Disinfection

Disinfection is usually synonymous with chlorination. That is because chlorine addition is by far the most common form of disinfection used today. In this section, the main emphasis will be on chlorination: how it works, safety, types of chlorine, basic chemistry of chlorine and an introduction to CT values.

What is Disinfection?

Disinfection is the process of killing microorganisms in water that might cause disease (pathogens). Disinfection, however, should not be confused with sterilization which is the destruction of all microorganisms. Disinfection is concerned only with killing pathogens.

Types of Disinfection

Disinfection can be accomplished by a variety of methods. Some are more economical, convenient or easier to apply than others while some are extremely hazardous. But all methods will fall into one of the following types:

1. Heat treatment
2. Radiation treatment
3. Chemical treatment

Heat treatment is probably the oldest form of disinfection known. This method consists of bringing water to a rolling boil for one minute. Boiling is used to disinfect water at campsites and when local health agencies issue a *boil water advisory* as a precautionary measure when water systems become contaminated. It is very effective for disinfecting small quantities of water.

Another means of disinfection is by radiation, which is usually accomplished with ultraviolet (UV) light. UV light works by subjecting water to light rays as water passes through a tube. There are two main drawbacks to the use of UV light. One is that interfering agents such as turbidity can screen pathogens from the UV light. The second disadvantage is that no residual is present in the water to continue disinfecting throughout the distribution system. For this reason, the Health Division requires that chlorination be added when UV light is used.

The third means of disinfection is by far the most commonly used: chemical treatment. This includes iodine, ozone and, of course, chlorine.

Iodine is not as cost effective as chlorine and therefore is normally used as an emergency treatment for small contaminated water systems. Over the long term, consumption may adversely effect some people. In Oregon there are only a handful of small systems that use iodine as a continual disinfection treatment.

Ozone is a strong disinfecting agent and is also used for control of taste and odor. Ozone is unstable and disappears quickly which means no residual is present. Ozone disinfection is recognized under the Surface Water Treatment Rule as a primary disinfectant, although chlorine is still required to maintain a residual in the distribution system.

Chlorination

Chlorination is by far the most widely used form of disinfection. Chlorine is also used as an oxidizing agent for iron, manganese and hydrogen sulfide and for controlling taste and odors. Its effectiveness as a disinfecting agent depends on factors such as pH, temperature, free chlorine residual, contact time and other interfering agents.

Forms of Chlorine

Calcium hypochlorite is the solid form of chlorine, usually found in the tablet or powder form, and contains 65% chlorine by weight. It is white or yellowish-white granular material and is fairly soluble in water. It is important to keep calcium hypochlorite in a dry, cool place. When mixing, always add the calcium hypochlorite to the correct volume of water.

Sodium hypochlorite is the liquid form of chlorine. It is clear and has a slight yellow color. Ordinary household bleach (5.25% chlorine by solution) is the most common form of sodium hypochlorite. Industrial strength is available at 12% and 15% solutions. Sodium hypochlorite can lose up to 4% of its available chlorine content per month and therefore should not be stored for more than 60 to 90 days. Sodium hypochlorite is also very corrosive and should be stored and mixed away from equipment.

Chlorine gas is usually used only on relatively large water systems. Smaller systems may find the initial cost of operation prohibitive. Chlorine gas is also dangerous and may even be fatal when directly inhaled. At room temperature, chlorine gas has a yellow-green color and is heavier than air. Chlorine gas is 99.5% pure chlorine.

Chloramination is the process of adding chlorine and ammonia to water. The chlorine reacts with the ammonia to form chloramines. Chloramines have two advantages to regular chlorination. For systems with extensive distribution systems, chloramines produce a longer lasting chlorine residual. Chloramination also may produce fewer by-products depending on the application. The chemistry of chloramination is beyond the scope of this text.

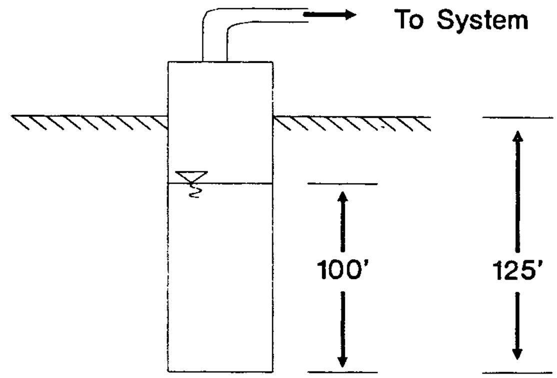
Applications of Chlorine

Chlorine disinfection is used both on a continuous and on an occasional basis. Continuous disinfection is used to treat water at all times, primarily surface water systems which may be exposed to pathogenic organisms. Occasionally, systems may experience bacterial growth in a well or distribution system or may need to disinfect a new line or well prior to use. They may need only to apply a single dose (25-200 ppm); this is called *shock* or *batch* chlorination.

Disinfection of Wells

Occasionally groundwater systems will need to chlorinate to eliminate organisms which may have entered through the source. The Division recommends that a solution consisting of 50 ppm chlorine be introduced into the well. This solution

Fig. 4-1. Example of how to shock chlorinate a well:



Example Well

Known: well depth = 125 ft.
water depth = 100 ft.
casing dia. = 6 inches
Looking at the chart below, we see there are 1.5 gallons of water per foot of depth for a six-inch diameter well.
Therefore, total water in well = 1.5 * 100 = 150 gallons.

A good rule of thumb is to add two cups of 5% bleach for each 100 gallons of water to obtain the proper disinfection dose of 50 ppm. Therefore three cups of bleach should be circulated through the well and let stand for 12 to 24 hours. This water should then be pumped to waste. It would probably be a good idea to dilute the chlorine before adding to the well by mixing it with about five gallons of water. After the chlorinated water is pumped out, follow the disinfection with a water quality test for coliform bacteria.

should stand for 24 hours and then be pumped to waste.

Well diameter, inches	Gallons/foot of depth
4	0.65
6	1.5
8	2.6
10	4.1
12	5.9
14	8.0

Disinfection of Water Lines

OHD rules require disinfection after the installation of new lines or repairs to old lines. A solution of at least 25 ppm chlorine shall be injected into the line with no less than 10 ppm free chlorine residual measured after a minimum of 24 hours. For each 100 gallons of water in a pipe, add one cup of 5% bleach to achieve a disinfection dose of 25 ppm. To calculate the volume of water in a section of pipe, use the following table:

Main diameter, inches	Gallons/foot of length
2	0.16
4	0.65
6	1.5
8	2.6
10	4.1
12	5.9

Example: Let's say you just installed 290 feet of 4" main. Before putting it into service, it needs to be disinfected. Calculate the volume of water in gallons from the above table.

One foot of 4" pipe contains 0.65 gallons of water per foot of length. Therefore: 0.65 x 290 = 190 gallons.

Since this is about 200 gallons, you would need to add two cups of 5% bleach to disinfect the line. Again, follow disinfection with a water quality test for coliform bacteria after flushing the highly chlorinated water from the main.

Continuous chlorination

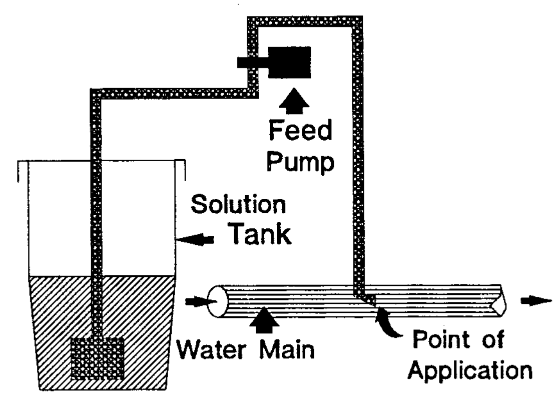
Generally, water from deep wells is free from pathogenic organisms. But other sources of water--shallow wells, streams, lakes and many springs--are open to pathogen contamination. To produce safe water from these sources, disinfection is needed. For surface water sources, filtration and chlorination are used in combination as a double barrier treatment.

Some systems that have deep, protected wells also chlorinate on a continuous basis. This provides a safety factor in case a problem such as a main break or cross connection occurs. It also controls bacteriological growth in the distribution system.

Continuous chlorination is usually applied through an injection (feed) pump (Fig. 4-2). The residual is much lower than the shock chlorination dose, generally in the 0.5 - 1.0 ppm range.

All systems which use continuous chlorination must record the free chlorine residual daily. These results do not have to be reported to the Division but should be available for review during field inspections.

Fig 4-2. Continuous chlorination



Using Chlorine

Chlorine can be added to water in either gas, liquid or solid form. There are three methods of chlorine injection.

1. Gas chlorinators are typically used in relatively large water systems. While they may be appropriate for large systems (because of application rates and cost), gas chlorinators are more expensive initially to install and require more maintenance than hypochlorinators (liquid chlorinators). In addition, gas chlorine is dangerous and can even be fatal when directly inhaled. Rigorous safety precautions must be taken when working with chlorine in gas form.
2. Erosion chlorinators (Fig. 4-3) are typically used in small water systems where flow is relatively small or a power source may not be available.
   They are easily maintained but keeping a consistent residual may be difficult. Solid chlorine tablets are placed in a dispenser and eroded by the flow of water.
3. Liquid chlorinators (hypochlorinators) are typically used by small- to medium-sized water

Fig. 4-3. Typical erosion chlorinator

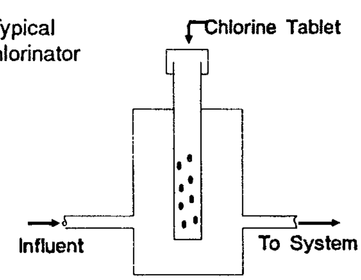


Photo 4-1. Chlorination setup for the injection of calcium hypochlorite solution.

systems. They consist of a chemical feed pump which injects a chlorine solution into a water transmission line. Hypochlorinators can be powered by electricity or water flow.

Liquid chlorine solutions can be made up of either purchased liquid chlorine or by dissolving chlorine powder in water. Liquid chlorine ranges in concentration strength from 5% available chlorine (in regular household bleach) to 12-15% available chlorine. Due to the limited shelf life of chlorine, do not- store it longer than a few months.

Powdered chlorine is about 70% chlorine by weight. It is commonly called HTH (high-test hypochlorite). Powdered chlorine is stable, losing only 3-5% of its strength per year. This means that a water system can stock powdered chlorine for longer periods of time than liquid chlorine. In terms of effectiveness, there is no difference between using liquid or powdered chlorine.

Safety and maintenance tips

1. For hypochlorinators:
   a. Always add chlorine chemical (concentrated liquid or powder) to water, not water to chemical.
   b. Use muriatic acid to clean chlorine spills.
   c. Keep chlorine dry. Do not put wet dippers into chlorine powder containers.
   d. Wear protective clothing including gloves.
2. For gas chlorinators
   a. Make sure your chlorine room has an adequate exhaust fan which is operable. Use it whenever you are in the room.
   b. Containers should be secured using safety brackets or chains.
   c. Work in pairs when changing gas cylinders.
   d. Keep a self-contained breathing apparatus handy and ready to use (not in the chlorine room).
   e. Replace piping and equipment (such as pigtails) often, before failures occur.
   f. Chlorine gas is heavier than air. If you are in a room with a chlorine gas leak, keep your head high to breathe. Chlorine gas can be fatal.
   g. Installation must be in accordance with the occupational safety and health requirements (OR-OSHA.)

CHEMISTRY OF CHLORINATION

As we discussed in the previous section, chlorine can be added as sodium hypochlorite, calcium hypochlorite or chlorine gas. When any of these is added to water, chemical reactions occur as these equations show:

$$\underset{\text{(chlorine gas)}}{Cl_2} + \underset{\text{(water)}}{H_2O} \leftrightarrow \underset{\text{(hypochlorous acid)}}{HOCl} + \underset{\text{(hydrchloric acid)}}{HCl}$$

$$\underset{\text{(calcium hypochlorite)}}{CaOCl} + \underset{\text{(water)}}{H_2O} \leftrightarrow \underset{\text{(hypochlorous acid)}}{2HOCl} + \underset{\text{(calcium hydroxide)}}{Ca(OH)}$$

$$\underset{\text{(sodium hypochlorite)}}{NaOCl} + \underset{\text{(water)}}{H_2O} \leftrightarrow \underset{\text{(hypochlorous acid)}}{HOCl} + \underset{\text{(sodium hydroxide)}}{Na(OH)}$$

All three forms of chlorine produce hypochlorous acid (HOCl) when added to water. Hypochlorous acid is a weak acid but a strong disinfecting agent. The amount of hypochlorous acid depends on the pH and temperature of the water.

Under normal water conditions, hypochlorous acid will also chemically react and break down into a hypochlorite ion (OCl^-):

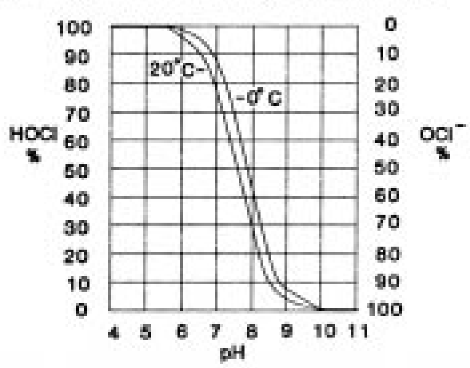
$$HOCl \leftrightarrow H^+ + OCl^-$$

(hypochlorous acid) (hydrogen) (hypochlorite ion)

The hypochlorite ion is a much weaker disinfecting agent than hypochlorous acid, about 100 times less effective.

Let's now look at how pH and temperature affect the ratio of hypochlorous acid to hypochlorite ions. As can be seen from the graph (Fig. 4-4), at a pH of about 7.5, the ratio is approximately 50-50. As the temperature is decreased, the ratio of hypochlorous acid increases. Temperature plays a small part in the acid ratio. Although the ratio of hypochlorous acid is greater at lower temperatures, pathogenic organisms are actually harder to kill. All other things being equal, higher water temperatures and a lower pH are more conducive to chlorine disinfection.

Fig. 4-4. Hypochlorous acid / hypochlorite ion ratio



Types of Residual

If water were pure, the measured amount of chlorine in the water should be the same as the amount added. But water is not 100% pure. There are always other substances (interfering agents) such as iron, manganese, turbidity, etc., which will combine chemically with the chlorine. This is called the *chlorine demand*. Naturally, once chlorine molecules are combined with these interfering agents they are not capable of disinfection. It is free chlorine that is much more effective as a disinfecting agent.

So let's look now at how free, total and combined chlorine are related. When a chlorine residual test is taken, either a total or a free chlorine residual can be read. Total residual is all chlorine that is available for disinfection.

Total chlorine residual = free + combined chlorine residual

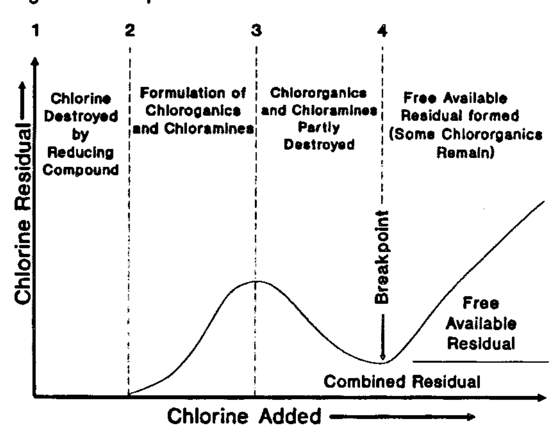
But remember that free chlorine residual is a much stronger disinfecting agent. Therefore, the Health Division requires that your daily chlorine residual readings be of free chlorine residual.

Now let's examine how residuals change as chlorine is added to water. From the graph (Fig. 4-5), we can see that as chlorine is initially added, it is used up by interfering agents. This is the section between graph points 1 and 2. Here, no chlorine residuals form and little or no disinfection occurs. Gradually, as more chlorine is added, the measured total chlorine residual increases between points 2 and 3. In this region, chlorine reacts with organics and ammonia and is all combined chlorine residual. Due to chemical reactions between points 3 and 4, the actual total residual decreases. It is in this area that most taste and odor problems occur, with many people complaining of a strong swimming pool smell. The solution is to increase the chlorine dose. This may seem contradictory but once you get beyond point 4, the residual becomes all free chlorine. Point 4 is called *break-point chlorination* because this is where any added chlorine is in the form of free chlorine residual.

Measuring Chlorine Residual

Chlorine residual is the amount of chlorine remaining in water which can be used for disinfection. A convenient, simple and inexpensive way to measure chlorine residual is to use a small portable kit with pre-measured packets of chemicals which are added to water. (Make sure you buy a test kit using the *DPD method*, and not the outdated orthotolodine method.)

Fig. 4-5. Breakpoint chlorination curve



Chlorine test kits are very useful in adjusting the chlorine dose you apply. You can measure what chlorine levels are being found in your system (especially at the far ends).

Free chlorine residuals need to be checked and recorded daily. These results do not need to be submitted to the Health Division but should be kept on file for inspection during a regular field visit.

Chlorination Systems and Contact lime

Under current rules, groundwater systems that use continuous chlorination must meet 30 minutes of contact time (Fig. 4-6). This can be achieved through distribution storage before the first customer or with the addition of storage (Fig. 4-7). To calculate contact time, you will need to know both the maximum anticipated water demand (gpm) and the volume of water between the chlorinator and the first water user (this includes reservoirs and piping). The volume of water in a main can be calculated by the following equation:

1. $$\text{Volume (gals.)} = 23.5 \times (\text{radius of pipe in feet})^2 \times \text{main length (feet)}$$

Contact time can then be calculated as follows:

2. $$\text{Contact time (minutes)} = \frac{\text{Volume (gallons)}}{\text{Flow (gpm)}}$$

Fig. 4-6. Minimum contact time

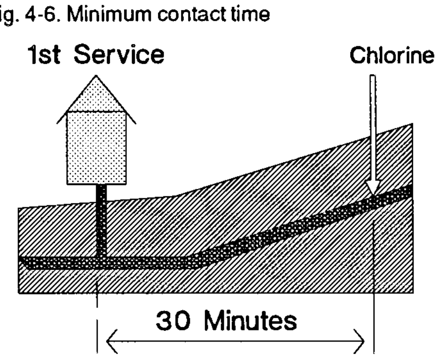
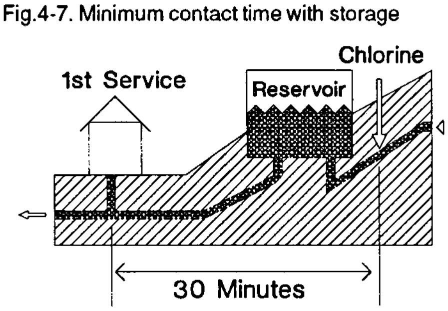


Fig.4-7. Minimum contact time with storage



If the value you calculate is less than 30 minutes, watch out! That's not enough to insure safe disinfection. Example:

Length of main = 200 feet
Diameter of main = 8"
Radius = 4" = 0.333 feet
Flow rate = 100 gpm

Using equation 1 from above:

$$\text{Volume} = 23.5 \times (0.333)^2 \times 200 = 522 \text{ gallons}$$

To calculate the contact time use equation 2:

$$\text{Contact time} = \frac{522 \text{ gallons}}{100 \text{ gpm}} = 5.22 \text{ minutes}$$

The system is below the allowable 30 minute contact time. The options are either moving the chlorinator or adding storage to increase contact time. Example:

Reservoir size = 40,000 gallons
Length of main = 200 feet
Diameter of main = 8"
Radius = 4" = 0.333 feet

As we will see in the section on effective storage capacity, the actual effective storage due to short circuiting is about 10% of the reservoir size (a tracer study may be performed to determine the actual contact time through the reservoir). For this example, we will assume 10% of the reservoir size for effective storage capacity or 4,000 gallons. Since the length and diameter of the main are the same as the previous example, we know there are 522 gallons of storage in the main. We also need to add the reservoir storage:

Total storage = 522 gallons + 4,000 gallons = 4,522 gallons

Again using equation 2 from above to calculate contact time:

$$\text{Contact time} = \frac{4{,}522 \text{ gallons}}{100 \text{ gpm}} = 45 \text{ minutes}$$

With the addition of the 40,000 gallon reservoir, the system now meets the required 30 minute contact time.

Chlorination Calculations

One of the common questions pertaining to the introduction of chlorine into a system is how much chlorine is needed, or the ratio of chlorine to water, to obtain a desired residual in the system. To answer this question, you will need to know the flow rate of the system, the desired chlorine residual, the strength of the solution being injected and the pump rate.

1. The flow rate of a system is generally the measured output of a well for groundwater systems or the filtration rate for surface water systems. It is expressed in gallons per day or gallons per minute. To use the following equations, flow should be expressed as gallons per minute (gpm).
2. The chlorine residual that is desired in the system varies. Some systems prefer to keep the free chlorine residual at detectable limits (around 0.2 ppm), while others prefer a stronger residual (0.5-2.0). Typically, systems run between 0.2 to 0.5 ppm.
3. The solution strength refers to the chlorine concentration that is being fed into the water line.
4. The chemical feed pump rate can be read from the pump setting and generally will range from 1 to 10. Chlorine feeder pumps should be calibrated occasionally to assure accurate readings.

Typically, the system flow rate, desired chlorine residual and the pump feed rate are known which leaves only the solution strength to be calculated. The following examples will help to illustrate how to calculate chlorine concentrations.

Concentration Units

Chlorine concentrations can be expressed as a percent (%) or as parts-per-million (ppm). One percent chlorine dose is equivalent to 10,000 ppm. So regular household bleach which is 5.25% chlorine solution has about 52,500 ppm.

1% = 10,000 ppm or 1 ppm = 0.0001%

Chemical feed equation;

$$C_F \times Q_F = C_S \times Q_S$$

C_F (Feed concentration) $\times$ Q_F (Feed flow) = C_S (System chlorine dose) $\times$ Q_S (Flow)

Both sides of the equation must match; if you use ppm for the system chlorine dose (C_S), then the feed concentration (C_F) must also be in ppm. Likewise, both the feed flow (Q_F) and the system flow (Q_S) need to be in the same units (either gallons per minute (gpm) or gallons per day (gpd)).

Example 1:

Feed solution: 5% bleach

Desired chlorine dose: 1 ppm

System flow: 120 gpm (flow when system runs)

Find: At what flow should the feed pump be set?

Equation: $CF \times QF = C_S \times Q_S$

C_F = 5% (10,000 ppm/%) = 50,000 ppm

Q_F = unknown

C_S = 1 ppm

Q_S = 120 gpm (1440 gpm/ 1 gpd) = 172,800 gpd

Solution:

$Q_F = (C_S \times Q5) / C_F$

= (1 ppm $\times$ 172,800 gpd) / 50,000 ppm

Q_F = 3.5 gallons / day

In this example, 3.5 gallons per day of 5% bleach must be injected into the system to achieve a 1.0 ppm continuous dose in the effluent water.

How does this relate to the mixture in the solution tank? Let's assume that the feed pump is set for 10 gpd. This can be checked by calibrating the pump. Since we know we need 3.5 gallons of the chlorine solution per day, the rest of the 10 gallons will be the mix water.

Gallons of chlorine per day + gallons of water = pump setting

3.5 gallons per day + gallons of water = 10 gallons per day

Therefore 6.5 gallons of water must be added to 3.5 gallons of chlorine to achieve 10 gallons per day of solution feed.

Example 2:

Feed solution: 5% bleach

Desired chlorine dose: 0.4 ppm

System flow: 100 gpm

Chlorine pump rate: 10 gpd = 0.0075 gpm

Find: What should be the ratio of chlorine to water in the solution tank?

C_F = unknown

Q_F = 10 gpd

C_S = 0.4 ppm

Q_S = 100 gpm (1440 gpm / 1 gpd) = 144,000 gpd

Solution:

$$C_F = (C_S \times Cl_S) / Q_F$$
$$= (0.4 \text{ ppm} \times 144{,}000 \text{ gpd}) / 10 \text{ gpd}$$
$$C_F = 5{,}760 \text{ ppm}$$

If the feed concentration must be 5,760 ppm, then the following equation must be used:

$$(\text{feed conc.}) \times (\text{X gallons solution}) = (Cl_2 \text{ conc.}) \times (1 \text{ gal. } H_2O)$$
$$(5{,}760 \text{ ppm}) \times (\text{X gallons solution}) = (50{,}000 \text{ ppm}) \times (1 \text{ gallon})$$
$$\text{X gallons solution} = 8.7$$

Therefore, a solution mix of 7.7 gallons water and 1 gallon chlorine for a total of 8.7 gallons of solution fed at a rate of 10 gpd will result in a free chlorine residual of 0.4 ppm.

Calculating CT

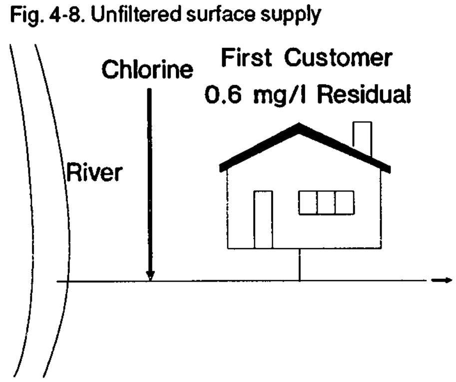
Under the Surface Water Treatment Rule, surface water systems or groundwater systems under the direct influence of surface water must calculate a value known as CT (C represents *concentration* of free chlorine residual in mg/1 and T is contact *time* in minutes). This value is used to illustrate the effectiveness of chlorine to inactivate *Giardia* cysts. Given the water quality parameters (temperature, free chlorine residual at first user, pH, along with chlorine contact time), the system must compute its actual CT. This can be calculated fairly easy using the following equation:

$$CT = \text{Concentration of free chlorine residual (mg/l)} \times \text{contactTime (min.)}$$

Once the actual CT is calculated, this number must be compared to a minimum CT value set by EPA.

To best illustrate the computation of CT values, we will go through a couple of examples. The first is an unfiltered surface supply as shown below (Fig. 4-8).

Fig. 4-8. Unfiltered surface supply



Water quality parameters:

pH=7.0
Temperature = 5° C
Contact time (based on flow) = 80 minutes
Free chlorine residual at first customer = 0.6 mg/l

To compute the actual CT, we will use the formula given above:

$$CT = \text{Concentration X time}$$
$$= 0.6 \text{ mg/l X } 80 \text{ minutes}$$
$$= 48$$

From the given water quality parameters, use Appendix Table 4-2 in the appendix. As an unfiltered water source, the system is required to achieved a 3-log removal/inactivation of *Giardia* cysts, a 99.9% reduction. Therefore, from the tables:

$$\text{Required CT} = CT_{99.9} = 143$$

The ratio of the actual CT (CT_{CALC}) to the required CT ($CT_{99.9}$) must be greater than or equal to 1.0 to ensure adequate disinfection.

$$CT_{CALC} / CT_{99.9} = 48/143 = 0.34$$

Since 0.34 < 1.0, this system fails to comply with the required level of disinfection needed to satisfy the SWTR in its present configuration. There are several options available to the system that enhance the disinfection process.

1. Increase the free chlorine residual: One option to increase the actual CT is to increase the free chlorine residual dose so as to obtain a measured residual of 1.2 mg/1 at the first customer. Then, recalculate the disinfection CT values.

$$\text{Actual CT} = CT_{CALC} = \text{Concentration} \times \text{Time}$$
$$= 1.2 \text{ mg/l} \times 80 \text{ minutes}$$
$$= 96$$

With pH = 7.0, temperature = 5° C and chlorine residual to the first customer = 1.2 mg/l, Appendix Table 4-2 gives the required CT value.

$$\text{Required CT} = CT_{99.9} = 152$$

Therefore,

$$CT_{CALC} / CT_{99.9} = 96/152 = 0.63$$

In this case, doubling the free chlorine residual alone does not provide the required level of disinfection necessary to achieve 3log removal/inactivation of *Giardia* cysts. In fact, for this example, it would require a free chlorine residual greater than 2.0 mg/1 to achieve the 3-log reduction. A second option should be investigated.

2. Adding storage for extra contact time prior to the first customer: From the previous example, a large reservoir has been installed prior to the first customer (Fig. 4-9) to achieve longer contact times. A tracer study has been done between the free chlorine injection point, through the reservoir and prior to the first customer. The results determine that the available contact time = 240 minutes. The free chlorine residual at the first customer = 0.6 mgA. Other water quality parameters remain unchanged.

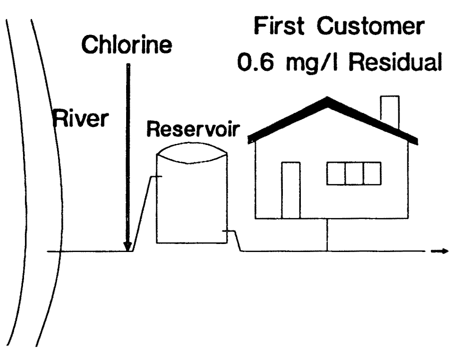
Actual CT $= CT_{CALC}$ = Concentration $\times$ time
$= 0.6$ mg/l $\times$ 240 minutes
$= 144$
Required CT = $CT_{99.9} = 143$

Therefore,

$CT_{CALC} / CT_{99.9} = 144/143 = 1.01$

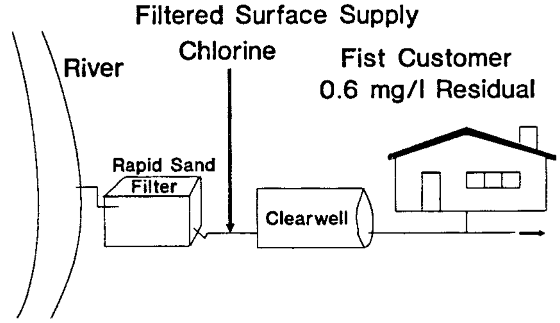
Here, the system meets the disinfection level required to achieve 3-log removal/ inactivation of *Giardia* cysts. The next option that could be available for this water system is adding some form of additional treatment.

Fig. 4-9. Unfiltered surface supply with added storage



3. Adding filtration to the treatment process (Fig. 4-10) reduces the reliance on disinfection to achieve the full removal/ inactivation of *Giardia* cysts. Instead, filtration and disinfection combine to form a multiple barrier approach which together will achieve the necessary reduction of cysts. The figure below shows that a conventional rapid sand filtration plant has now been installed in the system followed by injection of free chlorine with a contact time through a clearwell of 35 minutes (as determined by a tracer study).

Fig. 4-10. Filtered surface supply



Section 5.5.2 of the SWTR guidance manual lists expected log removals for each type of treatment technique and the necessary log removals needed through disinfection to achieve an overall 3-log reduction of *Giardia* cysts. For this example, conventional rapid sand filtration is credited with a 2.5-log removal/inactivation level. Therefore, a 0.5-log reduction is required from disinfection.

With pH = 7.0 and temp. = 5°C;
Actual CT $= CT_{CALC}$ = Concentration $\times$ time
$= 0.6$ mg/l $\times$ 35 minutes
$= 21$
Required CT = CT_{68} (FOR 0.5-log reduction) = 24

Therefore,

$CT_{CALC} / CT_{68} = 21/24 = 0.88$

At this point, the system will not meet the required overall level of 3.0-log removal/ inactivation for *Giardia* cysts. However, increasing the free chlorine residual to the first customer and/or increasing the contact time through the clearwell should prove effective. Assuming the same water quality parameters as before, the free chlorine residual measured at the first customer is increased to 1.0 mg/1.

Actual CT = CT_{CALC} = Concentration × time
= 1.0 mg/l × 35 minutes
= 35

Then, from Appendix Table 4-2,

Required CT = CT_{68} = 25
CT_{CALC} / CT_{68} = 35/25 = 1.40

Or, if the clearwell contact time is increased to 50 minutes,

Actual CT = CT_{CALC} = 0.6mg/l X 50 minutes
= 30
Required CT = CT_{68} = 24
CT_{CALC} / CT_{68} = 30/24 = 1.25

TRACER STUDIES AND BAFFLING

One aspect of the Surface Water Treatment Rule is the determination of available disinfectant contact time. In the past, theoretical detention time was calculated by dividing storage capacity by the flow rate. This calculation has proved to be inadequate due to short-circuiting through the reservoirs.

In order to get a fairly accurate determination of contact time, a tracer study should be performed. It is a generally accepted practice to refer to the actual contact time as 10% of the actual dose applied, measured at some endpoint. Therefore we will designate T10 as the detention time.

Conditions Affecting Contact Time

There are two main factors which affect available contact time: storage capacity and system flow rate. Although flow through a treatment plant usually remains fairly constant, clearwells and reservoirs can alter the flow rate through the system.

Ideally, tracer studies should be performed for four different flow rates. One at average flow, two greater than average, and one below average. The highest flow rate should be at least 91% of the greatest flow rate ever expected to occur. A normalized curve plotting concentration vs time can be used to find T_{10}.

Unfortunately, not all systems can perform four tracer studies. Some systems must limit the number to one. In this case, the flow rate should be no less than 91% of the greatest flow rate expected. The actual contact time can then be related by the following equation:

$$T_{10S} = T_{10T} \times (Q_T/Q_D)$$

where:

$T_{10S} = T_{10}$ at system flow rate
$T_{10T} = T_{10}$ at tracer flow rate
Q_T = tracer study flow rate
Q_D = system flow rate

Example: Let's say a tracer study was conducted at a flow rate of 100 gpm and detention time was found to be 50 minutes. Let's also say the flow rate for some operating day was 120 gpm. Now we need to calculate the actual effective contact time for this day.

Given:

T_{10T} = 50 minutes
Q_T = 100 gpm
Q_D = 120 gpm
T_{10S} = unknown

Using the equation above, the contact time for this system for this day is:

T_{10S} = 50 × (100/120)
T_{10S} = 41.67 minutes

Other systems may not have the capability to perform even one tracer study, in which case theoretical numbers must be used (see the table in the baffling section) that are generally much more conservative.

Fig. 4-11. No baffling

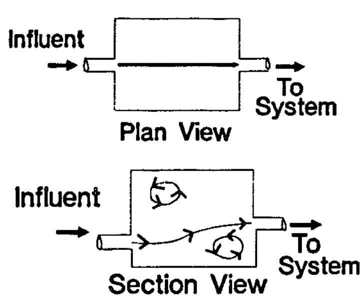


Fig. 4-12. Average baffling

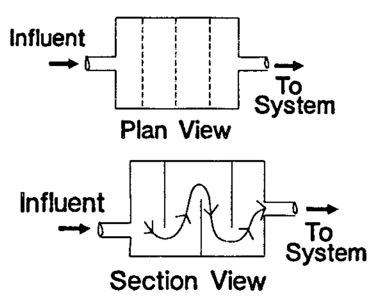
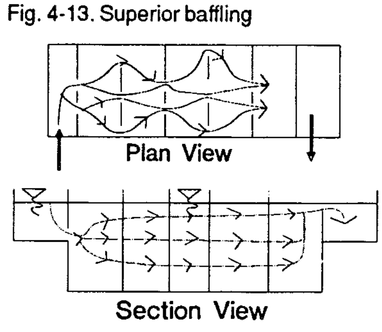


Fig. 4-13. Superior baffling



Tracer Study Methods

Tracer studies involve some sort of chemical injection into the system which can be measured with common test equipment. The two most common methods of tracer injection are the step-dose and slug-dose.

The step-dose method involves injection of a tracer chemical at a constant dose (much as is done by a chlorine feeder pump). Concentration is measured at a downstream point until it levels out. The detention time T_{10} can be found by plotting the normalized concentration vs time profile.

In the slug-dose method, a large instantaneous dose is applied to incoming water, then measured over time as it passes through the system. When 10% of the applied dose passes the endpoint, that is considered T_{10}. This method is advantageous in situations where a continuous feed system is not feasible.

Types of Tracer Chemicals

Chemical selection is a very important step in a tracer study. The chemical should be easy to monitor and acceptable in a potable water supply.

Many chemicals have been used in tracer studies. The most common are chloride, chlorine and fluoride. All are readily available and can be measured with common devices. In fact, systems using chlorine or adding fluoride after treatment have all the necessary equipment to conduct a tracer study. Other chemicals which can be used include potassium permanganate,, alum and sodium carbonate.

Baffling

Short circuiting can greatly reduce the disinfection contact time, which means the full potential of the reservoir is not realized. EPA suggests using the following table to roughly calculate the effective disinfection contact time.

Table 4-1. Baffling

Condition	T_{10}/T	Description
Unbaffled (mixed flow) (Fig. 4-11)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average (Fig. 4-12)	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior (Fig. 4-13)	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ratio, (pipeline flow), perforated inlet, outlet, and intra-basin baffles

DEFINITIONS:

1. Applied chlorine: the total amount of chlorine added to water (usually expressed in parts per million or ppm).
2. Chlorine demand: Some of the chlorine added will combine with other chemicals in the water, such as iron, hydrogen sulfide, manganese, nitrogen compounds and organics. Chlorine demand is that portion of the chlorine added which is used up in reactions other than disinfection.
3. Chlorine residual: The amount of chlorine not combined in other reactions and available for disinfection. Total residual is made up of both combined and free residuals.
4. Total residuals: Total chlorine residuals can be measured with a chlorine test kit. It is all the chlorine available for disinfection purposes.
5. Free and combined chlorine residuals: Free chlorine residuals are more effective in disinfecting water than are combined residuals. Free chlorine can also be measured

with a chlorine test kit. The amount of combined residual can be found if both the total and free chlorine residuals are measured, by the relationship:

Total chlorine = free chlorine + combined chlorine

6. pH: Better disinfection takes place when the pH is about 7.5 or lower.

7. Contact time: The amount of time the chlorine is in contact with the water before the first customer (usually expressed in minutes). Contact time should not be confused with CT. Contact time is one of the components used to compute CT.

References

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3. *Introduction to Water Treatment*, *Volume* 2, American Water Works Association, *6666* Quincy Ave., Denver, Colorado 80235

4. *Assessing Unfiltered Water Supplies*, David E. Leland and Paul A. Berg, American Water Works Association Journal, January 1988.

5. *Small Water System Operation and Maintenance*, California State University, Hornet Foundation Inc., 1987

Appendix Table 4-1.
CT Values for Inactivation of Giardia Cysts by Free Chlorine at 0.5° C

Chlorine Concentration mg/L < =	PH < 6 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	23	46	69	91	114	137
0.6	24	47	71	94	118	141
0.8	24	48	73	97	121	145
1	25	49	74	99	123	148
1.2	25	51	76	101	127	152
1.4	26	52	78	103	129	155
1.6	26	52	79	105	131	157
1.8	27	54	81	108	135	162
2	28	55	83	110	138	165
2.2	28	56	85	113	141	169
2.4	29	57	86	115	143	172
2.6	29	58	88	117	146	175
2.8	30	59	89	119	148	178
3	30	60	91	121	151	181

Chlorine Concentration mg/L < =	PH = 6.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	27	54	82	109	136	163
0.6	28	56	84	112	140	168
0.8	29	57	86	115	143	172
1	29	59	88	117	147	176
1.2	30	60	90	120	I50	180
1.4	31	61	92	123	153	184
1.6	32	63	95	126	158	189
1.8	32	64	97	129	161	193
2	33	66	99	131	164	197
2.2	34	67	101	134	168	201
2.4	34	68	103	137	171	205
2.6	35	70	I05	139	174	209
2.8	36	71	107	142	178	213
3	36	82	109	145	181	217

Chlorine Concentration mg/L < =	PH = 7.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	33	65	98	130	163	195
0.6	33	67	100	133	167	200
0.8	34	68	103	137	171	205
1	35	70	I05	140	175	210
1.2	36	72	108	143	179	215
1.4	37	74	111	147	184	221
1.6	38	75	113	ISI	188	226
1.8	39	77	116	154	193	231
2	39	79	118	157	197	236
2.2	40	81	121	161	202	242
2.4	41	82	124	165	206	247
2.6	42	84	126	168	210	252
2.8	43	86	129	171	214	257
3	44	87	131	174	218	261

Chlorine Concentration mg/L < =	PH < 7.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	40	79	119	158	198	237
0.6	40	80	120	159	199	239
0.8	41	82	123	164	205	246
1	42	84	127	169	211	253
1.2	43	86	130	173	216	259
1.4	44	89	133	177	222	266
1.6	46	91	137	182	228	273
1.8	47	93	140	186	233	279
2	48	95	143	191	238	286
2.2	50	99	149	198	248	297
2.4	50	99	149	199	248	98
2.6	51	101	152	203	253	304
2.8	52	103	I55	207	258	310
3	53	105	I58	211	263	316

Chlorine Concentration mg/L < =	PH = 8.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	46	92	139	185	231	277
0.6	48	95	143	191	238	286
0.8	49	98	148	197	246	295
1	51	101	I52	203	253	304
1.2	52	104	157	209	261	313
1.4	54	107	161	214	268	321
1.6	55	110	165	219	274	329
1.8	56	113	169	225	282	338
2	58	II5	173	231	288	346
2.2	59	118	177	235	294	353
2.4	60	120	181	241	301	361
2.6	61	123	184	245	307	368
2.8	63	125	188	250	313	375
3	64	127	191	255	318	382

Chlorine Concentration mg/L < =	PH = 8.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3 0
0.4	55	110	165	219	274	329
0.6	57	114	171	228	285	342
0.8	59	118	177	236	295	354
1	61	122	183	243	304	365
1.2	63	125	188	251	313	376
1.4	65	129	194	258	323	387
1.6	66	132	199	265	331	397
1.8	68	136	204	271	339	407
2	70	139	209	278	348	417
2.2	71	142	213	284	355	426
2.4	73	145	218	90	363	435
2.6	74	148	222	296	370	444
2.8	75	151	226	301	377	452
3	77	153	230	307	383	460

Chlorine Concentration mg/L < =	PH < 9.0 Log Inactivations 0.5	I.0	I.5	2.0	2.5	3.0
0.4	65	130	195	260	325	390
0.6	68	136	204	271	339	407
0.8	70	141	211	281	352	422
1	73	146	219	291	364	437
1.2	75	150	226	301	376	451
1.4	77	155	232	309	387	464
1.6	80	159	239	318	398	477
1.8	82	163	245	326	408	489
2	83	167	250	333	417	500
2.2	85	170	256	341	426	511
2 4	87	174	261	348	435	522
2.6	89	178	267	355	444	533
2.8	91	181	272	362	453	543
3	92	184	276	368	460	552

Note: CT = CT for 3-log inactivation, or 99.9% removal

APPENDIX TABLE 4-2.
CT VALUES FOR INACTIVATION OF GIARDIA CYSTS BY FREE CHLORINE AT 5.0° C

Chlorine Concentration mg/L < =	PH < 6 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0	PH = 6.5 Log Inactivations 0.5	1.0	I.5	2.0	2.5	3.0	PH = 7.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	16	32	49	65	81	97	20	39	59	78	98	117	23	46	70	93	116	139
0.6	17	33	50	67	83	100	20	40	60	80	100	120	24	48	72	55	119	143
0.8	17	34	52	69	86	103	20	41	61	81	102	122	24	49	73	97	122	146
1	18	35	53	70	88	I05	21	42	63	83	104	125	25	50	75	99	124	149
1.2	18	36	54	71	89	107	21	42	64	85	106	127	25	51	76	101	127	I52
1.4	18	36	55	73	91	109	22	43	65	87	108	130	26	52	78	103	129	I55
1.6	19	37	56	74	93	111	22	44	66	88	110	132	26	53	79	I05	132	158
1.8	19	38	57	76	95	114	23	45	68	90	113	135	27	54	81	108	135	162
2	19	39	58	77	97	116	23	46	69	92	115	138	28	55	83	110	138	165
22	20	39	59	79	98	118	23	47	70	93	117	140	28	56	85	113	141	169
2.4	20	40	60	80	100	120	24	48	72	55	119	143	29	57	86	115	143	172
2.6	20	41	61	81	102	122	24	49	73	97	122	146	29	58	88	117	146	175
2.8	21	41	62	83	103	124	25	49	74	99	123	148	30	59	89	119	148	178
3	21	42	63	84	105	126	25	50	76	101	126	151	30	61	91	121	I52	182

Chlorine Concentration mg/L < =	PH < 7.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0	PH = 8.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0	PH = 8.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	28	55	83	111	138	166	33	66	99	132	165	198	39	79	118	157	197	236
0.6	29	57	86	114	143	171	34	68	102	136	170	204	41	81	122	163	203	244
0.8	29	58	88	117	146	175	35	70	105	140	175	210	42	84	126	168	210	252
1	30	60	90	119	149	179	36	72	108	144	180	216	43	87	130	173	217	260
1.2	31	61	92	122	153	183	37	74	111	147	184	221	45	89	134	178	223	267
1.4	31	62	94	125	156	187	38	76	114	151	189	227	46	91	137	183	228	274
1.6	32	64	96	128	160	192	39	77	116	155	193	232	47	94	141	187	234	281
1.8	33	65	98	131	163	196	40	79	119	159	198	238	48	96	144	191	239	287
2	33	67	100	133	167	200	41	81	122	162	203	243	49	98	147	196	245	294
2.2	34	68	102	136	170	204	41	83	124	165	207	248	50	100	150	200	250	300
2.4	35	70	105	139	174	209	42	84	127	169	211	253	51	102	153	204	255	306
2.6	36	71	107	142	178	213	43	86	129	172	215	258	52	104	156	208	260	312
2.8	36	72	109	145	181	217	44	88	132	175	219	263	53	106	159	212	265	318
3	37	74	111	147	184	221	45	89	134	179	223	268	54	108	162	216	270	324

Chlorine Concentration mg/L < =	PH < 9.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	47	93	140	186	233	279
0.6	49	97	146	194	243	291
0.8	50	100	151	201	251	301
1	52	104	156	208	260	312
1.2	53	107	160	213	267	320
1.4	55	110	165	219	274	329
1.6	56	112	169	225	281	337
1.8	58	115	173	230	288	345
2	59	118	177	235	294	353
2.2	60	120	181	241	301	361
2.4	61	123	184	245	307	368
2.6	63	125	188	250	313	375
2.8	64	127	191	255	318	382
3	65	130	195	259	324	389

Note: CT = CT for 3-log inactivation, or 99.9% removal

Appendix Table 4-3.
CT Values for Inactivation of Giardia Cysts by Free Chlorine at 10° C

Chlorine Concentration	PH < 6						PH = 6.5						PH = 7.0					
mg/L < =	Log Inactivations						Log Inactivations						Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
0.4	12	24	37	49	61	73	15	29	44	59	73	88	17	35	52	69	87	104
0.6	13	25	38	50	63	75	15	30	45	60	75	90	18	36	54	71	89	107
0.8	13	26	39	52	65	78	15	31	46	61	77	92	18	37	55	73	92	110
1	13	26	40	53	66	79	16	31	47	63	78	94	19	37	56	75	93	112
1.2	13	27	40	53	67	80	16	32	48	63	79	95	19	38	57	76	95	114
1.4	14	27	41	55	68	82	16	33	49	65	82	98	19	39	58	77	97	116
1.6	14	28	42	55	69	83	17	33	50	66	83	99	20	40	60	79	99	119
1.8	14	29	43	57	72	86	17	34	51	67	84	101	20	41	61	81	102	122
2	15	29	44	58	73	87	17	35	52	69	87	104	21	41	62	83	103	124
2.2	15	30	45	59	74	89	18	35	53	70	88	105	21	42	64	85	106	127
2.4	15	30	45	60	75	90	18	36	54	71	89	107	22	43	65	86	108	129
2.6	15	31	46	61	77	92	18	37	55	73	92	110	22	44	66	87	109	131
2.8	16	31	47	62	78	93	19	37	56	74	93	111	22	45	67	89	112	134
3	16	32	48	63	79	95	19	38	57	75	94	113	23	46	69	91	114	137

Chlorine Concentration	PH < 7.5						PH = 8.0						PH = 8.5					
mg/L < =	Log Inactivations						Log Inactivations						Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2 .5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
0.4	21	42	63	83	104	125	25	50	75	99	124	149	30	59	89	118	148	177
0.6	21	43	64	85	107	128	26	51	M	102	128	153	31	61	92	122	153	183
0.8	22	44	66	87	109	131	26	53	79	105	132	158	32	63	95	126	158	189
1	22	45	67	89	112	134	27	54	81	108	135	162	33	65	98	130	163	195
1.2	23	46	69	91	114	137	28	55	83	111	138	166	33	67	100	133	167	200
1.4	23	47	70	93	117	140	28	57	85	113	142	170	34	69	103	137	172	206
1.6	24	48	72	96	120	144	29	58	87	116	145	174	35	70	106	141	176	211
1.8	25	49	74	98	123	147	30	60	90	119	149	179	36	72	108	143	179	215
2	25	50	75	100	125	150	30	61	91	121	152	182	37	74	111	147	184	221
2.2	26	51	M	102	128	153	31	62	93	124	155	186	38	75	113	150	188	225
2.4	26	52	79	105	131	157	32	63	95	127 1	158	190	38	77	115	153	192	230
2.6	27	53	80	107	133	160	32	65	97	129	162	194	39	78	117	156	195	234
2.8	27	54	82	109	136	163	33	66	99	131	164	197	40	80	120	159	199	239
3	28	55	83	111	138	166	34	67	101	134	168	201	41	81	122	162	203	243

Chlorine Concentration	PH < 9.0					
mg/L < =	Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0
0.4	35	70	105	139	174	209
0.6	36	73	109	145	182	218
0.8	38	75	113	151	188	226
1	39	78	117	156	195	234
1.2	40	80	120	160	200	240
1.4	41	82	124	165	206	247
1.6	42	84	127	169	211	253
1.8	43	86	130	173	216	259
2	44	88	133	177	221	265
2.2	45	90	136	181	226	271
2.4	46	92	138	184	230	276
2.6	47	94	141	187	234	281
2.8	48	96	144	191	239	287
3	49	97	146	195	243	292

Note: CT = CT for 3-log inactivation, or 99.9% removal

APPENDIX TABLE 4-4.
CT VALUES FOR INACTIVATION OF GIARDIA CYSTS BY FREE CHLORINE AT 15° C

PH < 6

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	8	16	25	33	41	49
0.6	8	17	25	33	42	50
0.8	9	17	26	35	43	52
1	9	18	27	35	44	53
1.2	9	18	27	36	45	54
1.4	9	18	28	37	46	55
1.6	9	19	28	37	47	56
1.8	10	19	29	38	48	57
2	10	19	29	39	49	58
2.2	10	20	30	39	50	59
2.4	10	20	30	40	51	60
2.6	10	20	31	41	51	61
2.8	10	21	31	41	52	62
3	11	21	32	42	53	63

PH = 6.5

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	10	20	30	39	49	59
0.6	10	20	30	40	50	60
0.8	10	20	31	41	51	61
1	11	21	32	42	53	63
1.2	11	21	32	43	53	64
1.4	11	22	33	43	54	65
1.6	11	22	33	44	55	66
1.8	11	23	34	45	57	68
2	12	23	35	46	58	69
2.2	12	23	35	47	58	70
2.4	12	24	36	48	60	72
2.6	12	24	37	49	61	73
2.8	12	25	37	49	62	74
3	13	25	38	51	63	76

PH = 7.0

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	12	23	35	47	58	70
0.6	12	24	36	48	60	72
0.8	12	24	37	49	61	73
1	13	25	38	50	63	75
1.2	13	25	38	51	63	76
1.4	13	26	39	52	65	78
1.6	13	26	40	53	66	79
1.8	14	27	41	54	68	81
2	14	28	42	55	69	83
2.2	14	28	43	57	71	85
2.4	14	29	43	57	72	86
2.6	15	29	44	59	73	88
2.8	15	30	45	59	74	89
3	15	30	46	61	76	91

PH < 7.5

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	14	28	42	55	69	83
0.6	14	29	43	57	72	86
0.8	15	29	44	59	73	88
1	15	30	45	60	75	90
1.2	15	31	46	61	77	92
1.4	16	31	47	63	78	94
1.6	16	32	48	64	80	96
1.8	16	33	49	65	82	98
2	17	33	50	67	83	100
2.2	17	34	51	68	85	102
2.4	18	35	53	70	88	105
2.6	18	36	54	71	89	107
2.8	18	36	55	73	91	109
3	19	37	56	74	93	111

PH = 8.0

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	17	33	50	66	83	99
0.6	17	34	51	68	85	102
0.8	18	35	53	70	88	105
1	18	36	54	72	90	108
1.2	19	37	56	74	93	111
1.4	19	38	57	76	95	114
1.6	19	39	58	77	97	116
1.8	20	40	60	79	99	119
2	20	41	61	81	102	122
2.2	21	41	62	83	103	124
2.4	21	42	64	85	106	127
2.6	22	43	65	86	108	129
2.8	22	44	66	88	110	132
3	22	45	67	89	112	134

PH = 8.5

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	20	39	59	79	98	118
0.6	20	41	61	81	102	122
0.8	21	42	63	84	105	126
1	22	43	65	87	108	130
1.2	22	45	67	89	112	134
1.4	23	46	69	91	114	137
1.6	24	47	71	94	118	141
1.8	24	48	72	96	120	144
2	25	49	74	98	123	147
2.2	25	50	75	100	125	150
2.4	26	51	M	102	128	153
2.6	26	52	78	104	130	156
2.8	27	53	80	106	133	159
3	27	54	81	108	135	162

PH < 9.0

Chlorine Concentration mg/L < =	Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	23	47	70	93	117	140
0.6	24	49	73	97	122	146
0.8	25	50	76	101	126	151
1	26	52	78	104	130	156
1.2	27	53	80	107	133	160
1.4	28	55	83	110	138	165
1.6	28	56	85	113	141	169
1.8	29	58	87	115	144	173
2	30	59	89	118	148	177
2.2	30	60	91	121	151	181
2.4	31	61	92	123	153	184
2.6	31	63	94	125	157	188
2.8	32	64	96	127	159	191
3	33	65	98	130	163	195

Note: CT = CT for 3-log inactivation, or 99.9% removal

Appendix Table 4-5.
CT Values for Inactivation of Giardia Cysts by Free Chlorine at 20° C

Chlorine Concentration	PH < 6						PH = 6.5						PH = 7.0					
mg/L < =	Log Inactivations						Log Inactivations						Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
0.4	6	12	18	24	30	36	7	15	22	29	37	44	9	17	26	35	43	52
0.6	6	13	19	25	32	38	8	15	23	30	38	45	9	18	27	36	45	54
0.8	7	13	20	26	33	39	8	15	23	31	38	46	9	18	28	37	46	55
1	7	13	20	26	33	39	8	16	24	31	39	47	9	19	28	37	47	56
1.2	7	13	20	27	33	40	8	16	24	32	40	48	10	19	29	38	48	57
1.4	7	14	21	27	34	41	8	16	25	33	41	49	10	19	29	39	48	58
1.6	7	14	21	28	35	42	8	17	25	33	42	50	10	20	30	39	49	59
1.8	7	14	22	29	36	43	9	17	26	34	43	51	10	20	31	41	51	61
2	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62
2.2	8	15	22	29	37	44	9	18	27	35	44	53	11	21	32	42	53	63
2.4	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	43	54	65
2.6	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66
2.8	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67
3	8	16	24	31	39	47	10	19	29	38	48	57	11	23	34	45	57	68

Chlorine Concentration	PH < 7.5						PH = 8.0						PH = 8.5					
mg/L < =	Log Inactivations						Log Inactivations						Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
0.4	10	21	31	41	52	62	12	25	37	49	62	74	15	30	45	59	74	89
0.6	11	21	32	43	53	64	13	26	39	51	64	77	15	31	46	61	77	92
0.8	11	22	33	44	55	66	13	26	40	53	66	79	16	32	48	63	79	95
1	11	22	34	45	56	67	14	27	41	54	68	81	16	33	49	65	82	98
1.2	12	23	35	46	58	69	14	28	42	55	69	83	17	33	50	67	83	100
1.4	12	23	35	47	58	70	14	28	43	57	71	85	17	34	52	69	86	103
1.6	12	24	36	48	60	72	15	29	44	58	73	87	18	35	53	70	88	105
1.8	12	25	37	49	62	74	15	30	45	59	74	89	18	36	54	72	90	108
2	13	25	38	50	63	75	15	30	46	61	76	91	18	37	55	73	92	110
2.2	13	26	39	51	64	77	16	31	47	62	78	93	19	38	57	75	94	113
2.4	13	26	39	52	65	78	16	32	48	63	79	95	19	38	58	77	96	115
2.6	13	27	40	53	67	80	16	32	49	65	81	97	20	39	59	78	98	117
2.8	14	27	41	54	68	81	17	33	50	66	83	99	20	40	60	79	99	119
3	14	28	42	55	69	83	17	34	51	67	84	101	20	41	61	81	102	122

Chlorine Concentration	PH < 9.0					
mg/L < =	Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0
0.4	18	35	53	70	88	105
0.6	18	36	55	73	91	109
0.8	19	38	57	75	94	113
1	20	39	59	78	98	117
1.2	20	40	60	80	100	120
1.4	21	41	62	82	103	123
1.6	21	42	63	84	105	126
1.8	22	43	65	86	108	129
2	22	44	66	88	110	132
2.2	23	45	68	90	113	135
2.4	23	46	69	92	115	138
2.6	24	47	71	94	118	141
2.8	24	48	72	95	119	143
3	24	49	73	97	122	146

Note: CT = CT for 3-log inactivation, or 99.9% removal

Appendix Table 4-6.
CT Values for Inactivation of Giardia Cysts by Free Chlorine at 25° C

Chlorine Concentration mg/L < =	PH < 6 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	4	8	12	16	20	24
0.6	4	8	13	17	21	25
0.8	4	9	13	17	22	26
1	4	9	13	17	22	26
12	5	9	14	18	23	27
1.4	5	9	14	18	23	27
1.6	5	9	14	19	23	28
1.8	5	10	15	19	24	29
2	5	10	15	19	24	29
2.2	5	10	15	20	25	30
2.4	5	10	15	20	25	30
2.6	5	10	16	21	26	31
2.8	5	10	16	21	26	31
3	5	11	16	2	27	32

Chlorine Concentration mg/L < =	PH = 6.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	5	10	15	19	24	29
0.6	5	10	15	20	25	30
0.8	5	10	16	21	26	31
1	5	10	16	21	26	31
12	5	11	16	21	27	32
1.4	6	11	17	22	28	33
1.6	6	11	17	22	28	33
1.8	6	11	17	23	28	34
2	6	12	18	23	29	35
2.2	6	12	18	23	29	35
2.4	6	12	18	24	30	36
2.6	6	12	19	25	31	37
2.8	6	12	19	25	31	37
3	6	13	19	25	32	38

Chlorine Concentration mg/L < =	PH = 7.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	6	12	18	23	29	35
0.6	6	12	18	24	30	36
0.8	6	12	19	25	31	37
1	6	12	19	25	31	37
12	6	13	19	25	32	38
1.4	7	13	20	26	33	39
1.6	7	13	20	27	33	40
1.8	7	14	21	27	34	41
2	7	14	21	27	34	41
2.2	7	14	21	28	35	42
2.4	7	14	22	29	36	43
2.6	7	15	22	29	37	44
2.8	8	15	23	30	38	45
3	8	15	23	31	38	46

Chlorine Concentration mg/L < =	PH < 7.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	7	14	21	28	35	42
0.6	7	14	22	29	36	43
0.8	7	15	22	29	37	44
1	8	15	23	30	38	45
1.2	8	15	23	31	38	46
1.4	8	16	24	31	39	47
1.6	8	16	24	32	40	48
1.8	8	16	25	33	41	49
2	8	17	25	33	42	50
2.2	9	17	26	34	43	51
2.4	9	17	26	35	43	52
2.6	9	18	27	35	44	53
2.8	9	18	27	36	45	54
3	9	18	28	37	46	55

Chlorine Concentration mg/L < =	PH = 8.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	8	17	25	33	42	50
0.6	9	17	26	34	43	51
0.8	9	18	27	35	44	53
1	9	18	27	36	45	54
1.2	9	18	28	37	46	55
1.4	10	19	29	38	48	57
1.6	10	19	29	39	48	58
1.8	10	20	30	40	50	60
2	10	20	31	41	51	61
2.2	10	21	31	41	52	62
2.4	11	21	32	42	53	63
2.6	11	22	33	43	54	65
2.8	11	22	33	44	55	66
3	11	22	34	45	56	67

Chlorine Concentration mg/L < =	PH = 8.5 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	10	20	30	39	49	59
0.6	10	20	31	41	51	61
0.8	11	21	32	42	53	63
1	11	22	33	43	54	65
1.2	11	22	34	45	56	67
1.4	12	23	35	46	58	69
1.6	12	23	35	47	58	70
1.8	12	24	36	48	60	72
2	12	25	37	49	62	74
2.2	13	25	38	50	63	75
2.4	13	26	39	51	64	77
2.6	13	26	39	52	65	78
2.8	13	27	40	53	67	80
3	14	27	41	54	68	81

Chlorine Concentration mg/L < =	PH < 9.0 Log Inactivations 0.5	1.0	1.5	2.0	2.5	3.0
0.4	12	23	35	47	58	70
0.6	12	24	37	49	61	73
0.8	13	25	38	50	63	75
1	13	26	39	52	65	78
1.2	13	27	40	53	67	80
1.4	14	27	41	55	68	82
1.6	14	28	42	56	70	84
1.8	14	29	43	57	72	86
2	15	29	44	59	73	88
2.2	15	30	45	60	75	90
2.4	15	31	46	61	77	92
2.6	16	31	47	63	78	94
2.8	16	32	48	64	80	96
3	16	32	49	65	81	97

Note: CT = CT for 3-log inactivation, or 99.9% removal