University Curriculum Development for Decentralized Wastewater Management

Disinfection

Module Text

Dr. Mark Gross
University of Arkansas

and

Dr. Kitt Farrell-Poe
University of Arizona

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Introduction

Disinfection is considered to be the primary mechanism for the inactivation/destruction of pathogenic organisms to prevent the spread of waterborne diseases to downstream users and the environment. The organisms of concern in domestic wastewater include pathogenic enteric bacteria, viruses, helminthes and their eggs, and protozoan cysts. In order for disinfection to be effective, wastewater must first be adequately pretreated to remove suspended solids and organic material. If an attempt is made to disinfect inadequately treated wastewater, the organic compounds can "steal" the disinfectant and allow pathogens to survive. Pathogens are associated with suspended solids, and removing the suspended solids is quite an effective way to remove pathogens. Pathogens can also "hide" within the suspended solids, making it more difficult for the disinfectant to come into contact with the pathogens.

In some cases the level of disinfection may affect the allowable (regulated) vertical separation between soil treatment areas and groundwater, seasonal water tables, fractured rock, or other restrictive or sensitive layers. Chlorination is not particularly effective as a disinfectant for Giardia cysts and Cryptosporidium oocysts, UV disinfection is not particularly effective on helminth eggs. If the wastewater is disinfected to the level of primary contact water or drinking water microbial standards, the vertical separation may be shallower than if the wastewater is not disinfected.

Disinfection is the destruction and inactivation of pathogenic organisms, and should not be confused with sterilization. Sterilization is freeing the wastewater stream of all life. We won't get into the discussion here as to whether or not viruses are living organisms. So, the goal of disinfection is to reduce the number of pathogens in the treated effluent so that the risk of disease is minimized.

Among the groups of organisms mentioned earlier some of the specific water-borne diseases include typhoid and paratyphoid fever, cholera, bacillary dysentery, Giardiasis, Crytosporidiosis, Amoebic dysentery, Poliomyelitis, Infectious Hepatitis, Aseptic meningitis, Encephalitis, Gastroenteritis, and chronic anemia. Although an unpleasant thought, all of these diseases are transmitted by the fecal-oral route.

Like centralized wastewater treatment, several processes can be employed in decentralized wastewater treatment to remove the pathogens from the wastewater stream. Among these disinfection processes are sedimentation, filtration, oxidation, dessication, cell-wall destruction, and disruption of the biological processes and reproduction.

With all of the disinfection processes, time is a critical factor. In fact, simply allowing the organisms time to die is one way to disinfect. In cases where a disinfecting agent is used, the product of concentration of disinfectant and the time that the wastewater is in contact with the disinfectant is called the “CT” value. CT stands for concentration multiplied by time, and this product is sometimes considered as the disinfectant “dose.”

Dose = Concentration of disinfectant X Time
(or intensity of energy)

The Great Lakes Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers “Recommended Standards for Wastewater Facilities” (10-states’ Standards) requires a minimum of 15 minutes of contact time following chlorine injection and mixing at peak flow. Following this concept, a very high concentration of disinfectant in contact with the pathogen for a very short time may result in the same effectiveness as a low concentration of disinfectant in contact with the wastewater for a long time. The product of concentration and time may be numerically the same. This concept is discussed later in this section. One of the implications of this concept is the variability of flow in a wastewater system. In all wastewater systems, whether municipal or individual onsite systems, a diurnal variation occurs. This variation may be exacerbated in an individual onsite system, since the variation is not buffered by multiple homes and multiple families using water on a varied work schedule. Since the CT value is a function of the detention time in the disinfection system – also simply a function of the wastewater flow rate – then the disinfection processes may need to be sized for the peak hourly flow expected in the home rather than the average daily flow. All of the hydraulic considerations for sizing the disinfection system and all treatment systems downstream of the septic tank should take into account the flow attenuation of the septic tank. If the system is dosed, the detention time may be governed by the dosing mechanism whether it is a pump, a dosing siphon, or other method. The flow rate from the dosing mechanism will be used to calculate the detention time in the CT value.

Again, disinfection is the destruction or inactivation of the disease-causing organisms. The goal is for the pathogens to be removed or inactivated to an acceptable level before the treated wastewater returns to the hydrologic cycle. In all cases, it is desirable for residential sewage to be disinfected. However, it may not be desirable to chemically-disinfect all residential sewage. When treated wastewater is discharged to surface water, chemical disinfection may be acceptable. When treated wastewater is discharged to soil treatment systems, chemical disinfection with a chemical that stays in the water (residual disinfectant) is not particularly desirable because the disinfectant could potentially harm the beneficial organisms providing treatment in the soil. The following material includes a discussion of disinfectants and their residual.

Looking at some of the processes in a simple onsite wastewater treatment system may help in the understanding of the treatment system's role in the disinfection process. As raw sewage moves into the septic tank, the heavier-than-water solids settle to the bottom (sedimentation) and the lighter-than-water solids float to the top (flotation). Pathogens tend to be associated with solids. The organisms may be attached to the solid particles, or "clumps" of organisms may even make up small settleable or flotable solids. As the solids are removed, the first step in disinfection is taking place in the septic tank. The discussion of the processes in the septic tank (see "Septic Tanks" module) will help to clarify the concept of sedimentation and flotation.

In addition to the physical processes, the septic tank tends to be a relatively harsh environment in terms of microbiological competition. The organisms may be in the tanks from 48 hours up to a week. The die-off organisms in the septic tank can be a factor in disinfection.

In onsite and decentralized wastewater treatment systems, pathogen removal can occur as septic tank effluent moves from the tank, into the soil absorption system, and through the biomat formed at the soil-gravel interface. Some of the larger organisms are physically filtered out by the soil and the biomat. Other processes such as adsorption and absorption occur, and may be responsible for the removal of pathogens including viruses. The biomat is an extremely active environment, and predation also occurs in that zone. Again, as the wastewater moves through the soil relatively slowly, and over a large surface area, die-off, starvation, and physical filtration occur. The natural transport and transportation processes in soil effect the disinfection of the wastewater. The method of dispersal of the wastewater over the soil treatment area may increase or decrease the effectiveness of the soil's disinfection process. Spatial and temporal considerations come into the picture here. The method and timing dosing to the soil treatment area may enhance the disinfection process. A fuller understanding of these processes may be gained by reviewing the section on Soil Treatment as well as reviewing the sections on dispersal.

Special consideration must be given for disinfection using processes that require the attention of a trained operator. Leaving the operation and management of disinfection systems to the homeowner has not proven to be effective When a treatment system requires addition of chemicals, changing components, or monitoring performance, a responsible management entity (RME) other than the homeowner is the reliable method for management. The U.S. EPA has provided guidance for management models for decentralized wastewater systems. In most cases, secondary treatment unit manufacturers' representatives provide operation and management services for their products. Contracting with these same service providers can be one option for reliable operation and maintenance of the disinfection system. Again, homeowner management, in general, has simply proven unreliable or ineffective in the past.

Process Description

Effective disinfection of wastewater is influenced by (1) contact time, (2) pH, (3) concentration and type of disinfecting agent, (4) wastewater demand, (5) temperature of wastewater, (6) flow rate, and (7) concentration of interfering substances. Although it is impractical to accurately identify all wastewater characteristics of small flows that are due to differences in location, water use, seasonal variations, waste-stream make-up, and others, it is important to have a general knowledge of the wastewater characteristics if the disinfection system is to perform its intended purpose.

Choosing a suitable disinfectant for a treatment system is dependent on the following criteria:

- ability to penetrate and destroy infectious agents under normal operating conditions;
- safe and easy handling, storage, and shipping;
- absence of toxic residuals and mutagenic or carcinogenic compounds after disinfection; and
- affordable capital and operation and maintenance costs.

In addition, disinfection methods for systems using soil treatment areas should not leave a residual disinfectant, as the residual has the potential to destroy the beneficial soil organisms that provide additional treatment when the wastewater enters the soil. For example, chlorination without dechlorination leaves a chlorine residual. Neither ultraviolet (UV) radiation nor ozone disinfection leave a residual disinfectant in the wastewater stream. When using soil-based dispersal, dechlorination should be used if UV or ozonation are not the disinfection methods.

There are basically three methods of disinfection for onsite wastewater treatment systems: chlorination, ultraviolet radiation, and ozone. In general, UV radiation and tablet chlorinators seem to be the most effective methods for disinfecting small wastewater flows. Ozonation also has potential, although further technology development may be necessary.

Chlorine

Chlorine is used in three forms in the disinfection of wastewater:

1. as a clear amber liquid or a greenish-yellow gas (elemental chlorine)
2. as a solid (calcium hypochlorite), or
3. in solution (sodium hypochlorite) form.

Most large sewage treatment facilities (greater than 1 MGD) use chlorine gas or liquid because of economics and availability. Chlorine is by far the most used disinfectant for wastewater in the United States today.

Although the use of chlorine to disinfect wastewater is quite common, many people have raised concerns about its public health and environmental impacts. Not only is chlorine toxic to aquatic life at low levels, it also combines with organic (humic) materials in wastewater to form trihalomethanes, which is a carcinogen.

When chlorine gas and hypochlorite salts are added to water, hydrolysis and ionization take place to form hypochlorous acid (HOCl) and hypochlorite ions (OCl^-), also referred to as free available chlorine. Free chlorine reacts quickly with ammonia in non-nitrified effluents to form combined chlorine, principally monochloramine, which is actually is the predominant chlorine species present.

For optimum performance, a chlorine disinfection system should display plug flow and be highly turbulent for complete initial mixing in less than one second. The goal of proper mixing is to enhance disinfection by initiating a reaction between the free chlorine in the chlorine solution stream with the ammonia nitrogen. This prevents prolonged chlorine concentrations from existing and forming other chlorinated compounds.

Chlorine destroys microorganisms by destroying the cell's enzymes once the disinfectant migrates through the cell wall. This process generally requires 30 to 60 minutes of contact time for typical concentrations used to treat wastewater, depending on wastewater flow and characteristics. If applied properly, chlorine can be quite effective in the destruction of bacteria, although it lacks the same success against viruses, Giardia cysts, and Cryptosporidium oocytes.

Clean water chlorine chemistry proceeds by the chlorine combining with water to form hypochlorous acid, hydrogen ions, and chloride ions. The hypochlorous acid further dissociates to form hydrogen ions and hypochlorite ions. The reactions are shown below.

$$Cl_2 + H_2O \leftrightarrow HOCl^- + H^+ + Cl^-$$

$$HOCl^- \leftrightarrow H^+ + OCl^-$$

The pH of the solution drives this reaction to the left or the right. As the pH is lowered, more $HOCl^-$ (hypochlorous acid) is formed. The hypochlorous acid is a more effective disinfectant than the hypochlorite ion (OCl^-). A pH below 7.4 s.u. is conducive to forming hypochlorous acid.

Chlorine combines with nitrogen compounds to form “chloramines.” Typically, chloramine production follows the chemical reactions shown below.

Monochloramine

$$NH_3^+ + HOCl^- \Leftrightarrow NH_2Cl + H_2O$$

Dichloramine

$$NH_2Cl + HOCl^- \Leftrightarrow NHCl_2 + H_2O$$

Trichloramine

$$NHCl_2 + HOCl^- \Leftrightarrow NCl_3 + H_2O$$

Until the nitrogen compounds are completely reacted with the chlorine, no “free” Cl_2 will appear in the water. This is called “breakpoint chlorination,” and is extensively covered in most environmental chemistry texts. Classical environmental chemistry texts include Stumm and Morgan’s Aquatic Chemistry (Wiley) and Sawyer and McCarty’s Chemistry for Environmental Engineering (McGraw-Hill), and Snoeyink and Jenkins’ Water Chemistry (Wiley).

Interferences

Among the other considerations for chlorine disinfection, is the interference of biochemical oxygen demand (BOD) with chlorine. The BOD can exert a chlorine demand since chlorine is an oxidizer. The chlorine may be used to oxidize the organic matter that exerts the BOD. Suspended solids (TSS) can interfere with the chlorination process by exerting a chlorine demand, as well as by providing “hiding places’ for the pathogens. The chlorine must come into contact with the pathogenic organism in order to destroy the cells. The suspended solids may shield the pathogens from contact with the disinfectant. Humic materials may exert a chlorine demand since they are organic compounds. Nitrite is oxidized by chlorine, and therefore may exert a chlorine demand. Chlorine may react with iron, manganese, and hydrogen sulfide in the treated wastewater. Not only will these substances exert a chlorine demand, but oxidation of these compounds results in precipitates that have the potential to clog downstream processes or to cause otherwise unexpected or undesirable colors in the treated wastewater. They do not represent harmful compounds, and they may be removed readily. Planning for their appearance gives the designer the flexibility to avoid the surprise and to implement their removal (filtration or sedimentation are some options).

Advantages and Disadvantages of Chlorine Disinfection

Chlorine is a disinfectant that has certain health and safety limitations, but at the same time, has a long history of being an effective disinfectant. Before deciding whether chlorine meets the onsite wastewater treatment's needs, it is necessary to understand the advantages and disadvantages of this disinfection method.

Advantages

- Chlorination is a well-established technology.
- Presently, chlorine is more cost-effective than either UV radiation or ozone disinfection (except when dechlorination is required and/or fire code requirements must be met).
- The chlorine residual that remains in the wastewater effluent can prolong disinfection even after initial treatment and can be measured to evaluate the effectiveness.
- Chlorine disinfection is reliable and effective against a wide spectrum of pathogenic organisms.
- Chlorine is effective in oxidizing certain organic and inorganic compounds.
- Chlorination has flexible dosing control.
- Chlorine can eliminate certain noxious odors during disinfection.

Disadvantages

- The chlorine residual, even at low concentrations, is toxic to aquatic life and treated wastewater discharging to aquatic environments may require dechlorination.
- All forms of chlorine are highly corrosive and toxic. Thus, storing, shipping, and handling pose a risk, requiring increased safety regulations.
- Chlorine oxidizes certain types of organic matter in wastewater, creating more hazardous compounds (e.g., trihalomethanes (THMs)).
- The level of total dissolved solids is increased in the treated effluent.
- The chlorine content of the wastewater is increased.
- Chlorine residual is unstable in the presence of high concentrations of chlorine-demanding materials, thus requiring higher doses to effect adequate disinfection.
- Some parasitic species have shown resistance to low doses of chlorine, including oocytes of *Cryptosporidium parvum*, cysts of *Endamoeba histolytica* and *Giardia lamblia*, and eggs of parasitic worms.
- Long-term effect of discharging dechlorinated compounds into the environment are unknown.

Chlorine Application Methods

<u>Erosion (tablet) Chlorinators</u>

Many methods exist to apply chlorine to wastewater, but most small treatment systems use tablet (erosion) chlorinators. Disinfection systems using tablet chlorinators generally have four components: a pretreatment system, a tube that holds the chlorine tablets, a contact device which puts the chlorine tablets into contact with the wastewater, and a storage reservoir, usually a pump tank, where the wastewater is stored before it is distributed.

Before being chlorinated, wastewater from a home is treated by a secondary treatment device, usually an aerobic treatment unit or a media filter. The wastewater moves from the treatment device through a pipe to the contact device. (See Figure 1.)

Figure 1.
Typical Tablet (Erosion) Chlorinator

Tablet chlorinators use calcium hypochlorite tablets (usually 70 percent available chlorine), the same chemical found in common household bleach. These tablets dissolve in the wastewater, releasing the hypochlorite, which then becomes hypochlorous acid, the primary disinfectant. Swimming pool chlorine tablets should not be used. They are often made with trichloroisocyanuric acid, which is not approved for use in wastewater treatment systems. These tablets make the chlorine available too slowly for them to be effective. If wetted repeatedly, they also can produce nitrogen chloride, which can be explosive.

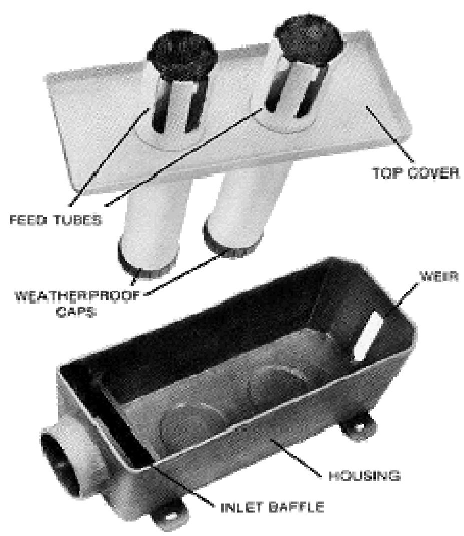

Figure
Erosion Chlorinator Interior

Figure 3
Chlorine Tablets

Wastewater flows through the contact device (chlorinator), where it comes into contact with the hypochlorite tablets through slits located at the bottom of the holding tubes. The bottom tablet in the tube is in contact with the wastewater (treatment system effluent) flowing through the basin. As that tablet dissolves and/or erodes, the tablet above it falls by gravity to replace it. (See Figure 2.) The number of tubes filled with tablets (tablet chlorinators contain two or four tubes) and the height of wastewater in the chlorinator (amount of contact between the wastewater and tablets) determine the amount of chlorine applied and thus chlorine residual in the effluent. A tablet can dissolve quickly or slowly, depending on the amount of wastewater coming into contact with it and the length of time it is in contact. The tablets in the chlorinator can "bridge," with the bottom tablet having an erosion channel, but holding up the tablets above it. In that case, the wastewater may pass through the chlorinator, but not receive an adequate dose for disinfection. Simply looking into the top of the tube could be misleading, since the tube would contain tablets, but they would be stuck inside the tube without contacting the wastewater. A better method to determine whether or not the wastewater is receiving a chlorine dose is by measuring the chlorine residual downstream from the chlorinator. In general, homeowner management of chlorinators has not been effective.

Tablet chlorinators are manufactured in several capacities from less than 1,500 gallons per day (gpd) to 50,000 gpd. (See Figures 4 and 5). If dechlorination is required following the chlorine contact chamber, dechlorination can also be provided by tablet chlorinators. Most manufacturers of tablet chlorinators and calcium hypochlorite tablets also sell sodium sulfite ($Na_2\ SO_3$) tablets for effluent dechlorination, which is particularly important for systems that discharge to surface waters. The reaction between chlorine and sodium sulfite is instantaneous. Generally 2 mg/L of sodium sulfite is required to neutralize 1 mg/L of chlorine.

Figure 4
Typical Tablet Chlorinator

Figure 5
Tablet Chlorinator with lid removed

With tablet chlorinators, the contact time must be provided for the disinfection to occur. Typically, and tank following the chlorinator is provided and the hydraulic detention time is calculated to provide a minimum of 15 minutes of contact time at the peak flow rate. An example calculation follows.

For an average daily flow of 10,000 gallons per day and a peaking factor of 2.5 times the average flow rate equals the peak flow rate, calculate the tank volume required to provide 15 minutes of detention time.

Average flow rate = 10,000 gallons per day ÷ 1440 minute per day = 6.9 gallons per minute.

Peak flow = 6.9 gpm X 2.5 = 17.4 gpm

Volume = Flow X detention time = 17.4 gallons per minute X 15 minutes = 260 gallons minimum contact tank volume.

Liquid Chlorinators

Chlorine may be applied relatively easily to small wastewater systems as liquid chlorine. A simple method includes a mixing tank with an attached metering pump with tubing connected to the wastewater piping. Figure 6 illustrates this type of system.

The chlorine is typically obtained by pouring common household bleach into the mixing tank. Household bleach is usually 6.0 percent calcium hypochlorite. If a particular concentration of chlorine is desired, the percentage of chlorine compound in the solution must be considered in the calculations.

EXAMPLE:
An example of calculations for selecting the liquid chlorination metering pump and the chlorine tank follows:

The desired final chlorine concentration is 3 mg/L for an average daily flow of 10,000 gallons per day and a peak wastewater flow of 20 gpm, using liquid chlorine bleach with a concentration of 6% by weight. The concentration in the chlorine day tank is 6 mg chlorine per 100 mg water or 60 grams chlorine per 1000 grams (1 liter) of water or 60,000 mg/L. For 3 mg/L in the wastewater, the concentration is

(3 mg/L ÷ 60,000 mg/L) X 20 gallons/minute = 0.001 gallons per minute of liquid chlorine bleach pumped into the wastewater stream. Typically, metering pumps are sized by gallons per hour, so this rate is 0.001 gallons per minute X 60 minutes/hour = 0.06 gallons per hour.

Choose a metering pump capable of 0.06 gallons per hour.

Metering pumps are typically either diaphragm pumps or peristaltic pumps with variable frequency motors, so the pumping rate can be adjusted to fit the application. The pump selected from the chemical metering pump technical information will have a range that covers the 0.06 gallon per hour requirement.

The total daily requirement for liquid chlorine bleach will be (3 mg/L ÷ 60,000 mg/L) X 10,000 gallons per day = 0.5 gallons per day. If a 10-gallon dosing tank is used, the liquid chlorine will need to be refilled every 20 days. Since chlorine is volatile, the bleach will be added more often, however, a 10-gallon tank will provide the capacity for 20 days of chlorine disinfection.

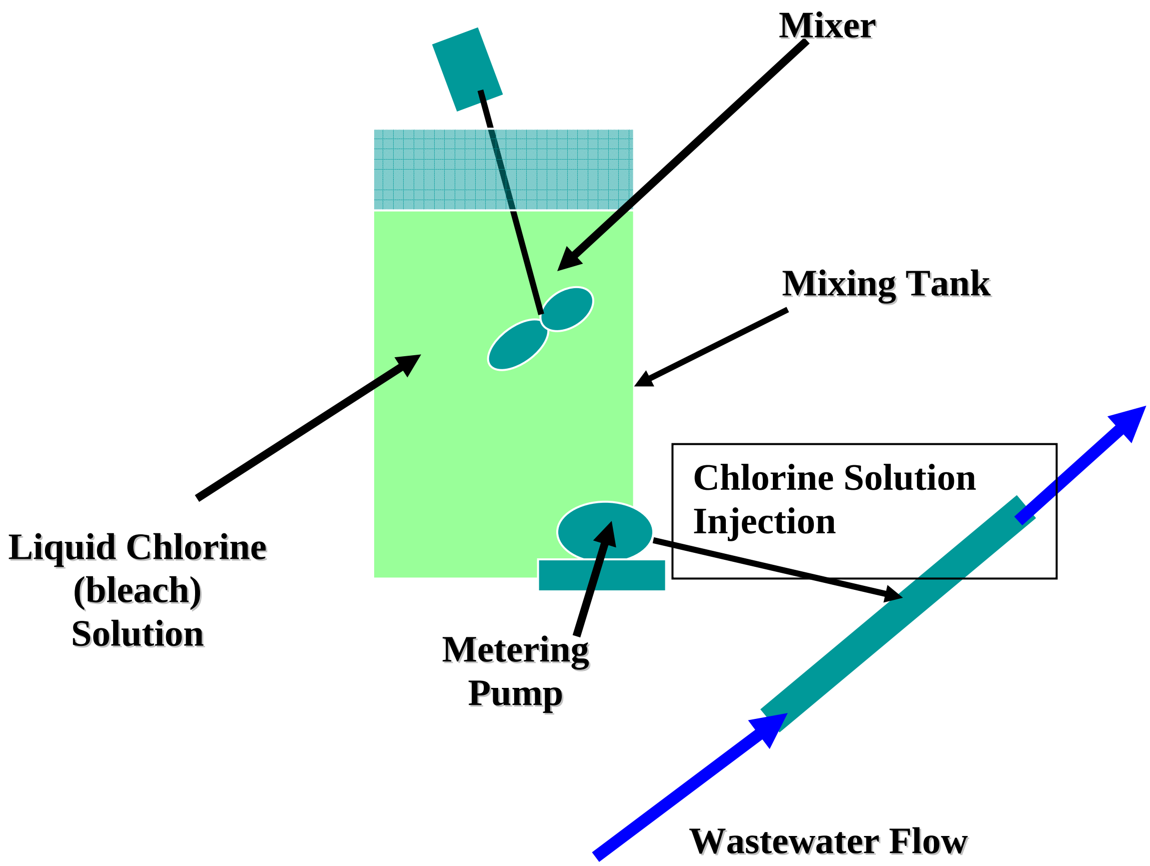

FIGURE 6
Typical Liquid Chlorination System

<u>Chlorine Gas</u>

Chlorination using chlorine gas is the traditional method of disinfection for large wastewater flows. However, environmental, health, and cost considerations are serious issues for onsite wastewater treatment systems. The major concern of using chlorine gas is with safety and handling of the highly toxic and corrosive gas.
To determine the concentration of chlorine entering the wastewater stream, simply divide the weight (pounds per minute) of chlorine injected by the volume of flow (gallons per minute) and

convert from pounds per gallon to milligram per liter. The gas is supplied in cylinders – typically either 100 pound or one-ton cylinders. The chlorine is pulled from the cylinders into a stream of wastewater by a vacuum created by a venturi. Typically a circulating pump brings water from the wastewater stream past the chlorine eductor and back into the main wastewater stream.

Since chlorine gas is heavier than air the chlorination building must be near the floor. A positive forced-air flow must occur when the door is opened, and the door must have a transparent window in it. Chlorine buildings may be purchased as fiberglass units since the fiberglass resists corrosion. The 10-States' Standards specifies the particular requirements for gas chlorination equipment and systems.

Contact Time

After chlorine addition, the wastewater enters the contact tank where the disinfection process is completed. The contact tank provides the "T" for the CT value. In some cases, states have required specific length to width ratios for the contact chamber to prevent preferential flow paths or "short circuiting" of the wastewater through the contact chamber. Baffled or "meander" tanks following the chlorinator may effectively satisfy this requirement. The contact chamber should be designed to have rounded corners to prevent dead flow areas and be baffled to minimize short-circuiting. This design allows for adequate contact time between the microorganisms and a minimal chlorine concentration for a specific period of time. Typically, the chlorination contact time is based upon the peak flow rate.

One model proposed by Collins, et al. for calculating the disinfection dose to effect a particular reduction in coliform numbers is as follows:

$$y/y_0 = [1 + 0.23\ Ct]^{-3}$$

Where
y = initial coliform concentration, MPN/100 mL
y_0 = final coliform concentration, MPN/100 mL
C = chlorine residual concentration, mg/L at the *end* of the contact time, t
t = contact time, minutes

The required degree of disinfection can be achieved by varying the dose and the contact time for any chlorine disinfection system. Chlorine dosage will vary based on chlorine demand, wastewater characteristics, and discharge requirements. The dose usually ranges from 5 to 20 mg/L. Table 1 describes some of the more common wastewater characteristics and their impact on chlorine. There are several other factors that ensure optimum conditions for disinfection and they include temperature, alkalinity, and nitrogen content. All key design parameters should be pilot tested prior to full-scale operation of a chlorine disinfection system.

Table 1. Wastewater characteristics affecting chlorination performance. Source: EPA, 1999a.

Wastewater Characteristic	Effects on Chlorine Disinfection
Ammonia	Forms chloramines when combined with chlorine.
BOD	The degree of interference depends on their functional groups and chemical structures.
Hardness, Iron, Nitrate	Minor effect, if any.
Nitrite	Reduces effectiveness of chlorine and results in THMs.
pH	Affects distribution between hypochlorous acid and hypochlorite ions and among the various chloramine species.
TSS	Shielding of embedded bacteria and chlorine demand.

Dechlorination

After disinfection, a chlorine residual can persist in the effluent for many hours. Most states will not allow the use of chlorination alone for wastewaters discharging to pristine receiving waters because of its effect on aquatic species. To minimize the effect, chlorinated wastewater must often be dechlorinated.

Dechlorination is the process of removing the free and combined chlorine residuals to reduce residual toxicity after chlorination and before discharge. Sulfur dioxide, sodium bisulfite, and sodium metabisulfite are the commonly used dechlorinating chemicals. Activated carbon has also been used. The total chlorine residual can usually be reduced to a level that is not toxic to aquatic life. Chlorine/dechlorination systems are more complex to operate and maintain than chlorination systems.

Dechlorination reactions occur very rapidly, therefore no detention (contact) basin is required downstream from the dechlorinator. The dechlorinator can be as simple as a tablet dechlorinator system, using exactly the same product as the chlorinator (without the contact basin), or dechlorinating chemicals such as sodium thiosulfate can be added using a metering pump and liquid solution tank similar to liquid chlorination.

Operation and Maintenance

A routine operation and maintenance (O&M) schedule should be developed and implemented for any chlorine disinfection system. Regular O&M activities include:

- Disassembling and cleaning the various components of the system, such as meters and floats, once every 6 months.
- Iron and manganese deposits should be removed with, for example, muriatic acid.
- Booster pumps should be maintained.
- Valves and springs should be inspected and cleaned annually.
- All manufacturer's O&M recommendations should be followed.
- Equipment must be tested and calibrated as recommended by the equipment manufacturer.
- An emergency response plan for onsite storage of gaseous chlorine must be developed.

Because chlorine gas collects in the tablet container, the container should be opened in a well-ventilated area. Chlorine gas can escape from the tablets and container, reducing the effectiveness of the tablets and possibly corroding metal products stored near the container.

When using chlorine, it is very important to properly and safely store all chemical disinfectants. The storage of chlorine is strongly dependent on the compound phase. For further details on the safe use and storage of chlorine, refer to the chemical's Material Safety Data Sheets (MSDS). Chlorine gas is normally stored in steel containers (150-pound or 1-ton cylinders) and transported in railroad cars and tanker trucks. Sodium hypochlorite solution must be stored in rubber-lined steel or fiberglass storage tanks. Calcium hypochlorite is shipped in drums or tanker trucks and stored with great care.

Ultraviolet Radiation

Disinfection by ultraviolet (UV) radiation is a physical process relying on the transfer of electromagnetic energy from a source (lamp) to an organism's genetic material (DNA and RNA). UV radiation destroys microorganisms by preventing their replication or causing death (Figure 7). UV radiation, generated by an electrical discharge through mercury vapor, penetrates the genetic material of microorganisms and retards their ability to reproduce. There is some evidence that exposure of the organisms to full-spectrum light following UV irradiation may allow the organisms to regenerate (akin to "self-healing"). Therefore the wastewater stream is covered or somehow kept in the dark immediately following the UV irradiation. Some have theorized that sunlight can provide adequate disinfection by UV irradiation. The evidence of full-spectrum lighting allowing the organisms to regenerate would appear to dispel this theory.

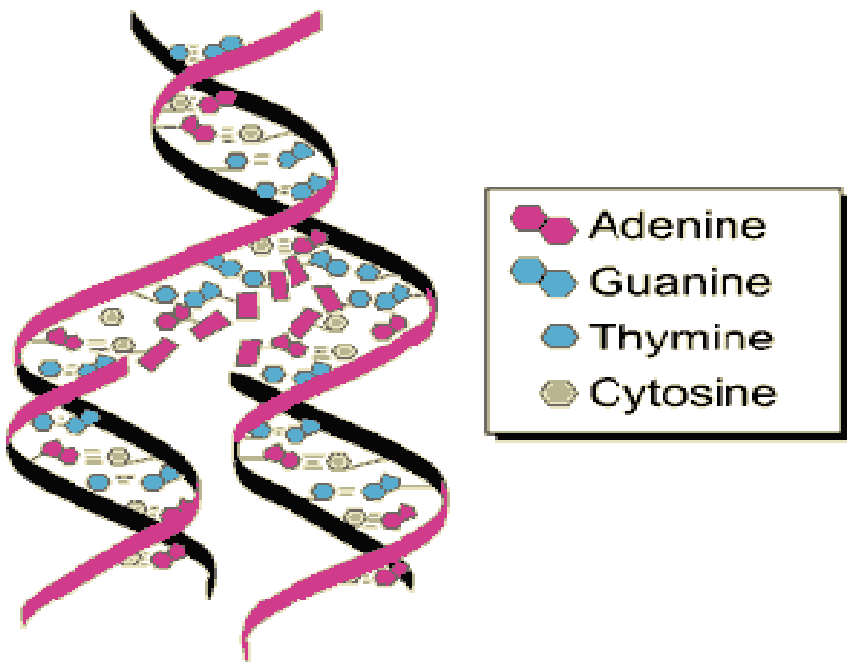

Figure 7
UV Radiation Effects on DNA

The effectiveness of a UV disinfection system depends on the characteristics of the wastewater, the intensity of UV radiation, the amount of time the microorganisms are exposed to the radiation, and the reactor configuration. For any one treatment plant, disinfection success is directly related to the concentration of colloidal and particulate constituents in the wastewater.

The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either a low-pressure or a medium-pressure mercury arc lamp with low or high intensities. See Figures 10 and 11.

The optimum wavelength to effectively inactivate microorganisms is in the range of 250 to 270 nanometers (nm). The intensity of the radiation emitted by the lamp dissipates as the distance from the lamp increases. The ideal lamp wall temperature is between 95 and 122 °F.

Today, the most widely used source of UV light is the low-pressure mercury arc lamp. Approximately 85 percent of its energy output is at a wavelength of 253.7 nm, which falls within the optimum wavelength range of 250 to 270 nm for germicidal effect. Low-pressure mercury vapor lamps are long, thin, transparent tubes (1.5 - 2 cm in diameter). The lamps are typically 0.75 and 1.5 m in length. Ballasts are used to provide starting voltage and to maintain constant current.

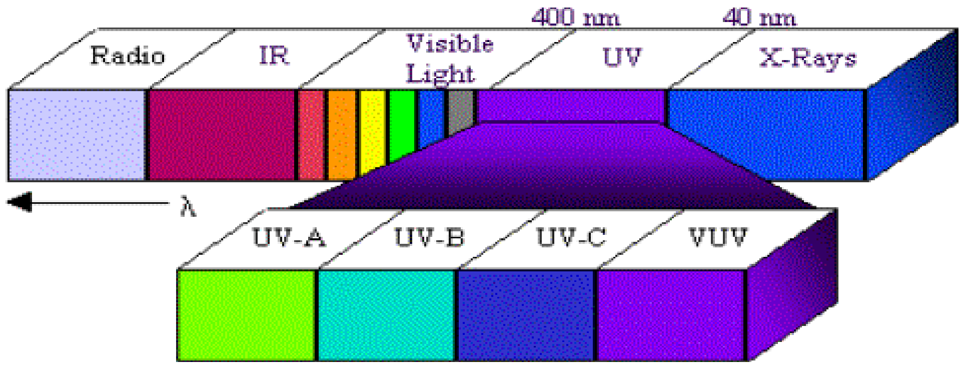

Figure 8
The Ultraviolet Spectrum

In addition to low-pressure mercury vapor lamps, medium-pressure mercury vapor lamps have been developed for use in higher-capacity UV disinfection systems. The lamps produce 25 to 30 times greater output than low-pressure lamps and use permanent transformers instead of ballasts to provide starting voltage. Medium-pressure lamps cost three to four times more than low-pressure lamps but operate half the life.

Presently, two general types of reactors are in use: quartz tube (or contact reactor) and Teflon-tube reactor. The quartz tube, or contact, reactor has its lamps submerged in wastewater. The lamps are sheathed in quartz jackets that are transparent to UV wavelengths and slightly larger than the lamps. Flow can be either parallel or perpendicular to the lamps. The quartz tube reactor can be further classified as the enclosed-vessel or open-channel system. In the enclosed vessel system, liquid flows under pressure through a sealed reaction chamber, which contains one or more lamps. In the open channel system, a group or battery of lamps are submersed into a plant's effluent channel.

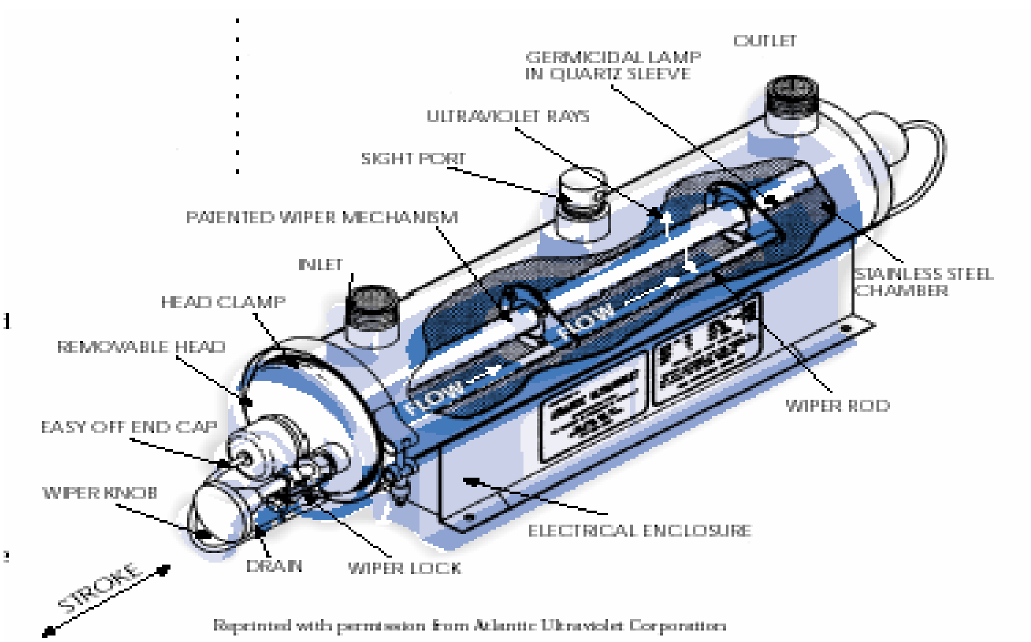

Figure 9
Ultraviolet Lamp Cutaway

The second general type of UV disinfection system is the Teflon tube reactor. In this reactor system, UV lamps are suspended outside Teflon tubes which transport the effluent to be disinfected. The Teflon tubes used to transport effluent are transparent to UV wavelengths, thus allowing disinfection to occur.

Open channel quartz tube and Teflon tube reactor systems are typically used for large sewage treatment facilities.

Choosing a UV disinfection system depends on three critical factors:

- **Hydraulic properties of the reactor:** Ideally, a UV disinfection system should have a uniform flow with enough axial motion (radial mixing) to maximize exposure to UV radiation. The path that an organism takes in the reactor determines the amount of UV radiation it will be exposed to before inactivation. A reactor must be designed to eliminate short-circuiting and/or dead zones, which can result in inefficient use of power and reduced contact time. This factor is primarily determined by the manufacturer.

- **Intensity of the UV radiation:** Factors affecting the intensity of the UV radiation are the age of the lamps, lamp fouling, and the configuration and placement of lamps in the reactor. UV disinfection units should have an intensity monitor to indicate the strength of the UV light being produced by the tube. Also, the units should have an indicator of whether or not the lamp is operating. See figures 12 and 13. Cleaning the tube is necessary maintenance, and the frequency of cleaning is dependent upon the wastewater characteristics. The useful bulb life for UV disinfection units is approximately one year, and typical (2003) replacement cost is approximately $40.00 U.S. This factor is affected by the unit's design and operation and maintenance (O&M) schedule.

- **Wastewater characteristics:** The wastewater characteristics that affect UV disinfection effectiveness include the flow rate, amount or presence of suspended and colloidal solids, initial bacterial density, and other physical and chemical parameters. Both the concentration of TSS and the concentration of particle-associated microorganisms determine how much UV radiation ultimately reaches the target organism. The higher these concentrations, the lower the UV radiation absorbed by the organisms. Various wastewater characteristics and their effects on UV disinfection are given in Table 2. UV disinfection can be used in plants of various sizes that provide secondary or advanced levels of treatment (those that remove turbidity and BOD). The wastewater should be highly treated and clear so that the ultraviolet light can pass through the water and strike the targeted microorganisms. Dissolved organic compounds (BOD, TSS, COD) inhibit the passage of UV light to the organisms. Organic iron compounds can also absorb UV light, and iron precipitates can coat the quartz glass tubes, inhibiting the passage of UV light through the wastewater to the organisms. This factor is controlled at the treatment facility.

Figure10
Ultraviolet Disinfection Unit
(Single Unit)

Figure11
Ultraviolet Disinfection System

(Four Units in Parallel)

Figure 12
Ultraviolet light Disinfection Assemblies

Figure 13
Ultraviolet Light Monitor
(Intensity Indicator)

Figure 14
UV Light Monitor

Table 2. Wastewater characteristics affecting UV disinfection performance. Source: EPA, 1999c.

Wastewater Characteristic	**Effects on UV Disinfection**
Ammonia	Minor effect, if any.
BOD	Minor effect, if any. Although, if a large portion of the BOD is humic and/or unsaturated (or conjugated) compounds, then UV transmittance may be diminished.
Hardness	Affects solubility of metals that can absorb UV light. Can lead to the precipitation of carbonates on quartz tubes.
Humic materials, Iron	High absorbency of UV radiation. Can Coat quartz glass tubes, inhibiting the passage of UV light to the organisms

Nitrate	Minor effect, if any.
Nitrite	Minor effect, if any.
pH	Affects solubility of metals and carbonates.
TSS	Absorbs UV radiation and shields embedded bacteria.

Operation and Maintenance

In a UV disinfection system, target organisms must come into direct contact with UV light if the disinfection is to be effective. The hydraulic properties of the reactor, the age and configuration of lamps, time frame and procedures for cleaning, the flow rate, contact time, and water quality all affect the system's efficiency.

Inadequate cleaning is one of the most common causes of a UV system's ineffectiveness. The quartz sleeves or Teflon tubes need to be cleaned regularly by mechanical wipers, ultrasonics, or chemicals. The cleaning frequency is very site-specific, i.e., some systems need to be cleaned more often than others.

Chemical cleaning is most commonly done with citric acid. Other cleaning agents include mild vinegar solutions and sodium hydrosulfite. A combination of cleaning agents should be tested to find the agent most suitable for the wastewater characteristics without producing harmful or toxic by-products. Non-contact reactor systems are most effectively cleaned by using sodium hydrosulfite. Any UV disinfection system should be pilot tested prior to full-scale operation to ensure that it will meet discharge permit requirements for a particular site.

The average lamp life ranges from 8,760 to 14,000 working hours, and the lamps are usually replaced after 12,000 hours of use. Operating times should be adjusted to reduce the on/off cycles of the lamps, since their efficacy is reduced with repeated cycles.

The ballast must be compatible with the lamps and should be ventilated to protect it from excessive heating, which may shorten its life or even result in fires. Although the life cycle of ballasts is approximately 10 to 15 years, they are usually replaced every 10 years. Quartz sleeves will last about 5 to 8 years but are generally replaced every 5 years.

Advantages and Disadvantages of UV Disinfection

Advantages

- UV disinfection is effective at inactivating most viruses, spores, and cysts.

- UV disinfection is a physical process rather than a chemical process, which eliminates the need to generate, handle, transport, or store toxic/hazardous or corrosive chemicals.
- There is no residual effect that can be harmful to humans or aquatic life.
- UV disinfection is user-friendly for operators.
- UV disinfection has a shorter contact time when compared with other disinfectants (approximately 20 to 30 seconds with low-pressure lamps).
- UV disinfection equipment requires less space than other methods.

Disadvantages
- Low dosage may not effectively inactivate some viruses, spores, and cysts.
- Organisms can sometimes repair and reverse the destructive effects of UV through a "repair mechanism," known as photo reactivation, or in the absence of light known as "dark repair."
- A preventive maintenance program is necessary to control fouling of tubes.
- Turbidity and total suspended solids (TSS) in the wastewater can render UV disinfection ineffective. UV disinfection with low-pressure lamps is not as effective for secondary effluent with TSS levels above 30 mg/L.
- UV disinfection is not as cost-effective as chlorination, but costs are competitive when chlorination/dechlorination is used.

Ozone

Ozone, like chlorine is a powerful disinfectant that destroys microorganisms through oxidation. However, it does not have to penetrate the cell wall to be effective, as does chlorine. Ozone is also much more effective against viruses than chlorine. The mechanisms of disinfection using ozone include:

- Direct oxidation/destruction of the cell wall with leakage of cellular constituents outside the cell.
- Reactions with radical by-products of ozone decomposition.
- Damage to the constituents of the nucleic acids (purines and primidines).
- Breakage of carbon-nitrogen bonds leading to depolymerization.

When ozone decomposes in water, the free radicals hydrogen peroxy (HO_2) and hydroxyl (OH) that are formed have great oxidizing capacity and play an active role in the disinfection process. It is generally believed that the bacteria are destroyed because of protoplasmic oxidation resulting in cell wall disintegration (cell lysis).

Simple ozone chemistry is as follows:

$$O_3 + H_2O \Rightarrow HO_3^+ + OH^-$$

$$HO_3^+ + OH^- \Rightarrow 2HO_2$$

$$O_3 + HO_2 \Rightarrow HO^- + 2O_2$$

$$HO^- + HO_2 \Rightarrow 2H_2O + O_2$$

As shown in the ozone chemistry equations, ozone eventually reacts to form water and oxygen, leaving no harmful or toxic residual in the water. The ozone is soluble in water up to about 5 mg/L.

Ozone is produced when oxygen (O_2) molecules are dissociated by an energy source into oxygen atoms and subsequently collide with an oxygen molecule to form an unstable gas, ozone (O_3), which is used to disinfect wastewater. Production of ozone in quantities of more than 1 gram per hour is done by passing an electrical current through air or oxygen in a controlled environment. This method of production is known as *electric discharge* or *corona discharge* and is used at wastewater treatment plants. Where large amounts of ozone are required, intake air must be dried to prevent damage to production equipment (corona discharge). Equipment required to dry intake air can be as expensive as the ozone production equipment itself. Many larger treatment facilities use pure oxygen to produce ozone at a higher rate than can be achieved by using ambient air. Generally, production of under 500 lbs/day is not economically feasible using oxygen.

Ozone can also be produced by a low-pressure mercury arc lamp operating at 190 to 270 nm. Quantities of less than 1 gram/hour can be produced by this method, which is a sufficient quantity to provide disinfectant for small sewage treatment systems. Manufacturers of ozone production lamps suggest a bulb life of 7,000 hours, although excessive starts reduce that time.

Ozone disinfection is the least used method in the U.S., although this technology has been widely accepted in Europe for decades. Ozone treatment has the ability to achieve higher levels of disinfection than either chlorine or UV, however, the capital costs as well as maintenance expenditures are not competitive with available alternatives. Ozone is, therefore, used only sparingly, primarily in special cases where alternatives are not effective.

Ozone disinfection is generally used at medium- to large-sized plants after at least secondary treatment. In addition to disinfection, another common use for ozone in wastewater treatment is odor control. Other ancillary benefits when using ozone to disinfect treated wastewater include reduction of the organic and inorganic content through oxidation and addition of oxygen to the wastewater.

The effectiveness of disinfection depends on the susceptibility of the target organisms, the contact time, and the concentration of the ozone. The components of an ozone disinfection system include feed-gas preparation, ozone generation, ozone contacting, and ozone destruction.

Air or pure oxygen is used as the feed-gas source and is passed to the ozone generator at a set flow rate. The energy source for production is generated by electrical discharge in a gas that contains oxygen. Ozone generators are typically classified by:

- The control mechanism (either a voltage or frequency unit).
- The cooling mechanism (either water, air, or water plus oil).
- The physical arrangement of the dielectrics (either vertical or horizontal).
- The name of the inventor.

Figure 15
Spa Ozonator Used for Wastewater Disinfection

The effectiveness of ozone disinfection depends upon the susceptibility of the target organisms, the contact time, and the concentration of the ozone.

The components of an ozone disinfection system include feed-gas preparation, ozone generation, ozone contacting, and ozone destruction.

The electrical discharge method is the most common energy source used to produce ozone. Extremely dry air or pure oxygen is exposed to a controlled, uniform, high-voltage discharge at a high or low frequency. The dew point of the feed gas must be -60 °C (-76 °F) or lower. The gas stream generated from air will contain about 0.5 to 3.0% ozone by weight, whereas pure oxygen will form approximately two to four times that concentration.

Figure 16
Venturi for Ozone Injection into Treated Wastewater

After generation, ozone is fed into a down-flow contact chamber containing the wastewater to be disinfected. The main purpose of the contactor is to transfer ozone from the gas bubble into the bulk liquid while providing sufficient contact time for disinfection. The commonly used contactor types include diffused bubble (co-current and counter-current) positive pressure injection, negative pressure (Venturi – Figure 16), mechanically agitated, and packed tower. Because ozone is consumed quickly, it must be contacted uniformly in a near plug-flow contactor.

The off-gases from the contact chamber must be treated to destroy any remaining ozone before release into the atmosphere. Therefore, it is essential to maintain an optimal ozone dosage for better efficiency. When pure oxygen is used as the feed-gas, the off-gases from the contact chamber can be recycled to generate ozone or for reuse in the aeration tank. The ozone off-gases that are not used are sent to the ozone destruction unit or are recycled.

The key process control parameters are dose, mixing, and contact time. An ozone disinfection system strives for the maximum solubility of ozone in wastewater, as disinfection depends on the transfer of ozone to the wastewater. The amount of ozone that will dissolve in wastewater at a constant temperature is a function of the partial pressure of the gaseous ozone above the water or in the gas feed stream.

It is critical that all ozone disinfection systems be pilot tested and calibrated prior to installation to ensure they meet discharge permit requirements for their particular sites.

Operation and Maintenance

Ozone generation uses a significant amount of electrical power. Thus, constant attention must be given to the system to ensure the power is optimized for controlled disinfection performance.

There must be no leaking connections in or surrounding the ozone generator. The operator must, on a regular basis, monitor the appropriate subunits to ensure that they are not overheated. Therefore, the operator must check for leaks routinely, since a very small leak can cause unacceptable ambient ozone concentrations. The ozone monitoring equipment must be tested and calibrated as recommended by the equipment manufacturer.

Like oxygen, ozone has limited solubility and decomposes more rapidly in water than in air. This factor, along with ozone reactivity, requires that the ozone contactor be well covered and that the ozone diffuses into the wastewater as effectively as possible.

Ozone, in gaseous form, is explosive once it reaches a concentration of 240 g/m^3. Since most ozonation systems never exceed a gaseous ozone concentration of 50 to 200 g/m^3, this is generally not a problem. However, gaseous ozone will remain hazardous for a significant amount of time thus, extreme caution is needed when operating the ozone gas systems.

It is important that the ozone generator, distribution, contacting, off-gas, and ozone destructor inlet piping be purged before opening the various systems or subsystems. When entering the ozone contactor, personnel must recognize the potential for oxygen deficiencies or trapped ozone gas in spite of best efforts to purge the system. The operator should be aware of all emergency operating procedures required if a problem occurs. All safety equipment should be available for operators to use in case of an emergency.

Key O&M parameters include:

- Clean feed gas with a dew point of -60 °C (-76 °F), or lower, must be delivered to the ozone generator. If the supply gas is moist, the reaction of the ozone and the moisture will yield a very corrosive condensate on the inside of the ozonator. The output of the generator could be lowered by the formation of nitrogen oxides (such as nitric acid).

- Maintain the required flow of generator coolant (air, water, or other liquid).
- Lubricate the compressor or blower in accordance with the manufacturer's specifications.
- Ensure that all compressor sealing gaskets are in good condition.
- Ensure that all compressor sealing gaskets are in good condition.
- Operate the ozone generator within its design parameters. Regularly inspect and clean the ozonator, air supply, and dielectric assemblies, and monitor the temperature of the ozone generator.
- Monitor the ozone gas-feed and distribution system to ensure that the necessary volume comes into sufficient contact with the wastewater.
- Maintain ambient levels of ozone below the limits of applicable safety regulations.

Advantages and Disadvantages of Ozone Disinfection

Advantages

- Ozone is more effective than chlorine in destroying viruses and bacteria.
- The ozonation process utilizes a short contact time (approximately 10 to 30 minutes).
- There are no harmful residuals that need to be removed after ozonation because ozone decomposes rapidly.
- After ozonation, there is no regrowth of microorganisms, except for those protected by the particulates in the wastewater stream.
- Ozone is generated onsite, and thus, there are fewer safety problems associated with shipping and handling.
- Ozonation elevates the dissolved oxygen (DO) concentration of the effluent. The increase in DO can eliminate the need for reaeration and can also raise the level of DO in the receiving stream.

Disadvantages

- Low dosage may not effectively inactivate some viruses, spores, and cysts.
- Ozonation is a more complex technology than is chlorine or UV disinfection, requiring complicated equipment and efficient contacting systems.
- Ozone is very reactive and corrosive, thus requiring corrosion-resistant material such as stainless steel.
- Ozonation is not economical for wastewater with high levels of suspended solids (SS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), or total organic

carbon (TOC).

- Ozone is extremely irritating and possibly toxic, so off-gasses from the contactor must be destroyed to prevent worker exposure.
- The cost of treatment can be relatively high in capital and power intensiveness.

Summary

The most important factor in disinfection is the quality of the wastewater being treated. If the wastewater is highly treated, it is easier to disinfect. That is, the disinfection is more effective, regardless of the disinfectant chosen.

The traditional, and most commonly-used disinfectant for individual onsite systems is solid chlorine tablet chlorination. However, homeowner operation and management of tablet chlorinators has proven ineffective.

For small wastewater treatment systems such as cluster systems, liquid or gas chlorination is somewhat less maintenance intensive, and the operation costs can be lower, however the initial capital investment can be higher.

When a sensitive environment or soil absorption system is downstream of the chlorine contact chamber, dechlorination is normally practiced to prevent chlorine from damaging the downstream water source or from killing the beneficial soil microorganisms.

Ultraviolet light disinfection has become more widely used as the UV disinfection technology has been developed for smaller flows – even individual home systems. Also, the cost of replacement bulbs is not particularly high, and, the long-term operation and maintenance costs are relatively low. With UV disinfection, the wastewater can safely be returned to the subsurface without harming the soil absorption system microbes.

Ozone has not been developed sufficiently so that small scale ozonation systems are readily available for the decentralized wastewater market – particularly for individual home applications. Ozone is relatively expensive in terms of capital cost as well as operation and maintenance as compared to chlorination and ultraviolet disinfection.

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