveness

Log Inactivation

The (proposed) LT2ESWTR listed the following UV doses required for 2-log inactivation of target pathogens:

- *Cryptosporidium* - 5.8 millijoules per square centimeter (mJ/cm^2)
- *Giardia* - 5.2 mJ/cm^2
- Viruses - 100 mJ/cm^2

Comparing UV to Other Disinfectants

Disinfection Effectiveness

- Common chemical disinfectants include chlorine, chlorine dioxide, chloramines, and ozone.
- Disinfectant dose requirements, in mg · min/L, are given in the table below. Doses are for 2.0-log inactivation at 10°C and a pH of 8.0.

Table 1.2 – Disinfectant Dose Requirements

	Cryptosporidium	*Giardia*	Viruses
Chlorine[2]	>7,200[1]	108	3
Chloramines	>7,200[1]	1,230	643
Chlorine Dioxide	553	15	4.2
Ozone	20	0.95	0.50

[1]Chlorine and chloramine are ineffective at disinfecting *Cryptosporidium* at normal water treatment doses. 7,200 mg · min/L is the reported concentration x time (CT) dose required for 1-log inactivation of *Cryptosporidium* with chlorine. Chloramines are less effective than chlorine for disinfection.
[2]*Giardia* value is for a chlorine concentration of 1.0 mg/L.

Disinfection Byproducts

- Chlorine will produce the most disinfection byproducts.
- Chloramines will substantially reduce the production of DBPs compared to chlorine.
- Chlorine dioxide will not produce halogenated organics, but will produce chlorite.
- Ozone may produce some halogenated organics and/or bromate if bromide is present in the source water.
- UV produces none of the regulated DBPs.

Disinfection Residual

- A disinfectant residual is required to be maintained in the distribution system for any system that uses surface water or GUDI.
- Chlorine, chloramines, and chlorine dioxide can maintain a residual in the water for a significant amount of time after being applied. Ozone and UV cannot. For this reason, ozone and/or UV cannot be the sole source of disinfection in a plant that treats surface water or GUDI.

Pretreatment

- Disinfectants are also used as oxidants. The application of a strong oxidant to the water can provide the following benefits:
  - Oxidation of iron and manganese
  - Zebra mussel control
  - Prevention of algal growth
  - Improvement of coagulation and filtration
  - Removal of color
  - Removal of taste and odor
- UV light is not an oxidant and will not provide the above benefits.
- Chlorine, chloramines, chlorine dioxide, and ozone are all strong oxidants.

Use of UV with Other Disinfectants

- Because UV light does not have a residual, it will be used in conjunction with a chemical disinfectant.
- Chemical disinfectants may be more practical for inactivation of viruses. Viruses are relatively easy to inactivate with chemical disinfectants, and relatively difficult to inactivate with UV.
- In Pennsylvania, it is required to have a minimum of 1.0-log inactivation of *Giardia* during treatment. If this inactivation is achieved using UV light instead of a chemical disinfectant, the use of chemical disinfectants can be minimized which will, in turn, minimize DBP formation.
- If chemical disinfectants are used as oxidants, the use of UV light will not reduce the dose of chemical disinfectant needed for this purpose.
- If a treatment plant has a *Cryptosporidim* concentration of 0.075 oocysts/L or greater in the source water, then UV light is one option for providing the additional removal/inactivation required under the LT2ESWTR. Chlorine or chloramines cannot be used for *Cryptosporidium* inactivation.

The UV Spectrum of Light

- UV light is divided into four categories based on wavelength:
  - UV-A: 315 to 400 nm
  - UV-B: 280 to 315 nm
  - UV-C: 200 to 280 nm
  - Vacuum UV: 100 to 200 nm

- Wavelengths from 200 to 300 nm are considered the practical germicidal range:
  - Above 300 nm, the light is not adsorbed strongly enough by the nucleotides to produce much damage.
  - Below 200 nm, the light is very effective at disinfection. However, vacuum UV is strongly adsorbed by water and so is not practical for use in water disinfection.

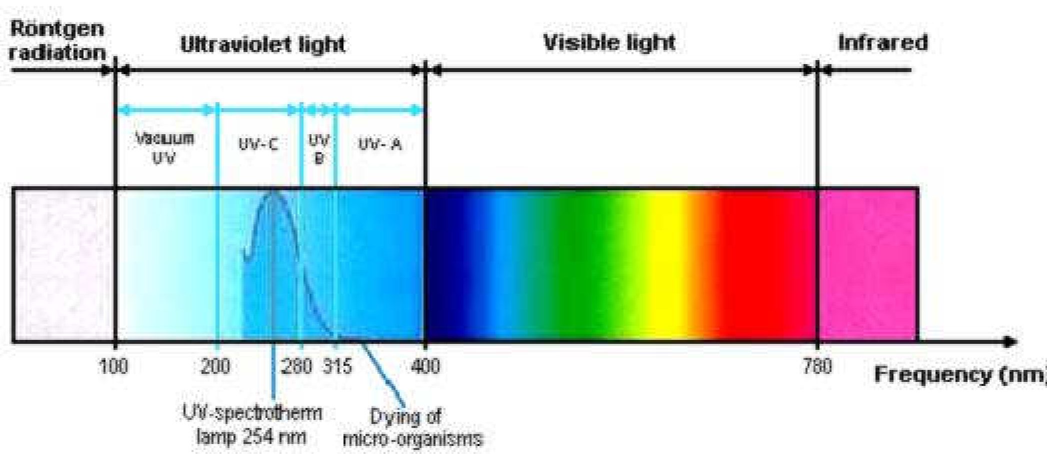

Figure 1.2 – DNA Absorption of UV Light[2]

How UV Light is Generated

UV light is typically generated by applying a voltage across a gas mixture. The energy is adsorbed by the gas and emitted in part as UV light. Nearly all UV installations for water treatment use a gas mixture containing mercury vapor. At certain temperatures and vapor pressures, the mercury vapor will emit UV light in the germicidal range when a voltage is applied. There are two ranges of vapor pressure where UV light is emitted:

- Low pressure
  - Vapor pressures between 2×10^{-5} and 2×10^{-3} psi
  - Temperature near 40°C
  - Produces nearly monochromatic light at 253.7nm
- High pressure
  - Vapor pressures between 2 and 200 psi
  - Temperatures between 600 and 900°C
  - Produces a range of wavelengths in the range of UV light
  - Higher intensity light than at low pressure

Interaction of UV Light with Its Surroundings

As light travels through air, water, and other materials it can be absorbed, reflected, refracted, or scattered.

- Absorption
  - Absorption is the transformation of light into other forms of energy.
  - Once UV light is absorbed by the surroundings, it can no longer provide disinfection of the target organism.
  - The amount of absorption that occurs depends on both the material the light is traveling through and the wavelength of the light.
  - Components of the reactor and the water in the reactor will all absorb UV light to some degree. The amount of absorption is different at each wavelength.
  - The compounds dissolved in the water will affect the amount of absorption.

- Reflection
  - Reflection is the change in direction of light travel that occurs when light is deflected at a surface rather than transmitted.
  - Some surfaces will reflect a portion of the light and transmit some of the light. Others do not transmit any light.
  - At smooth surfaces, light will be reflected at one angle (specular reflection).
  - At rough surfaces, light will be reflected at many angles (diffuse reflection).

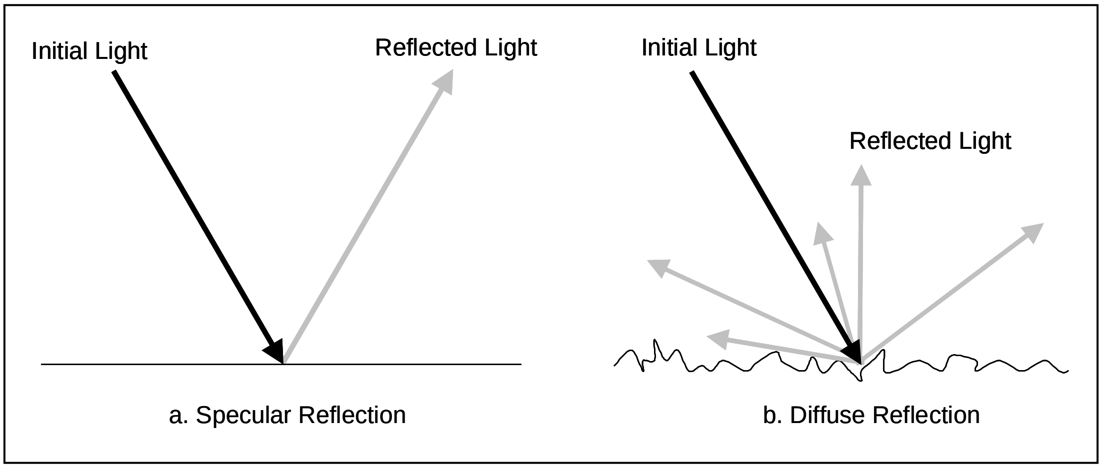

Figure 1.3 – Reflection

- Refraction
  - Refraction is the change in direction of light travel that occurs as light reaches an interface between two media. The difference in the densities of the materials causes the light to slow down or speed up and to change direction.
  - In a UV reactor, the light will be refracted at the boundaries between the reactor components.

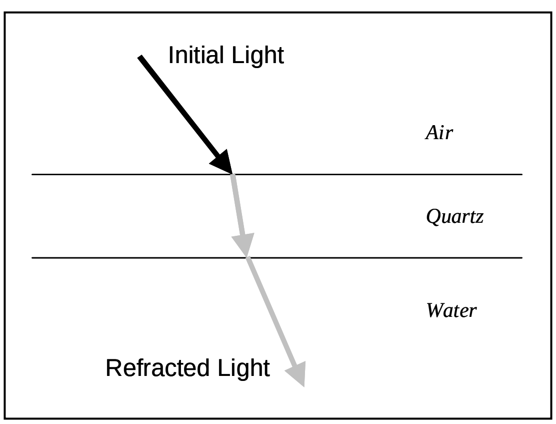

Figure1.4 – Refraction

- Scattering
  - Scattering is the change in direction of light travel that occurs as light interacts with small particles. Particles can cause light to travel in many directions.
  - The particles in the water being treated by UV light will cause the light to scatter.

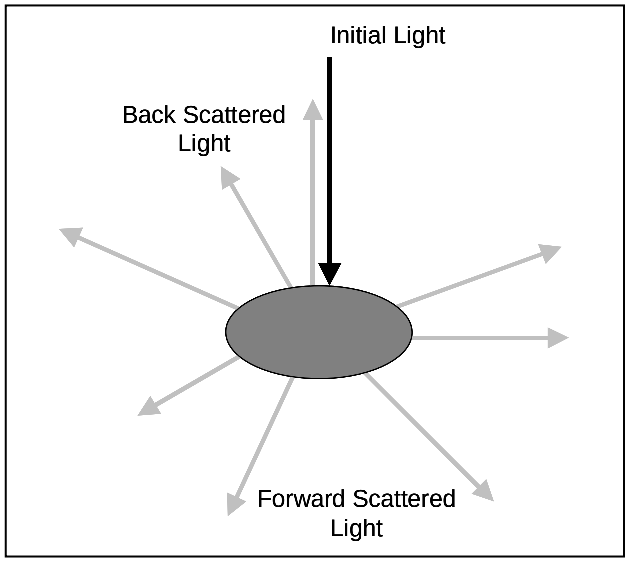

Figure 1.5 – Scattering

Water Quality as it Relates to UV Light

Absorbance

- Absorbance is a measurement of the decrease in the intensity of UV light as it travels through water.

- Absorbance = log (I_0/I)
  where: I_0 = the light intensity at the source
  I = the measured light intensity at some distance from the source.

- Absorbance is commonly reported for a pathlength of 1 centimeter (cm). For other pathlengths, the absorbance is calculated as follows:
  $A_2 = A_1$*P, where:
  P = pathlength (cm)
  A_2 = absorbance at pathlength P
  A_1 = absorbance at 1 cm

- UV absorbance is commonly measured at 254nm, which is the wavelength of the UV light output for low pressure mercury vapor lamps.

- Abbreviated as A or A_w, where ***w*** is the wavelength at which it was measured. (For example, A_{254}.)

- Absorbance is unitless, but is referenced by the pathlength or wavelength used.

- In water treatment, absorbance generally accounts for the effects of absorption and scattering that occur in the water.

Transmittance

- Transmittance (T) is the percent of the light that passes through a sample:
  T(%) = 100 * I/I_0

- Transmittance, as absorbance, is typically reported at a pathlength of 1 cm.

- Transmittance is related to absorbance by the following equation:
  T (%) = $100*10^{-A}$
  or
  A = -log(T/100)

- Transmittance is dependent upon the wavelength and pathlength used for measurement.

Example

The light intensity at the source is 50mW/cm^2. The measured light intensity at some distance from the source is 45mW/cm^2. What is the Absorbance? What is the Transmittance?

I_0 = 50mW/cm^2 (milliwatts per square centimeter)
I = 45mW/cm^2

Then A = log (50/45) = 0.0458
T = 100*10$^{-0.0458}$ = 90%

OR: T = 100 * 45/50 = 90%
A = -log (90/100) = 0.0458

Calculation

The transmittance of some water that will be disinfected using UV light has been measured at 95%. The UV intensity 1 cm away from the UV lamp must be 25 mW/cm^2 to adequately disinfect the water. What must the UV intensity be at the surface of the lamp? What must the UV intensity be at the surface of the lamp if the UV intensity needs to be 25mW/cm^2 at a distance of 2 cm from the lamp?

Unit 1 Exercise

T rue or False (circle)**:**

1. Ultraviolet Disinfection is one method of treatment that destroys or reduces the growth of harmful microorganism. T F

2. Ultraviolet light is measured with a volt-meter. T F

3. Ultraviolet light disinfects DNA or RNA. T F

4. Bacteria and Protozoan are made up of a single strand on DNA. T F

5. Ultraviolet light at wavelengths of 300nm will break the existing bond between the nitrogenous base. T F

Multiple Choice:

1. Disinfection regulations target three types of microorganisms for disinfection, which one does not apply.
   a. Cryptosporidium
   b. Filamentous Bacteria
   c. Giardia
   d. Viruses

2. The log removal for Giardia is:
   a. 1-log
   b. 2-log
   c. 3-log
   d. 4-log

3. Cryptosporidium is found in the:
   a. Surface water
   b. Ground water not under the direct influence of surface water
   c. After disinfection
   d. In the distribution system where the resident time is high.

4. One benefit to UV disinfection is that it does not cause Disinfection Byproducts. Which statement is not correct:
   a. UV does not have a residual.
   b. UV is not an oxidant.
   c. UV can be used a sole source of disinfection in a plant that treat GUDI.
   d. UV is one option for providing additional inactivation required under the LT2ESWTR.

5. Two common terms used to relate water quality to UV light are:
   a. Adsorption and Deflection
   b. Absorption and Transmittance
   c. Reflection and Refraction
   d. Pathlength and Pressure

6. If the light intensity of a UV lamp is 20.0 mW/cm^2. Three centimeters away from the lamp, the UV intensity is measure as 15.2 mW/cm^2. What is the absorbance of the water for the pathlength of 3 cm?

   Where $A = \log (I_0/I)$
   I_0 = 20 mW/cm^2
   I= 15.2 mW/cm^2

   a. 0.76 for the measured pathlength of 3 cm
   b. 0.76 for the measure pathlength of 1 cm
   c. 0.1192 for the measure pathlength of 1 cm
   d. 0.1192 for the measured pathlength of 3 cm

7. What is the absorbance for a pathlength of 1 cm above?

   Where $A_2=A_1*P$

   a. 0.0397
   b. 0.2533
   c. 0.3576
   d. 2.28

8. If a lamp UV intensity out put is 35 mW/cm^2, what UV intensity will be measured for 1 cm from the lamp surface if the lamp is submerged in water with a UVT of 93%?

   Where T(%) = 100* I/I_0

   a. 37.6 mW/cm^2
   b. 0.0266 mW/cm^2
   c. 32.55 mW/cm^2
   d. 0.0307 mW/cm^2

[1] www.schoolscience.co.uk/content/4/biology/abpi/genome/genome3.html

[2] http://www.excelwater.com/eng/b2c/water_tech_3.php?WL_Session=59e7ade16182cb7c0fc781b093afbf8b

Additional Resources

Ultraviolet Disinfection Guidance Manual, (United States Environmental Protection Agency, June, 2003), EPA 815-D-03-007.

Unit 2 – UV Equipment

Learning Objectives

- Describe the two basic configurations for UV reactors.
- List the major components of a UV reactor.
- List the major components of a UV disinfection system.

UV Reactor Configurations

- UV reactors are designed to efficiently deliver the UV dose required for pathogen inactivation. They include the UV lamps and other components designed to protect the lamps and maximize the light reaching the target pathogens.
- Reactors are found in two basic configurations:
  - Open channel - open basins with channels containing racks of UV lamps.
  - Closed channel - closed vessels containing UV lamps. Water flows through under pressure.
- Open channel reactors are most commonly used for wastewater treatment.
- Closed channel is the type currently used for drinking water treatment.

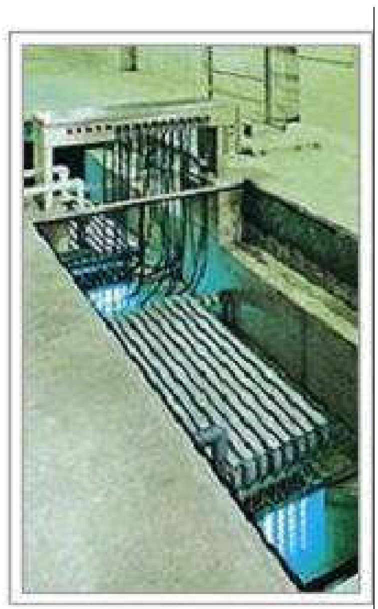

Figure 2.1 An Open Channel Reactor[1]

Figure 2.2 A Closed Channel Reactor[2]

UV Reactor Components

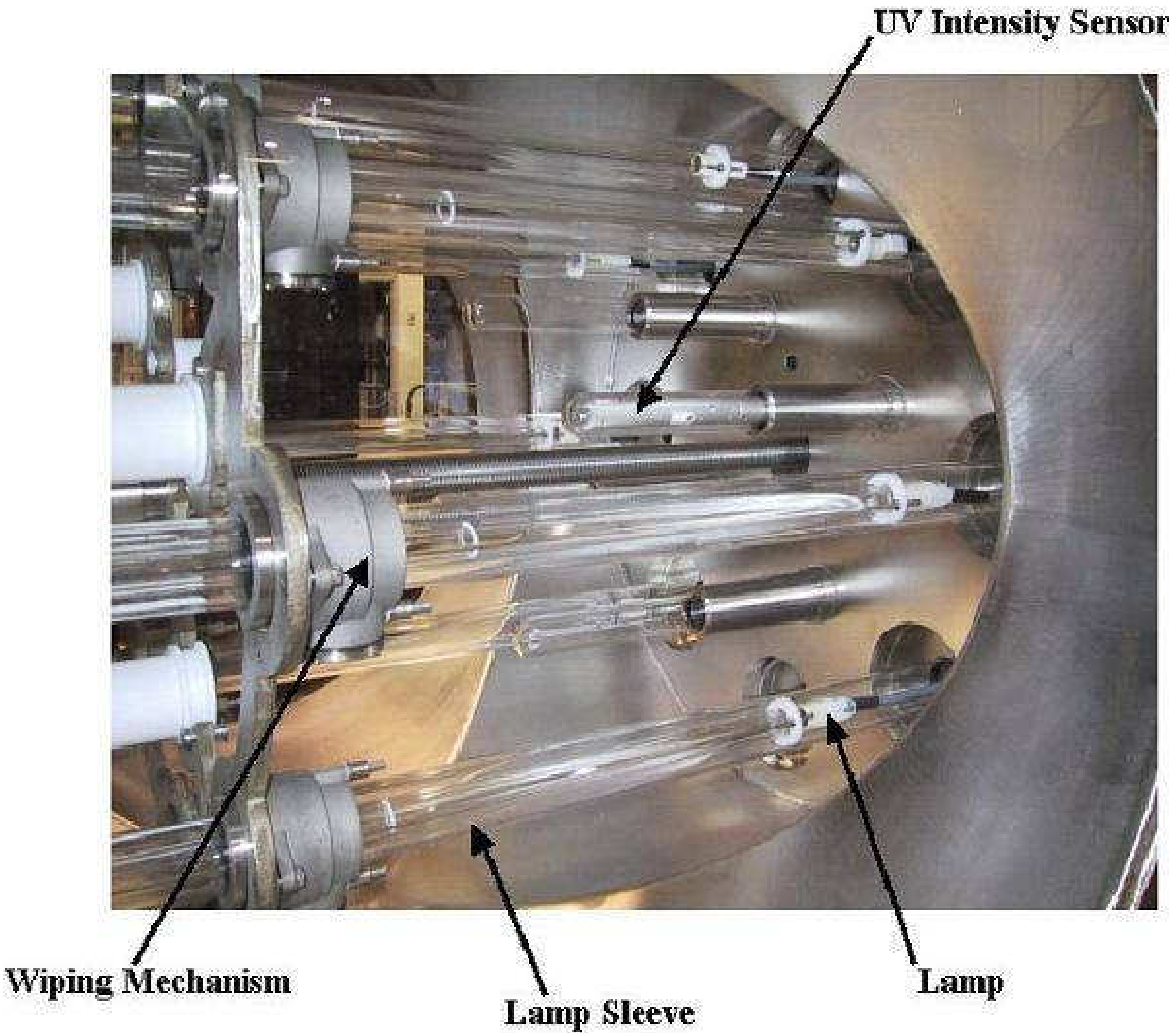

Figure 2.3 The Inside of a Reactor[3]

UV Lamps

Figure 2.4 – A UV Lamp[4]

- UV lamps used for water treatment generally fall into three categories:
  - Low pressure (LP)
  - Low pressure-high output (LPHO)
  - Medium pressure (MP)
- All three use mercury vapor to produce UV light.
- Lamp envelopes may be coated with materials that prevent transmission of low-wavelength (below 200nm) UV light.
- LP and LPHO lamps are similar to one another in design, except that LPHO lamps control the vapor pressure of the mercury so that higher intensity UV light can be created.
- Characteristics of the three lamp types are provided in the following table.

Table 2.1 –Characteristics of Lamp Types

	Low Pressure	Low Pressure- High Output	Medium Pressure
Mercury vapor pressure (torr)*	0.007	0.76	300 - 30,000
Operating temperature (°C)	40	130 - 200	600 – 900
Electrical input (W/cm^2)	0.5	1.5 - 10	50 – 250
Germicidal UV output (W/cm^2)	0.2	0.5 - 3.5	5 – 30
Efficiency of conversion from electrical to germicidal UV (%)	35 - 38	30 - 40	10 – 20
Relative number of lamps needed for a given dose	High	Intermediate	Low
Lifetime (hrs of operation)	8,000 - 10,000	8,000 - 12,000	4,000 - 8,000

* 1 torr = 1 mmHg at 0 °C

Table 2.2 – Advantages and Disadvantages of LP, LPHO, and MP

	Low Pressure/Low Pressure High Output	Medium Pressure
Advantages	• Higher efficiency conversion to germicidal wavelengths • Lower operating temperature reduces fouling (LP temp. lower than LPHO) • Longer lamp life • Lower electrical use for a given dose • Smaller reduction in dose if one lamp fails • Germicidal UV is nearly all at 254 nm	• Fewer lamps required • Less space required for reactors • Greater UV energy output
Disadvantages	• More lamps required (LPHO less than LP) • More space required for reactors	• Lower efficiency conversion to germicidal wavelengths • Higher operating temperature increases fouling • Shorter lamp life

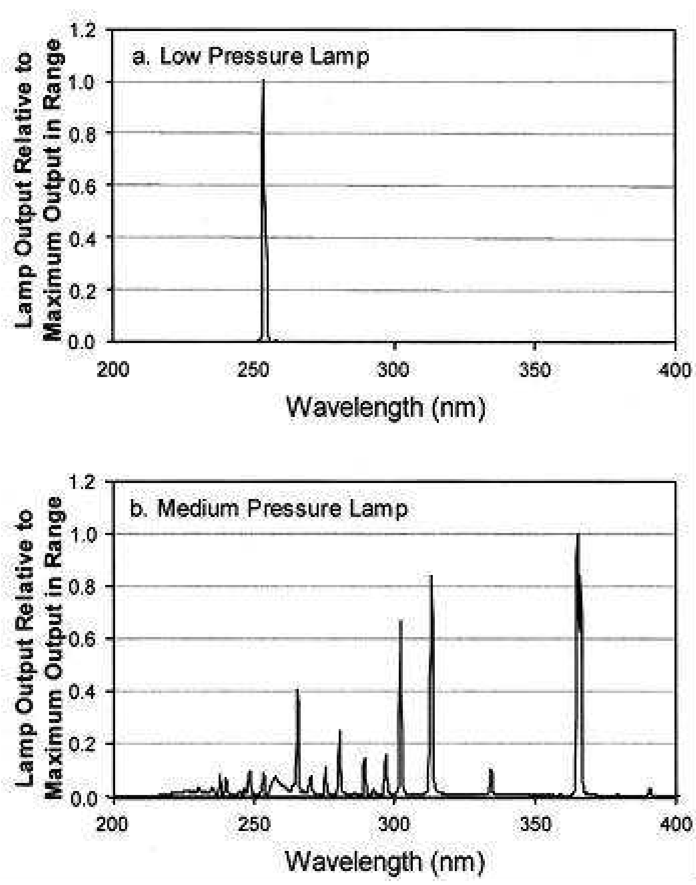

Figure 2.5 – UV Lamp Output: LP vs. MP[5]

Lamp Sleeves

- Lamp sleeves enclose the lamps and the associated electrical components.
- Sleeves are usually made out of quartz because of its high UV Transmittance (UVT) and resistance to high temperatures.
- Some LP or LPHO lamps use Teflon® or Teflon®-coated quartz because of its resistance to fouling, but Teflon® has a lower UVT than quartz, and the UVT decreases more rapidly over time.
- The lamp sleeve serves multiple functions:
  - Maintain the lamp at the optimal temperature by controlling heat transfer
  - Isolate the lamp and electrical connections from the water
  - Protect the lamp from thermal shock due to the difference in lamp and water temperatures
  - Protect the lamp from mechanical forces such as water hammer.
- Sleeves may be coated with other materials to prevent transmittance of low-wavelength (below 200 nm) UV light.
- The lamp is centered in the sleeve using rings of Teflon®, metal, or ceramic.

Lamp Power Supply

Operation of a UV lamp requires power at a specific current, voltage, and frequency to maximize the efficiency of UV light production. Several components can be used to control the quality of the electric energy.

Ballasts

- UV lamps require a power supply that can limit the current flow through the lamp. This is accomplished by use of a ballast.
- Ballasts are divided into two classifications:
  - Magnetic (or electromagnetic)
  - Electronic ballasts

Table 2.3 – Advantages and Disadvantages of Magnetic and Electronic Ballasts

	Magnetic Ballasts	Electronic Ballasts
Advantages	• Less potential for power interference • More resistant to power surges • More resistant to high temperatures • Less prone to interference with electronic devices • Less prone to electrode sputtering • Less expensive	• More efficient • Lighter weight • Smaller size • Less potential for heat generation • Less potential for noise • Capable of continuous power adjustment within given range • Longer lamp operating life
Disadvantages	• Less efficient • Heavier weight • Larger size • More potential for heat generation • More potential for noise • Power adjustment in steps • Shorter lamp life	• New technology • More potential for power interference (can be minimized by addition of capacitor) • Less resistant to power surges • Less resistant to high temperatures • More prone to interference with electronic devices • More prone to electrode sputtering • More expensive

- There are two types of magnetic ballasts:
  - Capacitive - uses capacitors
  - Inductive - uses inductors

Transformers

- Transformers change the voltage of the power supply.

- When lamps are starting up, the electrodes need to warm up before the lamps reach operating temperature. This can be done by applying a high voltage to the electrodes as they warm up, or by preheating the electrodes.

- For LP and LPHO lamps that do not preheat the electrodes, transformers are needed to increase (step-up) the voltage during lamp start up.

- For medium pressure lamps, the operating voltage is usually higher than normal supply voltage. In these cases, step-up transformers are needed during startup and operation of the lamps.

Frequency Converters

- For LP and LPHO lamps, a frequency converter may be used to increase the frequency to 20 - 100 kilohertz (kHz).
- Higher frequency has the following benefits:
  - Reduces electrode deterioration
  - Makes the lamps easier to start
  - Extends lamp life
  - Lamp efficiency increases
- However, there are power losses associated with frequency conversion

Sleeve Cleaning Systems

- As the reactor is operated, materials from the water can accumulate on the surface of the sleeve, causing the UVT to decrease. There are several ways to clean the sleeves:
  - Manual
  - Automatic
    - Offline chemical cleaning
    - Online mechanical cleaning
    - Online mechanical-chemical cleaning
- Manual cleaning is usually used for systems with few sleeves or low fouling rates. To manually clean, the sleeve is removed and wiped with a soft cloth and cleaning solution.
- Offline chemical cleaning is usually used for LP or LPHO systems. To chemically clean, the reactor is taken offline, drained, and flushed with a chemical solution.
  - The chemical solution is frequently citric or phosphoric acid. Some manufacturers use a proprietary solution.
  - The reactor is allowed to soak in the chemical solution for a period of time to allow the substances fouling the sleeve to dissolve.
  - The reactor is then rinsed and returned to service.

- Online cleaning is typically used by MP systems because the higher operating temperature increases fouling rates. The reactor remains in operation while the online cleaning occurs. Cleaning occurs with a wiper that moves along the length of the sleeve, electrically or pneumatically driven.
  - Online mechanical systems use a collar, normally made of Teflon® or stainless steel wire, to brush the fouling off of the sleeve.
  - Online mechanical-chemical systems use a collar filled with a chemical cleaning solution. The collar physically removes the fouling substances while the chemical acts to dissolve them.

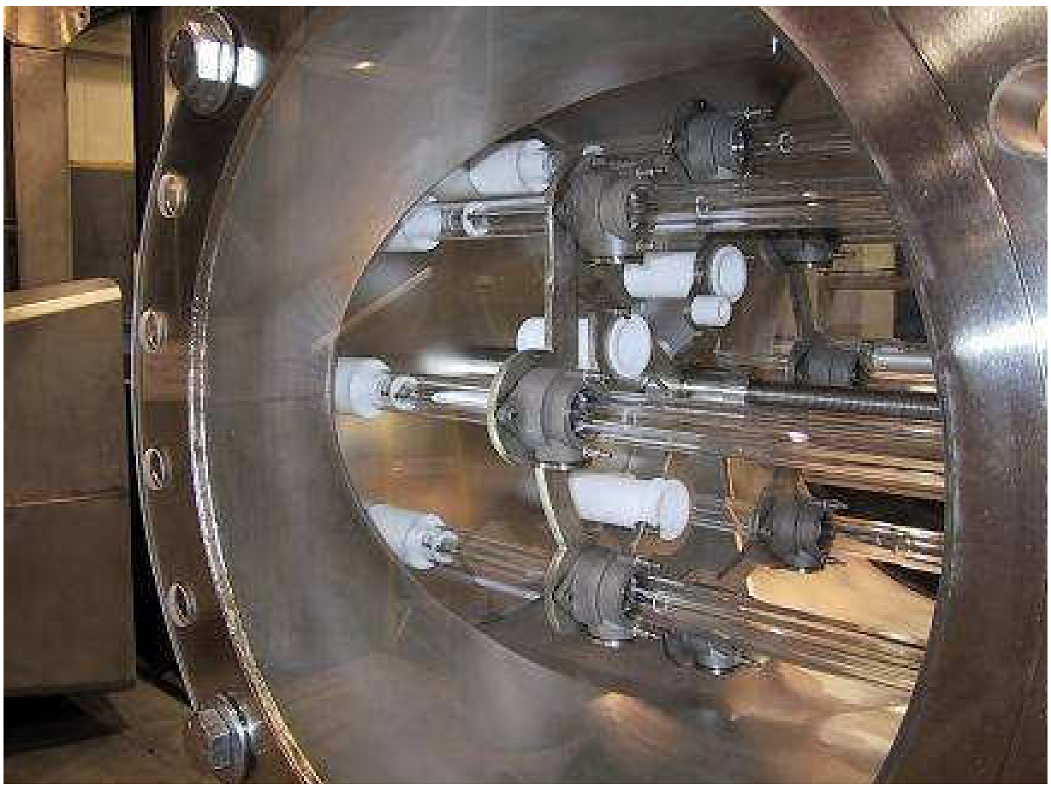

Figure 2.6 – Lamp Wipers[6]

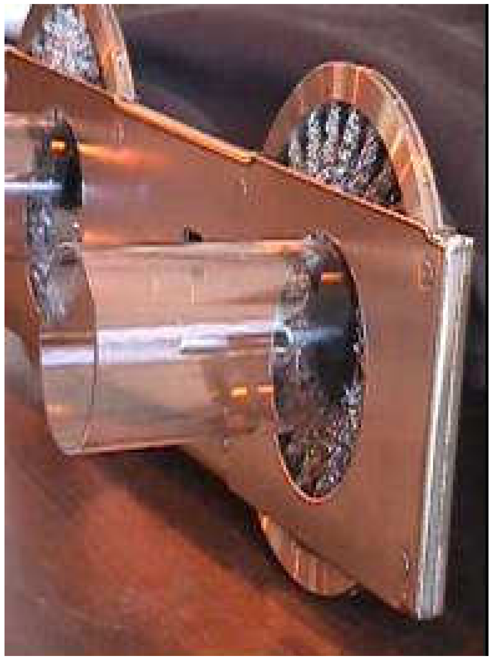

Figure 2.7 – Lamp Wipers[7]

UV Intensity Sensors

- The UV intensity sensors are the components that measure the intensity of the UV light at some distance away from the UV lamp.
- The sensors include a photodetector, a signal amplifier, the housing, an electrical connection, and various optical components that may include:
  - Monitoring window - disk, typically made of quartz, that allows the light to pass inside the housing
  - Light pipe - cylinder, typically made of quartz, that serves the same function as a monitoring window
  - Filter - filters prevent certain wavelengths of light from reaching the photodetector. Often, filters are used to remove light outside the germicidal wavelength range of 200 - 300nm
  - Diffuser - used to reduce the intensity of the UV light to protect the photodetector from degradation caused by UV light
  - Aperture - used to reduce the intensity of the UV light to protect the photodetector from degradation caused by UV light
- The photodetector converts light energy into an electrical signal.
- The amplifier increases the electrical signal to a measurable level, proportional to the UV intensity, used by the control instrumentation.

- The housing protects the rest of the components from the external environment and minimizes interferences. The housing should be electrically grounded to reduce background noise and bias.

- UV intensity sensors can be classified as wet or dry.
  - Wet sensors are in direct contact with the water flowing through the reactor.
  - Dry sensors are separated from the water by a monitoring window.

Figure 2.8 - Intensity Sensor[8]

UV Transmittance Monitors

- UVT monitors may be included with the UV system, depending on the control concept used (see section on Controls and Instrumentation below).
- A UVT monitor measures the transmittance of the water flowing through the reactor.
- A UVT monitor consists of multiple UV intensity sensors located at various distances from a UV lamp. The differences between the intensity readings are interpolated to determine the UVT of the water.
- UVT readings can be taken using an online monitor or samples can be collected manually and analyzed.

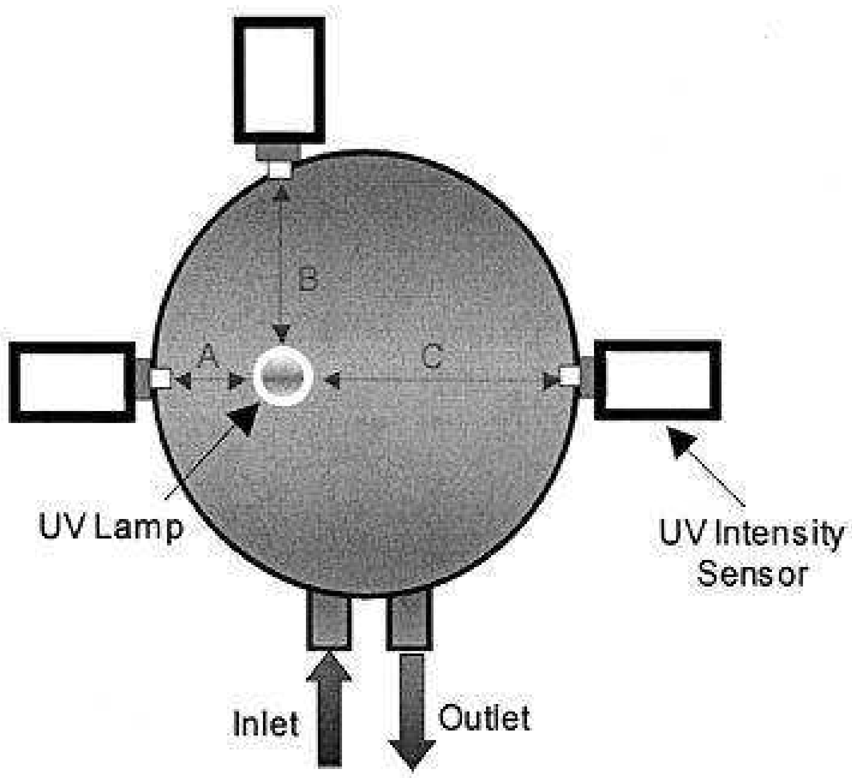

Figure 2.9 -- UVT Monitor Drawing[9]

Temperature Sensors

- Temperature sensors are located in the reactor to monitor the temperature of the water in the reactor or the temperature of the reactor wall.
- If the reactor overheats, the lamps and sleeves may break, releasing quartz and mercury into the water.

- Normally the water flowing through the reactor carries away excess heat; however the reactor may overheat if:
  - Flow through the reactor stops or is below minimum requirements
  - Lamps are exposed to air in the reactor
- If the temperature exceeds the setpoint, an alarm will be given. The system response will vary depending on the control settings, but may be programmed to shut the reactor off or increase flow to the reactor. Caution: If the reactor temperature is high and cold water is added to the reactor too rapidly, the sudden temperature change can cause the lamp sleeves and lamps to break.

Hydraulic Control Baffles

Baffling may be provided in the reactor to improve the distribution of water flow through the reactor, minimizing the chance that a portion of the water will not receive an adequate UV dose.

Controls and Instrumentation

Control Concepts

Operators can monitor the UV system performance and control the operations from the control panel operator interface. The level of effort required by the operator is specific for each installation. At some plants operation may be largely manual, and at other locations operation may be highly automated.

Indicators

Signals from various equipment are indicated at a control panel. These may include:

- UV reactor status
- UV lamp status
- UV intensity
- UVT
- Flowrate
- UV dose
- Reactor temperature
- Lamp cleaning cycle and history
- Age (i.e. total hours of operation) of each lamp
- Alarm status and history

Alarms

Alarms will activate to alert the operator to potential problems with the UV system. The level of the alarm will vary depending upon the severity of the trouble. Alarms may be audible or may just be displayed at the control panel. The type and level of the alarms will be specific to each installation. Some situations that may trigger alarms are:

- Lamp age is approaching or beyond the lamp life setpoint
- UV intensity sensor calibration needs checked, based on a calibration frequency setpoint
- Flow is greater than or less than validated operating range
- UVT is below validated operating range
- Low UV intensity
- Low UV dose
- High reactor temperature
- Low water level in the reactor
- Lamp failure
- Ballast failure
- Wiper failure

System Interlocks

System interlocks can be used to protect equipment or water quality. Generally, they prevent the operation of equipment unless certain conditions exist. Interlocks can be hardwired into the system, or can be software based. Some examples of possible system interlocks are:

- Reactor will shutdown or will not startup if flow is below minimum required to keep lamps cool
- Reactor will shutdown or will not startup if temperature is above setpoint

Electrical System

The electrical system components for a UV disinfection system may include power supply backup and should include ground fault indicators.

Power Supply Backup

- UV lamps will require restarting if the power sags or is lost for only a fraction of a second.
- The time to restart the lamps can range from 15 seconds to 10 minutes depending on the lamp type and how long the power anomaly lasts.
- If the UV system power source is not reliable, then the system may include an uninterruptible power supply (UPS) to prevent lamp outages.
- A UPS will:
  - Absorb small power surges
  - Provide power during sags
  - Provide power for a limited time during outages
  - Smooth out other noise in the power supply
- The UPS should be large enough to keep the UV system in operation until the backup power supply for the plant, or a separate backup power supply for the UV system, is in operation.
- If some amount of downtime is acceptable, or the power source is relatively reliable, the UV system may use the same backup power as the rest of the plant, or have its own backup power supply. Without a UPS, there will be some downtime as the backup supply comes online and the lamps restart.

Ground Fault Interrupters

- A ground fault interrupter (GFI) will detect if some of the current in a line is leaking and interrupt the power supply.
- Leaking current can cause an electrical shock unless a GFI is in place to cut off the power.
- If you are not an experienced electrician, do not attempt any electrical repair or modification unless you have experienced supervision.

Piping Components

Flow Split

- If multiple reactors are in operation at the same time, it is important to make sure the flow to each individual reactor is controlled. If the flow is not split correctly, it may result in one or more reactors operating at flows above the validated limit. There are two general methods to control the flow into the reactors:
    - Use dedicated flow monitors and flow control valves for each reactor.
    - Hydraulically split the flow and confirm flow split with pressure readings or flow monitors for each reactor.
- Possible components for splitting the flow hydraulically include:
    - Weirs
    - Orifices
- The flow may also be split hydraulically by design of the influent and effluent piping to provide equal headloss through each reactor train.

Meters

- Flow may be metered for each individual reactor, or the total flow can be measured upstream or downstream of the reactors. Different types of flow meters can be used, including:
    - Venturi meter
    - Magnetic meter
    - Turbine meter
    - Doppler meter
- If the flow is not metered at each individual reactor, meters that can be used for control of the UV reactor include:
    - Raw water meter - may not account for water losses through treatment
    - Finished water meter - may not account for water loss between the UV system and the finished water meter
    - Filtered water meter

Valves

- Isolation valves
- Flow control valves (for systems that do not use hydraulic flow split)

Unit 2 Exercise

Fill in the blank:

1. Reactors are found in two basic configurations _________channel and ________channel.

2. UV lamps fall into three categories; low pressure, low pressure-high output and _________ pressure.

3. All three use _____________ vapor to produce UV light.

4. Position the lamp in the ___________ ____________ can affect the UV does reaching the pathogens.

5. UV lamps require power at specific ______________, ___________ and frequency to maximum the efficiency of UV light.

6. Ballasts are used to limit the current flow through the lamp. The two classification of ballasts are: _________ and ____________.

7. A UV _________sensor measures the __________ of the UV light at some distance away form the UV lamp.

8. A UVT monitor measures the _____________________ of the water flowing through the reactor.

9. The major components of a UV disinfection systems are: controls and _____________, the ____________system and the _____________ components and the UV ______________.

[1]Courtesy of Trojan Technologies Inc., http://www.nishihara.co.jp/english/wte/wte.html.

[2]Calgon Carbon Corporation.

[3]Courtesy of Trojan Technologies Inc.

[4]http://www.uvo3.co.uk/images/UVO3ReplacementLamps.pdf

[5]*Ultraviolet Disinfection Guidance Manual*, (United States Environmental Protection Agency, June, 2003), EPA 815-D-03-007.

[6]Courtesy of Trojan Technologies Inc.

[7]Calgon Carbon Corporation.

[8]Calgon Carbon Corporation.

[9]*Ultraviolet Disinfection Guidance Manual*, (United States Environmental Protection Agency, June, 2003), EPA 815-D-03-007.

Unit 3 – UV Performance

Learning Objectives

- Indicate the three parameters that affect UV dose.
- Explain what UV reactor validation is and how it is performed.
- Explain the difference between the required UV dose and the target RED value.
- List six water quality characteristics that can affect the effectiveness of the UV disinfection system.
- Explain how lamp and sleeve aging can affect the UV disinfection system.

Target Organisms and Dose

- Required UV doses given in the (proposed) LT2ESWTR are listed below in mJ/cm^2:

Table 3.1 – Required UV Doses Under the (Proposes) LT2ESWTR

	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Viruses	39	58	79	100	121	143	163	186

- UV dose is calculated by the following formula:
  UV Dose = I x t, where:

  I = the UV intensity applied to the target organism
  t = length of exposure

- Typical units for water treatment:
  I - milliwatts per centimeter squared (mW/cm^2)
  t - seconds
  dose - millijoules per centimeter squared (mJ/cm^2)

Operating Conditions Affecting Dose

For a given reactor, three parameters will affect the UV dose achieved:

- UV Intensity
  - As the UV intensity increases, so will the dose
  - UV intensity can be adjusted by changing the amount of power going to the UV lamps, or by turning lamps on or off

- Flowrate
  - As the flowrate through the reactor increases, the dose will decrease because the length of time the water remains in the reactor decreases
  - As flowrate changes UV intensity can be adjusted to keep the dose constant
  - Flowrate should be kept within validated flow ranges
  - If flowrate is too low, some reactors may be taken offline to increase flow in the remaining reactors

- UV Transmittance
    - Depending on the control method, UVT may either be measured with a UVT monitor or may be indicated by changes in the UV intensity
    - As the UVT decreases, dose will decrease because less light reaches the target microorganism. (Less light is transmitted through the water)
    - If UVT is indicated by the UV intensity readings, as UVT decreases, the UV intensity reading will decrease
    - As UVT changes, the UV intensity can be adjusted to keep the dose constant

Hydraulics

Due to the flow patterns through the reactor, each organism will take a different path through the reactor

- The length of exposure, t, may be different for each individual microorganism
- The intensity of exposure, I, may be different for each individual microorganism
- This makes the actual dose difficult to calculate
- Reactor validation is used to determine the dose achieved in a reactor

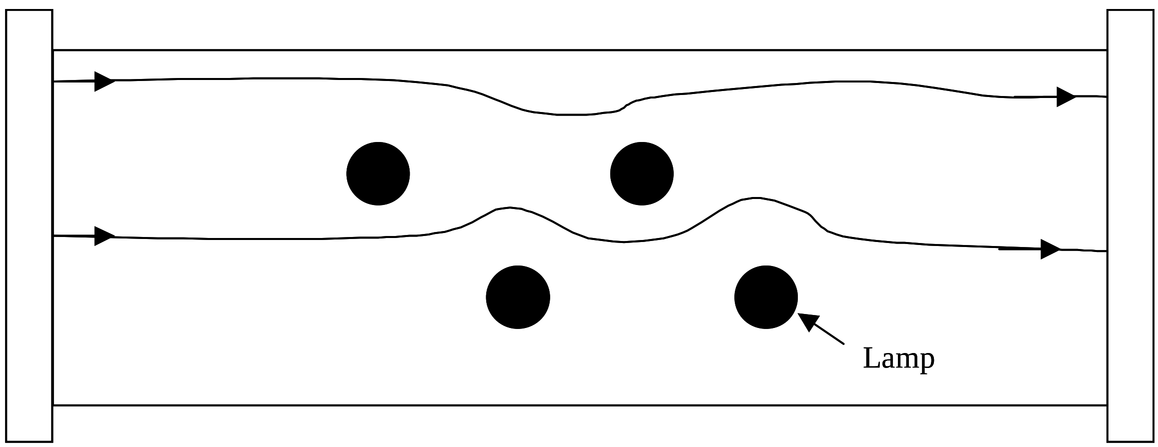

Figure 3.1 Reactor with Lamps.

Reactor Validation

During reactor validation, a reactor is tested at various UV intensities and flowrates, and possibly at various UV transmittances and lamp power levels.

- A challenge organism is used during validation and the amount of inactivation of the challenge organism is recorded for various test conditions.
- To determine the dose in the reactor, a test known as a collimated beam test is conducted.
  - The same challenge organism is dosed with a known intensity of UV light at 254 nm for a known length of time
  - The UV dose is calculated and the inactivation of the organism is measured
  - A curve is generated from the collimated beam test showing the inactivation achieved versus the UV dose. This is known as a dose-response curve

- The inactivation achieved in the UV reactor under the given test conditions is located on the dose-response curve.
- The corresponding UV dose is determined. That dose is known as the reduction equivalent dose (RED).
- The RED is the UV dose assigned to the reactor for the specific test conditions the reactor was operated under.

Uncertainty and Target RED Values

When performing a validation test and when operating a UV reactor in the field, the measurements obtained from sensors, microbial analysis, flowmeters, and other processes all have a certain level of uncertainty associated with them.

- The LT2ESWTR requires that during reactor validation, measurement uncertainties be accounted for when determining the dose achieved with the reactor.
- The US EPA *Ultraviolet Disinfection Guidance Manual* (June 2003) proposes that two methods can be used to account for various uncertainties during testing and operation:
  - Tier 1 - using the Tier 1 method, assigned safety factors are applied to the dose requirement listed in the LT2ESWTR. The resulting dose is the RED value that must be achieved during validation testing to be granted a specific level of pathogen inactivation, and is called the target RED. To be able to use the Tier 1 method, the UV system and validation test must meet certain criteria. Tables 3.2 and 3.3 list the target RED values proposed under the Tier 1 method
  - Tier 2 - the Tier 2 method is similar to the Tier 1 method, except that the safety factor is calculated based on the uncertainties specific to a system

Table 3.2 – Target RED Values for Reactors with LP and LPHO Lamps

Target RED Values for Reactors with LP and LPHO Lamps			
Log Inactivation Credit	RED Target Dose (mJ/cm^2)		
	Cryptosporidium	*Giardia*	Viruses
0.5	6.8	6.6	55
1.0	11	9.7	81
1.5	15	13	110
2.0	21	20	139
2.5	28	26	169
3.0	36	34	199
3.5	-	-	227
4.0	-	-	259

Table 3.3 – Target RED values for Reactors with MP Lamps

Target RED Values for Reactors with MP Lamps			
Log Inactivation Credit	RED Target Dose (mJ/cm^2)		
	Cryptosporidium	*Giardia*	Viruses
0.5	7.7	7.5	63
1.0	12	11	94
1.5	17	15	128
2.0	24	23	161
2.5	32	30	195
3.0	42	40	23
3.5	-	-	263
4.0	-	-	300

Off-Specification Water

The reactor is validated to provide a certain level of disinfection under specific conditions of UV Intensity, flowrate, lamp status, and possibly UVT. If the reactor is operated outside these validated conditions, the water that flows through the reactor during that time is not properly disinfected and is considered "off-specification". While some off-specification water is allowed to be sent to the distribution system (the exact amount has not yet been determined), production of off-specification water should be minimized to protect public health.

Fouling

- Fouling occurs when particles and substances dissolved in the water deposit onto the surface of the lamp sleeve.
- Over time, fouling will reduce the UV transmittance of the lamp.
    - As UVT decreases, the UV dose will decrease
    - More power will have to be applied to the lamps to maintain the required UV dose
- Fouling can be removed by routine mechanical wiping, chemical cleaning, or a combination of the two.
- The rate of fouling is affected by the quality of the water being treated. Following are some factors that influence the rate of fouling:
    - Hardness
    - Alkalinity
    - Temperature
    - pH
    - Iron concentration
    - Turbidity
- The rate of fouling will also tend to be higher with MP lamps than LP or LPHO lamps due to the higher operating temperature.
- The monitoring window of a UV intensity sensor can also become fouled, interfering with the intensity readings.

Transmittance

The UV transmittance (UVT) of the water is the water quality parameter that has the greatest impact on the operation of the UV system. As the UVT decreases, the power to the lamps must be increased to maintain the required dose.

- Dissolved iron will decrease the UVT.
- Dissolved ozone will decrease the UVT.
- Organics in the water will decrease the UVT.
  - By optimizing the upstream treatment to remove natural organic matter, the UVT can be maximized at the UV reactor
- Particles in the water will also decrease the UVT.
  - Turbidity should be minimized by upstream treatment before the UV reactor

Particles

- Particles will also scatter the UV light, decreasing the intensity of the UV light reaching the pathogens.
- If pathogens are attached to the particles, they may be shielded from the light entirely.

Upstream Treatment

- Upstream treatment can improve the operation of the UV system by increasing the UVT of the water.
  - Removing natural organic matter
  - Removing particles
- Some of the chemicals used in water treatment can decrease the UVT of the water:
  - Iron-based coagulants
  - Ozone
  - Potassium permanganate

Water Temperature

- Water temperature can affect the fouling rates. The effect will vary, depending upon what substance is causing the fouling.
- Water temperature has little effect on the disinfection effectiveness of UV light.

Algae

- Algae may grow in the reactor or nearby piping because of the visible light also produced by the reactor.
- There may be more algae growth near reactors with MP lamps than those with LP or LPHO lamps, because MP lamps produce more wavelengths in the visible light range.
- Algae growth can be a nuisance and can cause taste and odor problems in the finished water.

Lamp Intensity

- As a lamp ages, the intensity of the UV light decreases
  - The intensity of the UV light decreases faster at lower wavelengths
  - The intensity decreases faster at the beginning of lamp life than at the end
- Intensity will decrease more as:
  - Lamp is in operation for more hours
  - Lamp is turned on and off more frequently
  - Lamp is operated at higher power
- Rate of intensity decrease is also affected by:
  - Ballast type and operation
  - Water temperature
  - Vibration of the lamp sleeve caused by water flow
- The decrease in intensity is, in part, due to sputtering from the lamp electrode
  - As the electrode is heating during lamp start up, small particles from the electrode will break away from the electrode and coat the inside of the lamp
  - Lamps with a higher argon content will reduce sputtering
  - Preheating of the electrode before lamp start up will reduce sputtering
- Particles from the electrode may also coat the inside of the lamp if an MP lamp is operated at too high of a temperature.

UV Transmittance

- As lamp envelopes and sleeves age, they may undergo mechanical stresses that cause small fractures in the quartz. This will decrease the UV transmittance of the quartz.
- If electrode sputtering causes coating of the lamp envelope, the particles will absorb some of the UV light and decrease the lamp UVT.
- Particles on the lamp envelope absorbing UV light may also cause localized temperature increases.
  - High temperatures may cause the quartz to become crystalline, which decreases UVT.
  - High temperatures may also cause bubbles in the quartz, decreasing UVT.

Unit 3 Exercise

Multiple Choice:

1. UV _____________ increases the dose will increase, as ____________________ increase, the dose will decrease. As UV ______________________decreases, dose will decrease.

   a. flowrate, transmittance, intensity,
   b. intensity, flowrate, transmittance
   c. transmittance, flowrate, intensity

2. When a reactor is tested at various UV intensities and flowrates is called a ________ ____________.

   a. reactor validation
   b. reactor calibration
   c. reactor standardization

3. ________ will scatter the UV light, decreasing the intensity of the UV light reaching the pathogen.

   a. Algae
   b. Coagulates
   c. Particles

4. When particles and substances dissolve in the water deposit onto the surface of the lamp sleeve is called ___________________________.

   a. fouling
   b. deposition
   c. lamp coating

5. Improving operations of the UV system by increasing the UVT of the water can be accomplished by ________________ __________________.

   a. upstream treatment
   b. water treatment
   c. taking off-line

6. Water _______________ has little effect on the disinfection effectiveness of the UV light but can affect the fouling rates.

    a. pH
    b. temperature
    c. color

7. Algae growth can be __________; it can cause taste and odors problems in the finished water.

    a. beneficial
    b. overlooked
    c. a nuisance

8. The intensity of the UV light and UVT _______________ as a lamp and lamp sleeve age.

    a. decrease
    b. increase
    c. remain the same

Unit 4 – Operation

Learning Objectives

- Given the appropriate data, determine the UV intensity setpoint.
- Describe the three control strategies used to ensure an adequate UV dose is applied to the water.
- Indicate the advantages and disadvantages for each of the following operational strategies—single setpoint, variable setpoint, and setpoint interpolation.
- List the operational tasks associated with a UV system.
- Describe potential problems that may occur in the UV disinfection process, including their possible causes and solutions.
- Indicate which items must be monitored, recorded, and reported for each UV reactor under the (proposed) LT2ESWT.
- Specify safety issues pertaining to UV disinfection.

Verification

After the system is installed, proper operation of the components must be verified. Generally, this is accomplished by filling the reactor and confirming that the reactor and controls are working. Some items that should be checked include:

- Lamps
  - Ensure lamps are operating
  - Perform cold start of lamps in reactor
  - Perform shut down and restart of lamps in reactor
  - Check various power levels
- UV Intensity Sensors
  - Check calibration of sensors
- Valves
  - Check isolation valves
  - Check control valves
- Wipers
  - Check for smooth movement of wipers along the sleeve with no jamming or binding
  - Check to make sure the wiping mechanism extends fully
  - Check the wiper drive mechanism and motor for any slipping or binding
- Flowmeters
  - Check calibration
  - Determine uncertainty associated with measurement
- UVT Monitors
  - Calibrate
  - Verify readings using grab samples and lab measurement
- Ballasts, transformers, and frequency converters
  - Check condition of units

- Control Systems

  Operating simulations should be performed to verify operation of the system components, including:

  - Reactor startup
  - Reactor shutdown
  - Operation of the reactor on backup supply
  - Alarm situations
  - Operation in manual override
  - Generation of reports
  - System interlocks
  - Adjustment of UV intensity in response to flowrate or UVT changes

Performance Testing

Performance testing is the careful monitoring of performance during continuous operation to determine the accuracy, reliability, and repeatability of the reactor performance and to verify that the operating conditions meet those under which the reactor was validated. The exact goals of performance testing are dependent on the treatment plant, but may include:

- Operation of the reactor in automatic mode and confirmation that operating conditions remain within the constraints determined by validation testing.
- Confirmation of lamp power adjustments or reactor startup/ shutdown as required by varying water quality and flowrate.
- Testing adequacy of cleaning system by visually inspecting sleeve conditions at specified time intervals.
- Confirmation of long-term accuracy of UVT monitor and UV intensity sensor readings.
- Measurement of electrical usage as operating conditions change.
- Observation of switchover and operation on UPS or backup power supply.
- Verification that actual cleaning frequency matches set cleaning frequency.

Control Strategies

Three different control strategies are used to ensure adequate UV dose is applied to the water:

- UV Intensity Setpoint - under this control method, measurements made by the UV intensity sensors are used to control the reactor.
  - The UV intensity sensors are located some distance from the UV lamp, so that the UV light passes through the water before reaching the sensor
  - Because of the distance between the sensor and the lamp, the intensity reading accounts for changes in the UV intensity from the lamp and changes in water UVT
  - The power to the lamps is adjusted to change the intensity reading to match the intensity setpoint for a given flowrate
  - The UV intensity required to meet the disinfection requirements at a given flowrate is determined with validation testing
- UV Intensity and UVT Setpoint - under this control method, measurements from UV intensity sensors and from UVT monitors are used to control the reactor.
  - The UV intensity sensor is located close to the lamp, so it is only responding to changes in UV light output from the lamp
  - UVT is measured separately
  - The lamp power is adjusted to produce the set UV intensity reading for the measured UVT and flowrate
  - For example, the control matrix may look something like this:

Minimum Required UV Intensity Reading (mW/cm^2)			
Flow (gpm)	90% ≤ UVT ≤93%	93%<UVT≤96%	96%<UVT≤100%
25 - 100	12.1	6.0	1.7
100 - 200	17.3	9.2	3.1
200 - 300	23.7	12.9	5.8

  - The UV intensity required to provide the required level of disinfection for each combination of UVT and flowrate is determined through validation testing.
- UV Dose Calculation
  - Setup is similar to UV Intensity and UVT Setpoint method
  - UV intensity, UVT, and flowrate readings are used to calculate UV Dose, based on a computational algorithm validated with testing
  - Calculation of UV dose in reactor is manufacturer dependent
  - Lamp power is adjusted to maintain desired UV dose under various conditions

Operational Strategies

The operational strategy will vary according to specific plant needs and the control strategy selected. Three operational strategies are described below:

- Single Setpoint - a single UV intensity or dose setpoint is used for all flowrates and UVTs within the validated ranges.
- Variable Setpoint - multiple UV setpoints are used for given ranges of flowrate and UVT, as determined by validation testing.
- Setpoint Interpolation - the proper UV intensity setpoint for specific conditions is interpolated from the validation testing results.

Determining the UV Intensity Setpoint

The UV intensity setpoint will depend on the flowrate, the UVT, the level of disinfection required, and the operational strategy being used. Whatever setpoint is selected, it must be equal to or greater than the UV intensity or dose that was validated to meet the required inactivation under the operating flowrate and UVT.

- The intensity setpoint may be automatically or manually adjusted as the flowrate and water quality change. The dose setpoint may be adjusted if the inactivation requirements change.
- Data from the validation test is used to determine the required setpoint for various situations.
- If the reactor uses a UV Intensity Setpoint control strategy, then the UV intensity readings will account for any changes to the UVT. Because the intensity readings account for changes in both the UVT and the lamp output intensity, the intensity setpoint will depend only on the flowrate.
- If the reactor uses a UV Intensity and UVT Setpoint control strategy, then the UV intensity setpoint will be dependent on both the measured UVT and the flowrate.
- If the UV reactor uses a UV Dose Calculation control strategy, the dose setpoint is based on the level of inactivation required. The dose is calculated automatically from the UV intensity, UVT, and flowrate measurements, and the UV intensity is adjusted to maintain the UV dose at the setpoint as UVT and flowrate change.

Example 1

- The following data is collected during a validation test for a reactor using UV Intensity Setpoint control:

Flowrate (mgd)	UV Intensity (mW/cm^2)	Log Inactivation Credit
2	1.3	2.0
2	2.2	2.5
2	2.8	3.0
4	1.7	2.0
4	2.8	2.5
4	3.9	3.0
6	2.2	2.0
6	3.5	2.5
6	4.9	3.0
8	2.6	2.0
8	4.2	2.5
8	6.0	3.0

- This reactor is validated for operation between 2 and 8 mgd and up to 3.0-log inactivation of *Cryptosporidium*.

- For a Single Setpoint operational strategy, the UV intensity would be set at the intensity required to meet the desired log-inactivation at the highest flow rate. For this example, if 2.0-log inactivation were desired, then the intensity setpoint would be 2.6 mW/cm^2. If 3.0-log inactivation were desired, then the intensity setpoint would be 6.0 mW/cm^2. **The same setpoint would be used for all flowrates, regardless of the UVT.**

- For a Variable Setpoint operational strategy, the UV intensity would be set at a different intensity for each flow range. The intensity setpoint would be equal to the validated intensity at the highest flowrate in each range:

	UV Intensity Setpoint (mW/cm^2)	
Flow Range (mgd)	2.0-log inactivation	3.0-log inactivation
2.0 - 4.0	1.8	3.9
4.0 - 6.0	2.2	4.9
6.0 - 8.0	2.6	6.0

- For a Setpoint Interpolation operational strategy, an equation would be developed that accurately described the relationship between flowrate and UV intensity for a given log inactivation level. The following figure shows the plots of the data and the resulting equations describing the data.

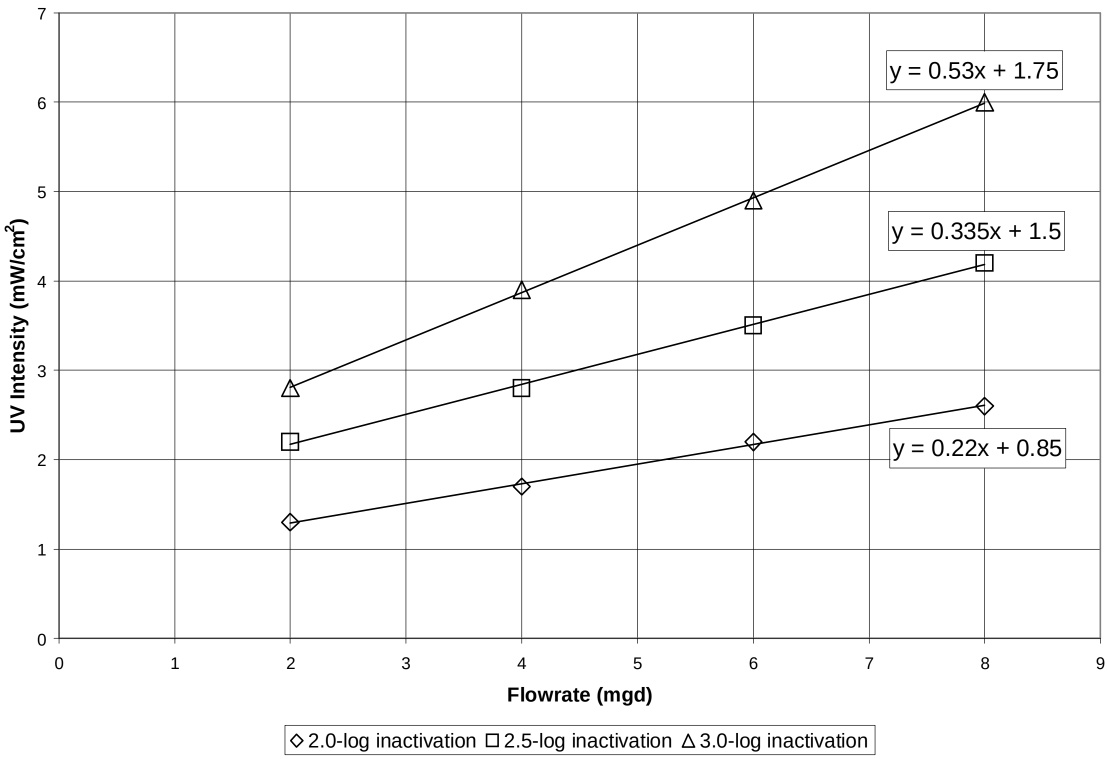

Figure 4.1 – UV Intensity Setpoint Interpolation Graph

- Using these equations, the intensity setpoint for any flow between 2 and 8 mgd could be determined for 2.0, 2.5, or 3.0-log inactivation. For example, at 3 mgd, and 3.0-log inactivation, the UV intensity setpoint would be calculated as:

  Intensity = 0.53 x 3.0mgd + 1.75 = 3.4 mW/cm^2

- The three operating strategies would be similar for the UV Dose Calculation control method, however, instead of adjusting the intensity setpoint as flowrate changes, the dose setpoint is adjusted if the desired level of inactivation changes.

Example

- A UV Intensity and UVT Setpoint control strategy was used and 3.0-log inactivation was met under the following conditions:

Flowrate (mgd)	UV Intensity (mW/cm^2)	UVT (%)
2	3.2	85
2	3.0	90
2	2.8	95
2	2.7	98
4	4.7	85
4	4.2	90
4	3.9	95
4	3.6	98
6	5.9	85
6	5.4	90
6	4.9	95
6	4.7	98
8	6.8	85
8	6.3	90
8	6.0	95
8	5.8	98

- For a Single Setpoint operational strategy with an inactivation of 3.0-log, a UV Intensity of 6.8 mW/cm^2 would be selected, because that intensity meets or exceeds the required intensity for all conditions.

- For a Variable Setpoint operational strategy with an inactivation of 3.0-log, the intensity setpoint could be based on flowrate alone, UVT alone, or a combination of the two. For each of these selections, the following intensity setpoint would be selected:
  - Flowrate

Flowrate Range (mgd)	UV Intensity Setpoint (mW/cm^2)
2.0 - 4.0	4.7
4.0 - 6.0	5.9
6.0 - 8.0	6.8

  - UVT

UVT Range (%)	UV Intensity Setpoint (mW/cm^2)
85 - 90	6.8
90 - 95	6.3
95 - 98	6.0

- Flowrate and UVT

	UV Intensity Setpoint (mW/cm2)		
Flowrate Range (mgd)	85 - 90% UVT	90 - 95% UVT	95 - 98% UVT
2.0 - 4.0	4.7	4.2	3.9
4.0 - 6.0	5.9	5.4	4.9
6.0 - 8.0	6.8	6.3	6.0

▶ The Setpoint Interpolation operational strategy is not used with the UV Intensity and UVT Setpoint control strategy because the combined effects of flowrate and UVT are too complicated for the required intensity to be easily interpolated.

Advantages and Disadvantages

Table 4.1 –Advantages and Disadvantages of Various Operational Strategies

Operational Strategy	Advantages	Disadvantages
Single Setpoint	Simple operation.	Poor energy efficiency because the unit is overdosing at flowrates below the maximum.
Variable Setpoint	Energy efficiency greater than Single Setpoint strategy. Less complex operation than Setpoint Interpolation.	More advanced controls may be necessary than for Single Setpoint strategy.
Setpoint Interpolation	Most energy efficient method. May require fewer operational hours if controls are automated.	Complex operation requires more advanced controls. More validation data is needed.

Automation

The UV system controls can be automated to varying degrees. At a minimum, shutdown of the reactors under critical alarm conditions should be automatic. At a maximum, the system can be fully automated. Some examples of steps that may be automatic are:

▶ Start up and shutdown of reactors as needed for variation in flowrate and UVT.

▶ Start up and shutdown of reactors after manual initiation.

▶ Adjustment to lamp power level to maintain desired UV intensity or UV dose as water quality or flowrate changes.

▶ Start up and shutdown of lamps or lamp banks as needed to optimize energy usage while meeting dose requirements.

Operational Tasks

The tasks required for operation of a UV system are dependent on the control strategy, the operational strategy, the level of automation, and specific plant conditions. The frequency with which the tasks are carried out will also vary and may be adjusted as operators become familiar with the equipment.

Operational tasks recommended in the UV Guidance Manual are:

- Daily
    - Perform visual inspection of all UV reactors
    - Ensure system control is on automatic control, if it should be
    - Check control panel display for the status of the system components and the alarm status and history
    - Ensure all on-line analyzers, flowmeters, and data recording equipment are operating normally
    - Review the 24-hour monitoring data to ensure that the reactors have been operating within the validated conditions
- Weekly
    - Initiate manual operation of weirs, if applicable, to ensure proper operation
- Monthly
    - Check lamp run time. Consider changing lamps if operating hours exceed design life or if UV intensity is low
- Semi-annually
    - Check all cooling fans for unusual noise
    - Check operation of automatic and manual valves

Reactor Startup and Shutdown

As the flowrate and water quality changes, reactors may be turned on or off. The reactor startup and shutdown procedures will be different for each system, and may be automated to varying degrees, so manufacturer's instructions should be followed. General procedures follow:

Startup

1. Remove lockouts and tag-outs of the control panel and power supply, following specific site procedures.

2. Ensure that all the lamp and ground connections are properly made.

3. Check that incoming power conductors, including ground conductors, are properly terminated.

4. Ensure that the lamp ends and other reactor ports are covered and/or sealed to eliminate any potential for operator exposure to UV light.

5. Ensure that the breakers are turned on and all electrical cabinets and equipment are closed and clear.

6. Initiate the reactor's startup sequence.

7. Begin flow to the reactor and gradually increase the flowrate until it is at the minimum flow required for cooling the reactor. Note: because the lamps are not yet warmed up at this point, the water exiting the reactor is not disinfected and is considered off-specification.

8. Check that the reactor is full.

9. Check for heat buildup at the top of the reactor. Heat buildup indicates pockets of air trapped inside the reactor.

10. Check the reactor control panel to see that all lamps are on and all of the indicators are displayed.

11. Check for any alarms and correct any problems.

12. Check the online analyzers for proper operation.

13. After the lamps are warmed up to the proper operating condition, increase flow to the reactor to the desired flowrate, which should be within the validated range.

14. Verify that the flow is being split correctly amongst the reactors by checking flowmeter or pressure gauge readings.

15. Verify that the reactor is operating within the validated ranges.

Shutdown

1. Throttle the effluent valve to reduce flow to the minimum required for cooling the reactor. It is possible that no flow may be required; in this case, close the effluent valve.

2. Turn off the reactor and allow it to cool down. Any water passing through the reactor while it is cooling down is off-specification and is not disinfected.

3. Close the effluent valve if not closed in Step 1.

4. If maintenance will be performed on the reactor, continue on to Steps 5 – 7. If it is to be placed on standby, the following steps are not necessary.

5. Perform lockout and tagout of the equipment, following plant procedures.

6. Drain the reactor if necessary for the maintenance being performed.

7. Inspect or repair equipment needing maintenance.

After an extended period out of service (more than 30 days), the reactor should be cleaned and then the lamp sleeves should be checked for fouling. If sleeves appear fouled, additional cleaning should be performed.

Winterization

If the reactor is located in an unheated area and freezing is a possibility, the reactor should be winterized if it will be out of service for a lengthy period of time. Manufacturer's instructions for winterization should be followed.

Troubleshooting

While operating a UV disinfection system, various problems may be encountered that could lead to production of off-specification water. In this section, potential problems and their possible causes and solutions are presented.

Low UV Intensity or UV Dose

While the control strategies using UV dose and UV intensity are different, a low UV dose will usually be caused by the same factors that cause low UV intensity. Therefore, the strategies for correcting a low UV intensity or a low UV dose will be similar.

- Factors that will affect the UV intensity or dose reading:
    - Lamp UV intensity output
    - Sleeve UV transmittance
    - Fouling of sleeves
    - Fouling of UV intensity sensor windows
    - UVT of water (for UV Intensity Setpoint or Calculated Dose control strategies)
    - Intensity sensor calibration
- Possible steps to improve the UV intensity:
    - Adjust UV system to increase UV intensity if not done automatically
    - Check the lamp age. If any lamps are past design life, replace the lamps and check the age of lamps in other reactors
    - Check the UVT. If UVT is low or below validated limits, then evaluate reason for low UVT and correct (see *Low UV Transmittance* section below)
    - Replace the duty UV intensity sensor with a reference sensor
    - Inspect the lamp sleeve and sensor window for fouling. If they are fouled, clean them and inspect other reactors for fouling
    - Check the age of the lamp sleeves. If any are beyond the design life, replace them and check sleeve age in other reactors
    - If the UV intensity/ dose remains low, contact the manufacturer to evaluate the problem. Until the problem is corrected, other reactors or other means of disinfection should be used

Low UV Transmittance

Low UVT may be a problem if it goes below the validated UVT or if it causes the UV intensity or UV dose to go below the validated conditions. A low UVT will also increase the lamp output that is required to provide a given dose or UV intensity reading, which increases the system power requirements, especially if a multiple or variable setpoint operational strategy is used.

- Possible causes of low UV transmittance:
  - UVT monitor or lab analyzer is out of calibration
  - Changes in source water quality
  - Changes in upstream treatment or treatment performance

- Steps to take:
  - Check the UVT reading:
    - If an online UVT monitor is used, perform a grab sample laboratory analysis for UVT. If the laboratory reading is significantly different, check the calibration of the laboratory analyzer. If the grab sample UVT is verified to be significantly different than the online UVT monitor reading, replace the UVT monitor with a spare and repair/ calibrate the duty monitor.
    - If grab samples are used to check the UVT, take another sample and confirm the UVT measurement. If the UVT reading is still low, check the calibration of the laboratory analyzer and recalibrate or repair if necessary.
  - If the low UVT reading is determined to be real, several measures could be taken to increase the UVT:
    - Check upstream processes to ensure that they are functioning properly. If they are not, correct the problem.
    - If multiple water sources are available, vary the source blending ratio.
    - Evaluate whether the coagulation process is optimized for removing natural organic matter (NOM). If possible, adjust the coagulant dose for better removal.
    - Increase oxidant dose prior to UV treatment, if possible.
    - Check for possible chemical interferences caused by upstream processes. If found, correct.
  - If the above options are not possible or do not improve the UVT then:
    - If the UVT is not below the validated level and is not causing the UV intensity or dose to go below the validated level, operation of the UV system can continue as normal.
    - If the UVT is below the validated level or is causing the UV intensity or UV dose to be below the validated range, the manufacturer should be contacted to further investigate the problem. Until conditions are back within the validated range, other disinfection methods should be utilized.

Unreliable UV Intensity Sensor Readings

UV intensity sensor readings are critical to proper operation of a UV system. If the intensity sensor is not operating properly it could lead to under dosing or overdosing. Under dosing would lead to inadequate disinfection, while overdosing would cause excess energy usage.

- Sensor readings can be considered unreliable if:
  - A calibration check is outside of the expected range of uncertainty in measurement, as specified in the validation testing
  - The readings have random fluctuations of 25% or more
  - The readings are biased, i.e. the intensity meter readings are offset from the reference sensor by a certain amount
- Unreliable sensor readings may be caused by:
  - UV intensity sensor failure
  - Condensation in the sensor or between the sensor and the sensor window
  - Lamp malfunction
  - Poor grounding
  - Degradation of the sensor electronics
  - Electronic short circuits
- To correct the problem:
  - Sensor and lamp electrical cables should be secured
  - If the readings are still unreliable, replace the sensor with a reference or standby sensor
  - If the reference sensor or standby sensor readings are reliable, send the duty sensor to the manufacturer to be repaired or recalibrated
  - If the replacement sensor also has unreliable readings, check the lamp age and see if it is past its design life. If so, replace the lamp. If not, contact the UV system manufacturer to further investigate the problem. Until intensity sensor readings are reliable, other reactors or other disinfection methods should be used

High or Low Flow

- As flow increases, it should be possible to maintain the appropriate dose by:
    - Increasing the power to the lamps
    - Using additional reactors
    - Turning on additional lamps or banks of lamps
- This will usually occur automatically, unless the reactor is manually operated.
- If the flow is higher than the validated limits and cannot be lowered by bringing more reactors into service or decreasing the plant flow, the calibration of the flowmeter or differential pressure meter should be checked.
    - If the calibration is accurate, blockages or flow split device failure may be responsible for uneven distribution of the water, resulting in a high flow rate through some reactors. Possible causes of uneven flow split should be evaluated and corrected if they exist
    - As long as the flow remains above the validated limits, the water must be reported as off-specification
- If the flow is lower than validated limits and cannot be increased by taking reactors off-line or increasing the plant flow, calibration of the flowmeter or differential pressure meter should be checked.
    - If the calibration is accurate, the water must be reported as off-specification for as long as the flow remains below the validated limits

Power Quality Problems

- Power quality issues that may cause a UV lamp to lose its arc include:
    - Voltage sag – a sag in voltage 10 to 15% or more below the nominal voltage for even a few cycles will cause the lamp to lose its arc.
    - Power interruption

- If the power outage is short term, or due to a voltage sag, the lamps will still be warm when the power returns to normal. The requirements for restart of the lamp, and the length of time for the lamp to restart will vary according to the type of lamp.
    - LP lamps do not need to cool down before restart and the arc can be restored quickly, normally within 15 seconds. So it will take only about 15 seconds to have the system operating at the appropriate temperature once power is restored
    - LPHO lamps do not need to cool down before restart, but the electrode must be warmed before the arc is struck and more time is needed to restrike the arc than for LP lamps. 4 to 7 minutes will be required to reach full power once the power is restored
    - MP lamps must be allowed to cool down before the arc can be restruck. The time needed to cool down will vary depending on the water temperature, but will normally take around 5 minutes. Then the arc must be restruck, which will take approximately 5 minutes to reach full power. So the total time to restart once power is restored will be 10 minutes
- If the power outage is long enough for the lamps to cool, then the time required to start LPHO and MP lamps will change. The time required for LP lamps will remain about the same, since the operating temperature is close to room temperature.
    - Once LPHO lamps are cool, more time will be needed to warm them up and restart the arc. The total time will normally be from 6 to 7 minutes to be at full power once the power supply is restored. If the water is colder, the warm up time may be slightly longer than when it is warm
    - If MP lamps are cool before the power is restored, then they will not have to be cooled after power is restored. They will take about 5 minutes to reach full power once power is restored
- The different nature of the lamps affects the operating strategy for restarting the lamps:
    - If the power supply anomaly is short, then the lamps in the reactors that were operating when the arc was lost will still be warm when power quality is restored
    - If the lamps are LPHO lamps, then reactors with lamps that are still warm should be used, because they will restart more rapidly than cold lamps
    - If the lamps are MP lamps, then reactors with cold lamps should be started up if any are available, because those lamps will not need to be cooled before they can be restarted
- If power is lost for a significant amount of time, then the lamps may be powered by a backup power supply or generator until the power is restored. However, it is likely that the lamps will again lose their arc when power is switched back to the normal power supply after the power is restored.
- If power quality fluctuations are frequent, then an uninterruptible power supply (UPS) should be considered. This will prevent loss of the arc during power quality fluctuations and short-term power loss. If power loss is lengthy, a UPS should allow the lamps to continue operating until a backup power supply or power generator can be used.
- Any water passing through the reactor when the lamps are not at full power is off-specification.

Monitoring, Recording, and Reporting

Under the (proposed) LT2ESWT, the following items must be monitored, recorded, and reported for each reactor:

- Monitoring
  - The system is required to monitor any parameters needed to determine whether the reactor is operating under the conditions that were validated to meet the required dose
  - At a minimum, the UV intensity, flow rate, and lamp outage must be monitored
  - Other monitoring requirements may be set by the state
- Recording
  - No specific recording requirements are set by the LT2ESWTR
  - The draft UV Guidance Manual recommends that the parameters that need to be monitored are recorded at least every 4 hours, if practical
  - Specific recording requirements may be set by the state
- Reporting
  - A summary of the percentage of water entering the distribution system that was off-specification must be reported to the state monthly, within 10 days after the month the data was collected
  - The LT2ESWTR requires that the UV intensity sensor calibration be verified and that the state approve the recalibration protocol. Calibration reporting may be required by the state
  - The state may require that other information be reported

Parameters

The parameters that need to be monitored to verify that the system is operating under validated conditions depend on the control strategy being used. Those parameters are listed below:

- UV Intensity Setpoint Control Strategy
  - UV intensity
  - Flowrate
  - Lamp status

- UV Intensity and UVT Setpoint Control Strategy
  - UV intensity
  - Flowrate
  - UVT
  - Lamp status
- UV Dose Setpoint Control Strategy
  - UV Dose
  - Flowrate
  - UVT
  - UV intensity
  - Lamp status

Examples of Off-Specification

Examples of causes for water to be considered off-specification include:

- UV intensity is below the setpoint for the operating flowrate (and UVT, if applicable).
- Lamp failure
- UV intensity sensor failure
- UVT is below the validated limit.
- UV dose is below the setpoint for the given flowrate.
- Flowrate is outside of the validated limits.
- UVT monitor failure

While not required, other parameters that should be monitored and recorded are listed below.

Table 4.2 –Other Parameters That Should be Monitored

Parameter	Recommended Monitoring Frequency	Recommended Recording Frequency	Notes
Power usage	Continuous	Every 4 hours	Power draw information can be correlated with operating conditions to determine the most energy efficient operating conditions.
Water temperature	Continuous	Daily	Monitor to ensure reactor is not overheating.
UV lamp on/off cycles	Continuous	Weekly (Total cycles in each week)	Monitor to assess lamp condition. On/off cycling affects the aging of a lamp and the number of cycles may be part of the lamp warranty.
Turbidity	Daily	Weekly	Monitor if a chemical (for example lime) is added post-filtration and before UV disinfection. Monitor to help assess effect of chemical addition on UVT.
pH	Weekly (reduce frequency if fouling is not prevalent)	Weekly	Monitor to help assess fouling issues, if necessary.
Iron			
Hardness			
Alkalinity			
UV intensity sensor calibration check	Monthly	Monthly	Record the date and results of the calibration check for each sensor. Note if a sensor was replaced. (Proposed) LT2ESWTR requires systems to verify the calibration of the intensity sensors (frequency is not stated) and requires states to approve the calibration protocol.
UVT monitor calibration check	Weekly	Weekly	Monitor to ensure proper dosage is being applied and to assess maintenance needs.
Age of: Lamps Ballasts Sleeves UV intensity sensors	Monthly	Monthly	Monitor to plan operation and maintenance budget, maintenance schedule, and part replacement ordering.
Flowmeter calibration check	Monthly	Monthly	Monitor to ensure proper dosage is being applied and to assess maintenance needs.
Failure of any equipment	Continuous	Each occurrence	Monitor for warranty issues and to assess maintenance scheduling and budget.

UV Exposure

Chronic exposure to low levels of UV light on the skin can increase the chances of developing skin cancer. Acute exposure to higher levels can cause tanning or sunburn of the skin, and conjunctivitis or burning of the cornea when the eyes are exposed. Although there are no enforceable limits set on UV light exposure, the American Conference of Governmental Industrial Hygienists (ACGIH) publishes recommended limits, called threshold limit values (TLVs) for many hazardous substances. The TLV for UV light depends upon the wavelength and intensity of the light, so the value should be determined based on the lamp being used in the UV disinfection system.

To prevent exposure:

- Before accessing a UV reactor, ensure that the lamps are off. There should be safeguards that automatically turn off the lamps if a reactor is opened.
- Wear protective clothing if exposure is possible:
  - Wear a UV resistant face shield
  - Cover other areas of exposed skin (gloves, etc.)
- Warning signs should be placed on or near the UV reactors to help prevent accidental exposure

Electrical

UV lamps require a source of electrical power. As such there is a risk of electrical shock when working on or near the equipment. To help prevent electrical shock, the following steps should be taken:

- Disconnect the main source of power to the reactors and wait for at least 5 minutes for the lamps to cool and energy to dissipate before performing any maintenance.
- Ensure the equipment is properly grounded.
- Follow proper lockout and tagout procedures.
- Ensure that proper electrical insulation is used and the insulation is in good condition.
- Install safety cut-off switches.
- Follow all other safety and operation precautions required by the National Electric Code (NEC), the Office of Safety and Health Administration (OSHA), local electric codes, and the UV manufacturer.

High Temperature

The UV lamps, UV reactor, ballasts, and transformers may all become hot during operation. Before approaching these items, the temperature should be assessed. If hot, they should be allowed to cool before they are contacted.

Lamp Breakage

- Two hazards are associated with a broken lamp:
  - Broken glass or quartz from the lamp sleeve or envelope
  - Mercury released from the lamp
- Prevention of lamp breakage should be the primary method of protection against these hazards.
- A site-specific response plan should be in place that details the actions to be taken in the event of a broken lamp.

Causes and Prevention of Lamp Breakage

- Lamp breakage can be defined as off-line or on-line breakage:
  - Off-line breakage is when the lamp is broken during shipping, handling, or storage and the lamp is not installed in a reactor. In this event, the breakage does not constitute a danger to the customer, but is a concern for water treatment plant personnel
  - On-line breakage occurs when the lamp breaks while the reactor is in operation. In this case, the mercury and the lamp and sleeve fragments are potentially a hazard for water consumers, as well as plant staff
- Off-line breakage is generally caused by mishandling or improper storage methods.
  - Lamps should be stored horizontally, in individual packaging
  - Lamps should not be stored vertically propped up against a wall or unpackaged. They may fall or bump against other lamps, causing fracture or breakage
  - Maintenance on lamps or sleeves should be performed according to the manufacturer's instructions to avoid fracturing or breaking of the lamp or sleeve
  - Operators and maintenance personnel should be trained in proper handling and maintenance of the lamps

- Possible causes of on-line lamp failure and preventative measures that may be taken are summarized in Table 4.3.

Table 4.3 –Possible Causes of On-Line Lamp Failure and Preventative Measures

Description of Cause	Preventative Measure
Debris: Debris in the water can impact the lamp sleeves and break the lamp. The debris may come from the source water (for example a stone or gravel), or may be an item that originated in the plant (for example a bolt or piece of concrete).	• Protective screens, baffles, or low velocity collection areas may be placed upstream of the reactors to remove large or heavy objects.
Overheating: Lamps may overheat if air is trapped in the reactor or if the flow is reduced below the minimum required for adequate cooling. Lamp breakage may be caused by the overheating or by cooling overheated lamps too rapidly.	• Provide air release valves or level sensors to ensure that the reactor is always full. • Use temperature sensors to monitor for overheating. • Provide automatic shutdown of the reactor in case of overheating. • Ensure that water is always flowing through an energized reactor. • Overheated lamps should not be rapidly cooled.
Water Pressure: Lamps and sleeves are designed to withstand a specific pressure. If this pressure is exceeded, it may cause cracking or breaking of the sleeve. This will leave the lamp vulnerable even if the lamp does not break due to the pressure. Small negative pressures can also compromise the sleeve integrity. Positive and negative pressures occur with water hammer, and if water hammer occurs, it may affect all the reactors and all the lamps could break at the same time.	• Lamps and sleeves should be designed to withstand the maximum operating pressure. • Surge analysis should be performed to evaluate water hammer potential and solutions to prevent it.
Procedural Errors: A lamp or sleeve that is damaged off-line or during maintenance may break under normal operating conditions. Over-tightening of the compression nuts when securing the lamp sleeve can cause fracturing of the sleeve or a leak in the seal between the lamp and the sleeve.	• Do not use any lamp or sleeve that has been damaged. • Follow manufacturer procedures when replacing a lamp or performing maintenance.
Electrical Issues: Electrical surges can cause short-circuiting and damage to the lamp socket. Power applied that exceeds the design rating of the lamp can cause a lamp to burst.	• Ensure that the circuit breakers and ground fault indicators are appropriate for preventing damage to the reactor. • Replacement lamps should be electrically compatible with the reactor.
Cleaning Mechanism: The cleaning mechanism may become misaligned and impact on the lamp sleeve. If the cleaning mechanism rests on the lamp, it may become fused to the lamp and cause damage if the mechanism attempts to move.	• Inspect the cleaning mechanism for any sign of failure or heat fusion. Maintain routinely according to manufacturer's instructions.
Material Selection: If materials are not thermally matched, they may be damaged during shipping, storage, or operation under certain thermal conditions.	• Ensure that the reactor was designed for the temperature conditions likely to be encountered during shipping, storage, and operation.

Broken Quartz or Glass

A broken sleeve or lamp may fracture into sharp pieces that can cut or pierce the skin. If possible, avoid handling the broken quartz or glass with the hands. Gloves and eye protection should be worn.

Mercury Release

- Inhalation of mercury vapor is the primary way mercury is absorbed into the body, although small amounts of mercury can be absorbed through the skin. Very little mercury is absorbed through ingestion.
  - Short-term exposure to high concentrations of mercury vapor can cause coughing, difficulty breathing, chest pain, nausea, vomiting, diarrhea, and/or fever
  - Effects of long-term exposure include shakiness, psychological changes, difficulty sleeping, emotional instability, loss of appetite and weight loss, and short-term memory loss
- It is possible to exceed the permissible exposure limit (PEL) set by the Occupational Safety and Health Administration (OSHA) if the mercury in a lamp is spilled, depending on the droplet dispersion, the air temperature, air currents, and the length of time the spill remains. However, if the spill is cleaned up promptly, the limit should not be exceeded.
  - Off-line lamp breakage cleanup
    - Mercury is regulated as a hazardous waste and must be disposed of appropriately. Small spills (about the amount contained in a thermometer – 0.6 to 2.25 grams) can be cleaned up with commercially available kits, while local authorities should be contacted for larger spills. Once cleaned up, the mercury and any items contaminated with mercury should be disposed of properly
    - Local authorities should be contacted to determine the appropriate cleanup procedures for various size spills
    - The proper cleanup procedures should be determined beforehand and included in the standard operating procedures for the plant
    - The amount of mercury in a lamp is specific to the manufacturer and type of lamp. In general, an MP lamp will contain more mercury than an LP or LPHO lamp. Typical reported values range from 0.005 to 0.4 grams of mercury per lamp, so normally multiple lamps would need to be broken to constitute a large spill

- On-line lamp breakage procedures
  - Because of the potential for mercury to be released into the distribution system, procedures for handling an on-line lamp breakage should be determined well ahead of time.
  - A response plan should include the following components:
    - Mercury containment procedures
    - Mercury sampling and compliance monitoring
    - Clean-up procedures
    - Reporting requirements
  - Local agencies should be contacted to help determine the appropriate sampling, monitoring, clean-up, and reporting procedures.
  - Sensors cannot differentiate between lamp breakage and other reasons for lamp failure, so it is recommended that a reactor be shut down in case of an online lamp failure alarm until the reason for the alarm is determined. This will help prevent the movement of any spilled mercury into the distribution system.
  - Operators should attempt to trap any mercury in the reactor or in downstream processes.
  - The residence time in a reactor is usually short, so it is likely that some mercury will escape unless the isolation valve is located far enough downstream to close before the mercury reaches it without causing water hammer.
  - Condensed mercury may settle in low velocity areas such as clearwells, pump sumps, or the bottom of a shut down reactor.
  - Provisions may be added so that potentially contaminated water may be drained into a waste container or truck.
  - Reporting requirements should be confirmed with state and local agencies. The federal maximum contaminant limit (MCL) for inorganic mercury in drinking water is 2 micrograms per liter. The Superfund Amendments and Reauthorization Act (SARA) regulations require that spills greater than or equal to 1 pound (454 grams) are reported.

Unit 4 Exercise

1. The following data is collected during validation testing of a reactor using UV Intensity Setpoint control. What would the UV intensity setpoint be for a flowrate of 7 mgd and 2.5-log inactivation using:

Flowrate (mgd)	UV Intensity (mW/cm^2)	Log Inactivation Credit
6	3.6	2.0
6	5.3	2.5
6	6.7	3.0
8	4.9	2.0
8	7.3	2.5
8	9.7	3.0
10	6.1	2.0
10	9.3	2.5
10	13.0	3.0

a) A Single Setpoint operational strategy. ______________________

b) A Variable Setpoint operational strategy ______________________

2. Assuming a linear interpolation, the Setpoint Interpolation Operational Strategy would be:

Where: $y_2 = (y_1 + \text{slope})(x_2 - x_1)$

Slope= 1 mW/cm2 per mgd

The liner interpolation = 6.3

The Flowrate (x_2) = 7 mgd

3. Match the UV control/operational strategies with their definitions.

____ 1. A UV intensity or dose setpoint is used for all flowrates and UVTs within the validated ranges.	A. UV Intensity Set point
____ 2. UV intensities would be set at a different intensity for each flowrate.	B. Setpoint Interpolation
____ 3. An equation would be developed that describes the relationships between flowrate and UV intensity.	C. UV Transmittance (UVT)
____ 4. Control method to make sure the UV intensity sensors control the reactors.	D. UV Dose
____ 5. Water quality parameter that has the greatest impact on the operated of the UV system. It is monitored to control the reactor.	E. Single Setpoint
____ 6. UV intensity, UVT and flowrate are used to calculate this.	F. Variable Setpoint

Multiply choice:

4. Potential problems in the UV disinfection process are: (may be more than one correct answer)
   a. Low UV intensity
   b. Low UVT
   c. Split flow
   d. Validated limits
   e. Unreliable sensor readings
   f. Power Interruptions

5. UV intensity, flow rate and ______________ must be monitored and recorded every four hours as proposed by the LT2ESWT.
   a. UV Dose
   b. Lamp outage
   c. UV Residual
   d. Lamp Breakage

6. Working with UV disinfection has it share of safety related issued to be concerned with. Which of the below <u>does not</u> apply to UV disinfection:
   a. UV exposure
   b. Chlorine Feed line leakage
   c. High temperatures
   d. Lamp Breakage

Unit 5 – Maintenance

Learning Objectives

- Identify eight components of a UV disinfection system that should be inspected.
- Describe calibration methods for flow meters, intensity sensors, and UVT monitors.
- List three components of a UV disinfection system that require cleaning and describe how they should be cleaned.
- Identify the pertinent issues to consider when replacing lamps and sleeves.

UVT Monitor

- The calibration of the UVT monitor should be checked weekly against a grab sample analyzed in the laboratory with a spectrophotometer. The frequency may be reduced if performance records indicate it is appropriate.
- The UVT monitor should be inspected for fouling.
- Electrical connections should be inspected to ensure they are properly made and insulation is intact.

UV Intensity Sensors

- Reference sensors are used to check the calibration of the duty sensors. The calibration of the duty sensors should be checked monthly.
- The reference sensor(s) should be sent to the manufacturer for calibration annually.
- The intensity sensor monitoring window should be checked for fouling.

Flow Meters

- The calibration of the flow meters should be checked as recommended by the manufacturer.

Pressure Gauges

- If pressure gauges are used to confirm that the flow is split evenly, rather than individual flow meters at each reactor, then the accuracy of the gauges should be confirmed by using a reference gauge or spare gauge.

Leak Check

- The seals on the reactor housing, the sleeves, and the wipers should be checked and replaced if damaged or leaking.

Sleeves

- The sleeves should be checked for fouling monthly if the cleaning system is an off-line system, and semi-annually if the cleaning system is an online system. After two or more years of operation, the inspection interval should be adjusted based on the system performance. The sleeves should also be inspected if it is suspected that fouling is the reason for a decline in UV intensity.
  - One sleeve (or bank of lamps) per reactor should be removed to check for fouling
  - If the sleeve appears fouled, it should be cleaned and the rest of the sleeves should be checked for fouling
  - If the sleeves are fouled enough that they are causing UV intensity to fall below the validated level and cleaning does not restore the UV intensity, the sleeves should be replaced
- If the sleeves are damaged or fractured, they should be replaced.
- If streaking is observed on a sleeve, it may indicate a problem with sleeve wipers.
- Discoloration of the sleeve is one indicator of fouling. To best observe discoloration, the sleeve may be laid on a clean, white, lint-free cloth next to a new sleeve.

Cleaning System

- The wiper blades should be checked for deformation or degradation whenever sleeves are checked.
- The drive mechanism should be inspected and maintained as recommended by the manufacturer.
- If an online cleaning system includes a chemical cleaning fluid reservoir, the fluid level should be checked about every six months.
  - If the level of the solution is low, add more solution
  - If the fluid is discolored, replace it
  - Also replace the fluid if the cleaning system is not effectively cleaning the sleeves

Electrical Components

- Ballast output should be monitored through the reactor control panels. If output becomes irregular or unstable, it may indicate a problem either with the electrical feed or the ballast.

- The ballast cooling system should be maintained in accordance with the manufacturer's recommendations.

- The GFI circuit breakers should be test-tripped annually to ensure proper operation. They should be maintained in accordance with the manufacturer's recommendations.

- If an uninterruptible power supply is used, it should also be maintained according to the manufacturer's recommendations.

Flow Meters

- The flow meter calibration should be checked at the frequency recommended by the manufacturer. Three possible methods of checking the calibration are:
  - Flow verificators can be used to evaluate the physical condition of the flow meter in comparison to its condition during the most recent factory calibration and to verify that the flow meter will still operate with the same degree of uncertainty.
  - A time-discharge test can be used to measure the volume passing through the meter in a given amount of time. The volume is measured in a container of known volume such as a tank or a clearwell.
  - A temporary reference flow meter can be used to measure the flow and those measurements can be compared to the values obtained from the permanent flow meter. The reference meter uncertainty should be taken into account when comparing the results.
- The measurement uncertainty of the permanent flow meter should be equal to or less than the uncertainty of the flow measurements taken during validation testing of the UV reactor.
- If a common flow meter is used and flow split is confirmed with pressure gauges, the calibration of the gauges should be checked periodically with reference pressure gauges in addition to the calibration check of the flow meter.

Intensity Sensors

The calibration of all duty intensity sensors should be checked monthly. The calibration procedures in the manufacturer's operation and maintenance manual should be followed. Follow instruction on measuring UV intensity with the duty and reference sensors.

- For some UV intensity sensors, the alignment of the sensor within the sensor port affects the intensity reading. When placing a sensor in the reactor, the sensor should be rotated until the lowest UV intensity reading is achieved. Alternatively, the sensor may be designed to only fit into the port in one rotational position.
- The reference sensor should be sent to the manufacturer for calibration annually.
  - To help maintain the accuracy of the reference sensor, it should be exposed to UV light as little as possible and stored under appropriate conditions as recommended by the manufacturer

UVT Monitor

- The measurements from an online UVT monitor should be checked weekly with a laboratory spectrophotometer. After continued checking of the calibration, the frequency of the test may be adjusted based on the performance of the UVT monitor.

Sleeves

- Reactors will come with either an offline or an online cleaning system. The frequency of the sleeve cleaning can be based either upon a specific time interval or a specific loss in UV intensity. The cleaning interval should be adjusted as the sleeve fouling rate changes or if there is significant fouling remaining on the sleeve after cleaning.

- If manual cleaning of the sleeves is required, great care should be exercised.
  - Follow manufacturer recommendations
  - Do not use abrasive cleaners or pads that may scratch the lamp sleeve. Scratches will decrease the UV transmittance of the lamp sleeve
  - Do not handle the lamp sleeve with bare skin. Wear clean cotton, powder-free latex, or vinyl gloves. Oils from the skin will damage the sleeve when it is operated
  - The inside of the sleeve should be dry before placing it back into the reactor. Water or solvents trapped between the sleeve and the lamp will absorb UV light and may form a coat on the surface of the lamp or sleeve
  - When reinstalling lamp sleeve care should be taken not to over-tighten the compression nuts. Over-tightening may result in cracking of the sleeve

Sensors

- When fouled, sensors or sensor windows should be cleaned following manufacturer's recommendations.

- An offline chemical cleaning system will clean the sensors or sensor windows as well as the lamp sleeves. An online mechanical cleaning system may or may not clean the sensors or sensor windows. If the sensors are not cleaned when the sleeves are cleaned, they will require more frequent manual cleaning.

UVT Monitor

- An online UVT monitor should be cleaned with a frequency and procedure in accordance with the manufacturer's recommendations.

The following table indicates the approximate expected life for various components of a UV system:

Table 5.1 –Expected Life for Components of a UV System

Component	Typical Design Life	Typical Guaranteed Life
Low pressure lamp	12,000 hours	8,000 to 12,000 hours
Medium pressure lamp	10,000 hours	4,000 to 8,000 hours
Lamp sleeve	8 to 10 years	1 to 3 years
UV intensity sensor	3 to 10 years	1 year
UVT monitor	3 to 5 years	1 year
Cleaning system	3 to 5 years	1 to 3 years
Ballasts	10 to 15 years	1 to 3 years

Lamps

- Lamps may be regulated as a hazardous waste because they contain mercury. The lamp manufacturer should indicate whether their lamp contains enough mercury to be considered hazardous waste.
  - If the lamps are considered a hazardous waste, they should be sent to a mercury recycling facility for recovery of the mercury. The state may be contacted for a list of local mercury recycling facilities
  - Alternatively, the lamp manufacturer may accept the lamps for recycling or proper disposal. The manufacturer should be contacted to see if they accept used lamps
- Lamps should be replaced either at the end of the design life or when UV intensity decreases below a specific amount.
- Replacement lamps must be the same as the lamps that were used during validation with regard to the following, or the reactor will be considered to be producing off-specification water:
  - Arc length
  - Lamp envelope material
  - Lamp envelope dimensions
  - Amount of mercury
  - Spectral output
- If lamps with different mercury content or a different power rating are used, the lamps must be assessed after burn-in to determine if the UV intensity is equivalent. If the UV intensity sensor readings are equal to or greater than the readings with the previous lamp, then the new lamp is acceptable.

Sleeves

- Similar to the lamps, replacement lamp sleeves should be identical to the sleeves used during the reactor validation:
  - Sleeve dimensions
  - Sleeve material
  - Sleeve thickness
- When replacing sleeves, care should be taken to not touch the sleeve with the bare skin, to avoid transferring oils to the sleeve.
- Again, care should be taken not to over-tighten the compression nuts on the sleeve.

Spare Parts

- An inventory of spare parts should be kept to avoid having a UV reactor out of service while waiting for replacement parts to arrive.
  - A general guideline is to have 5% of the installed number of a component, or a minimum of one unit, as spare parts inventory. Because lamps have a shorter expected lifetime, the number of spare lamps should be increased to a minimum of 10% or two lamps.
- With experience, the number of spare parts that is needed for a particular component can be better predicted.
- Components that should be included as spare parts include:
  - UV lamps
  - Lamp sleeves
  - O-ring seals
  - Online cleaning system wipers (if applicable)
  - Online cleaning system wiper drive mechanisms (if applicable)
  - Ballasts
  - Ballast cooling fan
  - Duty UV intensity sensors
  - Reference UV intensity sensors
  - Online UVT monitor (if applicable)

Unit 5 Exercise

True of False (circle):

1. Calibrating of the UVT monitors should be increased if performance records indicate consistent weekly results. T F

2. Intensity sensors do not have to be calibrated monthly but can wait for the annual manufactures calibration. T F

3. Pressure gauges may confirm spilt flow when individual flow meter to the reactors are not installed. T F

4. Discoloration of the sleeves is one indicator of fouling. T F

5. The cleaning system includes the wiper blades, drive mechanism, cleaning fluid reservoir and flow meter. T F

6. A GFI circuit breaker will trip when there is a problem with the ballast cooling system. T F

7. Flow meters should be taken off-line if the uncertainty of the flow meter is less than the uncertainty of the validation testing of the UV reactor. T F

8. UVT monitors should be check against a laboratory spectrophotometer. T F

9. When manually cleaning the sleeves, you should not use latex gloves because the latex will melt on the sleeve. T F

10. After replacing the lamp, you will be able discard the old lamp in the regular municipal trash it you roll it in bubble wrap or heavy paper so it does not break in handling. T F