APPENDIX A. HISTORY

This section describes the historical development of disinfection profiling and benchmarking procedures and is important in understanding the purpose and intent of these procedures under the IESWTR.

Regulatory Background

The Safe Drinking Water Act (SDWA) Amendments of 1996 mandate that EPA develop interrelated regulations to control microbial pathogens and disinfectants/disinfection byproducts (D/DBPs) in drinking water. These rules are collectively known as the microbial/disinfection byproducts (M-DBP) rules and are intended to address complex risk trade-offs between the desire to inactivate pathogens found in water and the need to reduce chemical compounds formed as byproducts during disinfection.

To address the complex risk trade-offs between chronic DBP health risks and acute pathogenic health risks, EPA promulgated the ICR in May 1996 as a means to obtain data from large systems (i.e., surface water systems serving more than 100,000 people and groundwater systems serving more than 50,000 people). Information requested in the ICR addresses source water quality, byproduct formation, and drinking water treatment plant design and operations. Since promulgation and implementation of the ICR was delayed, information from the ICR was unavailable for two rulings, therefore the profiling and benchmarking procedures were developed.

EPA is promulgating the M-DBP cluster of rules in two phases. The rules in the first phase, the Stage 1 DBPR and the IESWTR, were promulgated December 16, 1998. The Stage 1 DBPR applies to all community water systems and nontransient noncommunity water systems that treat their water with a chemical disinfectant for either primary or residual treatment and addresses the formation of DBPs during water treatment. The IESWTR applies to all public water systems that use surface water or GWUDI, and serve greater than 10,000 people. The IESWTR amends the Surface Water Treatment Rule (SWTR) and includes new and more stringent requirements for controlling waterborne pathogens including *Giardia*, viruses, and *Cryptosporidium.*

A Long-Term 1 ESWTR will be promulgated in December 2000 and will address treatment requirements for surface water systems serving fewer than 10,000 people. EPA had hoped to use ICR data for the IESWTR and Stage 1 DBPR, but delays in promulgation eliminated this potential data source.

The second phase, the Stage 2 DBPR and the Long-Term 2 ESWTR, will be promulgated in 2002 and will revisit the regulations for the formation of byproducts during disinfection for all systems and the inactivation and removal of pathogens for surface water systems, respectively. The key dates for these regulatory activities are provided in Table A-1.

Table A-1. Key Dates for Regulatory Activities

Date	Regulatory Action
December 2000	Promulgate Long-Term 1 Enhanced Surface Water Treatment Rule
May 2002	Promulgate Stage 2 Disinfectants and Disinfection Byproduct Rule
May 2002	Promulgate Long-Term 2 Enhanced Surface Water Treatment Rule

Convening of the Federal Advisory Committee

In May 1996, EPA initiated a series of public meetings to exchange information on issues related to M-DBP regulations. In 1997, the EPA established the M-DBP Advisory Committee under the Federal Advisory Committee Act (FACA) to facilitate stakeholder participation and to help meet the deadlines for the IESWTR and Stage 1 DBPR established by Congress in the 1996 SDWA Amendments. The purpose of this Advisory Committee was to collect, share, and analyze new information and data, as well as to build consensus on the regulatory implications of this new information.

The Advisory Committee was concerned that water systems would reduce disinfection (e.g., logs of *Giardia* inactivation) to meet Stage 1 DBPR requirements for DBPs. At the time the SWTR was issued, EPA had limited data concerning *Giardia* and *Cryptosporidium* occurrence in source waters and treatment efficiencies. The 3-log removal/inactivation of *Giardia* and 4-log removal/inactivation of enteric viruses required by the SWTR were developed to provide protection from most pathogens in source waters. However, additional data have become available since promulgation of the SWTR concerning source water occurrence and treatment efficiencies for *Giardia*, as well as for *Cryptosporidium* (LeChevallier et al., 1991a; 1991b).

The Advisory Committee was concerned that if water systems currently provide four or more logs of removal/inactivation for *Giardia*, such systems might reduce existing levels of disinfection to meet the DBP requirements of the Stage 1 DBPR. This change in disinfection practices could result in systems only marginally meeting the 3-log removal/inactivation requirement for *Giardia* specified in the current SWTR. Depending upon source water *Giardia* concentrations, such treatment changes could lead to significant increases in microbial risk (Regli et al., 1993; Grubbs et al., 1992; USEPA, 1994b).

The M-DBP Advisory Committee's recommendations to the EPA included tighter turbidity performance criteria and individual filter monitoring requirements as part of the IESWTR. The revised turbidity performance criteria would contribute to a key IESWTR objective, that is to establish a microbial backstop to prevent significant increases in microbial risk when systems implement the DBP standards under the Stage 1 DBPR. The Advisory Committee also agreed that another major component of a microbial backstop would be provisions for disinfection profiling and benchmarking.

Profiling and Benchmarking Procedures

The M-DBP Advisory Committee made recommendations to EPA on disinfection profiling and benchmarking procedures to assure that pathogen control is maintained while the Stage 1 DBPR provisions are implemented. In developing the profiling and benchmarking procedures, the Advisory Committee evaluated the following issues; what information systems should be gathered to evaluate current disinfection practices, how the profiling and benchmark procedures should operate, and how systems and States should work together to assure that microbial control is maintained.

Based on data provided by systems and reviewed by the Advisory Committee, the microbial inactivation baseline, expressed as logs of *Giardia* inactivation, demonstrated high variability. Inactivation varied by several logs on a day-to-day basis at any particular treatment plant and by 10 or more ten logs over a year due to changes in water temperature, flow rate (and consequently contact time), seasonal changes in residual disinfectant, pH, and disinfectant demand (and consequently disinfectant residual). There were also differences between years at individual plants.

To address these variations, the Advisory Committee recommended a disinfection profiling approach for a system to characterize their existing disinfection practices. In essence, this approach allows a plant to chart or plot its daily levels of *Giardia* inactivation on a graph that, when viewed on a seasonal or annual basis, represents a "profile" of the plant's inactivation performance. The system can use the profile to develop a baseline or "benchmark" of inactivation against which to measure possible changes in disinfection practices.

This approach makes it possible for a plant to change its disinfection practices to meet the Stage 1 DBPR maximum contaminant levels (MCLs), without a significant increase in microbial risk. The benchmarking approach and guidance in this manual provide tools for plants to understand potential impacts of modifying disinfection practices.

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APPENDIX B. LOG INACTIVATION METHODS

Development of the Log Inactivation Method under the SWTR

The disinfection profile is based on microbial inactivation. As part of the SWTR, EPA developed a method to calculate microbial inactivation for evaluating the effectiveness of disinfection in a water system. Chemical disinfection does not remove microorganisms from water but inactivates them so they can no longer infect consumers. Under the method developed for the SWTR, the actual plant disinfection conditions are converted to a theoretical level of inactivation of specific microorganisms.

The conversion from plant conditions to microbial inactivation is accomplished based on "CT tables" developed for the SWTR, where C is the residual disinfectant concentration (mg/L) and T is the time (in minutes) that water is in contact with the disinfectant. These tables relate CT values to levels of inactivation under various operating conditions. Different tables exist for different disinfectants. As the CT value is increased, a greater percentage of microorganisms are inactivated by chemical disinfection. The CT, and therefor the level of inactivation, can be increased by applying greater doses of the disinfectant or by increasing the time that the water is in contact with the disinfectant.

The level of inactivation is generally referred to in terms of "log inactivation" since inactivation is measured on a logarithmic scale (i.e., orders of magnitude reduction). For example, a 2-log inactivation and/or removal of *Giardia* corresponds to inactivating 99 percent of the *Giardia* cysts through the disinfection process while a 3-log inactivation and/or removal corresponds to a 99.9 percent inactivation.

Log inactivation is a measure of the percent of microorganisms that are inactivated during the disinfection process and is defined as:

$$\text{Log Inactivation} = \text{Log}\left(\frac{N_o}{N_T}\right)$$

Where,

N_o = initial (influent) concentration of viable microorganisms
N_T = concentration of surviving microorganisms
Log = logarithm to base 10

Log inactivation is related to the percent inactivation, defined as:

$$\text{Percent Inactivation} = \left(1 - \frac{N_T}{N_o}\right) * 100$$

Therefore, the relationship between log inactivation and percent inactivation is as follows:

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{\text{Log Inactivation}}}\right) * 100$$

or,

$$\text{Log Inactivation} = \text{Log}\left(\frac{100}{100 - \text{Percent Inactivation}}\right)$$

The following two examples illustrate the relationship between influent and effluent concentrations, percent inactivation, and log inactivation.

Example 1

A utility has an influent concentration (N_o) of active Giardia *of 10,000 cysts/100L and a concentration of surviving microorganisms at the first point in the distribution system (N_T) of 10 cysts/100L. What is the log inactivation of this treatment process?*

$$\text{Log Inactivation} = \text{Log}\left(\frac{N_o}{N_T}\right)$$

$$\text{Log Inactivation} = \text{Log}\left(\frac{10{,}000}{10}\right)$$

$$\text{Log Inactivation} = \text{Log } 1{,}000$$

$$\text{Log Inactivation} = 3$$

Example 2

Given that the utility has a 3-Log Inactivation of Giardia, *what is the percent inactivation of* Giardia*?*

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{\text{Log Inactivation}}}\right) * 100$$

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{3}}\right) * 100$$

$$\text{Percent Inactivation} = \left(1 - \frac{1}{1{,}000}\right) * 100$$

$$\text{Percent Inactivation} = (1\text{-}.001) * 100$$

$$\text{Percent Inactivation} = 99.9$$

As the two examples show, a 3-log inactivation equals 99.9 percent inactivation. Table B-1 presents similar calculations for different log inactivations and corresponding percent inactivations.

Table B-1. Log Inactivation and Percent Inactivation

Log Inactivation	*Percent Inactivation*
0.0	0.00
0.5	68.38
1.0	90.00
2.0	99.00
3.0	99.90
4.0	99.99
5.0	99.999
6.0	99.9999
7.0	99.99999

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APPENDIX C. CT VALUES FOR INACTIVATIONS ACHIEVED BY VARIOUS DISINFECTANTS

This appendix provides a reprint of the CT tables for determining inactivations achieved by various disinfectants. These tables were originally provided in EPA's *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Sources* (AWWA, 1991).

Table C-1. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at 0.5°C or Lower

CHLORINE CONCENTRATION	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 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
<=0.4	23	46	69	91	114	137	27	54	82	109	136	163	33	65	98	130	163	195	40	79	119	158	198	237
0.6	24	47	71	94	118	141	28	56	84	112	140	169	33	67	100	133	167	200	40	80	120	159	199	239
0.8	24	48	73	97	121	145	29	57	86	115	143	172	34	68	103	137	171	205	41	82	123	164	205	246
1	25	49	74	99	123	148	29	59	88	117	147	176	35	70	105	140	175	210	42	84	127	169	211	253
1.2	25	51	76	101	127	152	30	60	90	120	150	180	36	72	108	143	179	215	43	86	130	173	216	259
1.4	26	52	78	103	129	155	31	61	92	123	153	184	37	74	111	147	184	221	44	89	133	177	222	266
1.6	26	52	79	105	131	157	32	63	95	126	155	189	38	75	113	151	188	226	46	91	137	182	228	273
1.8	27	54	81	108	135	162	32	64	97	129	161	193	39	77	116	154	193	231	47	93	140	186	233	279
2	28	55	83	110	138	165	33	66	99	131	164	197	39	79	118	157	197	236	48	95	143	191	238	286
2.2	28	56	85	113	141	169	34	67	101	134	169	201	40	81	121	161	202	242	50	99	149	198	248	297
2.4	29	57	86	115	143	172	34	68	103	137	171	205	41	82	124	165	206	247	50	99	149	199	248	298
2.6	29	58	88	117	146	175	35	70	105	139	174	209	42	84	126	168	210	252	51	101	152	203	253	304
2.8	30	59	89	119	148	178	36	71	107	142	178	213	43	86	129	171	214	257	52	103	155	207	258	310
3	30	60	91	121	151	181	36	72	109	145	181	217	44	87	131	174	218	261	53	105	158	211	263	316
CHLORINE CONCENTRATION	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 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						
<=0.4	46	92	139	185	231	277	55	110	165	219	274	329	65	130	195	260	325	390						
0.6	48	95	143	191	238	286	57	114	171	228	285	342	68	136	204	271	339	407						
0.8	49	98	148	197	246	295	59	113	177	236	295	354	70	141	211	281	352	422						
1	51	101	152	203	253	304	61	122	183	243	304	365	73	146	219	291	364	437						
1.2	52	104	157	209	261	313	63	125	188	251	313	376	75	150	226	301	376	451						
1.4	54	107	161	214	268	321	65	129	194	258	323	387	77	155	232	309	387	464						
1.6	55	110	165	219	274	329	66	132	199	265	331	397	80	159	239	318	398	477						
1.8	56	113	169	225	282	338	68	136	204	271	339	407	82	163	245	326	408	489						
2	55	115	173	231	288	346	70	139	209	278	348	417	83	167	250	333	417	500						
2.2	59	118	177	235	294	353	71	142	213	284	355	426	85	170	256	341	426	511						
2.4	60	120	181	241	301	361	73	145	218	290	363	435	87	174	261	348	435	522						
2.6	61	123	184	245	307	368	74	148	222	296	370	444	89	178	267	355	444	533						
2.8	63	125	188	250	313	375	75	151	226	301	377	452	91	181	272	362	453	543						
3	64	127	191	255	318	382	77	153	230	307	383	460	92	184	276	369	460	552						

Source: AWWA, 1991.

Table C-2. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 5°C

CHLORINE CONCENTRATION	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 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
<=0.4	16	32	49	65	81	97	20	39	59	78	98	117	23	46	70	93	116	139	28	55	83	111	138	166
0.6	17	33	50	67	83	100	20	40	60	80	100	120	24	49	72	95	119	143	29	57	86	114	143	171
0.8	17	34	52	69	86	103	20	41	61	81	102	122	24	49	73	97	122	146	29	58	88	117	146	175
1	18	35	53	70	88	105	21	42	63	83	104	125	25	50	75	99	124	149	30	60	90	119	149	179
1.2	18	36	54	71	89	107	21	42	64	85	106	127	25	51	76	101	127	152	31	61	92	122	153	183
1.4	18	36	55	73	91	109	22	43	65	97	108	130	26	52	78	103	129	155	31	62	94	125	156	187
1.6	19	37	56	74	93	111	22	44	66	88	110	132	26	53	79	105	132	158	32	64	96	128	160	192
1.8	19	38	57	76	95	114	23	45	69	90	113	135	27	54	81	108	135	162	33	65	98	131	163	196
2	19	39	58	77	97	116	23	46	69	92	115	138	28	55	83	110	138	165	33	67	100	133	167	200
2.2	20	39	59	79	98	118	23	47	70	93	117	140	28	56	85	113	141	169	34	68	102	136	170	204
2.4	20	40	60	80	100	120	24	48	72	95	119	143	29	57	86	115	143	172	35	70	105	139	174	209
2.6	20	41	61	81	102	122	24	49	73	97	122	146	29	58	88	117	146	175	36	71	107	142	178	213
2.8	21	41	62	83	103	124	25	49	74	99	123	148	30	59	89	119	148	178	36	72	109	145	181	217
3	21	42	63	84	105	126	25	50	76	101	126	151	30	61	91	121	152	182	37	74	111	147	184	221
CHLORINE CONCENTRATION	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 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						
<=0.4	33	66	99	132	165	198	39	79	118	157	197	236	47	93	140	186	233	279						
0.6	34	68	102	136	170	204	41	81	122	163	203	244	49	97	146	194	243	291						
0.8	35	70	105	140	175	210	42	84	126	168	210	252	50	100	151	201	251	301						
1	36	72	108	144	180	216	43	87	130	173	217	260	52	104	156	208	260	312						
1.2	37	74	111	147	184	221	45	89	134	178	223	267	53	107	160	213	267	320						
1.4	38	76	114	151	189	227	46	91	137	183	228	274	55	110	165	219	274	329						
1.6	39	77	116	155	193	232	47	94	141	197	234	281	56	112	169	225	281	337						
1.8	40	79	119	159	198	238	48	96	144	191	239	287	58	115	173	230	288	345						
2	41	81	122	162	203	243	49	98	147	196	245	294	59	118	177	235	294	353						
2.2	41	83	124	165	207	248	50	100	150	200	250	300	60	120	181	241	301	361						
2.4	42	84	127	169	211	253	51	102	153	204	255	306	61	123	184	245	307	368						
2.6	43	86	129	172	215	258	52	104	156	208	260	312	63	125	189	250	313	375						
2.8	44	88	132	175	219	263	53	106	159	212	265	318	64	127	191	255	318	382						
3	45	89	134	179	223	268	54	108	162	216	270	324	65	130	195	259	324	389						

Source: AWWA, 1991.

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

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	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
<=0.4	12	24	37	49	61	73	15	29	44	59	73	88	17	35	52	69	87	104	21	42	63	83	104	125
0.6	13	25	38	50	63	75	15	30	45	60	75	90	18	36	54	71	89	107	21	43	64	85	107	128
0.8	13	26	39	52	65	78	15	31	46	61	77	92	18	37	55	73	92	110	22	44	66	87	109	131
1	13	26	40	53	66	79	16	31	47	63	78	94	19	37	56	75	93	112	22	45	67	89	112	134
1.2	13	27	40	53	67	80	16	32	48	63	79	95	19	38	57	76	95	114	23	46	69	91	114	137
1.4	14	27	41	55	68	82	16	33	49	65	82	98	19	39	58	77	97	116	23	47	70	93	117	140
1.6	14	28	42	55	69	83	17	33	50	66	83	99	20	40	60	79	99	119	24	48	72	96	120	144
1.8	14	29	43	57	72	86	17	34	51	67	84	101	20	41	61	81	102	122	25	49	74	98	123	147
2	15	29	44	58	73	87	17	35	52	69	87	104	21	41	62	83	103	124	25	50	75	100	125	150
2.2	15	30	45	59	74	89	18	35	53	70	88	105	21	42	64	85	106	127	26	51	77	102	128	153
2.4	15	30	45	60	75	90	18	36	54	71	89	107	22	43	65	86	108	129	26	52	79	105	131	157
2.6	15	31	46	61	77	92	18	37	55	73	92	110	22	44	66	87	109	131	27	53	80	107	133	160
2.8	16	31	47	62	78	93	19	37	56	74	93	111	22	45	67	89	112	134	27	54	82	109	136	163
3	16	32	48	63	79	95	19	38	57	75	94	113	23	46	69	91	114	137	28	55	83	111	138	166
CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation											
	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	25	50	75	99	124	149	30	59	89	118	148	177	35	70	105	139	174	209						
0.6	26	51	77	102	128	153	31	61	92	122	153	183	36	73	109	145	182	218						
0.8	26	53	79	105	132	158	32	63	95	126	158	189	38	75	113	151	188	226						
1	27	54	81	108	135	162	33	65	98	130	163	195	39	78	117	156	195	234						
1.2	28	55	83	111	138	166	33	67	100	133	167	200	40	80	120	160	200	240						
1.4	28	57	85	113	142	170	34	69	103	137	172	206	41	82	124	165	206	247						
1.6	29	58	87	116	145	174	35	70	106	141	176	211	42	84	127	169	211	253						
1.8	30	60	90	119	149	179	36	72	108	143	179	215	43	86	130	173	216	259						
2	30	61	91	121	152	182	37	74	111	147	184	221	44	88	133	177	221	265						
2.2	31	62	93	124	155	186	38	75	113	150	188	225	45	90	136	181	226	271						
2.4	32	63	95	127	158	190	38	77	115	153	192	230	46	92	138	184	230	276						
2.6	32	65	97	129	162	194	39	78	117	156	195	234	47	94	141	187	234	281						
2.8	33	66	99	131	164	197	40	80	120	159	199	239	48	96	144	191	239	287						
3	34	67	101	134	168	201	41	81	122	162	203	243	49	97	146	195	243	292						

Source: AWWA, 1991.

Table C-4. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 15°C

CHLORINE CONCENTRATION	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 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
<=0.4	8	16	25	33	41	49	10	20	30	39	49	59	12	23	35	47	58	70	14	28	42	55	69	83
0.6	8	17	25	33	42	50	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86
0.8	9	17	26	35	43	52	10	20	31	41	51	61	12	24	37	49	61	73	15	29	44	59	73	88
1	9	18	27	35	44	53	11	21	32	42	53	63	13	25	38	50	63	75	15	30	45	60	75	90
1.2	9	18	27	36	45	54	11	21	32	43	53	64	13	25	38	51	63	76	15	31	46	61	77	92
1.4	9	18	28	37	46	55	11	22	33	43	54	65	13	26	39	52	65	78	16	31	47	63	78	94
1.6	9	19	28	37	47	56	11	22	33	44	55	66	13	26	40	53	66	79	16	32	48	64	80	96
1.8	10	19	29	38	48	57	11	23	34	45	57	68	14	27	41	54	68	81	16	33	49	65	82	98
2	10	19	29	39	48	58	12	23	35	46	58	69	14	28	42	55	69	83	17	33	50	67	83	100
2.2	10	20	30	39	49	59	12	23	35	47	58	70	14	28	43	57	71	85	17	34	51	68	85	102
2.4	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86	18	35	53	70	88	105
2.6	10	20	31	41	51	61	12	24	37	49	61	73	15	29	44	59	73	88	18	36	54	71	89	107
2.8	10	21	31	41	52	62	12	25	37	49	62	74	15	30	45	59	74	89	18	36	55	73	91	109
3	11	21	32	42	53	63	13	25	38	51	63	76	15	30	46	61	76	91	19	37	56	74	93	111

CHLORINE CONCENTRATION	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 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
<=0.4	17	33	50	66	83	99	20	39	59	79	98	118	23	47	70	93	117	140
0.6	17	34	51	68	85	102	20	41	61	81	102	122	24	49	73	97	122	146
0.8	18	35	53	70	88	105	21	42	63	84	105	126	25	50	76	101	126	151
1	18	36	54	72	90	108	22	43	65	87	108	130	26	52	78	104	130	156
1.2	19	37	56	74	93	111	22	45	67	89	112	134	27	53	80	107	133	160
1.4	19	38	57	76	95	114	23	46	69	91	114	137	28	55	83	110	138	165
1.6	19	39	58	77	97	116	24	47	71	94	118	141	28	56	85	113	141	169
1.8	20	40	60	79	99	119	24	48	72	96	120	144	29	59	87	115	144	173
2	20	41	61	81	102	122	25	49	74	98	123	147	30	59	89	118	148	177
2.2	21	41	62	83	103	124	25	50	75	100	125	150	30	60	91	121	151	181
2.4	21	42	64	85	106	127	26	51	77	102	128	153	31	61	92	123	153	184
2.6	22	43	65	86	108	129	26	52	78	104	130	156	31	63	94	125	157	188
2.8	22	44	66	88	110	132	27	53	80	106	133	159	32	64	96	127	159	191
3	22	45	67	89	112	134	27	54	81	109	135	162	33	65	98	130	163	195

Source: AWWA, 1991.

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

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	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
<=0.4	6	12	18	24	30	36	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62
0.6	6	13	19	25	32	38	8	15	23	30	38	45	9	18	27	36	45	54	11	21	32	43	53	64
0.8	7	13	20	26	33	39	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66
1	7	13	20	26	33	39	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67
1.2	7	13	20	27	33	40	8	16	24	32	40	48	10	19	29	38	48	57	12	23	35	46	58	69
1.4	7	14	21	27	34	41	8	16	25	33	41	49	10	19	29	39	48	58	12	23	35	47	58	70
1.6	7	14	21	28	35	42	8	17	25	33	42	50	10	20	30	39	49	59	12	24	36	48	60	72
1.8	7	14	22	29	36	43	9	17	26	34	43	51	10	20	31	41	51	61	12	25	37	49	62	74
2	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62	13	25	38	50	63	75
2.2	7	15	22	29	37	44	9	18	27	35	44	53	11	21	32	42	53	63	13	26	39	51	64	77
2.4	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	43	54	65	13	26	39	52	65	78
2.6	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66	13	27	40	53	67	80
2.8	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67	14	27	41	54	68	81
3	9	16	24	31	39	47	10	19	29	38	48	57	11	23	34	45	57	68	14	28	42	55	69	83
CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation											
	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	25	37	49	62	74	15	30	45	59	74	89	19	35	53	70	88	105						
0.6	13	26	39	51	64	77	15	31	46	61	77	92	18	36	55	73	91	109						
0.8	13	26	40	53	66	79	16	32	48	63	79	95	19	38	57	75	94	113						
1	14	27	41	54	68	81	16	33	49	65	82	98	20	39	59	78	98	117						
1.2	14	28	42	55	69	83	17	33	50	67	83	100	20	40	60	80	100	120						
1.4	14	28	43	57	71	85	17	34	52	69	86	103	21	41	62	82	103	123						
1.6	15	29	44	58	73	87	18	35	53	70	88	105	21	42	63	84	105	126						
1.8	15	30	45	59	74	89	18	36	54	72	90	108	22	43	65	86	108	129						
2	15	30	46	61	76	91	18	37	55	73	92	110	22	44	66	88	110	132						
2.2	16	31	47	62	78	93	19	38	57	75	94	113	23	45	68	90	113	135						
2.4	16	32	48	63	79	95	19	38	58	77	96	115	23	46	69	92	115	139						
2.6	16	32	49	65	81	97	20	39	59	78	98	117	24	47	71	94	117	141						
2.8	17	33	50	66	83	99	20	40	60	79	99	119	24	48	72	95	119	143						
3	17	34	51	67	84	101	20	41	61	81	102	122	24	49	73	97	122	146						

Source: AWWA, 1991.

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

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	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
<=0.4	4	8	12	16	20	24	5	10	15	19	24	29	6	12	18	23	29	35	7	14	21	28	35	42
0.6	4	8	13	17	21	25	5	10	15	20	25	30	6	12	18	24	30	36	7	14	22	29	36	43
0.8	4	9	13	17	22	26	5	10	16	21	26	31	6	12	19	25	31	37	7	15	22	29	37	44
1	4	9	13	17	22	26	5	10	16	21	26	31	6	12	19	25	31	37	8	15	23	30	38	45
1.2	5	9	14	18	23	27	5	11	16	21	27	32	6	13	19	25	32	38	8	15	23	31	38	46
1.4	5	9	14	18	23	27	6	11	17	22	28	33	7	13	20	26	33	39	8	16	24	31	39	47
1.6	5	9	14	19	23	28	6	11	17	22	28	33	7	13	20	27	33	40	8	16	24	32	40	48
1.8	5	10	15	19	24	29	6	11	17	23	28	34	7	14	21	27	34	41	8	16	25	33	41	49
2	5	10	15	19	24	29	6	12	13	23	29	35	7	14	21	27	34	41	8	17	25	33	42	50
2.2	5	10	15	20	25	30	6	12	18	23	29	35	7	14	21	28	35	42	9	17	26	34	43	51
2.4	5	10	15	20	25	30	6	12	19	24	30	36	7	14	22	29	36	43	9	17	26	35	43	52
2.6	5	10	16	21	26	31	6	12	19	25	31	37	7	15	22	29	37	44	9	18	27	35	44	53
2.8	5	10	16	21	26	31	6	12	19	25	31	37	8	15	23	30	38	45	9	18	27	36	45	54
3	5	11	16	21	27	32	6	13	19	25	32	38	8	15	23	31	38	46	9	18	28	37	46	55
CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation											
	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	8	17	25	33	42	50	10	20	30	39	49	59	12	23	35	47	58	70						
0.6	9	17	26	34	43	51	10	20	31	41	51	61	12	24	37	49	61	73						
0.8	9	18	27	35	44	53	11	21	32	42	53	63	13	25	38	50	63	75						
1	9	19	27	36	45	54	11	22	33	43	54	65	13	26	39	52	65	78						
1.2	9	18	28	37	46	55	11	22	34	45	56	67	13	27	40	53	67	80						
1.4	10	19	29	38	48	57	12	23	35	46	58	69	14	27	41	55	68	82						
1.6	10	19	29	39	48	58	12	23	35	47	58	70	14	28	42	56	70	84						
1.8	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86						
2	10	20	31	41	51	61	12	25	37	49	62	74	15	29	44	59	73	89						
2.2	10	21	31	41	52	62	13	25	38	50	63	75	15	30	45	60	75	90						
2.4	11	21	32	42	53	63	13	26	39	51	64	77	15	31	46	61	77	92						
2.6	11	22	33	43	54	65	13	26	39	52	65	78	16	31	47	63	78	94						
2.8	11	22	33	44	55	66	13	27	40	53	67	80	16	32	48	64	80	96						
3	11	22	34	45	56	67	14	27	41	54	68	81	16	32	49	65	81	97						

Source: AWWA, 1991.

Table C-7. CT Values for Inactivation of Viruses by Free Chlorine, pH 6.0-9.0

Temperature (°C)																										
Inactivation (log)	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
2	6.0	5.8	5.3	4.9	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	1.0	1.0	1.0	1.0	1.0
3	9.0	8.7	8.0	7.3	6.7	6.0	5.6	5.2	4.8	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0
4	12.0	11.6	10.7	9.8	8.9	8.0	7.6	7.2	6.8	6.4	6.0	5.6	5.2	4.8	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-8. CT Values for Inactivation of Giardia Cysts by Chlorine Dioxide, pH 6.0-9.0

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
0.5	10.0	8.6	7.2	5.7	4.3	4.2	4.2	4.1	4.1	4.0	3.8	3.7	3.5	3.4	3.2	3.1	2.9	2.8	2.6	2.5	2.4	2.3	2.2	2.1	2.0
1	21.0	17.9	14.9	11.8	8.7	8.5	8.3	8.1	7.9	7.7	7.4	7.1	6.9	6.6	6.3	6.0	5.8	5.5	5.3	5.0	4.7	4.5	4.2	4.0	3.7
1.5	32.0	27.3	22.5	17.8	13.0	12.8	12.6	12.4	12.2	12.0	11.6	11.2	10.8	10.4	10.0	9.5	9.0	8.5	8.0	7.5	7.1	6.7	6.3	5.9	5.5
2	42.0	35.8	29.5	23.3	17.0	16.6	16.2	15.8	15.4	15.0	14.6	14.2	13.8	13.4	13.0	12.4	11.8	11.2	10.6	10.0	9.5	8.9	8.4	7.8	7.3
2.5	52.0	44.5	37.0	29.5	22.0	21.4	20.8	20.2	19.6	19.0	18.4	17.8	17.2	16.6	16.0	15.4	14.8	14.2	13.6	13.0	12.2	11.4	10.6	9.8	9.0
3	63.0	53.8	44.5	35.3	26.0	25.4	24.8	24.2	23.6	23.0	22.2	21.4	20.6	19.8	19.0	18.2	17.4	16.6	15.8	15.0	14.2	13.4	12.6	11.8	11.0

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-9. CT Values for Inactivation of Viruses by Chlorine Dioxide, pH 6.0-9.0

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
2	8.4	7.7	7.0	6.3	5.6	5.3	5.0	4.8	4.5	4.2	3.9	3.6	3.4	3.1	2.8	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.5	1.4
3	25.6	23.5	21.4	19.2	17.1	16.2	15.4	14.5	13.7	12.8	12.0	11.1	10.3	9.4	8.6	8.2	7.7	7.3	6.8	6.4	6.0	5.6	5.1	4.7	4.3
4	50.1	45.9	41.8	37.6	33.4	31.7	30.1	28.4	26.8	25.1	23.4	21.7	20.1	18.4	16.7	15.9	15.0	14.2	13.3	12.5	11.7	10.9	10.0	9.2	8.4

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-10. CT Values for Inactivation of Giardia Cysts by Chloramine, pH 6.0-9.0

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
0.5	635	568	500	433	365	354	343	332	321	310	298	286	274	262	250	237	224	211	198	185	173	161	149	137	125
1	1,270	1,136	1,003	869	735	711	687	663	639	615	592	569	546	523	500	474	448	422	396	370	346	322	298	274	250
1.5	1,900	1,700	1,500	1,300	1,100	1,066	1,032	998	964	930	894	858	822	786	750	710	670	630	590	550	515	480	445	410	375
2	2,535	2,269	2,003	1,736	1,470	1,422	1,374	1,326	1,278	1,230	1,184	1,138	1,092	1,046	1,000	947	894	841	788	735	688	641	594	547	500
2.5	3,170	2,835	2,500	2,165	1,830	1,772	1,714	1,656	1,598	1,540	1,482	1,424	1,366	1,308	1,250	1,183	1,116	1,049	982	915	857	799	741	683	625
3	3,800	3,400	3,000	2,600	2,200	2,130	2,060	1,990	1,920	1,850	1,780	1,710	1,640	1,570	1,500	1,420	1,340	1,260	1,180	1,100	1,030	960	890	820	750

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-11. CT Values for Inactivation of Viruses by Chloramine

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
2	1,243	1,147	1,050	954	857	814	771	729	686	643	600	557	514	471	428	407	385	364	342	321	300	278	257	235	214
3	2,063	1,903	1,743	1,583	1,423	1,352	1,281	1,209	1,138	1,067	996	925	854	783	712	676	641	605	570	534	498	463	427	392	356
4	2,883	2,659	2,436	2,212	1,988	1,889	1,789	1,690	1,590	1,491	1,392	1,292	1,193	1,093	994	944	895	845	796	746	696	646	597	547	497

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-12. CT Values for Inactivation of Giardia Cysts by Ozone

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
0.5	0.48	0.44	0.40	0.36	0.32	0.30	0.28	0.27	0.25	0.23	0.22	0.20	0.19	0.17	0.16	0.15	0.14	0.14	0.13	0.12	0.11	0.10	0.10	0.09	0.08
1.0	0.97	0.89	0.80	0.72	0.63	0.60	0.57	0.54	0.51	0.48	0.45	0.42	0.38	0.35	0.32	0.30	0.29	0.27	0.26	0.24	0.22	0.21	0.19	0.18	0.16
1.5	1.50	1.36	1.23	1.09	0.95	0.90	0.86	0.81	0.77	0.72	0.67	0.62	0.58	0.53	0.48	0.46	0.43	0.41	0.38	0.36	0.34	0.31	0.29	0.26	0.24
2.0	1.90	1.75	1.60	1.45	1.30	1.23	1.16	1.09	1.02	0.95	0.89	0.82	0.76	0.69	0.63	0.60	0.57	0.54	0.51	0.48	0.45	0.42	0.38	0.35	0.32
2.5	2.40	2.20	2.00	1.80	1.60	1.52	1.44	1.36	1.28	1.20	1.12	1.04	0.95	0.87	0.79	0.75	0.71	0.68	0.64	0.60	0.56	0.52	0.48	0.44	0.40
3.0	2.90	2.65	2.40	2.15	1.90	1.81	1.71	1.62	1.52	1.43	1.33	1.24	1.14	1.05	0.95	0.90	0.86	0.81	0.77	0.72	0.67	0.62	0.58	0.53	0.48

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-13. CT Values for Inactivation of Viruses by Ozone

	Temperature (°C)																								
Inactivation (log)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
2	0.90	0.83	0.75	0.68	0.60	0.58	0.56	0.54	0.52	0.50	0.46	0.42	0.38	0.34	0.30	0.29	0.28	0.27	0.26	0.25	0.23	0.21	0.19	0.17	0.15
3	1.40	1.28	1.15	1.03	0.90	0.88	0.86	0.84	0.82	0.80	0.74	0.68	0.62	0.56	0.50	0.48	0.46	0.44	0.42	0.40	0.37	0.34	0.31	0.28	0.25
4	1.80	1.65	1.50	1.35	1.20	1.16	1.12	1.08	1.04	1.00	0.92	0.84	0.76	0.68	0.60	0.58	0.56	0.54	0.52	0.50	0.46	0.42	0.38	0.34	0.30

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments

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APPENDIX D. DETERMINATION OF DISINFECTANT CONTACT TIME

This appendix originally appeared as Appendix C in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991). References to the main body of the report, section headers, and some terminology have been modified to relate better to the content of this *Disinfection Profiling and Benchmarking Guidance Manual*.

As indicated in Chapter 3, fluid passing through a pipe is assumed to have a detention time equal to the theoretical or mean residence time at a particular flow rate. However, in mixing basins, storage reservoirs, and other treatment plant process units, utilities will be required to determine the contact time for the calculation of CT through tracer studies or other methods approved by the Primacy Agency.

For the purpose of determining compliance with the disinfection requirements of the SWTR, the contact time of mixing basins and storage reservoirs used in calculating CT should be the minimum detention time experienced by 90 percent of the water passing through the unit. This detention time was designated as T_{10} according to the convention adopted by Thirumurthi (1969). A profile of the flow through the basin over time can be generated by tracer studies. Information provided by these studies is used for estimating the detention time, T_{10}, for the purpose of calculating CT.

This appendix is divided into three sections. The first section presents a brief synopsis of tracer study methods, procedures, and data evaluation. In addition, examples are presented for conducting hypothetical tracer studies to determine the T_{10} contact time in a clearwell. The second section presents a method of determining T_{10} from theoretical detention times in systems where it is impractical to conduct tracer studies. The third section provides examples on how to incorporate baffling classification and factors into CT calculations and provides detailed practical examples on the use of tracer studies and baffling conditions to calculate T_{10}/T.

D.1 Tracer Studies

D.1.1 Flow conditions

Although detention time is proportional to flow, it is not generally a linear function. Therefore, tracer studies are needed to establish detention times for the range of flow rates experienced within each disinfectant segment.

As discussed in Section 3.4.2, a single flow rate may not characterize the flow through the entire system. With a series of reservoirs, clearwells, and storage tanks, flow will vary between each portion of the system.

In filter plants, the plant flow is relatively uniform from the intake through the filters. An increase or reduction in the intake pumping capacity will impart a proportional change in flow through each process unit prior to and including the filters. Therefore, at a constant intake pumping rate flow variations between disinfectant segments within a treatment plant, excluding clearwells, are likely to be small, and the design capacity of the plant, or plant flow, can be considered the nominal flow rate through each individual process unit within the plant. Clearwells may operate at a different flow rate than the rest of the plant, depending on the pumping capacity.

Ideally, tracer tests should be performed for at least four flow rates that span the entire range of flow for the segment being tested. The flow rates should be separated by approximately equal intervals to span the range of operation, with one near average flow, two greater than average, and one less than average flow. The flows should also be selected so that the highest test flow rate is at least 91 percent of the highest flow rate expected to ever occur in that segment. Four data points will assure a good definition of the segment's hydraulic profile.

The results of the tracer tests performed for different flow rates should be used to generate plots of T_{10} vs. Q for each segment in the system. A smooth line is drawn through the points on each graph to create a curve from which T_{10} may be read for the corresponding Q at peak hourly flow conditions. This procedure is presented in Section D.1.8.

It may not be practical for all systems to conduct studies at four flow rates. The number of tracer tests that are practical to conduct is dependent on site-specific restrictions and resources available to the system. Systems with limited resources can conduct a minimum of one tracer test for each disinfectant segment at a flow rate of not less than 91 percent of the highest flow rate experienced at that segment. If only one tracer test is performed, the detention time determined by the test may be used to provide a conservative estimate in CT calculations for that segment for all flow rates less than or equal to the tracer test flow rate. T_{10} is inversely proportional to flow rate, therefore, the T_{10} at a flow rate other than that which the tracer study was conducted (T_{10S}) can be approximated by multiplying the T_{10} from the tracer study (T_{10T}) by the ratio of the tracer study flow rate to the desired flow rate, (i.e., $T_{10S} = T_{1OT} \cdot Q_T/Q_D$).

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

The most accurate tracer test results are obtained when flow is constant through the segment during the course of the test. Therefore, the tracer study should be conducted at a constant flow whenever practical. For a treatment plant consisting of two or more equivalent process trains, a constant flow tracer test can be performed on a segment of the

plant by holding the flow through one of the trains constant while operating the parallel train(s) to absorb any flow variations. Flow variations during tracer tests in systems without parallel trains or with single clearwells and storage reservoirs are more difficult to avoid. In these instances, T_{10} should be recorded at the average flow rate over the course of the test.

D.1.2 Other Tracer Study Considerations

In addition to flow conditions, detention times determined by tracer studies are dependent on the water level in the contact basin. This is particularly pertinent to storage tanks, reservoirs, and clearwells, which, in addition to being contact basins for disinfection, are also often used as equalization storage for distribution system demands and storage for backwashing. In such instances, the water levels in the reservoirs vary to meet the system demands. The actual detention time of these contact basins will also vary depending on whether they are emptying or filling.

For some process units, especially sedimentation basins which are operated at a near constant level (that is, flow in equals flow out), the detention time determined by tracer tests is valid for calculating CT when the basin is operating at water levels greater than or equal to the level at which the test was performed. If the water level during testing is higher than the normal operating level, the resulting concentration profile will predict an erroneously high detention time. Conversely, extremely low water levels during testing may lead to an overly conservative detention time. Therefore, when conducting a tracer study to determine the detention time, a water level at or slightly below, but not above, the normal minimum operating level is recommended.

For many plants, the water level in a clearwell or storage tank varies between high and low levels in response to distribution system demands. In such instances, in order to obtain a conservative estimate of the contact time, the tracer study should be conducted during a period when the tank level is falling (flow out greater than flow in). This procedure will provide a detention time for the contact basin, which is also valid when the water level is rising (flow out less than flow in) from a level that is at or above the level when the T_{10} was determined by the tracer study. Whether the water level is constant or variable, the tracer study for each segment should be repeated for several different flows, as described in the previous segment.

For clearwells that are operated with extreme variations in water level, maintaining a CT to comply with inactivation requirements may be impractical. Under such operating conditions, a reliable detention time is not provided for disinfection. However, the system may install a weir to ensure a minimum water level and provide a reliable detention time.

Systems comprised of storage reservoirs that experience seasonal variations in water levels might perform tracer studies during the various seasonal conditions. For these systems, tracer tests should be conducted at several flow rates and representative water levels that occur for each seasonal condition. The results of these tests can be used to develop hydraulic profiles of the reservoir for each water level. These profiles can be

plotted on the same axis of T_{10} vs. Q and may be used for calculating CT for different water levels and flow rates.

Detention time may also be influenced by differences in water temperature within the system. For plants with potential for thermal stratification, additional tracer studies are suggested under the various seasonal conditions that are likely to occur. The contact times determined by the tracer studies under the various seasonal conditions should remain valid as long as no physical changes are made to the mixing basin(s) or storage reservoir(s).

The portion of the system with a measurable contact time between two points of disinfection or residual monitoring is referred to as a segment. For systems that apply disinfectant(s) at more than one point, or choose to profile the residual from one point of application, tracer studies should be conducted to determine T_{10} for each segment containing process unit(s). The T_{10} for a segment may or may not include a length of pipe and is used along with the residual disinfectant concentration prior to the next disinfectant application or monitoring point to determine the CTcalc for that segment. The inactivation ratio for the segment is then determined. The total inactivation and log inactivation achieved in the system can then be determined by summing the inactivation ratios for all segments as explained in Section 3.5.

For systems that have two or more units of identical size and configuration, tracer studies only need to be conducted on one of the units. The resulting graph of T_{10} vs. flow can be used to determine T_{10} for all identical units.

Systems with more than one segment in the treatment plant may determine T_{10} for each segment:

- By individual tracer studies through each segment, or
- By one tracer study across the system.

If possible, tracer studies should be conducted on each segment to determine the T_{10} for each segment. In order to minimize the time needed to conduct studies on each segment, the tracer studies should be started at the last segment of the treatment train prior to the first customer and completed with the first segment of the system. Conducting the tracer studies in this order will prevent the interference of residual tracer material with subsequent studies.

However, it may not always be practical for systems to conduct tracer studies for each segment because of time and manpower constraints. In these cases, one tracer study may be used to determine the T_{10} values for all of the segments at one flow rate. This procedure involves the following steps:

- Add tracer at the beginning of the furthest upstream disinfection segment.
- Measure the tracer concentration at the end of each disinfection segment.

- Determine the T_{10} to each monitoring point, as outlined in the data evaluation examples presented in Section D.1.7.

- Subtract T_{10} values of each of the upstream segments from the overall T_{10} value to determine the T_{10} of each downstream segment.

This approach is valid for a series of two or more consecutive segments as long as all process units within the segments experience the same flow condition. This approach is illustrated by Hudson (1975) in which step-dose tracer tests were employed to evaluate the baffling characteristics of flocculators and settling basins at six water treatment plants. At one plant, tracer chemical was added to the rapid mix, which represented the beginning of the furthest upstream disinfection segment in the system. Samples were collected from the flocculator and settling basin outlets, and analyzed to determine the residence-time characteristics for each segment. Tracer measurements at the flocculator outlet indicated an approximate T_{10} of 5 minutes through the rapid mix, interbasin piping, and flocculator. Based on tracer concentration monitoring at the settling basin outlet, an approximate T_{10} of 70 minutes was determined for the combined segments, including the rapid mix, interbasin piping, flocculator, and settling basin. The flocculator T_{10} of 5 minutes was subtracted from the combined segments' T_{10} of 70 minutes, to determine the T_{10} for the settling basin alone (65 minutes).

This approach may also be applied in cases where disinfectant application and/or residual monitoring is discontinued at any point between two or more segments with known T_{10} values. These T_{10} values may be summed to obtain an equivalent T_{10} for the combined segments.

For ozone contactors, flocculators or any basin containing mixing, tracer studies should be conducted for the range of mixing used in the process. In ozone contactors, air or oxygen should be added in lieu of ozone to prevent degradation of the tracer. The flow rate of air or oxygen used for the contactor should be applied during the study to simulate actual operation. Tracer studies should then be conducted at several air/oxygen to water ratios to provide data for the complete range of ratios used at the plant. For flocculators, tracer studies should be conducted for various mixing intensities to provide data for the complete range of operations.

D.1.3 Tracer Study Methods

This section discusses the two most common methods of tracer addition employed in water treatment evaluations, the step-dose method and the slug-dose method. Tracer study methods involve the application of chemical dosages to a system, and tracking the resulting effluent concentration as a function of time. The effluent concentration profile is evaluated to determine the detention time, T_{10}.

While both tracer test methods can use the same tracer materials and involve measuring the concentration of tracer with time, each has distinct advantages and disadvantages with respect to tracer addition procedures and analysis of results.

The step-dose method entails introduction of a tracer chemical at a constant dosage until the concentration at the desired end point reaches a steady-state level. Step-dose tracer studies are frequently employed in drinking water applications for the following reasons:

- The resulting normalized concentration vs. time profile is directly used to determine T_{10}, the detention time required for calculating CT, and
- Very often, the necessary feed equipment is available to provide a constant rate of application of the tracer chemical

One other advantage of the step-dose method is that the data may be verified by comparing the concentration versus elapsed time profile for samples collected at the start of dosing with the profile obtained when the tracer feed is discontinued.

Alternatively, with the slug-dose method, a large instantaneous dose of tracer is added to the incoming water and samples are taken at the exit of the unit over time as the tracer passes through the unit. A disadvantage of this technique is that very concentrated solutions are needed for the dose in order to adequately define the concentration versus time profile. Intensive mixing is therefore required to minimize potential density-current effects and to obtain a uniform distribution of the instantaneous tracer dose across the basin. This is inherently difficult under water flow conditions often existing at inlets to basins. Other disadvantages of using the slug-dose method include:

- The concentration and volume of the instantaneous tracer dose must be carefully computed to provide an adequate tracer profile at the effluent of the basin;
- The resulting concentration vs. time profile cannot be used to directly determine T_{10} without further manipulation; and
- A mass balance on the treatment segment is required to determine whether the tracer was completely recovered.

One advantage of this method is that it may be applied where chemical feed equipment is not available at the desired point of addition, or where the equipment available does not have the capacity to provide the necessary concentration of the chosen tracer chemical. Although, in general, the step-dose procedure offers the greatest simplicity, both methods are theoretically equivalent for determining T_{10}. Either method is acceptable for conducting drinking water tracer studies, and the choice of the method may be determined by site-specific constraints or the system's experience.

D.1.4 Tracer Selection

An important step in any tracer study is the selection of a chemical to be used as the tracer. Ideally, the selected tracer chemical should be readily available, conservative (that is, not consumed or removed during treatment), easily monitored, and acceptable for use in potable water supplies. Historically, many chemicals have been used in tracer

studies that do not satisfy all of these criteria, including potassium permanganate, alum, chlorine, and sodium carbonate. However, chloride and fluoride are the most common tracer chemicals employed in drinking water plants that are nontoxic and approved for potable water use. Rhodamine WT can be used as a fluorescent tracer in water flow studies in accordance with the following guidelines:

- Raw water concentrations should be limited to a maximum concentration of 10 mg/L;
- Drinking water concentrations should not exceed 0.1 ug/L;
- Studies that result in human exposure to the dye must be brief and infrequent; and
- Concentrations as low as 2 mg/L can be used in tracer studies because of the low detection level in the range of 0.1 to 0.2 ug/L.

The use of Rhodamine B as a tracer in water flow studies is not recommended by the EPA.

The choice of a tracer chemical can be made based, in part, on the selected dosing method and also on the availability of chemical feeding equipment. For example, the high density of concentrated salt solutions and their potential for inducing density currents usually precludes chloride and fluoride as the selected chemical for slug-dose tracer tests.

Fluoride can be a convenient tracer chemical for step-dose tracer tests of clearwells because it is frequently applied for finished water treatment. However, when fluoride is used in tracer tests on clarifiers, allowances should be made for fluoride that is absorbed on floc and settles out of water (Hudson, 1975). Additional considerations when using fluoride in tracer studies include:

- It is difficult to detect at low levels,
- Many states impose a finished water limitation of 1 mg/L, and
- The federal secondary and primary drinking water standards (i.e., the MCLs) for fluoride are 2 and 4 mg/L, respectively.

For safety reasons, particularly for people on dialysis fluoride is not recommended for use as a tracer in systems that normally do not fluoridate their water. The use of fluoride is only recommended in cases where the feed equipment is already in place. The system may wish to turn off the fluoride feed in the plant for 12 or more hours prior to beginning the fluoride feed for the tracer study. Flushing out fluoride residuals from the system prior to conducting the tracer study, is recommended to reduce background levels and avoid spiked levels of fluoride that might exceed EPA's MCL or SMCL for fluoride in drinking water.

In instances where only one of two or more parallel units is tested, flow from the other units would dilute the tracer concentration prior to leaving the plant and entering the distribution system. Therefore, the impact of drinking water standards on the use of fluoride and other tracer chemicals can be alleviated in some cases.

D.1.5 Tracer Addition

The tracer chemical should be added at the same point(s) in the treatment train as the disinfectant to be used in the CT calculations.

D.1.5.1 Step-dose Method

The duration of tracer addition is dependent on the volume of the basin, and hence, it's theoretical detention time. In order to approach a steady-state concentration in the water exiting the basin, tracer addition and sampling should usually be continued for a period of two to three times the theoretical detention time (Hudson, 1981). It is not necessary to reach a steady-state concentration in the exiting water to determine T_{10}; however, it is necessary to determine tracer recovery. It is recommended that the tracer recovery be determined to identify hydraulic characteristics or density problems. Generally, a 90 percent recovery is considered to provide reliable results for the evaluation of T_{10}.

In all cases, the tracer chemical should be dosed in sufficient concentration to easily monitor a residual at the basin outlet throughout the test. The required tracer chemical concentration is generally dependent upon the nature of the chosen tracer chemical including its background concentration, and the mixing characteristics of the basin to be tested. Recommended chloride doses on the order of 20 mg/L (Hudson, 1975) should be used for step-method tracer studies where the background chloride level is less than 10 mg/L. Also, fluoride concentrations as low as 1.0 to 1.5 mg/L are practical when the raw water fluoride level is not significant (Hudson, 1975). However, tracer studies conducted on systems suffering from serious short-circuiting of flow may require substantially larger step-doses. This would be necessary to detect the tracer chemical and to adequately define the effluent tracer concentration profile.

D.1.5.2 Slug-dose Method

The duration of tracer measurements using the slug-dose method is also dependent on the volume of the basin, and hence, it's theoretical detention time. In general, samples should be collected for at least twice the basin's theoretical detention time, or until tracer concentrations are detected near background levels. In order to get reliable results for T_{10} values using the slug-dose method it is recommended that the total mass of tracer recovered be approximately 90 percent of the mass applied. This guideline requires sampling until the tracer concentration recedes to the background level. The total mass recovered during testing will not be known until completion of the testing and analysis of the data collected. The sampling period needed is very site specific. Therefore, it may be helpful to conduct a first run tracer test as a screen to identify the appropriate sampling period for gathering data to determine T_{10}.

Tracer addition for slug-dose method tests should be instantaneous and provide uniformly mixed distribution of the chemical. Tracer addition is considered instantaneous if the dosing time does not exceed 2 percent of the basin's theoretical detention time (Marske and Boyle, 1973). One recommended procedure for achieving instantaneous tracer dosing is to apply the chemical by gravity flow through a funnel and hose apparatus. This method is also beneficial because it provides a means of standardization, which is necessary to obtain reproducible results.

The mass of tracer chemical to be added is determined by the desired theoretical concentration and basin size. The mass of tracer added in slug-dose tracer tests should be the minimum mass needed to obtain detectable residual measurements to generate a concentration profile. As a guideline, the theoretical concentration for the slug-dose method should be comparable to the constant dose applied in step-dose tracer tests, (i.e., 10 to 20 mg/L and 1 to 2 mg/L for chloride and fluoride, respectively). The maximum mass of tracer chemical needed is calculated by multiplying the theoretical concentration by the total basin volume. This is appropriate for systems with high dispersion and/or mixing. This quantity is diluted as required to apply an instantaneous dose, and minimize density effects. It should be noted that the mass applied is not likely to get completely mixed throughout the total volume of the basin. Therefore, the detected concentration might exceed theoretical concentrations based on the total volume of the basin. For these cases, the mass of chemical to be added can be determined by multiplying the theoretical concentration by only a portion of the basin volume. An example of this is shown in Section D.1.7.2 for a slug-dose tracer study. In cases where the tracer concentration in the effluent must be maintained below a specified level, it may be necessary to conduct a preliminary test run with a minimum tracer dose to identify the appropriate dose for determining T_{10} without exceeding this level.

D.1.6 Test Procedure

In preparation for beginning a tracer study, the raw water background concentration of the chosen tracer chemical must be established. The background concentration is essential, not only for aiding in the selection of the tracer dosage, but also to facilitate proper evaluation of the data.

The background tracer concentration should be determined by monitoring for the tracer chemical prior to beginning the test. The sampling point(s) for the pre-tracer study monitoring should be the same as the points to be used for residual monitoring to determine CT values. The monitoring procedure is outlined in the following steps:

If the tracer chemical is normally added for treatment, discontinue its addition to the water in sufficient time to permit the tracer concentration to recede to its background level before the test is begun.

- Prior to the start of the test, regardless of whether the chosen tracer material is a treatment chemical, the tracer concentration in the water is monitored at the

sampling point where the disinfectant residual will be measured for CT calculations.

- If a background tracer concentration is detected, monitor it until a constant concentration, at or below the raw water background level is achieved. This measured concentration is the baseline tracer concentration.

Following the determination of the tracer dosage, feed and monitoring point(s), and a baseline tracer concentration, tracer testing can begin.

Equal sampling intervals, as could be obtained from automatic sampling, are not required for either tracer study method. However, using equal sample intervals for the slug-dose method can simplify the analysis of the data. During testing, the time and tracer residual of each measurement should also be recorded on a data sheet. In addition, the water level, flow, and temperature should be recorded during the test.

D.1.6.1 Step-dose Method

At time zero, the tracer chemical feed will be started and left at a constant rate for the duration of the test. Over the course of the test, the tracer residual should be monitored at the required sampling point(s) at a frequency determined by the overall detention time and site-specific considerations As a general guideline, sampling at intervals of 2 to 5 minutes should provide data for a well-defined plot of tracer concentration vs. time. If on-site analysis is available, less frequent residual monitoring may be possible until a change in residual concentration is first detected. As a guideline, in systems with a theoretical detention time greater than 4 hours, sampling may be conducted every 10 minutes for the first 30 minutes, or until a tracer concentration above the baseline level is first detected. In general, shorter sampling intervals enable better characterization of concentration changes; therefore, sampling should be conducted at 2 to 5-minute intervals from the time that a concentration change is first observed until the residual concentration reaches a steady-state value. A reasonable sampling interval should be chosen based on the overall detention time of the unit being tested.

If verification of the test is desired, the tracer feed should be discontinued, and the receding tracer concentration at the effluent should be monitored at the same frequency until tracer concentrations corresponding to the background level are detected. The time at which tracer feed is stopped is time zero for the receding tracer test and must be noted. The receding tracer test will provide a replicate set of measurements that can be compared with data derived from the rising tracer concentration versus time curve. For systems which currently feed the tracer chemical, the receding curve may be generated from the time the feed is turned off to determine the background concentration level.

D.1.6.2 Slug-dose Method

At time zero for the slug-dose method, a large instantaneous dose of tracer will be added to the influent of the unit. The same sampling locations and frequencies described for step-dose method tests also apply to slug-dose method tracer studies. One exception with

this method is that the tracer concentration profile will not equilibrate to a steady-state concentration. Because of this, the tracer should be monitored frequently enough to ensure acquisition of data needed to identify the peak tracer concentration.

Slug-dose method tests should be checked by performing a material balance to ensure that all of the tracer fed is recovered, or, mass applied equals mass discharged.

D.1.7 Data Evaluation

Data from tracer studies should be summarized in tables of time and residual concentration. These data are then analyzed to determine the detention time, T_{10}, to be used in calculating CT. Tracer test data from either the step-dose or slug-dose method can be evaluated graphically, numerically, or by a combination of these techniques.

D.1.7.1 Step-dose Method

The graphical method of evaluating step-dose test data involves plotting a graph of dimensionless concentration (C/Co) versus time and reading the value for T_{10} directly from the graph at the appropriate dimensionless concentration. Alternatively, the data from step-dose tracer studies may be evaluated numerically by developing a semi-logarithmic plot of the dimensionless data. The semi-logarithmic plot allows a straight line to be drawn through the data. The resulting equation of the line is used to calculate the T_{10} value, assuming that the correlation coefficient indicates a good statistical fit (0.9 or above). Drawing a smooth curve through the data discredits scattered data points from step-dose tracer tests.

An illustration of the T_{10} determination will be presented in an example of the data evaluation required for a clearwell tracer study.

D.1.7.2 Slug-dose Method

Data from slug-dose tracer tests is analyzed by converting it to the mathematically equivalent step-dose data and using techniques discussed in Section D.1.7.1 to determine T_{10}. A graph of dimensionless concentration versus time should be drawn which represents the results of a slug-dose tracer test. The key to converting between the data forms is obtaining the total area under the slug-dose data curve. This area is found by graphically or numerically integrating the curve. The conversion to step-dose data is then completed in several mathematical steps involving the total area.

A graphical technique for converting the slug-dose data involves physically measuring the area using a planimeter. The planimeter is an instrument used to measure the area of a plane closed curve by tracing its boundary. Calibration of this instrument to the scale of the graph is required to obtain meaningful readings.

The rectangle rule is a simple numerical integration method that approximates the total area under the curve as the sum of the areas of individual rectangles. These rectangles

have heights and widths equal to the residual concentration and sampling interval (time) for each data point on the curve, respectively. Once the data has been converted, T_{10} may be determined in the same manner as data from step-dose tracer tests.

Slug-dose concentration profiles can have many shapes, depending on the hydraulics of the basin. Therefore, slug-dose data points should not be discredited by drawing a smooth curve through the data prior to its conversion to step-dose data. The steps and specific details involved with evaluating data from both tracer study methods are illustrated in the following examples.

Example for Determining T_{10} in a Clearwell

Two tracer studies employing the step-dose and slug-dose methods of tracer addition were conducted for a clearwell with a theoretical detention time, T, of 30 minutes at an average flow of 2.5 MGD. Because fluoride is added at the inlet to the clearwell as a water treatment chemical, necessary feed equipment was in place for dosing a constant concentration of fluoride throughout the step-dose tracer test. Based on this convenience, fluoride was chosen as the tracer chemical for the step-dose method test. Fluoride was also selected as the tracer chemical for the slug-dose method test. Prior to the start of testing, a fluoride baseline concentration of 0.2 mg/L was established for the water exiting the clearwell.

Step-dose Method Test

For the step-dose test a constant fluoride dosage of 2.0 mg/L was added to the clearwell inlet. Fluoride levels in the clearwell effluent were monitored and recorded every 3 minutes. The raw tracer study data, along with the results of further analyses are shown in Table D-1.

The steps in evaluating the raw data shown in the first column of Table D-1 are as follows. First, the baseline fluoride concentration, 0.2 mg/L, is subtracted from the measured concentration to give the fluoride concentration resulting from the tracer study addition alone. For example, at elapsed time = 39 minutes, the tracer fluoride concentration, C, is obtained as follows:

$$C = C_{measured} - C_{baseline}$$

$$= 1.85 \text{ mg/L} - 0.2 \text{ mg/L}$$

$$= 1.65 \text{ mg/L}$$

This calculation was repeated at each time interval to obtain the data shown in the third column of Table D-1. As indicated, the fluoride concentration rises from 0 mg/L at t = 0 minutes to the applied fluoride dosage of 2 mg/L, at t = 63 minutes.

The next step is to develop dimensionless concentrations by dividing the tracer concentrations in the second column of Table D-1 by the applied fluoride dosage, Co = 2 mg/L. For time = 39 minutes, C/Co is calculated as follows:

$$C/Co = (1.65 \text{ mg/L})/(2.0 \text{ mg/L})$$

$$= 0.82$$

The resulting dimensionless data, presented in the fourth column of Table D-1, is the basis for completing the determination of T_{10} by either the graphical or numerical method.

TABLE D-1. CLEARWELL DATA - STEP-DOSE TRACER TEST[1,2,3]

	Fluoride Concentration		
t (minutes)	Measured (mg/L)	Tracer (mg/L)	Dimensionless (C/Co)
0	0.20	0	0
3	0.20	0	0
6	0.20	0	0
9	0.20	0	0
12	0.29	0.09	0.045
15	0.67	0.47	0.24
18	0.94	0.74	0.37
21	1.04	0.84	0.42
24	1.44	1.24	0.62
27	1.55	1.35	0.68
30	1.52	1.32	0.66
33	1.73	1.53	0.76
36	1.93	1.73	0.86
39	1.85	1.65	0.82
42	1.92	1.72	0.86
45	2.02	1.82	0.91
48	1.97	1.77	0.88
51	1.84	1.64	0.82
54	2.06	1.86	0.93
57	2.05	1.85	0.92
60	2.10	1.90	0.95
63	2.14	1.94	0.96

1. Baseline conc. = 0.2 mg/L, fluoride dose = 2.0 mg/L
2. Measured conc. = Tracer conc. + Baseline conc.
3. Tracer conc. = Measured conc. - Baseline conc.

In order to determine T_{10} by the graphical method, a plot of C/Co vs. time should be generated using the data in Table D-1. A smooth curve should be drawn through the data as shown on Figure D-1.

T_{10} is read directly from the graph at a dimensionless concentration (C/Co) corresponding to the time for which 10 percent of the tracer has passed at the effluent end of the contact basin (T_{10}). For step-dose method tracer studies, this dimensionless concentration is C/Co = 0.10 (Levenspiel, 1972).

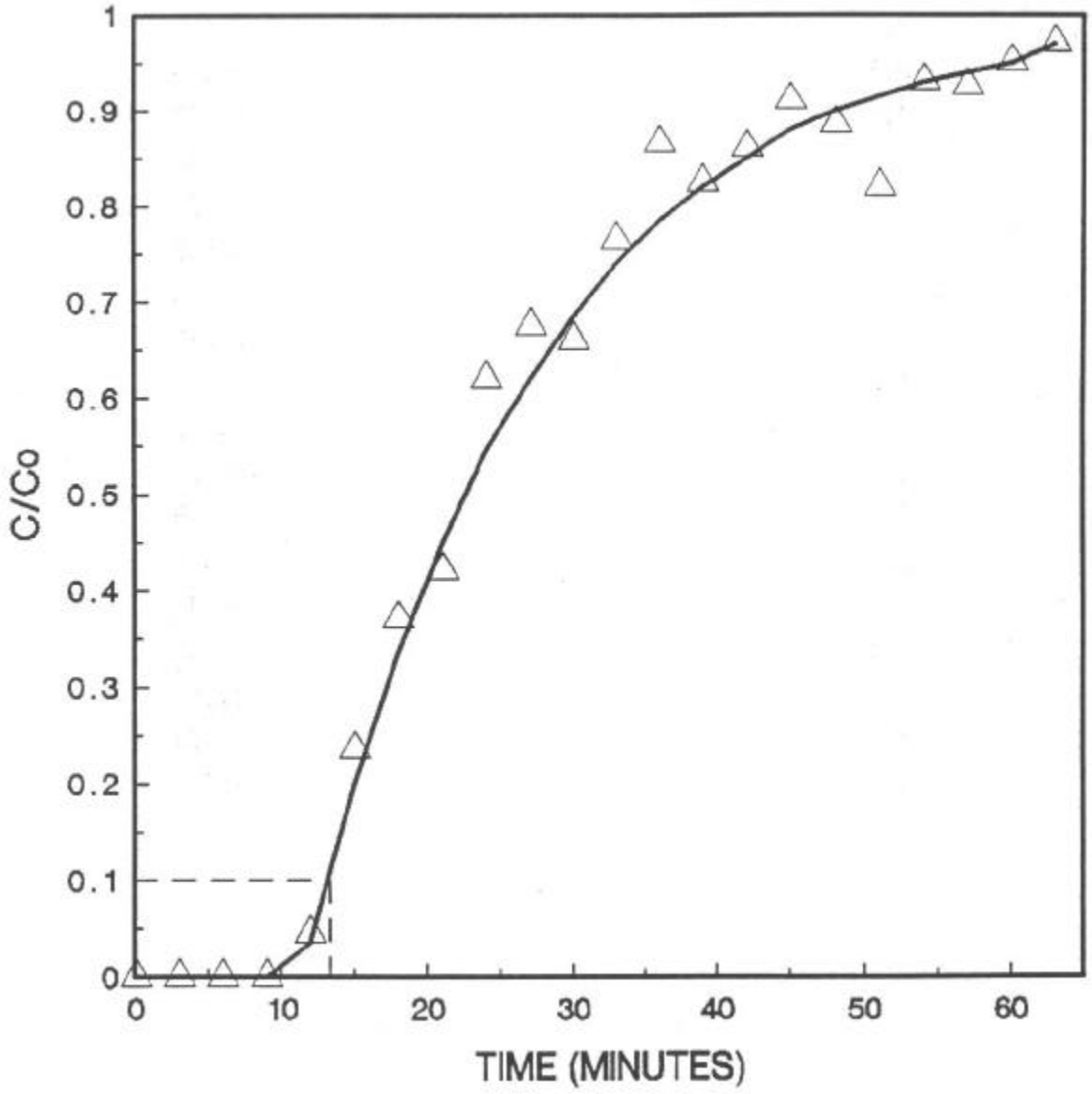


Figure D-1. C/Co vs. Time — Graphical Analysis for T_{10}

T_{10} should be read directly from Figure D-1 at C/Co = 0.1 by first drawing a horizontal line (C/Co = 0.1) from the Y-axis (t = 0) to its intersection with the smooth curve drawn through the data. At this point of intersection, the time read from the X-axis is T_{10} and may be found by extending a vertical line downward to the X-axis. These steps were performed as illustrated on Figure D-1, resulting in a value for T_{10} of approximately 13 minutes.

For the numerical method of data analysis, several additional steps are required to obtain T_{10} from the data in the fourth column of Table D-1. The forms of data necessary for determining T_{10} through a numerical solution are $\log_{10}$ (1-C/Co) and t/T, the elapsed time divided by the theoretical residence time. These are obtained by performing the required mathematical operations on the data in the fourth column of Table D-1. For example, recalling that the theoretical detention time, T, is 30 minutes, the values for $\log_{10}$ (1-C/Co) and t/T are computed as follows for the data at t = 39 minutes:

$$1\log_{10}(1\text{-}C/Co) = \log_{10}(1\text{-}0.82)$$
$$= \log_{10}(0.18)$$
$$= -0.757$$
$$t/T = 39\ \text{min}/30\ \text{min} = 1.3$$

This calculation was repeated at each time interval to obtain the data shown in Table D-2. These data should be linearly regressed as $1\log_{10}$ (1-C/Co) versus t/T to obtain the fitted straight-line parameters to the following equation:

$$\textbf{(1)} \qquad \mathbf{1\log_{10}(1\text{-}C/Co) = m(t/T) + b}$$

In equation 1, m and b are the slope and intercept, respectively, for a plot of $1\log_{10}$ (1-C/Co) vs. t/T. This equation can be used to calculate T_{10}, assuming that the correlation coefficient for the fitted data indicates a good statistical fit (0.9 or above).

A linear regression analysis was performed on the data in Table D-2, resulting in the following straight-line parameters:

$$\text{slope} = m = -0.774$$
$$\text{intercept} = b = 0.251$$
$$\text{correlation coefficient} = 0.93$$

Table D-2. Data For Numerical Determination Of T_{10}

t / T	Log_{10} (1-C/Co)
0	0
0.1	0
0.2	0
0.3	0
0.4	-0.020
0.5	-0.116
0.6	-0.201
0.7	-0.237
0.8	-0.420
0.9	-0.488
1.0	-0.468
1.1	-0.629
1.2	-0.870
1.3	-0.757
1.4	-0.854
1.5	-1.046
1.6	-0.939
1.7	-0.745
1.8	-1.155
1.9	-1.125
2.0	-1.301
2.1	-1.532

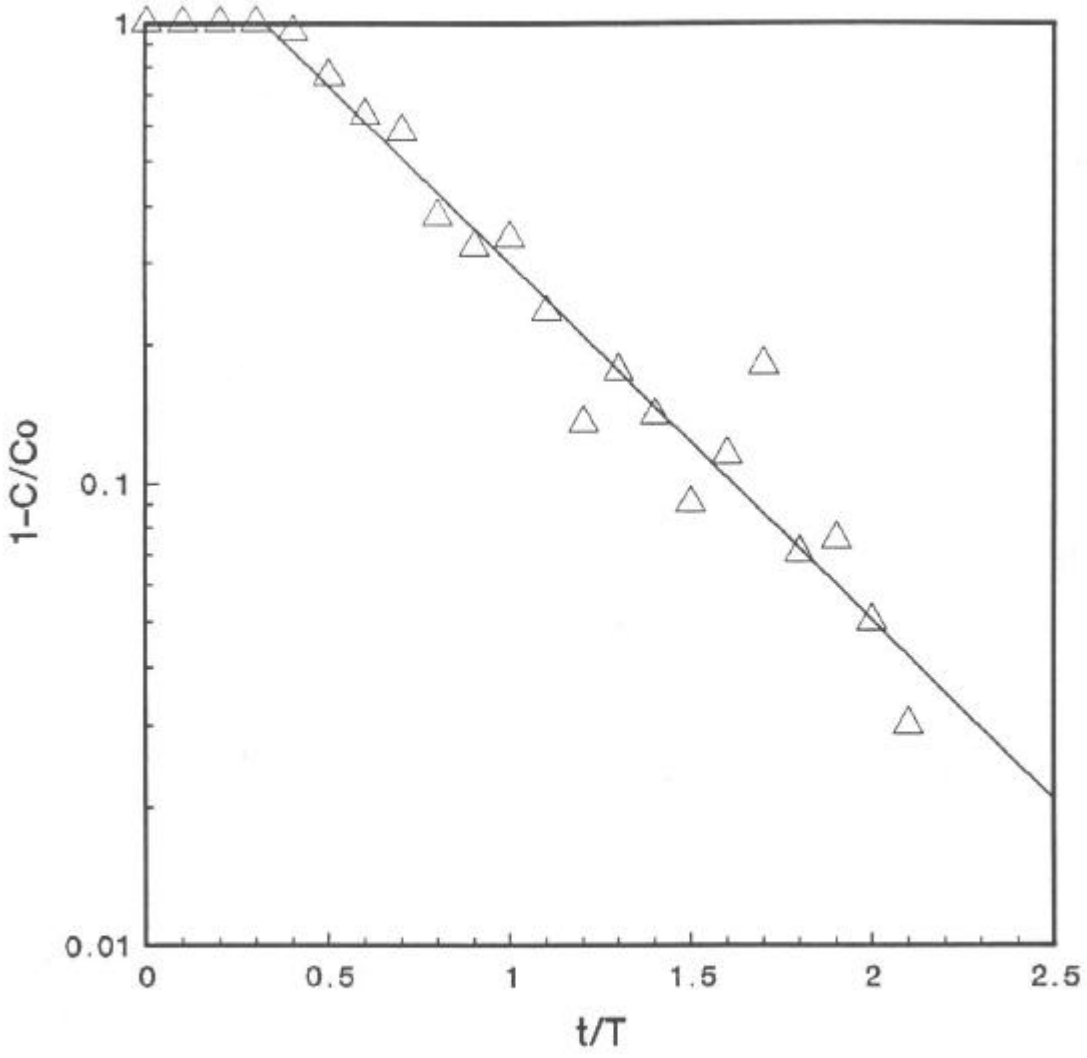
Although these numbers were obtained numerically, a plot of $1og_{10}$ (1-C/Co) versus t/T is shown for illustrative purposes on Figure D-2 for the data in Table D-2. In this analysis, data for time = 0 through 9 minutes were excluded because fluoride concentrations above the baseline level were not observed in the clearwell effluent until t = 12 minutes.

Equation 1 is then rearranged in the following form to facilitate a solution for T_{10}:

$$\textbf{(2)} \qquad T_{10}/T = (\log_{10}(1 - 0.1) - b)/m$$

In equation 2, as with graphical method, T_{10} is determined at the time for which C/Co = 0.1. Therefore, in equation 2, C/Co has been replaced by 0.1 and t (time) by T_{10}. To obtain a solution for T_{10}, the values of the slope, intercept, and theoretical detention time are substituted as follows:

$$T_{10}/30 \text{ min.} = (1\log_{10}(1 - 0.1) - 0.251)/(-0.774)$$
$$T_{10} = 12 \text{ minutes}$$



Slope, m = -0.774
Intercept, b = 0.251

Correlation Coefficient = 0.93

10

In summary both the graphical and numerical methods of data reduction resulted in comparable, but not identical values for T_{10}. With the numerical method, T_{10} was determined as the solution to an equation based on the straight-line parameters to a linear regression analysis of the tracer study data instead of an "eyeball' estimate from a data plot.

Slug-dose Method Test

A slug-dose tracer test was also performed on the clearwell at a flow rate of 2.5 mgd. A theoretical clearwell fluoride concentration of 2.2 mg/L was selected. The fluoride dosing volume and concentration were determined from the following considerations:

Dosing Volume

- The fluoride injection apparatus consisted of a funnel and a length of copper tubing. This apparatus provided a constant volumetric feeding rate of 7.5 liters per minute (L/min) under gravity flow conditions.

- At a flow rate of 2.5 mgd, the clearwell has a theoretical detention time of 30 minutes. Since the duration of tracer injection should be less than 2 percent of the clearwell's theoretical detention time for an instantaneous dose, the maximum duration of fluoride injection was:

  Max. dosing time = 30 minutes x .02 = 0.6 minutes

- At a dosing rate of 7.5 L/min, the maximum fluoride dosing volume is calculated to be:

  Max. dosing volume = 7.5 L/min. x 0.6 minutes = 4.5 L

For this tracer test, a dosing volume of 4 liters was selected, providing an instantaneous fluoride dose in 1.8 percent of the theoretical detention time.

Fluoride Concentration

- The theoretical detention time of the clearwell, 30 minutes, was calculated by dividing the clearwell volume, 52,100 gallons or 197,200 liters, by the average flow rate through the clearwell, 2.5 mgd.

- Assuming the tracer is completely dispersed throughout the total volume of the clearwell, the mass of fluoride required to achieve a theoretical concentration of 2.2 mg/L is calculated as follows:

  $$\text{Fluoride mass (initial)} = 2.2\ \text{mg/L} \times 197{,}200\ \text{L} \times \frac{1g}{1000mg} = 434\text{g}$$

- The concentration of the instantaneous fluoride dose is determined by dividing this mass by the dosing volume, 4 liters:

  $$\text{Fluoride concentration} = \frac{434g}{4L} = 109\ \text{g/L}$$

Fluoride levels in the exit to the clearwell were monitored and recorded every 3 minutes. The raw slug-dose tracer test data are shown in Table D-3.

The first step in evaluating the data for different times is to subtract the baseline fluoride concentration, 0.2 mg/L, from the measured concentration at each sampling interval (Table D-3). This is the same as the first step used to evaluate step-dose method data and gives the fluoride concentrations resulting from the tracer addition alone, shown in the third column of Table D-3. As indicated, the fluoride concentration rises from 0 mg/L at t = 0 minutes to the peak concentration of 3.6 mg/L at t = 18 minutes. The exiting fluoride concentration gradually recedes to near zero at t = 63 minutes. It should be noted that a maximum fluoride concentration of 2.2 mg/L is based on assuming complete mixing of the tracer added throughout the total clearwell volume. However, as shown in Table D-3, the fluoride concentrations in the clearwell effluent exceeded 2.2 mg/L for about 6 minutes between 14 and 20 minutes. These higher peak concentrations are caused by the dispersion of tracer throughout only a portion of the total clearwell volume. If a lower tracer concentration is needed in the effluent because of local or federal regulations, the mass to be added should be decreased accordingly.

The dimensionless concentrations in the fourth column of Table D-3 were obtained by dividing the tracer concentrations in the third column by the clearwell's theoretical concentration, Co = 2.2 mg/L. These dimensionless concentrations were then plotted as a function of time, as is shown by the slug-dose data on Figure D-3. These data points were connected by straight lines, resulting in a somewhat jagged curve.

The next step in evaluating slug-dose data is to determine the total area under the slug-dose data curve on Figure D-3. Two methods exist for finding this area - graphical and numerical. The graphical method is based on a physical measurement of the area using a planimeter. This involves calibration of the instrument to define the units' conversion and tracing the outline of the curve to determine the area. The results of performing this procedure may vary depending on instrument accuracy and measurement technique. Therefore, only an illustration of the numerical technique for finding the area under the slug-dose curve will be presented for this example.

The area obtained by either the graphical or numerical method would be similar. Furthermore, once the area is found, the remaining steps involved with converting the data to the step-dose response are the same.

Table D-3. Clearwell Data — Slug-Dose Tracer Test[1,2,3]

	Fluoride Concentration		
T (Minutes)	Measured (mg/L)	Tracer (mg/L)	Dimensionless (C/Co)
0	0.2	0	0
3	0.2	0	0
6	0.2	0	0
9	0.2	0	0
12	1.2	1	0.45
15	3.6	3.4	1.55
18	3.8	3.6	1.64
21	2.0	1.8	0.82
24	2.1	1.9	0.86
27	1.4	1.2	0.55
30	1.3	1.1	0.50
33	1.5	1.3	0.59
36	1.0	0.8	0.36
39	0.6	0.4	0.18
42	1.0	0.8	0.36
45	0.6	0.4	0.18
48	0.8	0.6	0.27
51	0.6	0.4	0.18
54	0.4	0.2	0.09
57	0.5	0.3	0.14
60	0.6	0.4	0.18
63	0.4	0.2	0.09

1. Measured conc. = Tracer conc. + Baseline conc.
2. Baseline conc. = 0.2 mg/L, fluoride slug dose conc. = 109 g/L, theoretical conc. = 2.2 mg/L.
3. Tracer conc. = Measured conc. – Baseline conc.

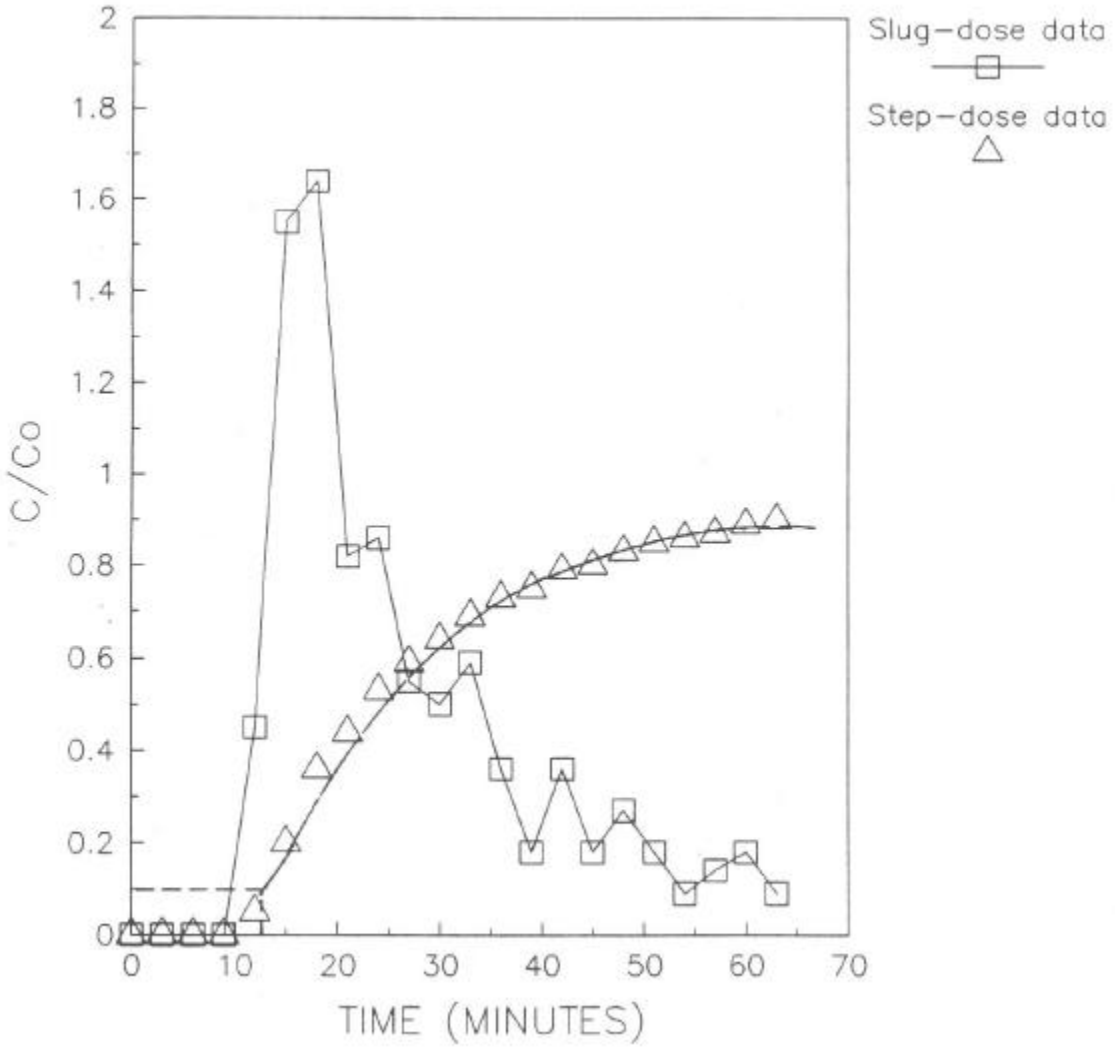

Slug–dose data
Step–dose data
C/Co
TIME (MINUTES)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
10
20
30
40
50
60
70

Table D-4 summarizes the results of determining the total area using a numerical integration technique called the rectangle rule. The first and second columns in Table D-4 are the sampling time and fluoride concentration resulting from tracer addition alone, respectively. The steps in applying these data are as follows. First, the sampling time interval, 3 minutes, is multiplied by the fluoride concentration at the end of the 3-minute interval to give the incremental area, in units of milligram minutes per liter. For example, at elapsed time, t = 39 minutes, the incremental area is obtained as follows:

Incremental area = sampling time interval x fluoride conc.

= 39-36) minutes x 0.4 mg/L

= 0.2 mg-min/L

This calculation was repeated at each time interval to obtain the data shown in the third column of Table D-4.

If the data had been obtained at unequal sampling intervals, then the incremental area for each interval would be obtained by multiplying the fluoride concentration at the end of each interval by the time duration of the interval. This convention also requires that the incremental area be zero at the first sampling point, regardless of the fluoride concentration at that time.

As is shown in Table D-4, all incremental areas were summed to obtain 59.4 mg-min/L, the total area under the slug-dose tracer test curve. This number represents the total mass of fluoride that was detected during the course of the tracer test divided by the average flow rate through the clearwell.

To complete the conversion of slug-dose data to its equivalent step-dose response requires two additional steps. The first involves summing, consecutively, the incremental areas in the third column of Table D-4 to obtain the cumulative area at the end of each sampling interval. For example$_1$ the cumulative area at time, t = 27 minutes is found as follows:

Cumulative area = 0 + 0 + 0 + 0 + 3 + 10.2 + 10.8 + 5.4 + 5.7 + 3.6

= 38.7 mg-min/L

The cumulative areas for each interval are recorded in the fourth column of Table D-4.

Table D-4. Evaluation of Slug-Dose Data

T (Minutes)	Fluoride (mg/L)	Incremental Area (mg-min/L)	Cumulative Area (mg-min/L)	Equivalent Step-Dose Data
0	0	0	0	0
3	0	0	0	0
6	0	0	0	0
9	0	0	0	0
12	1	3	3	0.05
15	3.4	10.2	13.2	0.22
18	3.6	10.8	24.0	0.40
21	1.8	5.4	29.4	0.49
24	1.9	5.7	35.1	0.59
27	1.2	3.6	38.7	0.65
30	1.1	3.3	42.0	0.71
33	1.3	3.9	45.9	0.77
36	0.8	2.4	48.3	0.81
39	0.4	1.2	49.5	0.83
42	0.8	2.4	51.9	0.87
45	0.4	1.2	53.1	0.89
48	0.6	1.8	54.9	0.92
51	0.4	1.2	56.1	0.94
54	0.2	0.6	56.7	0.95
57	0.3	0.9	57.6	0.97
60	0.4	1.2	58.8	0.99
63	0.2	0.6	59.4	1.00
Total Area = 59.4				

The final step in converting slug-dose data involves dividing the cumulative area at each interval by the total mass applied. Total area based on applied mass is calculated as follows:

$$\text{Total area mass applied/average flow} = 434 \text{ g} \times 1000 \frac{mg}{g} \; / \; 6{,}570 \frac{L}{\text{min}}$$

$$= 66.1 \frac{mg\text{-}min}{L}$$

For time = 39 minutes, the resulting step-dose data point is calculated as follows:

$$C/Co = 49.5 \text{ mg-min/L} \; / \; 59.4 \text{ mg-min/L}$$
$$= 0.83$$

The result of performing this operation at each sampling interval is the equivalent step-dose data. These data points are shown in the fifth column of Table D-4 and are also plotted on Figure D-3 to facilitate a graphical determination of T_{10}. A smooth curve was fitted to the step-dose data as shown on the figure.

T_{10} can be determined by the methods illustrated previously in this example for evaluating step-dose tracer test data. The graphical method illustrated on Figure D-3 results in a reading of T_{10} = 15 minutes.

D.1.7.3 Additional Considerations

In addition to determining T_{10} for use in CT calculations, slug-dose tracer tests provide a more general measure of the basin's hydraulics in terms of the fraction of tracer recovery. This number is representative of short-circuiting and dead space in the unit resulting from poor baffling conditions and density currents induced by the tracer chemical. A low tracer recovery is generally indicative of inadequate hydraulics. However, inadequate sampling in which peaks in tracer passage are not measured will also result in an under estimate of tracer recovery. The tracer recovery is calculated by dividing the mass of fluoride detected by the mass of fluoride dosed.

The dosed fluoride mass was calculated previously and was 434 grams. The mass of detected fluoride can be calculated by multiplying the total area under the slug-dose curve by the average flow, in appropriate units, at the time of the test. The average flow in the clearwell during the test was 2.5 mgd or 6,570 L/min. Therefore, the mass of fluoride tracer that was detected is calculated as follows:

$$\text{Detected fluoride mass} = \text{total area} \times \text{average flow}$$

$$= 59.4 \ \frac{mg - min}{L} \times \frac{1\ g}{1000\ mg} \times 6{,}570 \ \frac{L}{min}$$

$$= 390 \text{ g}$$

Tracer recovery is then calculated as follows:

$$\text{Fluoride recovery} = \text{detected mass/dosed mass} \times 100$$

$$= 390 \text{ g} / 434 \text{ g} \times 100$$

$$= 90 \%$$

This is a typical tracer recovery percentage for a slug-dose test, based on the experiences of Hudson (1975) and Thirumurthi (1969).

D.1.8 Flow Dependency of T_{10}

For systems conducting tracer studies at four or more flows, the T_{10} detention time should be determined by the above procedures for each of the desired flows. The detention times should then be plotted versus flow. For the example presented in the previous section, tracer studies were conducted at additional flows of 1.1, 4.2, and 5.6 MGD. The T_{10} values at the various flows were:

Flow	T_{10}
1.1	25
2.5	13
4.2	7
5.6	4

T_{10} data for these tracer studies were plotted as a function of the flow, Q, as shown in Figure D-4.

If only one tracer test is performed, the flow rate for the tracer study should be not less than 91 percent of the highest flow rate experienced for the segment. The hydraulic profile to be used for calculating CT would then be generated by drawing a line through points obtained by multiplying the T_{10} at the tested flow rate by the ratio of the tracer study flow rate to each of several different flows in the desired flow range.

For the example presented in the previous section, the clearwell experiences a maximum flow at peak hourly conditions of 6.0 mgd. The highest tested flow rate was 5.6 mgd, or 93 percent of the maximum flow. Therefore, the detention time, T_{10} = 4 minutes, determined by the tracer test at a flow rate of 5.6 mgd may be used to provide a conservative estimate of T_{10} for all flow rates less than or equal to the maximum flow rate, 6.0 mgd. The line drawn through points found by multiplying T_{10} = 4 minutes by the ratio of 5.6 mgd to each of several flows less than 5.6 mgd is also shown in Figure D-4 for comparative purposes with the hydraulic profile obtained from performing four tracer studies at different flow rates.

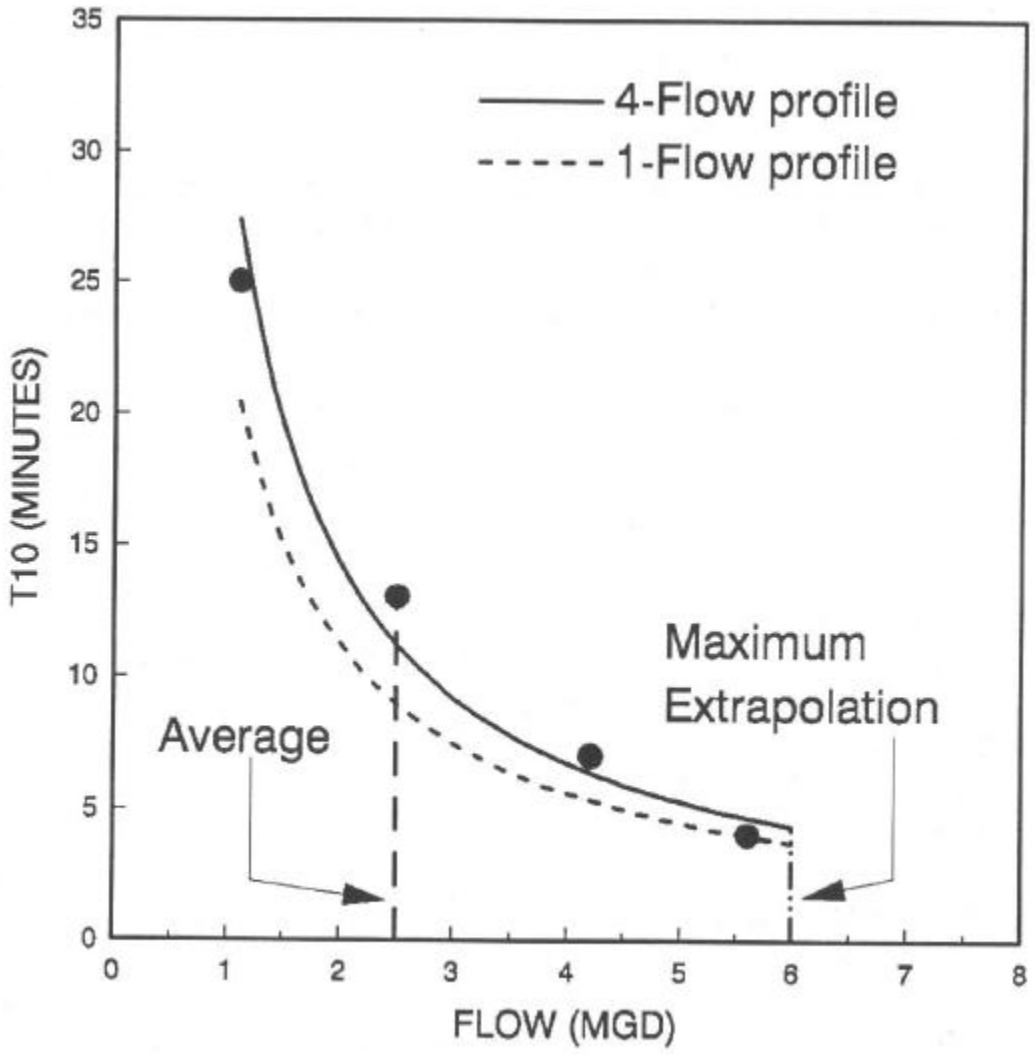


Figure D-4. Detention Time vs. Flow

D.2 Determination of T_{10} without Conducting a Tracer Study

In some situations, conducting tracer studies for determining the disinfectant contact time, T_{10}, may be impractical or prohibitively expensive. The limitations may include a lack of funds, manpower or equipment necessary to conduct the study. For these cases, the Primacy Agency may allow the use of "rule of thumb" fractions representing the ratio of T_{10} to T, and the theoretical detention time, to determine the detention time, T_{10}, to be used for calculating CT values. This method for finding T_{10} involves multiplying the theoretical detention time by the rule of thumb fraction, $T_{.10}/T$, that is representative of the particular basin configuration for which T_{10} is desired. These fractions provide rough estimates of the actual T_{10} and are recommended to be used only on a limited basis.

Tracer studies conducted by Marske and Boyle (1973) and Hudson (1975) on chlorine contact chambers and flocculators/settling basins, respectively, were used as a basis in determining representative T_{10}/T values for various basin configurations. Marske and Boyle (1973) performed tracer studies on 15 distinctly different types of full-scale chlorine contact chambers to evaluate design characteristics that affect the actual detention time. Hudson (1975) conducted 16 tracer tests on several flocculation and settling basins at six water treatment plants to identify the effect of flocculator baffling and settling basin inlet and outlet design characteristics on the actual detention time.

D.2.1 Impact of Design Characteristics

The significant design characteristics include: length-to-width ratio, the degree of baffling within the basins, and the effect of inlet baffling and outlet weir configuration. These physical characteristics of the contact basins affect their hydraulic efficiencies in terms of dead space, plug flow, and mixed flow proportions. The dead space zone of a basin is basin volume through which no flow occurs. The remaining volume where flow occurs is comprised of plug flow and mixed flow zones. The plug flow zone is the portion of the remaining volume in which no mixing occurs in the direction of flow. The mixed flow zone is characterized by complete mixing in the flow direction and is the complement to the plug flow zone. All of these zones were identified in the studies for each contact basin. Comparisons were then made between the basin configurations and the observed flow conditions and design characteristics.

The ratio T_{10}/T was calculated from the data presented in the studies and compared to its associated hydraulic flow characteristics. Both studies resulted in T_{10}/T values that ranged from 0.3 to 0.7. The results of the studies indicate how basin baffling conditions can influence the T_{10}/T ratio, particularly baffling at the inlet and outlet to the basin. As the basin baffling conditions improved, higher T_{10}/T values were observed, with the outlet conditions generally having a greater impact than the inlet conditions.

As discovered from the results of the tracer studies performed by Marske and Boyle (1973) and Hudson (1975), the effectiveness of baffling in achieving a high T_{10}/T fraction is more related to the geometry and baffling of the basin than the function of the basin.

For this reason, T_{10}/T values may be defined for five levels of baffling conditions rather than for particular types of contact basins. General guidelines were developed relating the T_{10}/T values from these studies to the respective baffling characteristics. These guidelines can be used to determine the T_{10} values for specific basins.

D.2.2 Baffling Classifications

The purpose of baffling is to maximize utilization of basin volume, increase the plug flow zone in the basin, and minimize short circuiting. Some form of baffling at the inlet and outlet of the basins is used to evenly distribute flow across the basin. Additional baffling may be provided within the interior of the basin (intra-basin) in circumstances requiring a greater degree of flow distribution. Ideal baffling design reduces the inlet and outlet flow velocities, distributes the water as uniformly as practical over the cross section of the basin, minimizes mixing with the water already in the basin, and prevents entering water from short circuiting to the basin outlet as the result of wind or density current effects. Three general classifications of baffling conditions - poor, average, and superior - were developed to categorize the results of the tracer studies for use in determining T_{10} from the theoretical detention time of a specific basin. The T_{10}/T fractions associated with each degree of baffling are summarized in Table D-5. Factors representing the ratio between T_{10} and the theoretical detention time for plug flow in pipelines and flow in a completely mixed chamber have been included in Table D-5 for comparative purposes. However, in practice the theoretical T_{10}/T values of 1.0 for plug flow and 0.1 for mixed flow are seldom achieved because of the effect of dead space. Conversely, the T_{10}/T values shown for the intermediate baffling conditions already incorporate the effect of the dead space zone, as well as the plug flow zone, because they were derived empirically rather than from theory.

Table D-5. Baffling Classifications

Baffling Condition	T_{10}/T	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities. Can be approximately achieved in flash mix tank
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	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

As indicated in Table D-5, poor baffling conditions consist of an unbaffled inlet and outlet with no intra-basin baffling. Average baffling conditions consist of intra-basin baffling and either a baffled inlet or outlet. Superior baffling conditions consist of at least

a baffled inlet and outlet, and intra-basin baffling to redistribute the flow throughout the basin's cross-section.

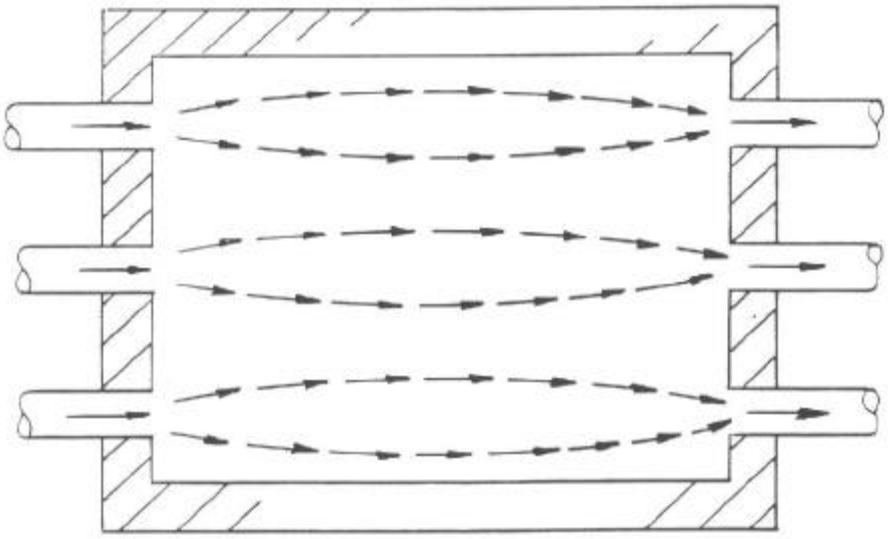
The three basic types of basin inlet baffling configurations are: a target-baffled pipe inlet, an overflow weir entrance, and a baffled submerged orifice or port inlet. Typical intra-basin baffling structures include: diffuser (perforated) walls; launders; cross, longitudinal, or maze baffling to cause horizontal and/or vertical serpentine flow; and longitudinal divider walls, which prevent mixing by increasing the length-to-width ratio of the basin(s). Commonly used baffled outlet structures include free-discharging weirs, such as sharp-crested and multiple V-notch, and submerged ports or weirs. Weirs that do not span the width of the contact basin, such as Cipolleti weirs, should not be considered baffling as their use may substantially increase weir overflow rates and the dead space zone of the basin.

D.2.3 Examples of Baffling

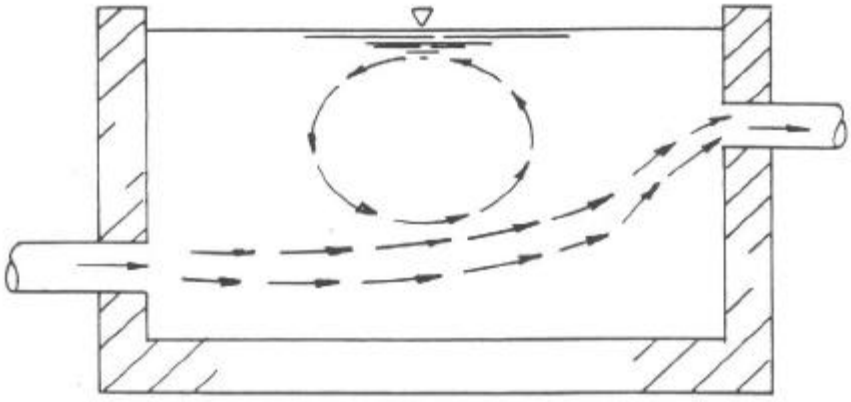
Examples of these levels of baffling conditions for rectangular and circular basins are explained and illustrated in the following section. Typical uses of various forms of baffled and unbaffled inlet and outlet structures are also illustrated.

The plan and section of a rectangular basin with poor baffling conditions, which can be attributed to the unbaffled inlet and outlet pipes, is illustrated on Figure D-5. The flow pattern shown in the plan view indicates straight-through flow with dead space occurring in the regions between the individual pipe inlets and outlets. The section view reveals additional dead space from a vertical perspective in the upper inlet and lower outlet corners of the contact basin. Vertical mixing also occurs as bottom density currents induce a counter-clockwise flow in the upper water layers.

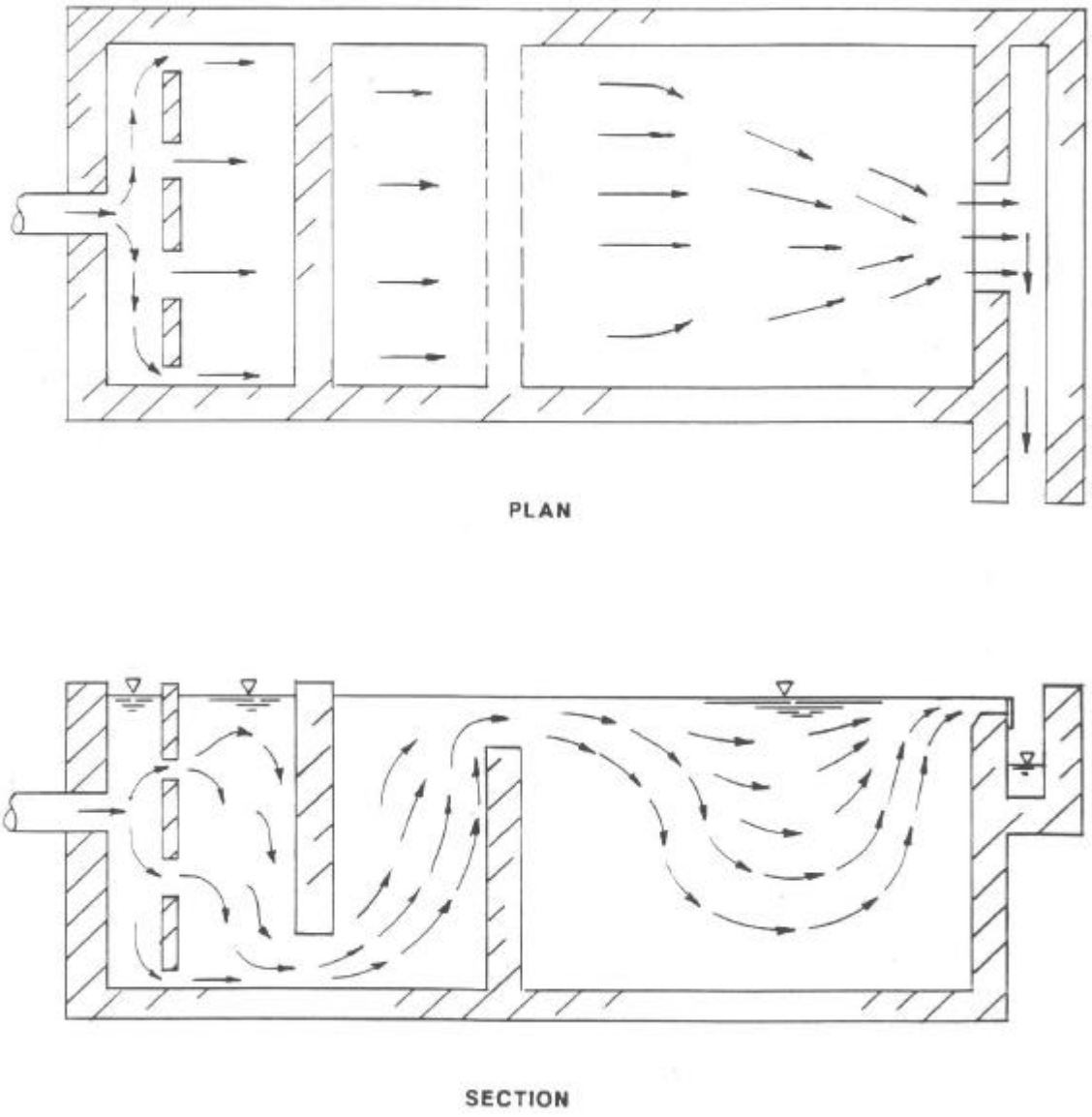
The inlet flow distribution is markedly improved by the addition of an inlet diffuser wall and intra-basin baffling as shown on Figure D-6. However, only average baffling conditions are achieved for the basin as a whole because of the inadequate outlet structure - a Cipolleti weir. The width of the weir is short in comparison with the width of the basin.



PLAN



SECTION



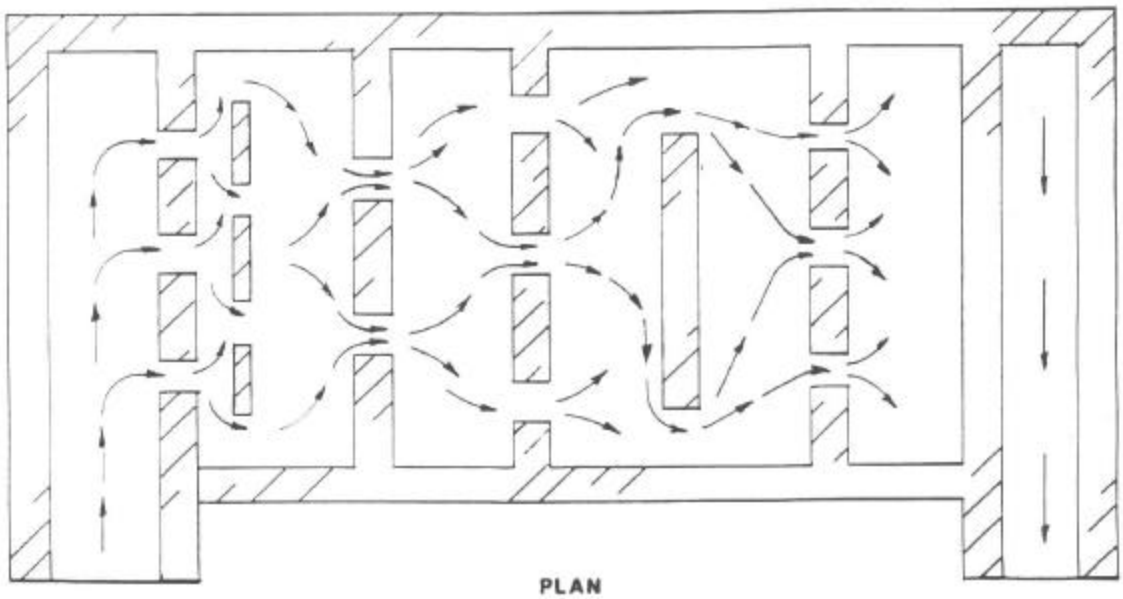
Basin

Consequently, dead space exists in the corners of the basin, as shown by the plan view. In addition, the small weir width causes a high weir overflow rate, which results in short circuiting in the center of the basin.

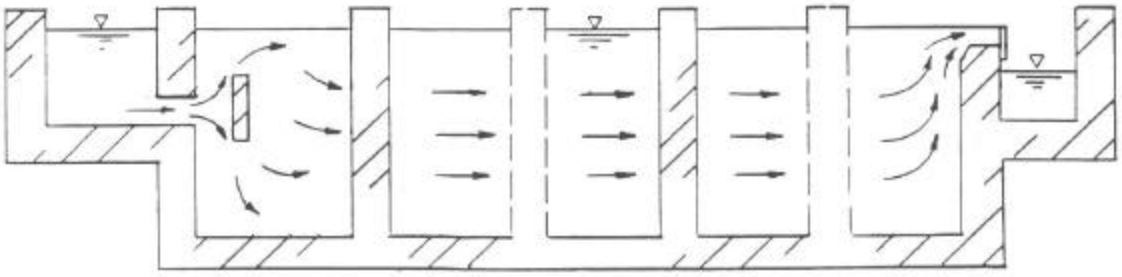
Superior baffling conditions are exemplified by the flow pattern and physical characteristics of the basin shown on Figure D-7. The inlet to the basin consists of submerged, target-baffled ports. This inlet design serves to reduce the velocity of the incoming water and distribute it uniformly throughout the basin's cross-section. The outlet structure is a sharp-crested weir that extends for the entire width of the contact basin. This type of outlet structure will reduce short circuiting and decrease the dead space fraction of the basin, although the overflow weir does create some dead space at the lower corners of the effluent end. These inlet and outlet structures are in some cases by themselves sufficient to attain superior baffling conditions; however, maze-type intra-basin baffling was included as an example of how this type of baffling aids in flow redistribution within a contact basin.

The plan and section of a circular basin with poor baffling conditions, which can be attributed to flow short circuiting from the center feed well directly to the effluent trough is shown on Figure D-8. Short circuiting occurs in spite of the outlet weir configuration because the center feed inlet is not baffled. The inlet flow distribution is improved somewhat on Figure D-9 by the addition of an annular ring baffle at the inlet which causes the inlet flow to be distributed throughout a greater portion of the basin's available volume. However, the baffling conditions in this contact basin are only average because the inlet center feed arrangement does not entirely prevent short circuiting through the upper levels of the basin.

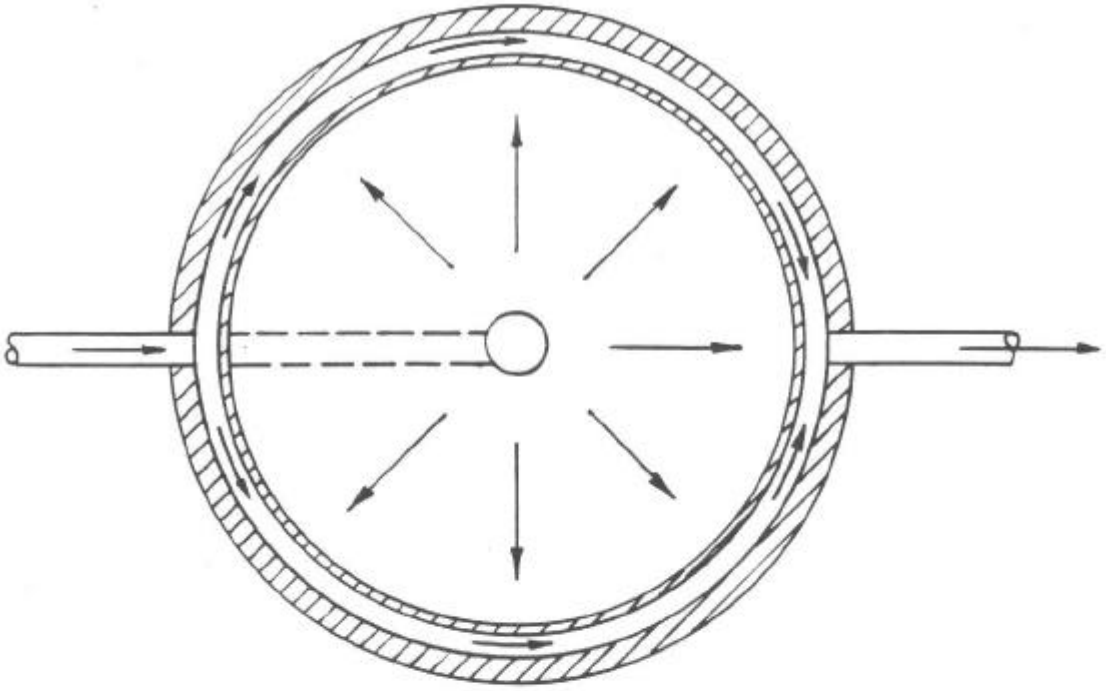
Superior baffling conditions are attained in the basin configuration shown on Figure D-10 through the addition of a perforated inlet baffle and submerged orifice outlet ports. As indicated by the flow pattern, more of the basin's volume is utilized due to uniform flow distribution created by the perforated baffle. Short circuiting is also minimized because only a small portion of flow passes directly through the perforated baffle wall from the inlet to the outlet ports.



PLAN



SECTION



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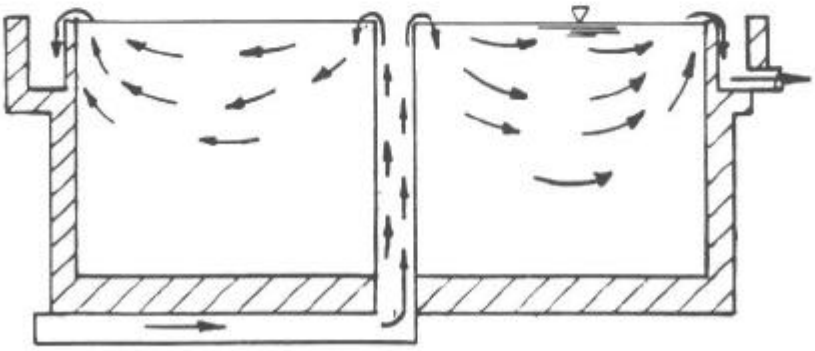

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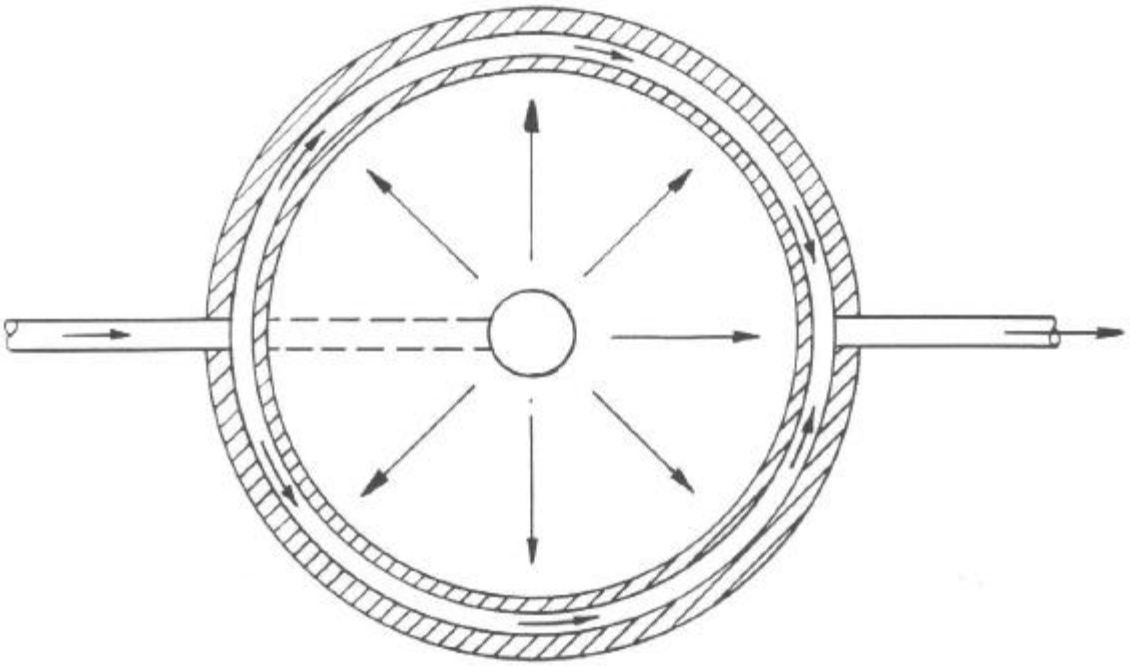

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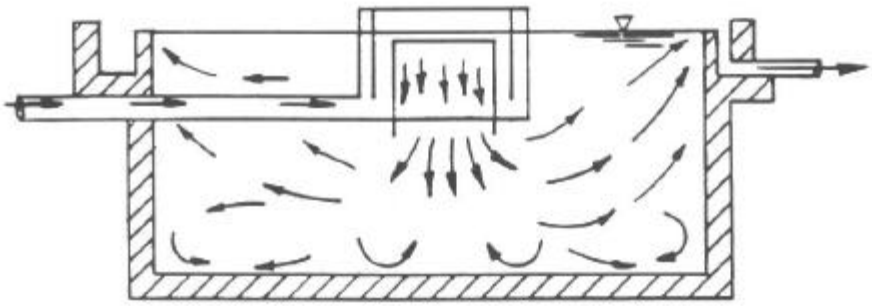

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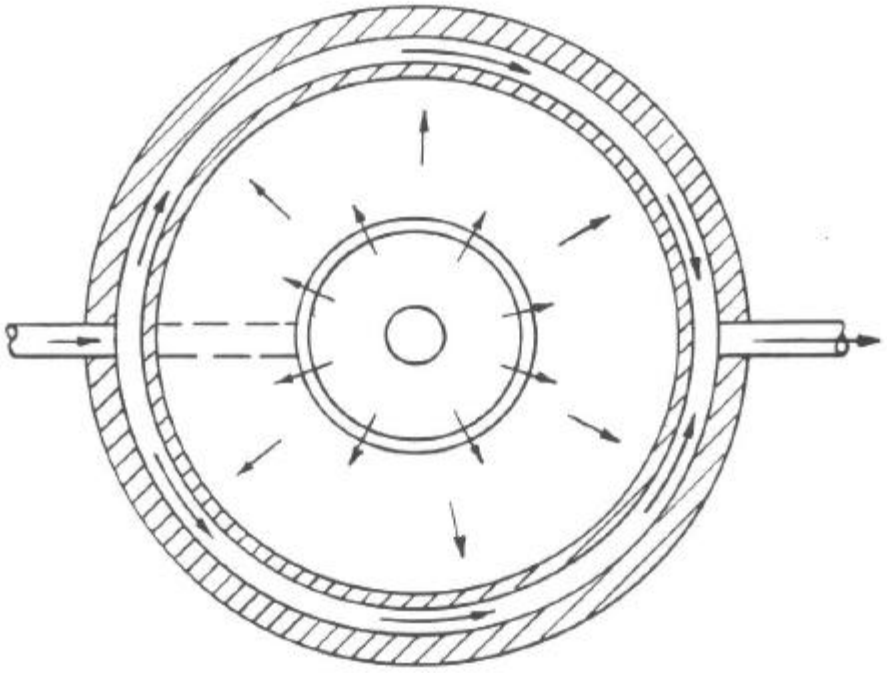

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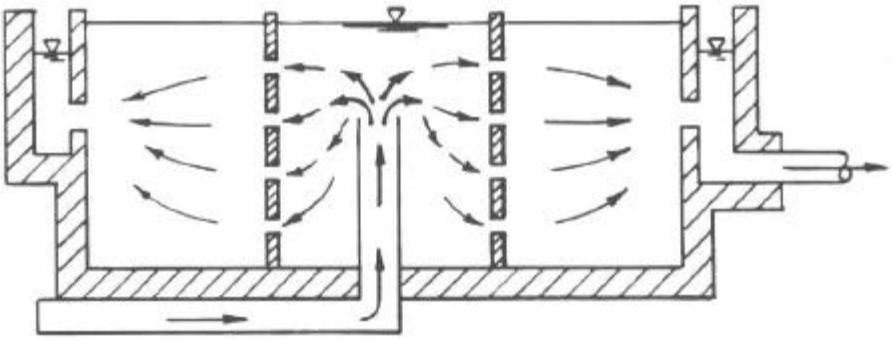

SECTION

D.2.4 Additional Considerations

Flocculation basins and ozone contactors represent water treatment processes with slightly different characteristics from those presented in Figures D-5 through D-10 because of the additional effects of mechanical agitation and mixing from ozone addition, respectively. Studies by Hudson (1975) indicated that a single-compartment flocculator had a T_{10}/T value less than 0.3, corresponding to a dead space zone of about 20 percent and a very high mixed flow zone of greater than 90 percent. In this study, two four-compartment flocculators, one with and the other without mechanical agitation, exhibited T_{10}/T values in the range of 0.5 to 0.7. This observation indicates that not only will compartmentation result in higher T_{10}/T values through better flow distribution, but also that the effects of agitation intensity on T_{10}/T are reduced where sufficient baffling exists. Therefore, regardless of the extent of agitation, baffled flocculation basins with two or more compartments should be considered to possess average baffling conditions (T_{10}/T = 0.5), whereas unbaffled, single-compartment flocculation basins are characteristic of poor baffling conditions (T_{10}/T = 0.3).

Similarly, multiple stage ozone contactors are baffled contact basins, which show characteristics of average baffling conditions. Single stage ozone contactors should be considered as being poorly baffled. However, circular, turbine ozone contactors may exhibit flow distribution characteristics that approach those of completely mixed basins, with a T_{10}/T of 0.1, as a result of the intense mixing.

In many cases, settling basins are integrated with flocculators. Data from Hudson (1975) indicates that poor baffling conditions at the flocculator/settling basin interface can result in backmixing from the settling basin to the flocculator. Therefore, settling basins that have integrated flocculators without effective inlet baffling should be considered as poorly baffled, with a T_{10}/T of 0.3, regardless of the outlet conditions, unless intra-basin baffling is employed to redistribute flow. If intra-basin and outlet baffling is utilized, then the baffling conditions should be considered average with a T_{10}/T of 0.5.

Filters are special treatment units because their design and function is dependent on flow distribution that is completely uniform. Except for a small portion of flow that short-circuits the filter media by channeling along the walls of the filter, filter media baffling provides a high percentage of flow uniformity and can be considered superior baffling conditions for the purpose of determining T_{10}. As such, the T_0 value can be obtained by subtracting the volume of the filter media, support gravel, and underdrains from the total volume and calculating the theoretical detention time by dividing this volume by the flow through the filter. The theoretical detention time is then multiplied by a factor of 0.7, corresponding to superior baffling conditions, to determine the T_{10} value.

D.2.5 Conclusions

The recommended T_{10}/T values and examples are presented as a guideline for use by the Primacy Agency in determining T_{10} values in site specific conditions and when tracer studies cannot be performed because of practical considerations. Selection of T_{10}/T

values in the absence of tracer studies was restricted to a qualitative assessment based on currently available data for the relationship between basin baffling conditions and their associated T_{10}/T values. Conditions which are combinations or variations of the above examples may exist and warrant the use of intermediate T_{10}/T values such as 0.4 or 0.6. As more data on tracer studies become available, specifically correlations between other physical characteristics of basins and the flow distribution efficiency parameters, further refinements to the T_{10}/T fractions and definitions of baffling conditions may be appropriate.

D.3 Use of Baffling Conditions and Tracer Studies to Determine Contact Time

This section provides further discussion and practical examples for using baffling factors and tracer studies to determine the contact time.

Use of Baffling Conditions to Determine Contact Time

To determine a contact time using baffling factors, data about the treatment system are needed. These data include volumes of the unit processes, the peak hourly flow rate, and the baffling factors of each unit process based on the baffling condition. The volume of the unit process is the volume of water in that portion of the treatment system. This volume does not include equipment such as filter media that take up a portion of the basin volume. Thus, the volume of a filtration process used in determining contact time will be the volume of filtration basin beneath the minimum water level minus the volume occupied by the filter media and underdrain. The peak hourly flow rate is the maximum quantity of water passing through the process during a one-hour period within the 24-hour duration. The peak hourly flow rate should be determined from the system operation records.

For example, suppose a unit process within a disinfection segment is composed of a flocculation basin with unbaffled conditions. Thus, from Table 3-2 the T_{10}/T value is 0.1. In this example the volume of the basin is 969,500 gallons and the peak hourly flow rate is 10,651 gpm. The TDT can be calculated as follows:

$$TDT = V/Q = 969{,}500 \text{ gallons} / 10{,}651 \text{ gpm} = 91.0 \text{ minutes}$$

If the theoretical detention time for the unit process is 91.0 minutes, then the resulting contact time is 9.1 minutes. That is,

$$T_{10} \text{ (contact time)} = 91.0 \text{ minutes} * 0.1 = 9.1 \text{ minutes}$$

If the disinfection segment consists of several unit processes, then the theoretical detention time should be calculated for each unit process. The T_{10} should be determined

from the TDT and baffling factor for each unit process in the segment. The segment T_{10} is the sum of the T_{10}s from each unit process.
The following list is a summary of the steps required to determine the contact time with baffling factors:

- Determine peak hourly flow rate, Q, based on operation records;
- Determine the volume of each unit process;
- Calculate the Theoretical Detention Time, where TDT = V/Q;
- Determine the Baffling Factor based on the unit processes baffling conditions;
- Calculate the Contact Time, where T_{10} = TDT * T_{10}/T; and
- Determine the segment T_{10} by summing the T_{10}s of the unit processes in the segment.

Determining Contact Time Using a Tracer Study

A tracer study uses a chemical tracer to determine the detention time of water flowing through a unit process, segment, or system as stated earlier in Chapter 3. Typical chemical tracers include chloride ions, fluoride ions, and Rhodamine WT. Ideally, the selected tracer chemical should be readily available, conservative, easily monitored, and acceptable for use in potable water supplies. By conservative it is meant that the tracer is not consumed or removed during treatment. Fluoride ions can generally be used in lower concentrations than chloride because they are typically present in lower concentrations in the water. Rhodamine is a fluorescent tracer that if selected must be used following guidelines presented earlier in this appendix. Selection of a particular chemical tracer may depend on the unit processes and the salt concentrations present in the water. If a tracer study is needed in order to find T_{10}, a water system should consult the latest tracer study guidance from the state.

The tracer chemical should be added at the same points in the treatment train as the disinfectant to be used in the CT calculations, since it will be used to determine T_{10} for the disinfection segment. Two common methods of tracer addition are the step-dose method and the slug-dose method. In the step-dose method, the tracer chemical is injected at a constant dosage and the endpoint concentration is monitored. To determine a 90 percent recovery for the tracer, endpoint sampling should continue until the tracer concentration reaches a steady-state level. With the slug-dose method, a large dose of tracer chemical is injected, instantaneously. An effective way to achieve instantaneous addition is to use a gravity-fed tube to release the single dose. The tracer concentration is monitored at the endpoint, until the entire dose has passed through the system. Unlike the step-dose method, a mass balance is required to determine whether the entire tracer dose was recovered. Additional mathematical manipulation is required to determine T_{10} from the concentration versus time profile.

Data from tracer studies should be summarized in tables of time and residual concentration. These data are then analyzed to determine the detention time, T_{10}, to be used in calculating CT. Tracer test data from either the step or slug-dose method can be evaluated graphically, numerically, or by a combination of these techniques. The graphical method of evaluating step-dose test data involves plotting a graph of

dimensionless concentration (C/C_0) versus time and reading the value for T_{10} directly from the graph at the appropriate dimensionless concentration. C_0 is the dosage concentration injected into the system and C is the tracer concentration at any time during the test. Alternatively, the data from step-dose tracer studies may be evaluated numerically by developing a semi-logarithmic plot of the dimensionless data (see Section D.1). The semi-logarithmic plot allows a straight line to be drawn through the data. The resulting equation of the line is used to calculate the T_{10} value, assuming there is a good statistical fit. That is, the data points are not too scattered and the line drawn is a reasonable approximation of the data points. The slug-dose method, however, requires data to be analyzed by converting it to the mathematically equivalent step-dose data and using techniques discussed above for step-dose data evaluation. This procedure is more complicated and the details to evaluate the slug-dose data are found in Section D.1.7.2.

Several other considerations when conducting a tracer study are the temperature, flow rates, and water levels in the basins. Detention time may be influenced by differences in water temperature within the system. For plants with potential for thermal stratification, additional tracer studies are suggested under the various seasonal conditions that are likely to occur. The contact times determined by the tracer studies under the various seasonal conditions should remain valid as long as no physical changes are made to the mixing basin(s) or storage reservoir(s).

Detention time is proportional to flow. However, it is not always a linear relationship. Therefore, it is best to conduct tracer studies over a range of flow rates typical of the disinfectant segment. Flow rates may vary throughout the treatment system as the water travels through the unit processes. The goal of the tracer tests is to determine an accurate portrayal of the contact time within each unit process. Thus, it is important to select the flows carefully. Ideally, tracer tests should be performed for at least four flow rates that span the entire range of flow for the section being tested. The flow rates should be separated by approximately equal intervals to span the range of operation. The four flow rates should be one near the average flow, two greater than average, and one less than average flow. The flows should also be selected so that the highest test flow rate is at least 91 percent of the highest flow rate expected to ever occur in that section.

It may not be practical for all systems to conduct studies at four flow rates. The number of tracer tests that are practical to conduct is dependent on site-specific restrictions and resources available to the system. Systems with limited resources can conduct a minimum of one tracer test for each disinfectant segment at a flow rate of not less than 91 percent of the highest flow rate experienced at that section. If only one tracer test is performed, the detention time determined by the test may be used to provide a conservative estimate in CT calculations for that section for flow rates less than or equal to the tracer test flow rate. See Section D.1.1 for calculating a T_{10} at a different flow rate than the tracer test flow rate.

Tracer studies should be conducted during periods when the water level is maintained in accordance with normal plant operation. For basins that have constant water level, the recommended procedure is to maintain the basin's water level at or slightly below, but not above, the normal level. For basins that are operated at extreme water levels,

particularly clearwells, disinfectant contact time should not be used to compute the total CT value because reliable detention time is not provided for disinfection. The recommended water levels during the tracer study for several unit processes are summarized in Table D-6.

Table D-6. Recommended Water Levels during a Tracer Study

Unit Process	Recommended Water Levels
Sedimentation Basins – Operating at a Near Constant Level	Water levels at or slightly below, but not above, the normal minimum operating level.
Clearwell and Storage Tanks	Conduct study during a period when tank level is falling.
Clearwells Operated with Extreme Variation in Water Level	Does not provide a reliable detention time. However, the system may install a weir to ensure a minimum water level and provide a reliable detention time.
Storage Reservoirs – Experiencing Seasonal Variations	Perform studies during various seasonal conditions by using representative water levels for each seasonal condition.

As stated earlier in Chapter 3, the tracer must be added at the same locations in the plant where the disinfectant is added. The duration of tracer addition should be sufficient to approach steady-state conditions which is usually two to three times the theoretical detention time. Tracer dosage should be in sufficient concentration to easily monitor the concentration in the effluent. If there is low background tracer concentration, the dosage can be fairly low (i.e., in the range of 1 to 2 mg/L for fluoride ions). However, for basins with serious short-circuiting, substantially larger dosages are necessary to detect the tracer and to define the effluent tracer profile adequately. The test procedure for determining the Contact Time with a tracer study is generally as follows:

- The system determines the flow rate or rates to be used in the study.
- The system selects the tracer chemical and determine the raw water background concentration of the tracer chemical. The background level is needed to both determine the quantity of chemical to feed and to evaluate the data properly.
- The system determines the tracer addition locations, plan the sample collection logistics and frequency, and determine the appropriate tracer dosage. Sampling frequencies depend on the size of the basin—the larger the basin the easier it is to obtain an adequate profile with less frequent sampling. Small basins need more frequent sampling.
- The system conducts the tracer test using either the step-dose or slug-dose methods.
- The system compiles and analyzes the data.
- The system calculates $T_{10.}$

Additional references for information on tracer studies and details concerning how to conduct one are listed below:

- Hudson, H.E., Jr. 1975. "Residence Times in Pretreatment." *J. AWWA*. January:45-52.

- Hudson, H.E., Jr. 1981. *Water Clarification Processes: Practical Design and Evaluation*. Van Nostrand Reinhold Company, New York.

- Levenspiel, O. 1972. *Chemical Reaction Engineering*, second edition. John Wiley and Sons, New York.

- Marske, D.M. and J.D. Boyle. 1973. "Chlorine Contact Chamber Design – A Field Evaluation." *Water and Sewage Works*. January:70-77.

- Missouri Department of Natural Resources, Public Drinking Water Program. 1991. *Guidance Manual for Surface Water System Treatment Requirements*.

- Teefy S.M. and P.C. Singer. 1990. "Performance and Analysis of Tracer Tests to Determine Compliance of a Disinfection Scheme with the SWTR." *J. AWWA*. 82(12):88-98.

- Thirumurthi, D. 1969. "A Breakthrough in the Tracer Studies of Sedimentation Tanks." *J. WPCF*. R405-R418. November.

- TNRCC. 1995. *Public Water Supply Technical Guidance Manual*, Chapt. 27, Texas Natural Resources Conservation Commission, Austin, TX.

APPENDIX E. USING THE REGRESSION METHOD

E.1 Using the Regression Method to Find $CT_{3\text{-log, }Giardia}$ When Using Chlorine

Plants may choose to use the Regression Method to determine the value of $CT_{3\text{-log, Giardia}}$ when using free chlorine. This method is useful to calculate the $CT_{3\text{-log, Giardia}}$ for a long historical data set of pH, temperature and residual disinfection concentrations. Unlike the Approximation Method, the operator is not required to manually look up values in a table for each day of the historical record. (Recall that systems that are required to create a disinfection profile must do so for one to three years of daily data.) Instead of having to look up CT values for each day in the record, the Regression Method allows the operator to simply use a formula that is a function of pH, temperature and residual disinfection concentration. Using this formula in a spreadsheet should greatly reduce the time required to calculate the disinfection profile. The following section presents the equations and demonstrates its utility in calculating $CT_{3\text{-log,, Giardia}}$.

An empirical model was developed by Smith et al. (1995), that directly predicts CT values that are equal to or greater than the original CT values in the SWTR over the entire range of variables covered in the SWTR Guidance Manual. The equations below can be used to directly compute CT values for chlorine inactivation:

$$CT = (0.353*I)(12.006+e^{(2.46-0.073*temp+0.125*C+0.389*pH)}) \quad \textbf{Equation 3-3}$$

(for temperature < 12.5 °C)

$$CT = (0.361*I)(-2.261+e^{(2.69-0.065*temp+0.111*C+0.361*pH)}) \quad \textbf{Equation 3-4}$$

(for temperature ≥ 12.5 °C)

Where:

I = 3, the number of logs inactivation required
Temp= temperature in degrees Celsius
C = residual chlorine concentration in mg/L
pH = the negative log concentration of hydrogen ion
e = 2.7183, the base for the natural logarithm

The SWTR did not include log inactivation credit for waters with pH greater than 9.0. As such, if the plant operates at a pH level higher than 9.0, the Approximation Method described above should be used to calculate the $CT_{3\text{-log, Giardia}}$. Systems should apply State requirements, however, in the absence of state regulations, the utility should default to using CT values calculated for a pH less than 9.0.

Procedure:

- Determine whether the temperature is above or below 12.5 ^{o}C to select between Equations 3-3 and 3-4 to directly compute the CT values for *Giardia* inactivation. using chlorine (If using a spreadsheet an "IF" statement can be used to select the correct equation based on the temperature.)
- Use daily temperature (^{o}C,) residual disinfectant concentration (mg/L), pH, and I = 3 in the appropriate equation to calculate the $CT_{3\text{-log, Giardia}}$

Example:

Find the value of $CT_{3\text{-log, Giardia}}$ for a water temperature of 11^{o}C, a pH of 8.2, and a residual of 2.5 mg/L for a plant that is using free chlorine as the disinfectant.

Using Equation 3-3 since temperature is less than 12.5 ^{o}C, then:

$$CT = (0.353I)(12.006+e^{(2.46-0.073temp+0.125C+0.389pH)})$$

$$CT = (1.059)(12.006+e^{(2.46-0.073*11+0.125*2.5+0.389*8.2)})$$

$$CT = (1.059)(12.006+e^{(2.46-.803+.3125+3.189)})$$

$$CT = (1.059)(12.006+e^{(5.1585)})$$

$$CT = (1.059)(12.006+173.90)$$

$$CT = 196.87$$

The $CT_{3\text{-log, Giardia}}$ of 197 as calculated by the Regression Method more closely approximates the actual $CT_{3\text{-log, Giardia}}$ than the values calculated using the Approximation Method that estimates the $CT_{3\text{-log, Giardia}}$ at 234 (see Section 3.5).

E.2 Calculation of Estimated Log Inactivation Using the Regression Method

Required CT values for 3-log inactivation of *Giardia* using chlorine can be determined using CT tables as provided in Appendix C, or can be calculated using disinfectant-

specific equations, such as the chlorine equations developed by Smith et al (1995). These equations predict required CT values for 3-log inactivation that are greater than or equal to the original values in the SWTR over the entire range of independent variables covered in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991). Using these equations, CT values for inactivation of *Giardia* using chlorine can be computed.

- For Temperature < 12.5 °C:
  $CT = (0.353\ I)(12.006+e^{(2.46-0.073\ temp+0.125\ C+\ 0.389\ pH)})$
- For Temperature ≥ 12.5 °C:
  $CT = (0.361\ I)(-2.261+e^{(2.69-0.065\ temp+0.111\ C+\ 0.361\ pH)})$

Where:

I = 3, log removal of *Giardia*

e = 2.7183, the base of the natural logarithm

C = chlorine residual concentration (mg/L)

Temp = temperature in °C

Once the CT required for inactivation of 3-log *Giardia* and 4-log viruses is determined, the actual log inactivation for that segment can be estimated as:

Estimated Segment Log Inactivation of *Giardia* = $3.0 * CT_{actual} / CT_{3\text{-log, Giardia}}$

Estimated Segment Log Inactivation of viruses = $4.0 * CT_{actual} / CT_{4\text{-log, virus}}$

The total plant estimated log inactivation due to chemical disinfection is:

Total Plant Estimated Inactivation due to chemical disinfection = Σ segment inactivation

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