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TO: Office of Drinking Water Staff

THROUGH: J. Wesley Kleene, Ph.D., P.E., Director
Office of Drinking Water

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SUBJECT: Design & Construction - Ozone Treatment & Disinfection Credit

Revision Highlights:
Ozone monitoring requirements revised based on April 2010 (final) LT2 Toolbox Guidance Manual.

SUMMARY STATEMENT:
Ozone is a powerful oxidant which may be used as a primary disinfectant in potable water treatment, as well as for taste and odor control, color removal, oxidation of iron, manganese, synthetic and volatile organic compounds and algae control. This memo addresses the process design features and controls, approval procedures, waterworks and operator classification, monitoring and reporting requirements for all systems which employ ozone treatment, and determination of inactivation credit for ozone.

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I. BACKGROUND

There are presently five conventional surface water treatment plants in Virginia that employ ozonation of water. All plants apply ozone following coagulation, flocculation and clarification (either sedimentation or dissolved air flotation), but before filtration. All but one have discontinued pre-chlorination and have realized a significant reduction in chlorine disinfection byproducts (TTHMs and HAA5) in their distribution systems.[1] The plants that do not pre-chlorinate are designed for biological filtration for removal of biodegradable dissolved organic carbon (BDOC). (BDOC typically increases following ozonation, and may contribute to biological growth in the distribution system if not removed through a downstream process at the plant.)

I. DESIGN FEATURES

A. General

The ozonation process used in water treatment has five basic components: an oxygen source, an ozone generator, an ozone contactor, an off-gas destruction system and an ozone liquid quench of the effluent leaving the contactors. Until specific design criteria are adopted into the *Waterworks Regulations*, ozone system design should comply with the Great Lakes Upper Mississippi River Board of State Health & Environmental Managers Recommended Standards for Water Works (Ten States Standards), 2003.

Current regulations require pre-chlorination to be provided. Therefore a Design Exception will be required if this feature is not included.

B. Process Control and Monitoring Features

Instrumentation must be installed to measure ozone concentration for process control and for compliance determination. A minimum of two dedicated, on-line monitors per ozone contactor are required for systems that claim disinfection credit for ozone, at locations suited to the CT method used. Ozone residual levels must be monitored continuously and recorded. (Calibration and reporting requirements are included in subsequent sections of this memo.) A portable ozone monitor is also recommended as a back up.

Sample lines must be designed to minimize the reaction time (typically detention < 10 sec).

Alarms are required for the operator to properly manage and control the ozone process. Automatic shutdown features should be considered.

II. APPROVAL PROCEDURES

A. Preliminary Engineering

A Preliminary Engineering Conference is required for all ozone treatment proposals. One or more Preliminary Engineering Reports must be submitted for review, which include treatability studies and pilot or bench scale tests to determine optimal point of ozone application (considering water quality, ozone demand and byproduct formation) and dose. Treatment objectives (e.g. disinfection credit or oxidation only), major design elements including basic components and their capacity, ozone mixing method, contactor configuration, and control methods must be identified. Provisions for biological filtration must be reviewed.

If disinfection credit is a treatment objective, then a report must also clearly describe the ozone monitoring scheme as well as establish the method for determining inactivation of Giardia,

[1] The Harwoods Mill WTP is continuing to pre-chlorinate to address a manganese problem, but desires to eliminate this when another solution is found.

viruses and cryptosporidium. The appropriate method will depend on the contactor configuration and the amount of process monitoring and evaluation proposed.

B. Final Design & Start-Up

Submission of plans and specifications, issuance of a Construction Permit will follow the procedures in the Waterworks Regulations. Full scale performance testing will be required for the ozone system during the start-up period, and must be documented in the Engineer's Statement of Completion prior to final inspection and acceptance.

The specifications must require a detailed, site specific, Operation and Maintenance (O&M) Manual for the ozone process and controls. The operator(s) in responsible charge should have sufficient time to review the O & M Manual prior to the manufacturer's onsite training and start up period.

Tracer studies will be required to verify T_{10} values prior to granting disinfection credit for ozone. Prior to validating the T_{10} values by tracer studies, no disinfection credit will be given.

III. INACTIVATION CREDIT

A. General

Ozone decomposes rapidly[2] and produces a variable residual, which impacts how ozone is effectively applied and measured, and how inactivation credit is computed. The Surface Water Treatment Rule (SWTR) and the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) generally measure disinfection effectiveness by *CT* (*C*, the disinfectant residual concentration in mg/l, and *T*, the contact time in minutes). The SWTR addresses Giardia and virus inactivation, and the LT2ESWTR addresses inactivation of Cryptosporidium. The CT values for inactivation of Giardia and viruses are tabulated in the *Waterworks Regulations,* and are in accordance with the SWTR. Tables for Cryptosporidium inactivation by ozone are published in the LT2ESWTR and will soon be incorporated into the *Waterworks Regulations.* The SWTR and the LT2ESWTR require daily CT monitoring conducted during peak hourly flow to meet log inactivation requirements.

Due to the powerful but reactive nature of ozone, disinfection credit is also given without CT calculations, if an ozone residual from the first (dissolution) chamber is measured, and this chamber is $\geq$ the largest downstream chamber. In accordance with the SWTR Guidance Manual, if the ozone concentration, $C_{out} > 0.1$ mg/L, then 1-log virus inactivation credit is granted. If $C_{out} > 0.3$ mg/l, then 0.5-log Giardia inactivation credit is given. (No credit is given for Cryptosporidium from this measurement.)

[2] This decay is very rapid, and ozone disinfection often bears little similarity to chlorine disinfection. By example, an initial ozone residual of 1 mg/l may decay to non-detectable in 5 minutes. This dose could correspond to a CT of 1 mg/l-min (2-log at 9°C).

B. Measuring Ozone Residual

Continuous, on-line ozone residual measurements will be required to insure that adequate disinfection is being provided. Ozone averaging shall not exceed the contactor hydraulic detention time[3]; averaging of no more than ½ hydraulic detention time is recommended for better process control response. Disinfection credits for ozone chambers/contactors will be based on only the chambers/contactors that have measured ozone residual (at least the probe detection limit) [4]. The ozone monitors must have calibration checks performed at least weekly, during peak hourly flow, as outlined in EPA's Guidance Manuals. (The calibration protocol is described in Appendix C.3 of the LT2 ESWTR Toolbox Guidance Manual. The indigo colorimetric method is described in Standard Method 4500-Ozone-B, 20th Edition, 1998.)

C. Calculating CT

There are many different CT calculation methods presented in the LT2 Toolbox Guidance Manual. All of the ozone systems in Virginia use multiple, consecutive chambers, and inject gaseous ozone with fine bubble diffusers in the initial chambers (dissolution chambers) that have an over-under flow pattern. Two methods for computing log inactivation of Giardia and viruses that are most appropriate to systems such as these are the **$C_{effluent}T_{10}$ Method**, and the **Log Integration CT_{10} Method** [5].

- The **Effluent Method** is simple but underestimates the amount of disinfection provided. It takes the concentration at the end of a segment and uses that value as the average concentration for the whole segment.
- The **Log Integration Method** is more complicated than the Effluent Method, but less complicated than the other methods in the Toolbox Guidance Manual, and it accurately estimates the amount of disinfection provided. It takes the concentration in and out of a segment and determines the geometric average concentration using a first order decay between those two values $\{C_{avg} = (C_{in} * C_{out})^{\wedge}0.5\}$.

When calculating CT (specifically log-inactivation) for multiple (parallel) contactors, averaging of all contactors can introduce errors (over estimating inactivation). For typical chlorine levels these errors are very minor. For ozone, these errors can be significant. To avoid over-estimations, when evaluating multiple contactors, use the minimum value from all contactors in service. (See Appendix II for an example.)

IV. MONITORING & REPORTING

Parameters that must be monitored continuously at each plant in addition to operational information:

- Inlet water temperature (The CT values for microbial inactivation by ozone are temperature-dependent. Sensors at the contactor, *or closest to the contactor* should be used in the computation)
- Ozone applied, (lbs and mg/L)
- Ozone residual, initial (mg/L) from the last dissolution chamber of each contactor

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[3] Typical on-line measurements have averaging somewhere in the measurement system (probe, controller, PLC, & SCADA), because ozone residual measurements are, by their nature, highly variable. Averaging is also called, rolling average, dampening, buffering or filtering. Following EPA's LT2 Toolbox Guidance Manual (Appendix B), total averaging of the entire measurement system shall not exceed the HDT (hydraulic detention time = volume / design flow).

[4] A value of 0.01 mg/L is the detection limit for the visual procedure for the indigo colorimetric method in *Standard Methods*. Most on-line continuous ozone monitors use electrolytic sensors employing an amperometric method.

[5] The Log Integration Method (also referred to as Geometric Mean or extended integrated-CT_{10}) has been evaluated extensively by the Metropolitan Water District of Southern California (MWD), for zone contactor configurations similar to Virginia's. It is considered most accurate because it includes more detailed information on ozone residual decay and the contactor hydrodynamics. It is most often used to compute inactivation of Cryptosporidium; rarely is it used for *Giardia* and virus computations.

- Ozone residual, final (mg/L) from last detectable chamber of each contactor

Parameters that must be reported in the Monthly Operation Report for each plant:
- Minimum and average ozone concentration (mg/L) of all contactors in service , daily
- Minimum ozone concentration (mg/L) from all contactors @ peak flow, daily
- Log Inactivation for Giardia, virus and, if applicable, Cryptosporidium by ozone, daily at peak flow
- Bromate concentration (mg/L), at the entry point to the distribution system, 1/month[6]

Disinfection Profiling & Benchmarking must comply with requirements of the LT2 ESWT Rule.

V. WATERWORKS CLASSIFICATION & OPERATOR REQUIREMENTS

Surface water plants using ozone treatment shall be designated as Class I, regardless of plant capacity, and will require the Operator in Responsible Charge to have a Class I license.

VI. REFERENCES

Regulatory Rules and Guidance:
- EPA Guidance Manual - Alternative Disinfectants and Oxidants, April 1999, Chapter 3.
- EPA Guidance Manual - Surface Water Treatment Rule, March 1991, Appendix O; and Chapters 3-5
- EPA Guidance Manual - LT2 Toolbox, 2010, Chapter 11 and Appendix B.
- Recommended Standards for Water Works (Ten States Standards), Great Lakes Upper Mississippi River Board of State Health & Environmental Managers, 2003.

Technical Publications:
- "On-Line Monitoring of Ozone Disinfection Effectiveness Within An Over/Under-Baffled Contactor", Brad Coffey et al, Metropolitan District of Southern California, AWWA Annual Conference, June 1995.
- Ozone in Drinking Water Treatment, Kerwin L. Rakness, AWWA, © 2005.
- Ozone Essentials: Equipment and Process Control/Optimization, AWWA Professional Development Seminar Participant Manual, 1998.

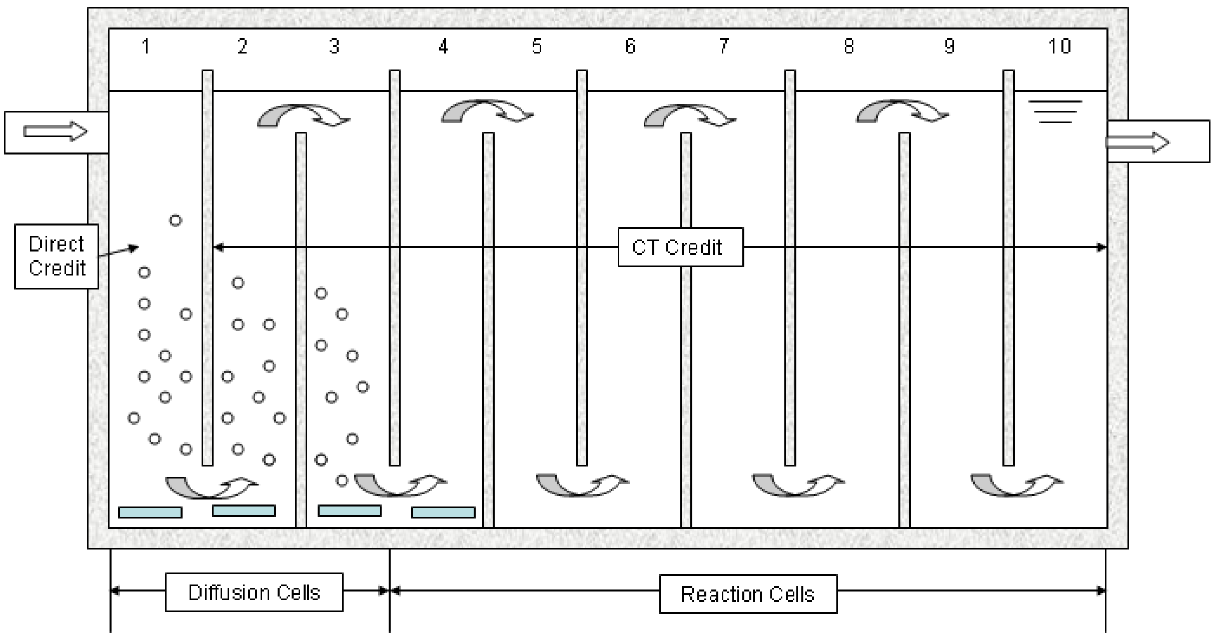
Examples of Ozone Monitoring Instrumentation:

On-Line Sensors/Analyzers	Model	Accuracy
Analytical Technology, Inc. (ATi)	Q45H/64	± 0.020 ppm
Rosemount Analytical Dissolved O3 Monitor	499AOZ	depends on calibration method
HACH Ozone Amperometric Sensor	9185sc	± 0.010 ppm

[6] The DDBP Rule allows reduced monitoring of bromate from monthly to quarterly, if the average source water bromide concentration < 0.05 mg/L. Refer to Rule for further guidance.

APPENDIX A
OZONE CONTACTOR ELEVATION DRAWING

Example of an Ozone Contactor with vertical baffles and bubble diffusers operating in cells 1-3. Water in cells 1 & 3 flows in a “counter-current” direction; cell 2 flow is “co-current”.



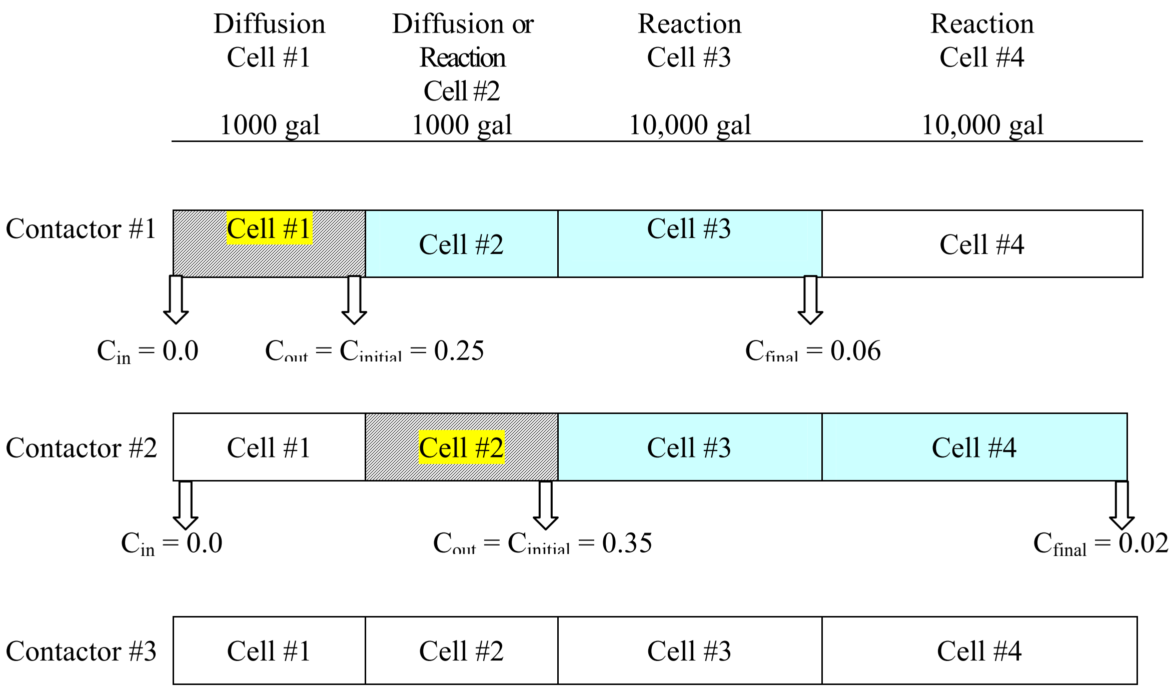
APPENDIX B
OZONE CT CALCULATION EXAMPLE

The ozone system has 3 parallel contactors. Each contactor has two diffusion cells and two reaction cells, for a total of 4 cells. (The 2nd diffusion cell also becomes a reaction cell if ozone is only applied in the 1st cell).

For this example, the ozone application point and measurement point are different for contactors #1 and #2; and contactor #3 is out of service. The applied ozone dose is 1.3 mg/L [7]. After ozone demand and transfer inefficiency, the ozone concentration measured 0.25 mg/L in contactor #1 and 0.35 mg/L in contactor #2. The final ozone residuals measured 0.06 mg/L in contactor #1 and 0.02 mg/L in contactor #2.

EPA nomenclature is used here:

- C_{in} is the ozone concentration going into the contactor (prior to ozone addition through the diffusers), which is assumed to be 0 mg/l.
- C_{out} is the concentration leaving the first diffusion cell. It is often the same as $C_{initial}$, which is the concentration at the start of the reaction cells.
- C_{final} is the last measured concentration at the end of the reaction cell.



Flow is 2000 gpm, split evenly between contactor #1 and 2.
$T_{10} = 0.6*T$.
Temperature is 9°C .

[7] Doses can be expected between 1 mg/l for Giardia and 4 mg/l for crypto. Transfer efficiency should be >90%. Initial ozone demand can be 1 mg/l, and usually occurs in the diffusion cell. Minor variations in field conditions can easily lead to the C_{out} values (0.25 and 0.35) noted above. Using a half-life of 5 minutes, concentration will fall by 1/16 in 20 minutes.

CT is calculated as follows for the two different methods, and Log Inactivation (LI) determined using Table L14 (for Giardia) and Table L15 (for virus) in Appendix L of the *Waterworks Regulations*:

EFFLUENT METHOD	Derivation	Contactor #1	Contactor #2	Contactor #3	System Total
Flow = Q (gpm)	Measured	1,000	1,000	O/S	2,000
$C_{initial} = C_{out} = C_o$(mg/l)	Measured	0.25	0.35		
Direct Virus LI Credit	If $C_o > 0.1$	1-log	1-log		
Direct Giardia LI Credit	If $C_o > 0.3$	0	0.5-log		
$C_{final} = C_f$ = C for CT (mg/l)	Measured	0.06	0.02		
Reactor Volume = V(gal)	V=∑ parts	11,000	20,000		
Time, total = T (min)	T= V/Q	11	20		
Time, T_{10} (min)	T_{10}=0.6*T	6.6	12		
CT (mg/l-min)	C_f*T_{10}	0.40	0.24		
Virus Inactivation	WW Regs App L	1.5-log	1-log		
Giardia Inactivation	WW Regs App L	0.7-log	0.5 log		
Total Virus Inactivation	∑direct+CT	2.5-log	2.0-log		2.0-log
Total Giardia Inactivation	∑direct+CT	0.7-log	1.0-log		0.7-log

Use minimum for all contactors

LOG INTEGRATION METHOD	Derivation	Contactor #1	Contactor #2	Contactor #3	System Total
Flow = Q (gpm)	Measured	1,000	1,000	O/S	2,000
$C_{initial} = C_{out} = C_o$(mg/l)	Measured	0.25	0.35		
Direct Virus LI Credit	If $C_o > 0.1$	1-log	1-log		
Direct Giardia LI Credit	If $C_o > 0.3$	0	0.5-log		
$C_{final} = C_f$(mg/l)	Measured	0.06	0.02		
C_{geo} = C for CT (mg/l)	(C_o*C_f)^.5	0.12	0.08		
Reactor Volume = V (gal)	V=∑ parts	11,000	20,000		
Time, total = T(min)	T = V/Q	11	20		
Time, T_{10} (min)	T_{10}=0.6*T	6.6	12		
CT (mg/l-min)	C_{geo}*T_{10}	0.79	1.0		
Virus Inactivation	WW Regs App L	3.0-log	4.0-log		
Giardia Inactivation	WW Regs App L	1.5-log	2.0 log		
Total Virus Inactivation	∑direct+CT	4.0-log	5.0-log		4.0-log
Total Giardia Inactivation	∑direct+CT	1.5-log	2.5-log		1.5-log

Use minimum for all contactors

The following side-by-side comparison of different ozone doses is presented for information. Ozone doses of 1.1 mg/L, 1.3 mg/L (in previous example), 1.5 mg/L and 4.0 mg/L are tabulated below, for the flow pattern in contactor #2, using the Log-Integration method. The first three columns show how minor fluctuations (15%) in dose (or demand) can make significant changes in log inactivation. The fourth column shows some sample numbers for 1-log crypto removal, based on the table published in the LT2 ESWT Rule.

LOG INTEGRATION METHOD	Derivation	Ozone Dose= 1.1 mg/L	Ozone Dose= 1.3 mg/L	Ozone Dose= 1.5 mg/L	Ozone Dose= 4.0 mg/L
Flow = Q(gpm)	Measured	1,000	1,000	1,000	1,000
$C_{out} = C_{initial}$ (mg/l)	Measured	0.1	0.31	0.5	3.0
Direct Virus LI Credit	If $C_o > 0.1$	0	1-log	1-log	1-log
Direct Giardia LI Credit	If $C_o > 0.3$	0	0	0.5-log	0.5-log
C_{final} (mg/l)	Measured	0.006 *	0.02	0.03	0.2
C_{geo}, for CT (mg/l)	(C_i*C_f)^.5	0 *	0.08	0.12	0.75
Reactor Volume (gal)	V=∑ parts	20,000	20,000	20,000	20,000
Time, total = T(min)	T = V/Q	20	20	20	20
Time, T_{10} (min)	T_{10}=0.6*T	12	12	12	12
CT (mg/l-min)	$C_{geo}*T_{10}$	0	1.0	1.4	9
Virus Inactivation	Regs App L	0 -log	4.0-log	5.6-log	40-log
Giardia Inactivation	Regs App L	0 -log	2.0-log	2.8-log	19-log
Total Virus Inactivation	∑direct+CT	0 -log	5.0-log	6.6-log	41-log
Total Giardia Inactivation	∑direct+CT	0 -log	2.0-log	3.3-log	19.5-log
Total Cryptosporidium Inactivation	LT2 ESWTR	**	**	**	1-log

* C_{final} is less than detectable (<0.02). This contactor gets no disinfection credit.
** Log Inactivation levels (around 0.1) are not calculated at these lower doses, because they are not intended to provide cryptosporidium inactivation.