Application of the *Ct* Concept for Determining the Disinfection of Microorganisms in Water

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Recreational waters such as swimming pools and hot tubs are a potential source of microbial disease transmission among children and adults. In order to control disease transmission it is necessary to maintain an adequate level of chemical disinfectant. To accomplish this, the Ct concept can be used, where C is the disinfectant concentration and t the time required to inactivate a certain percentage of microorganisms in water. The multiplication of the two values produces a number which assesses the efficiency of a disinfectant. Ct allows for comparison of disinfectant effectiveness in general and with respect to different microbes or water conditions. The Ct concept, when applied to the disinfection of recreational waters, helps professionals in the field determine the amount of disinfectant needed to control pathogenic microorganisms in water and prevent the spread of disease.

Water disinfection is the process by which pathogens (disease causing microorganisms) are destroyed. The amount of disinfectant added to water is critical in ensuring the destruction of microorganisms in swimming pools and hot tubs. The effectiveness of disinfection is a complex function of several variables, including the type and dose of disinfectant, concentration, time the organism is exposed to the disinfectant, temperature, and water quality characteristics. In an effort to predict the dose needed to kill a certain organism under a defined water condition based upon experimental data, several models have been developed.

The principal disinfection model used today is the Chick–Watson model. This model combines Chick's rate law and Watson's function. According to Chick's rate law, the number of microorganisms destroyed per unit of time is proportional to the number remaining for a given disinfection concentration. Thus, Chick's law assumes that the reaction between a chemical disinfectant and a microorganism follow first order kinetics; microorganisms are destroyed at a constant rate (Figure 1). This law, however, does not account for the effect of decreasing disinfectant concentration as it is used up to inactivate the microorganism. The incorporation of Watson's function into Chick's rate law produces the Chick–Watson first order rate law.

The equation is written as:

$$N_t/N_0 = e^{-kt} \text{ or } \ln N_t/N_0 = -kt$$

where N_t is the number of microorganisms at time t, N_0 equals the number of microorganisms at time 0, k is the decay constant (1/time), and t is the time in minutes.

The logarithm of the survival rate (N_t/N_0) is graphed as a straight line versus time (Figure 2). Unfortunately, laboratory data and field applications have shown that inactivation of microorganisms cannot always be modeled by

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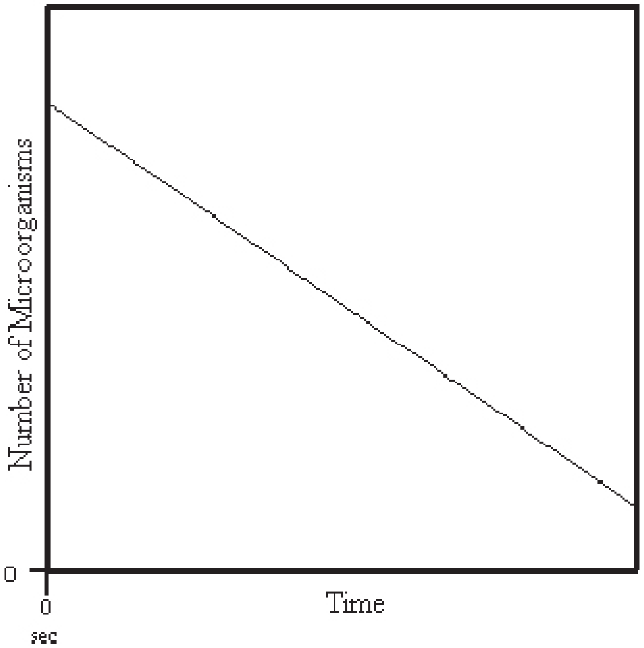

Figure 1 – Chick's Law assumes a linear relationship

a linear function. In practice, many disinfection curves are seen. Shoulder curves may result from clumps of microorganisms or the necessity to destroy several sites on each microorganism before inactivation occurs. Curves of this type are common in the disinfection of coliform bacteria by chloramines (Montgomery 1988). The tailing–off curve is often seen with many disinfectants, and may be explained by the survival of a resistant sub–population as a result of protection by interfering substances. These factors may include the following: suspended matter in the water (i.e. turbidity), clumping of microorganisms, or resistant microbes within the population.

In water applications, disinfectant effectiveness can be expressed as Ct, where C is the disinfectant concentration and t is the time required to inactivate a certain percentage of the microorganism under a specific set of conditions (usually pH and temperature). Typically, a level of 99% inactivation is used when comparing Ct values. Instead of referring to "percent of microorganisms" the $\log_{10}$ value is used, often simply referred to as "log" or "logs of inactivation". Thus, 90% inactivation corresponds to one log reduction and 99.99% inactivation corresponds to a 4 log reduction. In general, the lower the Ct value, the more effective the disinfectant. The Ct method allows a general comparison of the effectiveness of a given disinfectant on different microorganisms (Table 1) and compares the effectiveness of different disinfectants on the same microorganism (Table 2). The Ct method is used by the drinking water industry in the United States to determine how much disinfectant must be applied during treatment to achieve a given reduction in pathogenic microorganisms. The United States Environmental Protection Agency has published a series of tables giving Ct requirements for Giardia and viruses by various disinfectants. (EPA 1990 1998). Because the inactivation curve for microorganisms in not always linear, some safety factors have been added to the values in these tables. (For EPA and American Water Works Association values, see Tables 4 through 8.)

Bacteria are usually inactivated fairly rapidly by most disinfectants in contrast to Giardia and some viruses. Application of Ct values for enteric viruses and parasites will ensure inactivation of disease-causing bacteria.

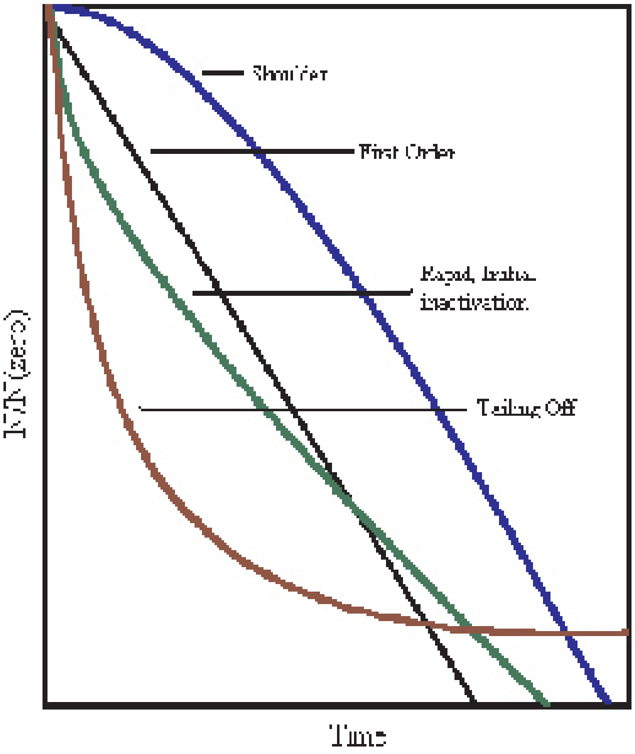

Figure 2 – Types of inactivation curves observed for microorganisms
Source: Maier et al, 2000

Organism	°C	pH	Ct
Bacteria			
E. *coli*	5	6.0	0.04
E. *coli*	23	10.0	0.6
L. *pneumophila*	20	7.7	1.1
Viruses			
Poliovirus 1	5	6.0	1.7
Hepatitis A (99.99% inactivation)	5	6.0	3.3
Protozoa			
G. *lamblia* cysts	5	6.0	54-87
G. *lamblia* cysts	5	7.0	83-133
G. *lamblia* cysts	5	8.0	119-192
G. *muris* cysts	5	6.0	250
Cryptosporidium oocysts	25	7.0	>7200

Table 1 – Ct values for chlorine inactivation of microorganisms in water (99% inactivation)

Source: Maier et al, 2000, Sobsey et al, 1988

Factors affecting the disinfection of microorganisms

Many factors influence the effectiveness of disinfectants in water (Table 1). The physical makeup of a microorganism has great bearing on its resistance to disinfection. Bacteria are often surrounded by a semi–permeable membrane, which provides ample surface area and reactivity for disinfectant chemicals. Disruption of the bacterial membrane causes the cell to lose its ability to retain intracellular salts. Eventually, the difference in salt concentration between water and the inside of the bacterium causes rupture and death. Many protozoa, on the other hand, form hard shells, called cysts, in the environment. This is of particular importance during water disinfection, because a high concentration of disinfectant may be required to inactivate the cysts. In practice, an encysted protozoan is the most difficult microorganism to inactivate. Viruses, however, have variable levels of sensitivity to disinfectants. This is a function of their unique morphology. Viruses are composed of nucleic acids (DNA or RNA) surrounded by a protein coat which offers protection from the environment and means to "attach" to a given host. In some cases, the protein coat is also surrounded by a fatty envelope.

Disinfectant	*Ct*
chlorine	1.7
chloramines	1420
chlorine dioxide	0.2-6.7
ozone	0.2

Table 2 – Ct values vary for different disinfectants: Poliovirus Ct at 5°C, pH 7.0 (chloramine 9.0) 99% inactivation

Source: Maier et al, 2000

pH
Organic Matter
Turbidity
Temperature
Salts (cations, anions)
Type of microorganism

Table 3 – Factors affecting disinfectants in water

In order to inactivate a virus, one of two events must take place; the structures which the virus uses to attach to or penetrate a host cell must be damaged, or the nucleic acids within the protein coat must be destroyed.

Halogen disinfectants such as chlorine, bromine and iodine are sensitive to the effects of pH in water. Chlorine, like other halogen disinfectants, is a strong oxidizing agent. When added to water, it forms a mixture of hypochlorous acid (HOCl) and hydrochloric acid (HCl). Hypochlorous acid readily dissociates to hydrogen ion and hypochlorite ion (OCl^-). This is important because the ratio of hypochlorous acid to hypochlorite ion depends on the pH of the water and plays a role in the efficiency of disinfection and Ct value. At acidic or neutral pH, hypochlorous acid is the main constituent of the mixture, which imparts greater disinfection ability. The same phenomenon occurs with bromine and iodine disinfectants.

Temperature is integral to the efficiency of disinfectants in recreational waters. Increased temperatures alone can reduce the survival time of microorganisms in water. When increased temperatures are coupled with chemical disinfection, more rapid disinfection results. High temperatures increase the rate of chemical reactions and consequently increase the oxidizing capabilities of ozone and halogen disinfectants. Ozone disinfection is a special case. Ozone gas is more soluble in water at 4 degrees than at 20 degrees Celsius, which means that effective residual concentrations of ozone may be harder to achieve at high temperatures, such as those found in hot tubs. However, ozone takes longer to kill microorganisms at lower temperatures (Driedger 2001).

The amount of organic matter in water can influence the properties, and even composition of disinfectants. Generally, an increase in suspended organic matter corresponds to an increased Ct value. This is due to the increase in available oxidizable (or interfering) matter as well as the creation of new, less effective disinfectant compounds (Bitton 1999). Organic matter in water interferes with halogen disinfection. Using chlorination as an example, organic matter provides multiple sites of oxidation for the free chlorine molecules, effectively reducing the chances that a microorganism will be oxidized and inactivated. The organic matter can also bind with free chlorine to form less efficient disinfectant chemicals such as chloramines. In the case of ozonation, organic matter will often destroy ozone intended for microbial components. This results in oxidation of all organic matter in the water and increased survival of microorganisms.

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	Log Reduction		
Temperature (Degrees C)	2.0	3.0	4.0
10	3	4	6
15	2	3	4
20	1	2	3
25	1	1	2

Table 4 – Ct Values for Inactivation of Viruses by Free Chlorine (pH 6–9)

Adapted from EPA Guidance Manual for Disinfection Profiling and Benchmarking (EPA 1998)

Organism	2 log inactivation (99.0%)	3 log inactivation (99.9%)	4 log inactivation (99.99%)
viruses	1.0	2.0	3.0
Giardia	45	68	n/a*

*n/a = not available

Adapted from the EPA Guidance Manual for Disinfection Profiling and Benchmarking and the Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Sources (EPA 1998, AWWA 1991).

Table 5 – Ct values for disinfection of *Giardia* cysts and viruses by free chlorine in water 20° C, pH 7.0

Example Problem #1:

Question: Fecal matter is observed in a community pool at 20° C and pH 7.0. It is suspected that a child infected with *Giardia* is responsible. How long will you disinfect the pool with 3, 10 and 20 mg/L chlorine to ensure 3–log inactivation of *Giardia* Cysts? See Table 5.

Answer: In order to ensure a 3–log inactivation of the cysts, a Ct value of 68 must be achieved. This value can be obtained by solving for t in the equation Ct = (C)(t). Because the concentration (3, 10 and 20 mg/L) and Ct value are known, the time can be calculated by dividing Ct by C. Thus, for 3, 10 and 20 mg/L the times needed for disinfection are 22.7 minutes, 6.8 and 3.4 minutes, respectively. It is important to recognize that the free chlorine value must be 3, 10 and 20 mg/L after the indicated time to meet the Ct requirements.

Example problem #2:

Question: A child who is suspected of infection with Norwalk virus vomits in a community pool at 20° C and pH 7.0. Norwalk virus causes diarrhea and is spread by vomit. How long will you disinfect the pool at 3, 10 and 20 mg/L chlorine to ensure a 4–log inactivation of virus? See Table 5.

Answer: Because the Ct values for the disinfection of viruses are significantly lower than those for Giardia cysts, one needs less time to disinfect the pool. The times needed for disinfection at 3, 10 and 20 mg/L chlorine are 1 minute, <1 minute and <1 minute, respectively.

	Log Reduction					
Temperature (Degrees C)	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
10	0.23	0.48	0.72	0.95	1.2	1.43
15	0.16	0.32	0.48	0.63	0.79	0.95
20	0.12	0.24	0.36	0.48	0.60	0.72
25	0.08	0.16	0.24	0.32	0.40	0.48

Table 6 – Ct Values for Inactivation of Giardia Cysts by Ozone (any pH)

Adapted from EPA Guidance Manual for Disinfection Profiling and Benchmarking (EPA 1998)

Chlorine Concentration	pH 7.0 Log Inactivation						pH 7.5 Log Inactivation						pH 8.0 Log Inactivation						pH 8.5 Log Inactivation					
(mg/L)	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	0.5	1.0	1.5	2.0	2.5	3.0
0.6	9	18	27	36	45	54	11	21	32	43	53	64	13	26	39	51	64	77	15	31	46	61	77	92
0.8	9	18	28	37	46	55	11	22	33	44	55	66	13	26	40	53	66	79	16	32	48	63	79	95
1.0	9	19	28	37	47	56	11	22	34	45	56	67	14	27	41	54	68	81	16	33	49	65	82	98
1.2	10	19	29	38	48	57	12	23	35	46	58	69	14	28	42	55	69	83	17	33	50	67	83	100
1.4	10	19	29	39	48	58	12	23	35	47	58	70	14	28	43	57	71	85	17	34	52	69	86	103
1.6	10	20	30	39	49	59	12	24	36	48	60	72	15	29	44	58	73	87	18	35	53	70	88	105
1.8	10	20	31	41	51	61	12	25	37	49	62	74	15	30	45	59	74	89	18	36	54	72	90	108
2.0	10	21	31	41	52	62	13	25	38	50	63	75	15	30	46	61	76	94	18	37	55	73	92	110
2.2	11	21	32	42	53	63	13	26	39	51	64	77	16	31	47	62	78	96	19	38	57	75	94	113
2.4	11	22	33	43	54	65	13	26	39	52	65	78	16	32	48	63	79	95	19	38	58	77	96	115
2.6	11	22	33	44	55	66	13	27	40	53	67	80	16	32	49	65	81	97	20	39	59	78	98	117
2.8	11	22	34	45	56	67	14	27	41	54	68	81	17	33	50	66	83	99	20	40	60	79	99	119
3.0	11	23	34	45	57	68	14	28	42	55	69	83	17	34	51	67	84	101	20	41	61	81	102	122

Table 7 – Ct Values for Inactivation of Giardia Cysts by Free Chlorine at 20°C

Chlorine Concentration (mg/L)	pH 7.0 Log Inactivations						pH 7.5 Log Inactivations						pH 8.0 Log Inactivations						pH 8.5 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	0.5	1.0	1.5	2.0	2.5	3.0
0.6	6	12	18	24	30	36	7	14	22	29	36	43	9	17	26	34	43	51	10	20	31	41	51	61
0.8	6	12	19	25	31	37	7	15	22	29	37	44	9	18	27	35	44	53	11	21	32	42	53	63
1.0	6	12	19	25	31	37	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	43	54	65
1.2	6	13	19	25	32	38	8	15	23	31	38	46	9	18	28	37	46	55	11	22	34	45	56	67
1.4	7	13	20	26	33	39	8	16	24	31	39	47	10	19	29	38	48	57	12	23	35	46	58	69
1.6	7	13	20	27	33	40	8	16	24	32	40	48	10	19	29	39	48	58	12	23	35	47	58	70
1.8	7	14	21	27	34	41	8	16	25	33	41	49	10	20	30	40	50	60	12	24	36	48	60	72
2.0	7	14	21	27	34	41	8	17	25	33	42	50	10	20	31	41	51	61	12	25	37	49	62	74
2.2	7	14	21	28	35	42	9	17	26	34	43	51	10	21	31	41	52	62	13	25	38	50	63	75
2.4	7	14	22	29	36	43	9	17	26	35	43	52	11	21	32	42	53	63	13	26	39	51	64	77
2.6	7	15	22	29	37	44	9	18	27	35	44	53	11	22	33	43	54	65	13	26	39	52	65	78
2.8	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	44	55	66	13	27	40	53	67	80
3.0	8	15	23	31	38	46	9	18	28	37	46	55	11	22	34	45	56	67	14	27	41	54	68	81

Table 8 – Ct Values for Inactivation of Giardia Cysts by Free Chlorine at 25°C