Disinfection

Disinfection - the destruction of pathogenic microorganisms. Definition does not apply to non-pathogenic microorganisms or to pathogens which may be in the spore state. Sterilization is the term that applies to all living organisms.

Disinfection

Disinfection is a complex rate process which is dependent upon:

1) physico - chemistry of the disinfectant
2) cellular - chemical nature and physical state of pathogens
3) physical and chemical factors of the water
    a) temperature
    b) pH
    c) electrolytes
    d) interfering substances

Disinfection

Classification of Disinfectants:

1) Oxidizing Agents (ozone, halogens, halogen compounds)
2) Cations of Heavy Metals (silver, mercury, copper)
3) Organic compounds
4) Gaseous Agents
5) Physical Agents (heat, UV, pH, ionizing radiation)

Disinfection

Four major pathogen groups in decreasing order of their resistance to disinfection is:

1) Bacterial Spores or Cysts

2) Protozoan Spores

3) Viruses

4) Vegetative Bacteria.

Disinfection Characteristics

One measure of a disinfectant's ability to oxidize organic compounds is the standard reduction potential.

The standard reduction potential is an electrochemical characteristic of the disinfectant that varies depending upon the oxidant.

Disinfection Characteristics

Table 1 - Standard Potentials of Selected Chemical Disinfectants (from JMM)

Compound	Formula	Potential (V)	Assumed Reactions
Chlorine	Cl_2	1.36	$Cl_2 + 2e^- \Leftrightarrow 2Cl^-$
Bromine	Br_2	1.09	$Br_2 + 2e^- \Leftrightarrow 2Br^-$
Iodine	I_2	0.54	$I_2 + 2e^- \Leftrightarrow 2Br^-$
Ozone	O_3	2.07	$O_3 + 2e^- + 2H^+ \Leftrightarrow O_2 + H_2O$
Chlorine Dioxide	ClO_2	1.91	$ClO_2 + 5e^- + 2H_2O \Leftrightarrow 2Cl^-$

Disinfection Chemistry

Chlorine

The disinfection power of chlorine depends on its chemical form in water.

f(pH, temperature, organic content, and other water quality factors).

Gaseous chlorine rapidly hydrolyzes in water to hypochlorous acid (HOCl) and HCl.

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

Disinfection Chemistry

Chlorine

In dilute solution and pH values above 4, the reaction proceeds to completion.

HOCl undergoes further reaction including:

1) Disinfection

2) Reaction with organic and inorganic compounds

3) Dissociation to hydrogen and hypochlorite ions

$$HOCl \Leftrightarrow H^{+} + OCl^{-}$$

Disinfection Chemistry

Chloroamines

Cl_2 reacts with ammonia (NH_3) in water to form compounds called chloroamines or called combined chlorine.

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O \quad \text{(monochloroamine)}$$

$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O \quad \text{(dichloroamine)}$$

$$NH_2Cl + HOCl \rightarrow NCl_3 + H_2O \quad \text{(trichloroamine)}$$

pH > 7.0 monochloroamine is predominant.

pH < 7.0 dichloroamine in significant amounts.

pH < 4.4 trichloroamine will be present.

Disinfection Chemistry

The formation of chloroamine species are dependent upon the ratio of Cl_2 to NH_3-N, chlorine dosage, temperature, pH, and alkalinity.

At low pH values other reactions such as these can take place:

$$NH_2Cl + H^+ \Leftrightarrow NH_3Cl^-$$

$$NH_3Cl^- + NH_2Cl \Leftrightarrow NHCl_2 + NH_4^+$$

Disinfection Chemistry

When ammonia is present in the raw as a natural constituent or added to produce combined chlorine, a hump shaped breakpoint curve is observed as shown below:

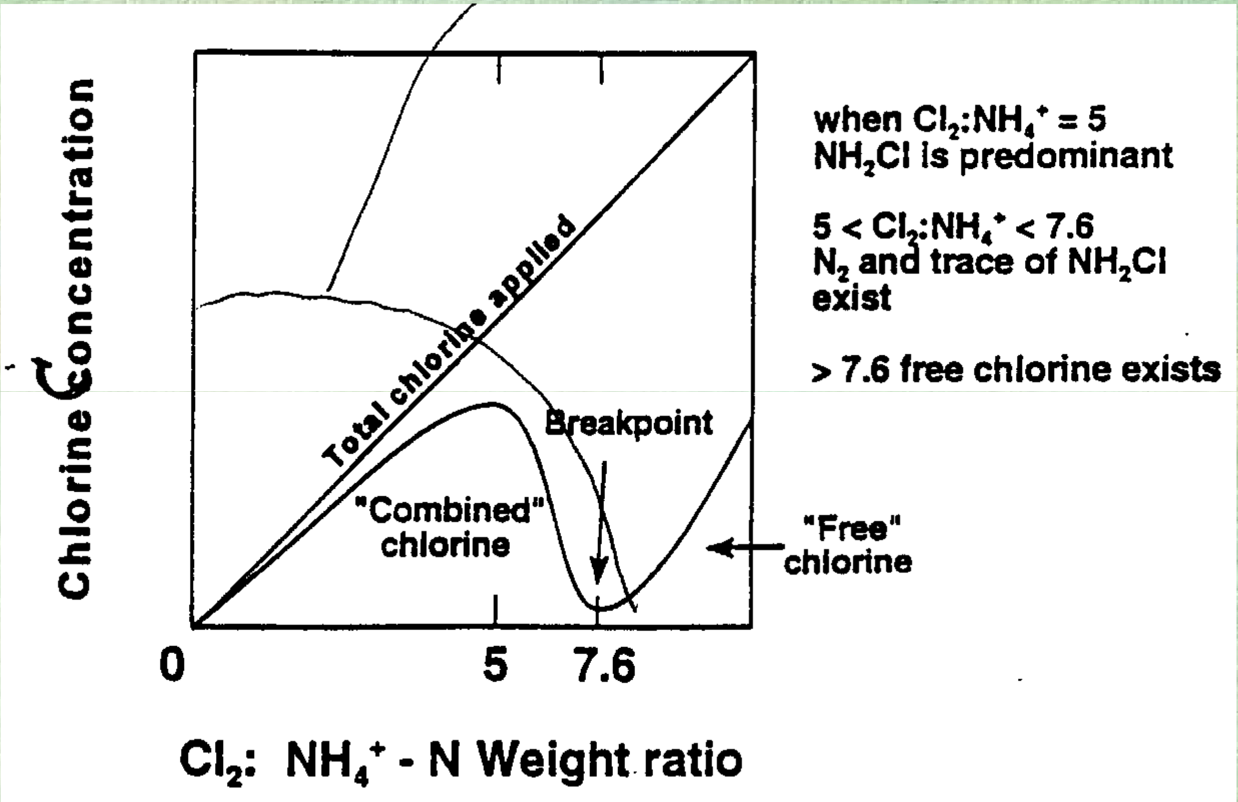


FIGURE 12-16. Breakpoint curve. (Source: White, 1978.)

Disinfection Chemistry

Chlorine Dioxide

Although ClO_2 has not been widely used in the past, there is recent interest in its use because it does not produce significant amounts of THMs as by-products from reactions with organic compounds. Chlorine chemistry is complex. In an acidic solution, reduction to chloride predominates.

$$ClO_2 + 5e^- + 4H^+ \Leftrightarrow Cl^- + 2H_2O$$

ClO_2 has 1.4 times the oxidation power as Cl_2

At neutral pH values typically found in natural waters, ClO_2 has only about 70% of the oxidizing capacity as Cl_2.

Disinfection Chemistry

ClO_2 is generated on-site prior to injection into the water.

ClO_2 is explosive at elevated temperatures, on exposure to light, or in the presence of organic substances. It is usually obtained from the chlorine-chlorite process:

$$NaClO_2 + Cl_2 \rightarrow 2ClO_2 + NaCl$$

ClO_2 gas generated from this process is only 60-70% pure and contains much chlorine.

ClO_2 is non-reactive with ammonia or nitrogenous compounds and does not produce THMs.

ClO_2 produces inorganic byproducts such as chlorite (ClO_2^-) and chlorate (ClO_3^-) for which health effects are not well understood.

Disinfection Chemistry

Ozone

Ozone (O_3) is a powerful oxidizing agent and is used as a disinfectant in water treatment.

O_3 is a highly reactive gas formed by electrical discharges in the presence of O_2.

$$3O_2 + \text{energy} \Leftrightarrow 2O_3$$

O_3 is energy intensive because a large amount of energy is usually required to split the stable oxygen covalent bond to form ozone.

O_3 readily reverts to elemental oxygen during oxidation-reduction reactions.

Disinfection Chemistry

Ozone reaction pathways

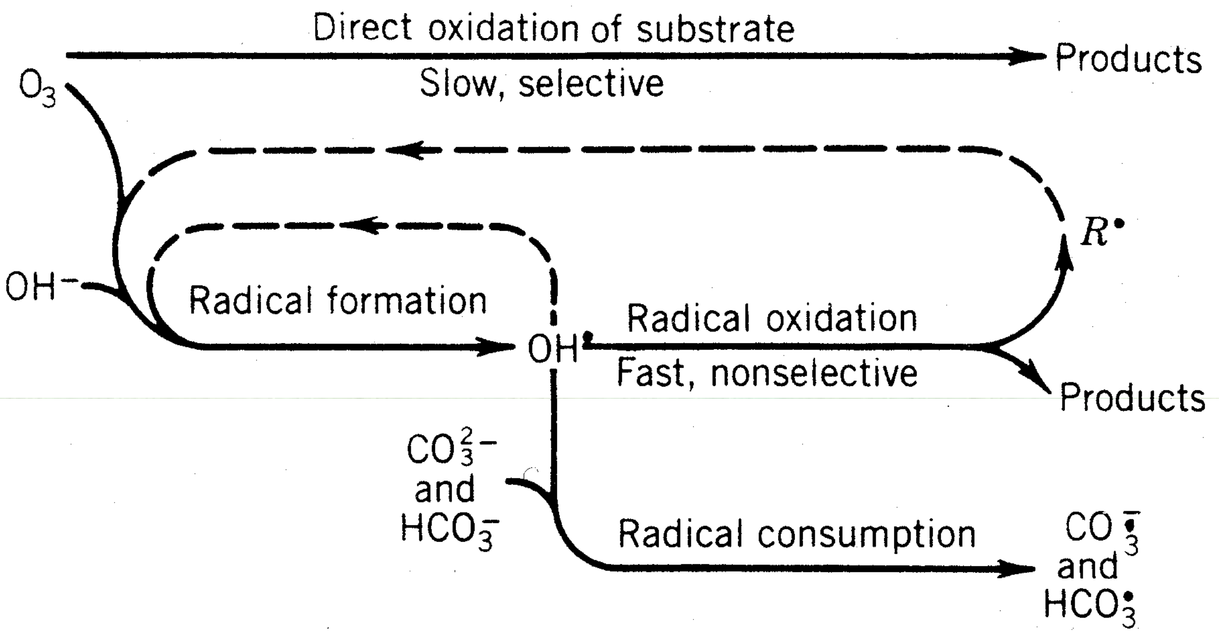


FIGURE 12-18. Reaction pathways of ozone. (Source: Hoigne and Bader, 1976.)

Disinfection Chemistry

TABLE 12-4. Summary of Disinfectant Characteristics

Characteristics	Free Chlorine	Chloramines	Chlorine Dioxide	Ozone	Ultraviolet Radiation
Disinfection					
Bacteria	Excellent (as HOCl)	Moderate	Excellent	Excellent	Good
Viruses	Excellent (as HOCl)	Low (good at long contact times)	Excellent	Excellent	Good
pH influence	Efficiency decreases with increase in pH	Dichloramine predominates pH 5 and below; monochloramine predominates pH 7 and above. Overall relatively independent of pH. pH 4.5-8.5	Slightly more efficient at higher pH's	Residuals last longer at low pH	Insensitive
Residual in distribution system	Yes	Yes	Yes	No	No
By-products					
THM formation	Yes	Unlikely	Unlikely	Unlikely	Unlikely
Other	Uncharacterized chlorinated and oxidized intermediates; chloramines; chlorophenols	Unknown	Chlorinated aromatic compounds; chlorate chlorite	Aldehydes; aromatic carboxylic acids; phthalates	Unknown
Experience	Widespread use in the U.S.	Widespread use in the U.S.	Widespread use in Europe; limited in the U.S.	Widespread use in Europe and Canada; limited in the U.S.	Use limited to small systems
Typical applied dose, mg/L	2–20	0.5–3.0	[a]	1–5	[a]
\$/lb[b]	0.07	0.16[c]	1.44[d]	0.48[e]	—
Pound equivalent weight[f]	35.5	25.8[g]	13.4[h]	24	—
Cost per pound equivalent weight (\$/lb)	2.49	4.13	19.3	11.5	—

[a] Insufficient operating knowledge
[b] Effective January 1982. Does not include shipping.
[c] Assumes 1.4 lb Cl_2 + .46 lb $NH_3 \rightarrow$ 1 lb NH_2Cl
[d] Assumes 0.5 lb Cl_2 + 1.4 lb $NaClO_2 \rightarrow$ 1 lb ClO_2 + NaCl
[e] Assumes 12 kw-hr per lb O_3; energy cost = \$0.04 per kw-hr
[f] Weight of compound per 1 electron change in oxidation-reduction reaction, based on equations in Table 12-1.
[g] Assumes $NH_2Cl + 2e^- + H_2O \rightarrow NH_3 + Cl^- + OH^-$
[h] Assumes complete reaction: $ClO_2 + 5e^- + 2H_2O \rightarrow Cl^- + 4OH^-$

SOURCES: National Academy of Science (1980), EPA (1981), Lawrence et al. (1980).

Types of Disinfection

Surface Water:

Oxidizing Agents (chlorination)

Coagulation

Filtration

Types of Disinfection

Ground Water:

(not under direct influence of surface water)

Well Head Protection - natural disinfection by filtration through soil

Chlorination

Concept of Ct

Inactivation of pathogens is a function of disinfectant concentration and contact time. It is also a function of the following:

Type of Disinfectant

chlorine, chlorine dioxide,

chloroamines, ozone

pH

free chlorine influenced

Chlorine dioxide, chloroamines, ozone are not influenced at pH values between 6 - 9.

Concept of Ct

Inactivation of pathogens is also a function of:

Temperature

10 Deg C increase results in a 2 to 3 fold increase in pathogen inactivation for all disinfectants.

Pathogen Viability

bacteria < viruses < protozoa cysts < helminth eggs

viability varies from the laboratory and field

Turbidity

Concept of Ct

Table 1 - Ct values for 99.9 percent (3-log) inactivation of Giardia lamblia cysts by free chlorine at various temperatures.

Free Residual Chlorine (mg/L)	pH	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
< 0.4	6.5	163	117	88	44
	7.0	195	139	104	52
	7.5	237	166	125	62
	8.0	277	198	149	74
1.0	6.5	176	125	94	47
	7.0	210	149	112	56
	7.5	253	179	134	67
	8.0	304	216	162	81
2.0	6.5	197	138	104	52
	7.0	236	165	124	62
	7.5	286	200	150	75
	8.0	346	243	182	91
3.0	6.5	217	151	113	57
	7.0	261	182	137	68
	7.5	316	221	166	83
	8.0	382	268	201	101

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

Concept of Ct

Table 2 - Ct values for 0.5-log and 1.0-log inactivation of Giardia lamblia cysts at various temperatures and pH.

	pH	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	6.0	0.5	25	18	13	9	7
	6.0	1.0	49	35	26	18	13
	7.0	0.5	35	25	19	13	9
	7.0	1.0	70	50	37	25	18
	8.0	0.5	51	36	27	18	14
	8.0	1.0	101	72	54	36	27
Preformed chloroamine[b,c,e]	6-9	0.5	640	370	310	250	190
	6-9	1.0	1300	740	620	500	370
Chlorine Dioxide[b,c]	6-9	0.5	10	4.3	4.0	3.2	2.5
	6-9	1.0	21	8.7	7.7	6.3	5.0
Ozone[b,d]	6-9	0.5	0.48	0.32	0.23	0.16	0.12
	6-9	1.0	0.97	0.63	0.48	0.24	0.24

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L and animal infestivity studies.

[b]Based on laboratory studies using Giardia Muris cysts.

[c]Safety factor of 1.5 was used to compensate for invitro excystation rather than animal infectivity studies.

[d]Safety factor of 2.0 was used to compensate for invitro excystation rather than animal infectivity studies.

[e]No safety factor - chloroamination is more effective than preformed chlorine.

Concept of Ct

Table 3 - Ct values for inactivation of viruses at various temperatures based on laboratory studies using invitro excystation.

	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	2.0	6	4	3	2	1
	3.0	9	6	4	3	2
	4.0	12	8	6	4	3
Preformed chloroamine[c]	2.0	1200	860	640	430	320
	3.0	2100	1400	1100	710	530
Chlorine Dioxide[b]	2.0	8.4	5.6	4.2	2.8	2.1
	3.0	25.6	17.1	12.8	8.6	6.4
Ozone[d]	2.0	0.9	0.6	0.5	0.3	0.2
	3.0	1.4	0.9	0.8	0.5	0.4

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L, Hepatitus A virus, and a safety factor of 3.0.

[b]Based on inactivation studies using Hepatitus A virus, and a safety factor of 2.0.

[c]Based on inactivation studies using rotavirus with no safety factor.

[d]Based on inactivation studies using polio virus with a safety factor of 3.0.

Concept of Ct

The EPA Ct Guidance Manual

The Ct for a system is the summation of individual Ct values for tanks, reservoirs and distribution piping for the disinfected water before it reaches the first customer.

The C is free chlorine or the disinfectant residual concentration measured at the end of the chlorinating segment in milligrams per liter.

The t is the calculated time of the segment in minutes.

Concept of Ct

The EPA Ct Guidance Manual

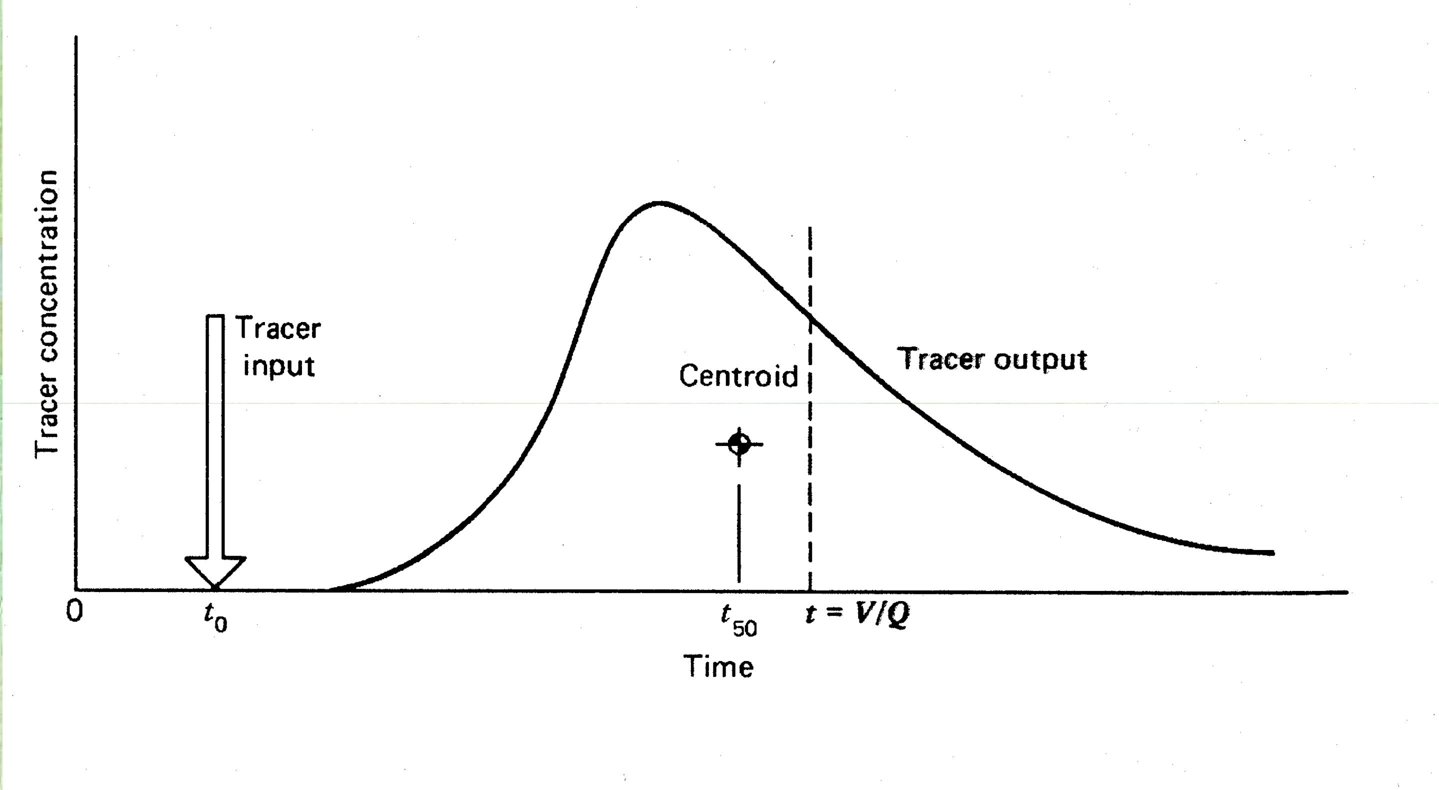
For example, chlorine added at a pumping station and again as the water was discharged into a contact tank, the overall Ct would be the chlorine residual measured in the discharge of the pipeline multiplied by the contact time in transit plus the residual at the discharge of the contact tank multiplied by the t_{10} time.

The t in the pipeline is calculated from the product of the velocity and length of pipe.

The t_{10} in the tank is the length of time 10 percent of the water entering the tank is discharged from the tank.

Concept of Ct

Hydraulic Character of a Tank or Reservoir



Concept of Ct

Hydraulic Character of a Tank or Reservoir

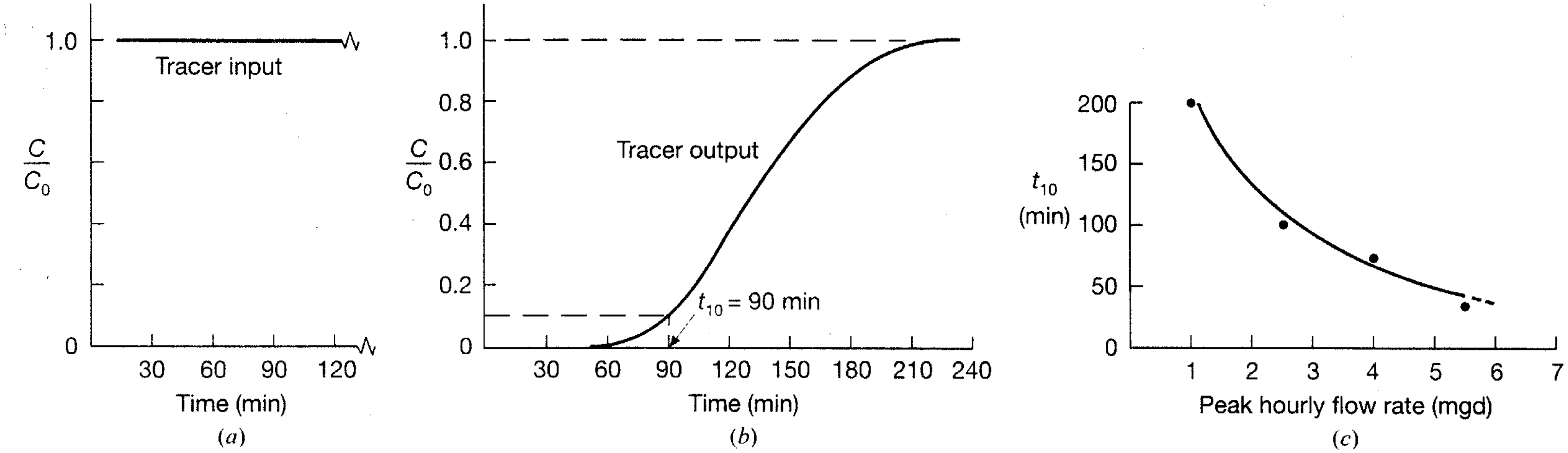


Figure 7-32 Tracer study diagrams to determine t_{10} times for calculating $C \bullet t$ values at peak hourly flow rates by the step-dose method. (*a*) Tracer input at a constant concentration. (*b*) Normalized residual tracer output. (*c*) The t_{10} times for four tracer analyses at different peak hourly rates of flow.

Surface Water Treatment Rule

Requires compliance with a treatment technique rather than an MCL.

Includes:

1) Criteria under which filtration is required and procedures by which the States are to determine which systems must install filtration.

2) Disinfection requirements

Surface Water Treatment Rule

Filtration and disinfection requirements are treatment technique requirements to protect against the adverse health effects of exposure to Giardia Lamblia, viruses, Legionella, hetertropic bacteria and other pathogenic organisms removed by these treatment techniques.

Surface Water Treatment Rule

The SWTR also contains certain limits on turbidity as criteria for:

1) determining whether a public water system is required to filter.

2) determining whether filtration, if required, is adequate.

Surface Water Treatment Rule

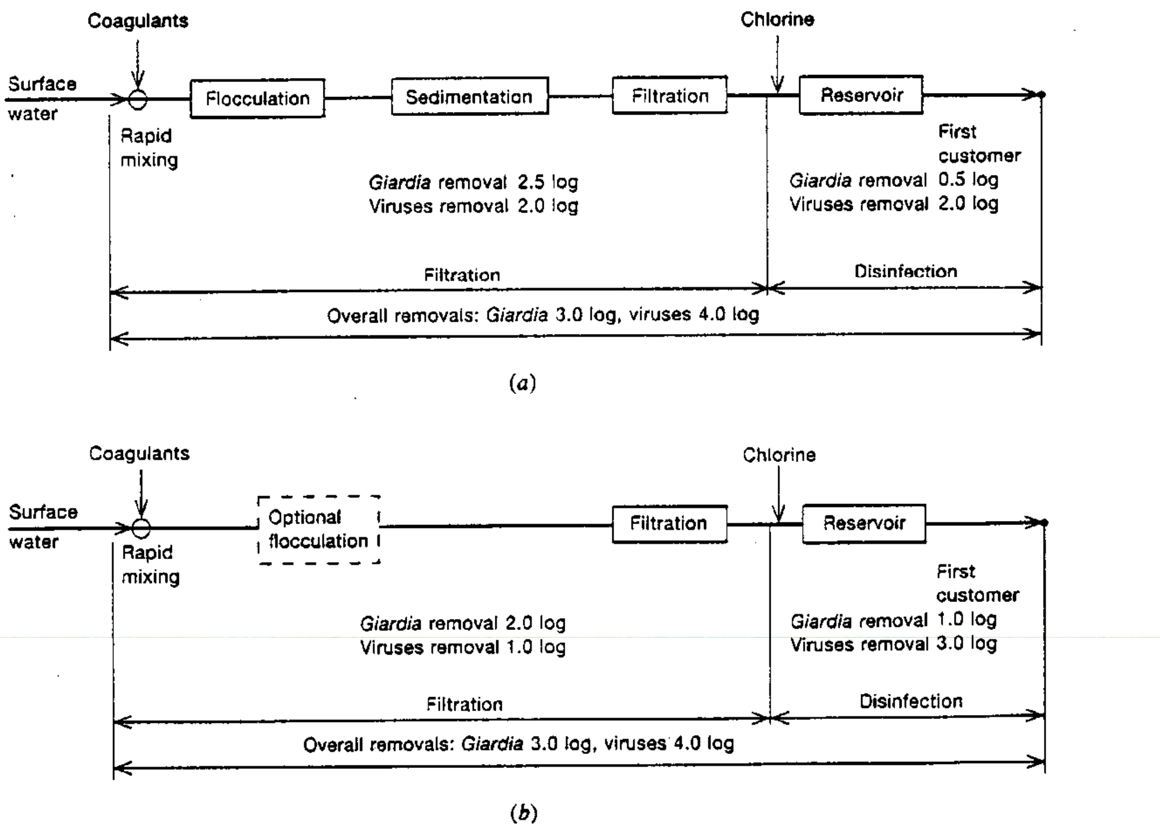


Figure 3. - Surface water treatment schemes listing the expected removals of Giardia and viruses in filtration and minimum inactivation of Giardia and viruses in disinfection. (a) conventional water treatment. (b) Direct filtration treatment.

Important Drinking Water Treatment Rules

Surface Water Treatment Rule Summary:

99.9% (3-Log) removal/disinfection of Giardia Lamblia cycts

99.99 % (4-Log) removal/inactivation of Enteric Viruses

Less than 0.5 NTU turbidity in 95% of monthly measurements not exceeding 5 NTU at any time.

Free chlorine residual in distribution system cannot be less than 0.2 mg/L for more than 4 hours.

Important Drinking Water Treatment Rules

Surface Water Treatment Rule Summary:

Chlorine residual must be detectable in over 95% of samples tested each month. If not detectable, heterotropic plate count not exceeding 500 per ml may be replaced as a detectable chlorine residual.

Source water cannot exceed a fecal coliform concentration of 20 per 100 ml, or total coliform concentration of 100 per 100 ml in at least 90 % of the samples tested.

Turbidity in the influent cannot exceed 5 NTU except in the case of an unexpected event but not more than two events in the past 12 months.

Important Drinking Water Treatment Rules

Draft Groundwater Treatment Rule Summary:

MCLG of zero for viruses.

No MCLG for heterotropic plate count bacteria.

Possible MCLG of zero for Legionella.

Important Drinking Water Treatment Rules

Draft Groundwater Treatment Rule Summary:

All community and non-community public water systems using groundwater must disinfect the source water from each well or well field unless either:

1) one or more wells meet "natural disinfection" criteria, in which case the water utility is not required to disinfect water from the well.

Natural disinfection is defined by EPA as source water treatment via virus attenuation by natural subsurface processes such as virus inactivation, dispersion (dilution), and irreversible adsorption to aquifer solids matrix. A well or well field that is not vulnerable to viral contamination is considered to meet the criteria of natural disinfection.

or

Important Drinking Water Treatment Rules

Draft Groundwater Treatment Rule Summary:

2) the system qualifies for the following variance:

1) absence of outbreaks of waterborne disease in the system served by the well, or approved modifications if an outbreak has occurred.

2) compliance with coliform testing regulations.

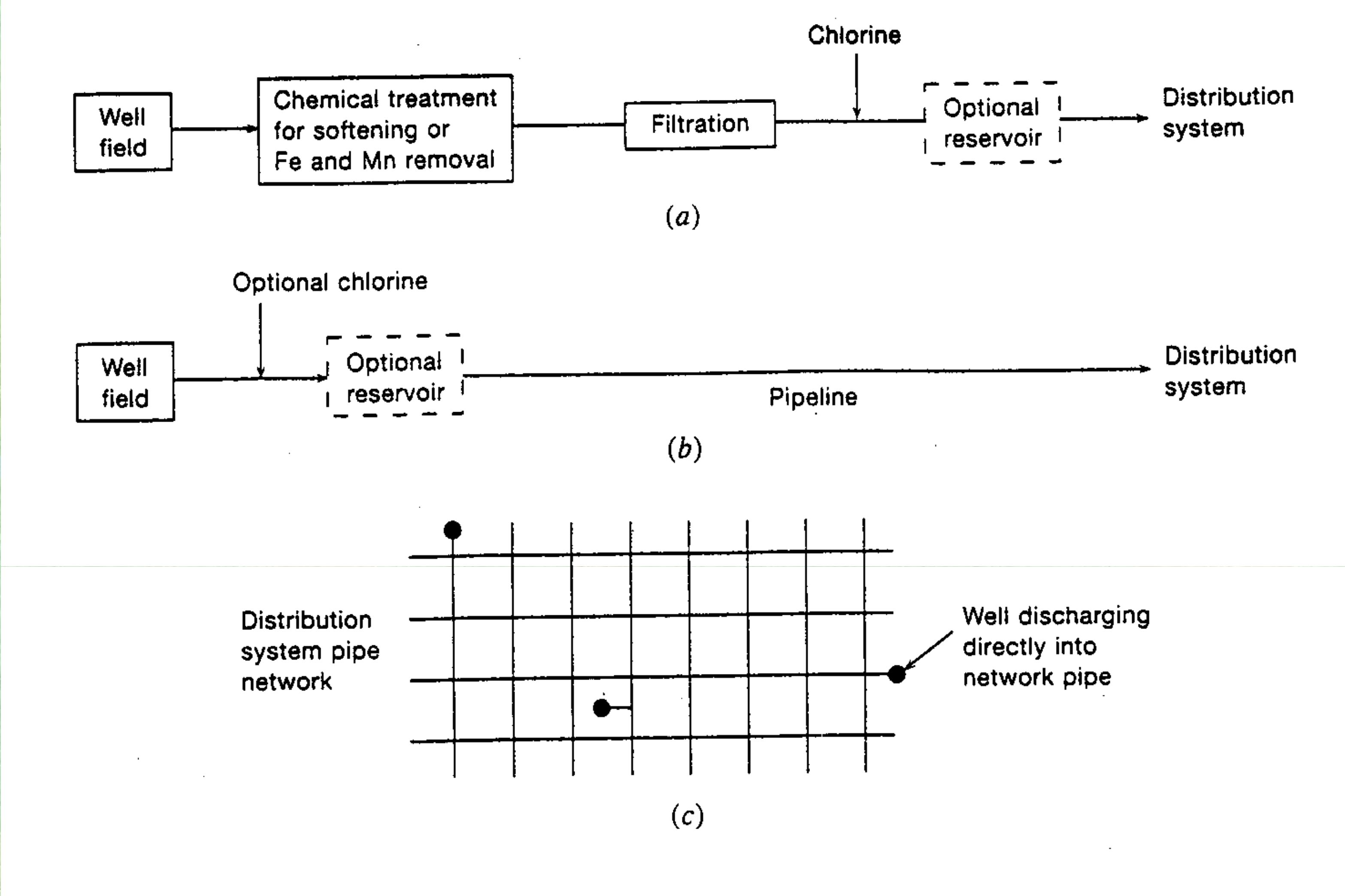
3) a sanitary survey that evaluates the vulnerability of fecal contamination every five years with a satisfactory report.

4) approved well construction.

5) a cross-connection control program to prevent backflow or back-siphonage of contaminated waters into the distribution system.

The state must provide notice and opportunity for public hearing before issuance on a variance.

Groundwater Treatment Schemes



Example Problem 1

A new baffled reservoir at a surface-water treatment plant was constructed for storage of filtered water prior to distribution and for disinfection by free chlorine residual. A tracer study by the step-dose method was performed at the design flow of 2.5 mgd to determine t_{10}. The volume of the water in the full reservoir at the time of testing was 0.25 million gallons, which is equivalent to a theoretical detention time of 144 min. The tracer was fluoride ion by applying fluosilicic acid with a metering pump at a dosage of 2.0 mg/l. The concentration of fluoride ion in the discharge from the reservoir was measured every 6 min from time zero (when the tracer was started at the inlet) for the first hour and then at intervals of 12 min or more. The tracer test data are listed in the following Table. Calculate the reduced concentration (C/C_o) values, plot C/C_o versus t, and determine t_{10}.

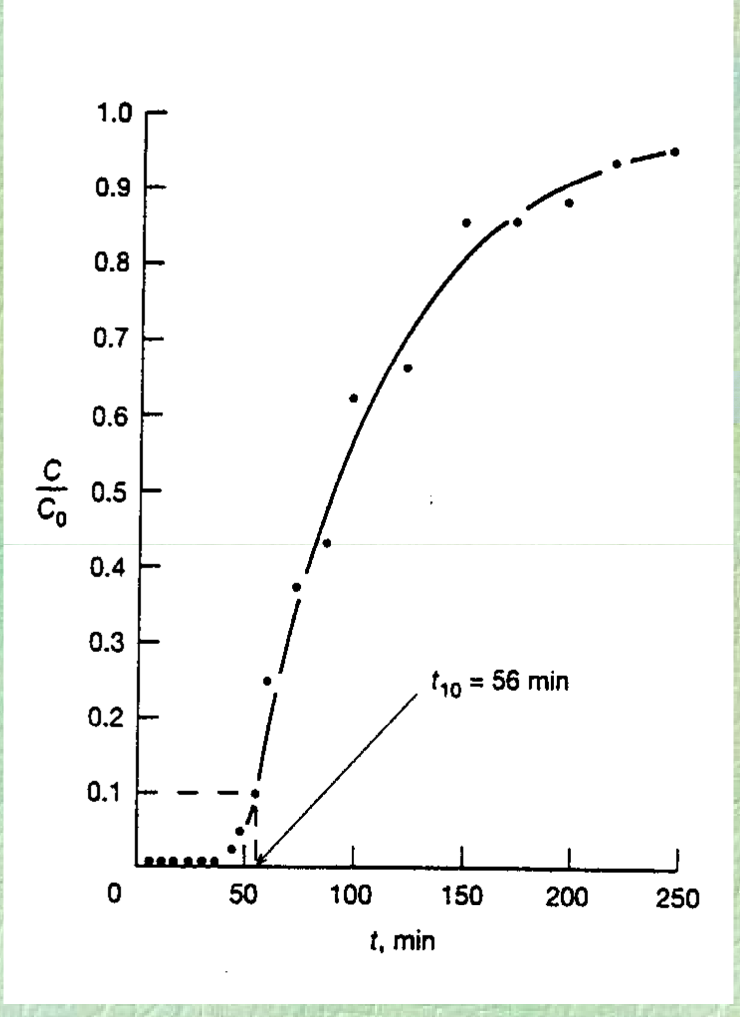
Example Problem 1

Tracer Test Data for Example Problem 1 (C_c = 2.0 mg/L)

Measurement Time, t (min)	Fluoride Tracer, C (mg/L)	Calculated C/C_o (---)
6	0	0
12	0	0
18	0	0
24	0	0
30	0	0
36	0	0
42	0	0
48	0.09	0.045
54	0.22	0.11
60	0.47	0.24
72	0.74	0.37
84	0.84	0.42
96	1.24	0.62
120	1.32	0.66
144	1.73	0.86
168	1.72	0.86
192	1.77	0.88
216	1.86	0.93
240	1.90	0.95

Example Problem 1

Tracer Test Data for Example Problem 1 (C_c = 2.0 mg/L)



Solution:

Calculated values for C/Co were plotted as shown below and t_{10} was determined graphically to be 56 minutes

Example Problem 2

A conventional surface water plant with coagulant addition, flocculation, sedimentation, and filtration produces a filtered water with a turbidity less than 0.4 NTU, pH 7, and temperature of $10^{o}C$ at design flow of 2.5 mgd. After filtration, the water is chlorinated in a baffled reservoir with a hydraulic character as shown in example problem 1. What is the required disinfection of the filtered water using free chlorine? If the plant were direct filtration without sedimentation, what would be the required disinfection of the filtered water.

Example Problem 2

Solution (Conventional Plant):

For conventional treatment, Giardia removal is 2.5 log and virus is 2.0 log by filtration leaving 0.5 log inactivation of Giardia and 2.0 log inactivation of virus for disinfection. The Ct required for 0.5 log inactivation of Giardia from Table 2 is 19 mg-min/L based on a free residual of 1.0 mg/L. (The Ct at a lower chlorine residual would be slightly lower)
The Ct required for 2-log inactivation of viruses is 3 mg-min/L, which is considerably less than for Giardia.

Concept of Ct

Table 2 - Ct values for 0.5-log and 1.0-log inactivation of Giardia lamblia cysts at various temperatures and pH.

	pH	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	6.0	0.5	25	18	13	9	7
	6.0	1.0	49	35	26	18	13
	7.0	0.5	35	25	19	13	9
	7.0	1.0	70	50	37	25	18
	8.0	0.5	51	36	27	18	14
	8.0	1.0	101	72	54	36	27
Preformed chloroamine[b,c,e]	6-9	0.5	640	370	310	250	190
	6-9	1.0	1300	740	620	500	370
Chlorine Dioxide[b,c]	6-9	0.5	10	4.3	4.0	3.2	2.5
	6-9	1.0	21	8.7	7.7	6.3	5.0
Ozone[b,d]	6-9	0.5	0.48	0.32	0.23	0.16	0.12
	6-9	1.0	0.97	0.63	0.48	0.24	0.24

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L and animal infestivity studies.

[b]Based on laboratory studies using Giardia Muris cysts.

[c]Safety factor of 1.5 was used to compensate for invitro excystation rather than animal infectivity studies.

[d]Safety factor of 2.0 was used to compensate for invitro excystation rather than animal infectivity studies.

[e]No safety factor - chloroamination is more effective than preformed chlorine.

Concept of Ct

Table 3 - Ct values for inactivation of viruses at various temperatures based on laboratory studies using invitro excystation.

	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	2.0	6	4	3	2	1
	3.0	9	6	4	3	2
	4.0	12	8	6	4	3
Preformed chloroamine[c]	2.0	1200	860	640	430	320
	3.0	2100	1400	1100	710	530
Chlorine Dioxide[b]	2.0	8.4	5.6	4.2	2.8	2.1
	3.0	25.6	17.1	12.8	8.6	6.4
Ozone[d]	2.0	0.9	0.6	0.5	0.3	0.2
	3.0	1.4	0.9	0.8	0.5	0.4

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L, Hepatitus A virus, and a safety factor of 3.0.

[b]Based on inactivation studies using Hepatitus A virus, and a safety factor of 2.0.

[c]Based on inactivation studies using rotavirus with no safety factor.

[d]Based on inactivation studies using polio virus with a safety factor of 3.0.

Example Problem 2

Solution:

From Figure 5 at design flow of 2.5 mgd, the t_{10} is equal to 56 minutes. Therefore, required free chlorine residual in the discharge for the baffled reservoir is

$$C = \frac{\left(19 \frac{mg \bullet \min}{l}\right)}{\left(56 \min\right)} = 0.34 \frac{mg}{l}$$

This chlorine residual also satisfies the requirement of a minimum residual of 0.2 mg/l for water entering the distribution system. Also, the drinking water will be acceptable to the taste of most consumers. Free chlorine residual greater than 0.5 mg/l is objectionable to most consumers.

Example Problem 2

Solution (Direct Filtration):

For direct filtration treatment, Giardia is a 2-log removal and virus is a 1-log removal leaving 1.0-log of Giardia and 3-log of virus inactivation by disinfection. The Ct required for 1.0-log inactivation of Giardia is 37 mg-min/l based on a free chlorine residual of 1.0 mg/l. The Ct required for 3-log inactivation of viruses is 4.0 and t_{10}. The required free chlorine residual in the discharge from the reservoir is

$$C = \frac{\left(37 \frac{mg \bullet \min}{l}\right)}{\left(56 \min\right)} = 0.66 \frac{mg}{l}$$

This residual is more than adequate for the minimum 0.2 mg/l required but will most likely be objectionable to consumers in the district where water from the reservoir enters the pipe network.

Concept of Ct

Table 2 - Ct values for 0.5-log and 1.0-log inactivation of Giardia lamblia cysts at various temperatures and pH.

	pH	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	6.0	0.5	25	18	13	9	7
	6.0	1.0	49	35	26	18	13
	7.0	0.5	35	25	19	13	9
	7.0	1.0	70	50	37	25	18
	8.0	0.5	51	36	27	18	14
	8.0	1.0	101	72	54	36	27
Preformed chloroamine[b,c,e]	6-9	0.5	640	370	310	250	190
	6-9	1.0	1300	740	620	500	370
Chlorine Dioxide[b,c]	6-9	0.5	10	4.3	4.0	3.2	2.5
	6-9	1.0	21	8.7	7.7	6.3	5.0
Ozone[b,d]	6-9	0.5	0.48	0.32	0.23	0.16	0.12
	6-9	1.0	0.97	0.63	0.48	0.24	0.24

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L and animal infestivity studies.

[b]Based on laboratory studies using Giardia Muris cysts.

[c]Safety factor of 1.5 was used to compensate for invitro excystation rather than animal infectivity studies.

[d]Safety factor of 2.0 was used to compensate for invitro excystation rather than animal infectivity studies.

[e]No safety factor - chloroamination is more effective than preformed chlorine.

Concept of Ct

Table 3 - Ct values for inactivation of viruses at various temperatures based on laboratory studies using invitro excystation.

	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	2.0	6	4	3	2	1
	3.0	9	6	4	3	2
	4.0	12	8	6	4	3
Preformed chloroamine[c]	2.0	1200	860	640	430	320
	3.0	2100	1400	1100	710	530
Chlorine Dioxide[b]	2.0	8.4	5.6	4.2	2.8	2.1
	3.0	25.6	17.1	12.8	8.6	6.4
Ozone[d]	2.0	0.9	0.6	0.5	0.3	0.2
	3.0	1.4	0.9	0.8	0.5	0.4

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L, Hepatitus A virus, and a safety factor of 3.0.

[b]Based on inactivation studies using Hepatitus A virus, and a safety factor of 2.0.

[c]Based on inactivation studies using rotavirus with no safety factor.

[d]Based on inactivation studies using polio virus with a safety factor of 3.0.

Example Problem 3

Disinfection of the groundwater from a well field is required for virus inactivation of 99.9 percent (3-log). The proximity of the river that recharges the well field does not provide adequate natural disinfection based on site evaluation by state authority. The transmission main from the well field to the first customer is 2.0 miles, the velocity of flow at peak pumping capacity is 3 ft/s, water temperature is 5ºC, and the pH is 7.5. If chlorine is applied at the well field, is disinfection adequate before the water arrives at the first customer?

Concept of Ct

Table 3 - Ct values for inactivation of viruses at various temperatures based on laboratory studies using invitro excystation.

	Log Inactivation	Ct values for 0.5°C Water Temperature (mg-min/L)	Ct values for 5°C Water Temperature (mg-min/L)	Ct values for 10°C Water Temperature (mg-min/L)	Ct values for 15°C Water Temperature (mg-min/L)	Ct values for 20°C Water Temperature (mg-min/L)
Free chlorine[a]	2.0	6	4	3	2	1
	3.0	9	6	4	3	2
	4.0	12	8	6	4	3
Preformed chloroamine[c]	2.0	1200	860	640	430	320
	3.0	2100	1400	1100	710	530
Chlorine Dioxide[b]	2.0	8.4	5.6	4.2	2.8	2.1
	3.0	25.6	17.1	12.8	8.6	6.4
Ozone[d]	2.0	0.9	0.6	0.5	0.3	0.2
	3.0	1.4	0.9	0.8	0.5	0.4

Source: Adapted from Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Source, U.S.E.P.A.

[a]Free chlorine values are based on a residual of 1.0 mg/L, Hepatitus A virus, and a safety factor of 3.0.

[b]Based on inactivation studies using Hepatitus A virus, and a safety factor of 2.0.

[c]Based on inactivation studies using rotavirus with no safety factor.

[d]Based on inactivation studies using polio virus with a safety factor of 3.0.

Example Problem 3

Solution:

From Table 3, the Ct for 3.0-log virus inactivation by free chlorine at 5°C is 6.0. The travel time in the transmission main equals

$$\frac{(2.0mi)\left(5280\frac{ft}{mi}\right)}{\left(3.0\frac{ft}{s}\right)\left(60\frac{s}{\min}\right)}=57\min \qquad C=\frac{\left(6\frac{mg-\min}{l}\right)}{(57\min)}=0.11\frac{mg}{l}$$

If the state authority were to require the water entering the distribution system to have a residual of 0.2 mg/l, the chlorine dosage would have to be increased. The actual Ct would then be 0.2 mg/l times 57 min or 11 mg-min/l, which is more than adequate for 99.99 percent (4-log) virus inactivation.

Comments on the SWTR and the Ct Regulations

1) The Ct regulations were not based on sound engineering analysis but rather on scientific analysis combined with empiricism and guess.

2) In general, the SWTR gives less credit for disinfection than is predicted for most types of reactor configurations when the log inactivation is low (< 3 log), although in some cases, the SWTR gives credit for more disinfection than would be predicted from sound engineering analysis.