

# **Bromate Control During Ozonation of High-Bromide Drinking Water**

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## **Abstract**

When water that contains bromide is treated with ozone, a number of disinfection byproducts (DBPs) can be formed. One of the worst DBPs is bromate, a carcinogen. This project was undertaken at the 40 MGD (1.55 m<sup>3</sup>/s) Jonathon Rogers Water Treatment plant in the City of El Paso. Its objective was to find a way to keep the bromate concentration below the 10 ppb MCL.

Both laboratory and full plant studies were conducted. At the laboratory scale, two liters of raw water were ozonated at 1.0, 1.5, and 2.0 L/min for times ranging from 1 to 10 minutes. The ozone concentration was measured at each time interval and the respective samples were analyzed for bromates. At the plant scale, samples were collected at various points in the treatment process, including at the influent and effluent of the ozone contactor, and analyzed for ozone and bromates. This was done at plant flow rates ranging from 35% to 110% of the design flow rate (to insure that a wide range of detention times would be evaluated).

The results showed that the bromate concentration in both the plant and lab samples was highly correlated with the integrated product of the ozone concentration in the water and the total ozonation time (i.e.  $CT_T$ ). A plot of the bromate concentration versus  $CT_T$  yielded a straight line with an  $R^2$  value of over 0.95 for both the laboratory and the plant results, with nearly identical regression equations. A bromate concentration of 10 ppb is associated with a  $CT_T$  value of 1.14. Thus, the bromate concentration in the product water could be controlled to 10 ppb at any flow rate simply by adjusting the power input to the ozone generator (and thereby changing the residual ozone concentration in the water). Any desired bromate concentration could be obtained by selecting the appropriate  $CT_T$  value from the graph (or by using the regression equation) and then adjusting the power to produce an ozone concentration that will yield that  $CT_T$  value at any given flow rate.

## **Introduction**

In recent years, disinfection byproduct (DBP) control in drinking water has become an increasingly important consideration in water treatment plant operations. Although trihalomethanes have received the most attention from governmental control agencies, bromates are receiving more attention because of their possible formation when water that contains significant amounts of bromide is ozonated. This project was directed toward identifying procedures that would minimize the formation of bromates during ozonation of water at the Jonathan Rogers Water Treatment Plant (JRWTP) in the City of El Paso, TX.

## **Background**

The results contained in this document were generated between March and July of 2001, but this project was initially started in the summer of 2000. At that time, hydrogen peroxide was injected at the end of Cell 1 of the ozonation unit in order to study the effect of peroxone treatment on bromate control. That study showed that hydrogen peroxide neither reduced nor increased the bromate concentration through the plant, but it did have a favorable effect on turbidity removal through the GAC filters<sup>1</sup>. During that study, it was noted that the bromate concentration increased dramatically at the low water production levels that characteristically occur at the beginning and end of the plant operating season. Therefore, this study focused on trying to understand the relationship between residual ozone concentration, ozonation time (i.e. detention time in Cell 1), and bromate formation.

## **Procedure**

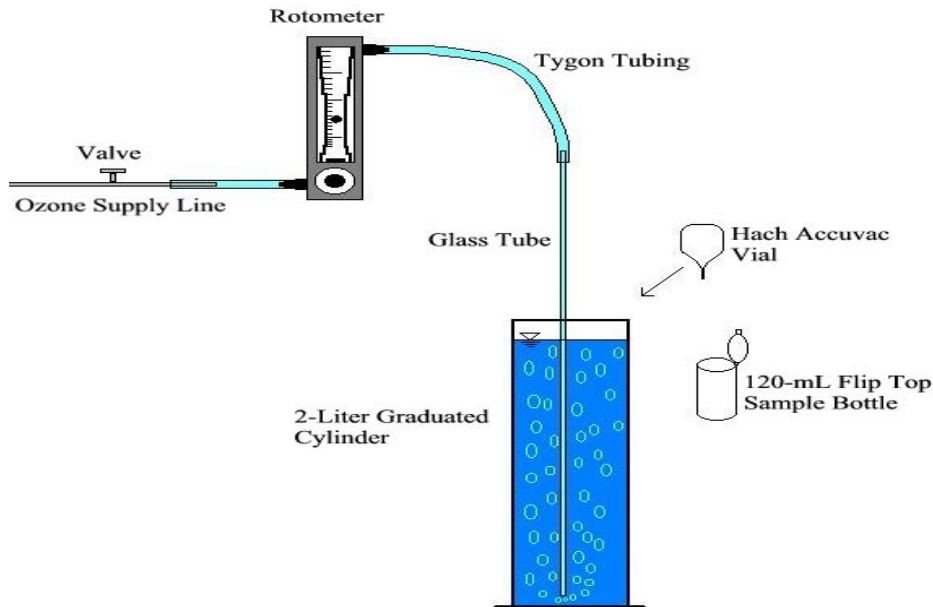
Data for this project were obtained at both the laboratory and full plant level. At the laboratory level, two liters of settled water were taken from the influent to the plant and ozonated at four different rates ranging from 1 L/min to 2.5 L/min for 10 minutes. The experimental set-up is shown in Figure 1. For each ozonation time studied, a new sample of settled water was used. The ozone concentration was measured directly from the ozonation cylinder (using Hach Accuvac vials) at 1 to 2 minute intervals. Two hundred ml of sample were removed from the cylinder for bromate analysis immediately after the ozone vial was inserted. The samples were then transported to the El Paso Water Utilities laboratory at the Canal Street water treatment plant for bromate analysis.

$CT_T$  values were calculated for each sample by multiplying the average ozone concentration by the ozonation time (the subscript 'T' is used to differentiate this CT value from the disinfection CT value). The average ozonation concentration was obtained by interpolating the readings to one-half minute intervals and averaging those values over the entire ozonation period. For example, the 0.5, 1.5, 2.5 and 3.5 minute interpolated

values were averaged to obtain the ozone concentration for the four-minute ozonation period.

Plant samples were collected at the end of Cell 1 of the ozonation unit and at various places upstream and downstream from there. The plant water production rates at the times the samples were collected varied from a low settled water flow of 15 MGD ( $0.66 \text{ m}^3/\text{s}$ ) to full capacity flow of 46 MGD ( $2.02 \text{ m}^3/\text{s}$ ). As with the laboratory samples, the plant samples were analyzed at the EPWU laboratory at Canal Street. The residual ozone concentrations at the time the samples were collected were obtained from the daily sheets of the plant operating records. The ozone concentration was multiplied by the theoretical detention time (based on the flow when the sample was collected) to obtain the  $CT_T$  value at that time. The bromate concentration associated with a particular  $CT_T$  value was obtained by subtracting the bromate concentration entering Cell 1 from the bromate concentration leaving.

The theoretical detention time in Cell 1 was calculated by dividing its volume (obtained from a tracer study report<sup>2</sup>) by the flow rate at the time the samples were taken.



**Figure 1. Experimental set-up**

## Results and Discussion

The raw and interpolated data from the laboratory studies are contained in Appendix A. The ozonation rates, ozonation times, average ozone residuals, and bromate concentrations are shown in the first four columns of Table 1. Column (3) was obtained by adding the residual ozone values and dividing by the number of values added together through the respective times (see Appendix B for sample calculations). Column (5) is the  $CT_T$  value, in mg-min/L, obtained by multiplying the average ozone concentration (i.e. Col 3) by the ozonation time in col (2). Figure 2 shows the graph obtained when the bromate concentrations (i.e. Col 4) are plotted against the  $CT_T$  values of column (5).

**Table 1.  $CT_T$  Values From Laboratory Data**

Ozonation Rate (L/min)	Ozonation Time (min)	Avg Ozone Residual (mg/L)	Bromate Conc (ppb)	$CT_T$ (mg-min/L)
1.5	1	0.00	0	0.00
1.5	2	0.00	0	0.00
1.5	4	0.02	0	0.07
1.5	6	0.05	0	0.27
1.5	8	0.08	0	0.60
1.5	10	0.10	5	1.02
2.0	1	0.00	0	0.00
2.0	2	0.03	0	0.07
2.0	4	0.11	3	0.44
2.0	6	0.19	6	1.12
2.0	8	0.26	11	2.05
2.0	10	0.31	19	3.10
2.5	1	0.03	0	0.03
2.5	2	0.07	0	0.13
2.5	4	0.19	4	0.75
2.5	6	0.29	9	1.77
2.5	8	0.39	16	3.08
2.5	10	0.45	22	4.49
1.5	1	0.00	0	0.00
1.5	2	0.00	0	0.00
1.5	4	0.00	0	0.01
1.5	6	0.02	3	0.12
1.5	8	0.04	4	0.34
1.5	10	0.07	7	0.66
2.0	1	0.00	0	0.00
2.0	2	0.03	2	0.06
2.0	4	0.10	3	0.38
2.0	6	0.17	5	0.99
2.0	8	0.22	9	1.78
2.0	10	0.27	13	2.65
2.5	1	0.00	0	0.00
2.5	2	0.04	2	0.07
2.5	4	0.15	6	0.60
2.5	6	0.26	10	1.57
2.5	8	0.36	16	2.88
2.5	10	0.44	22	4.35

The equation of the regression line is  $Y = 5.2823x$ , where Y is the bromate concentration in ppb and x is the  $CT_T$  value in mg-min/L. The high R-squared value of 0.96 obviously means that the bromate concentrations are very highly correlated with the  $CT_T$  values calculated from the laboratory results.

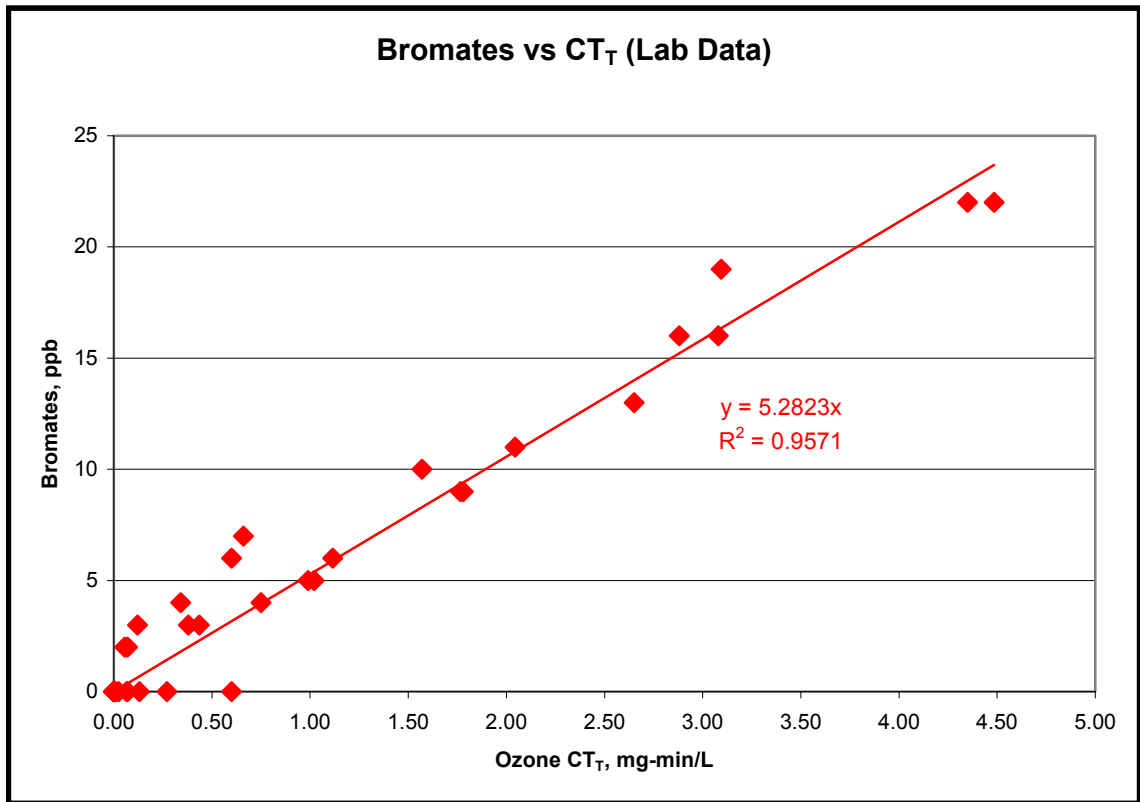


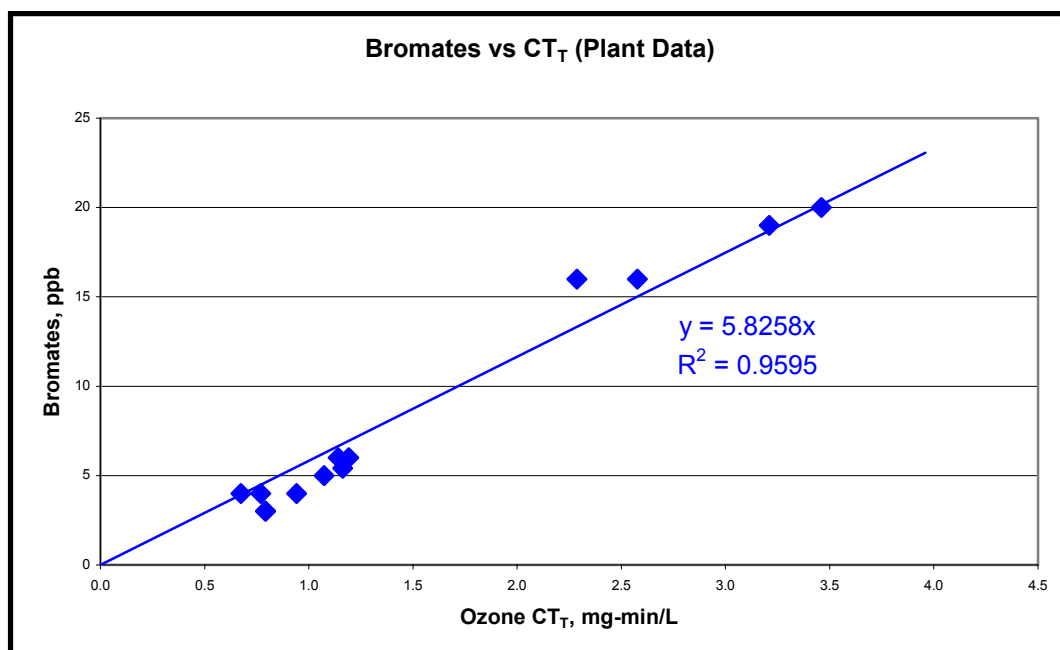
Figure 2. Plot of Bromate Concentrations versus Lab  $CT_T$  Values

The plant results are shown in the first five columns of Table 2. The last column is the  $CT_T$  value obtained by multiplying the residual ozone concentration (i.e. Col 4) by the theoretical detention time (Col 3). Figure 3 is a plot of the bromate concentrations versus the plant  $CT_T$  values. Again, the high R-squared value of 0.96 indicates that there is a

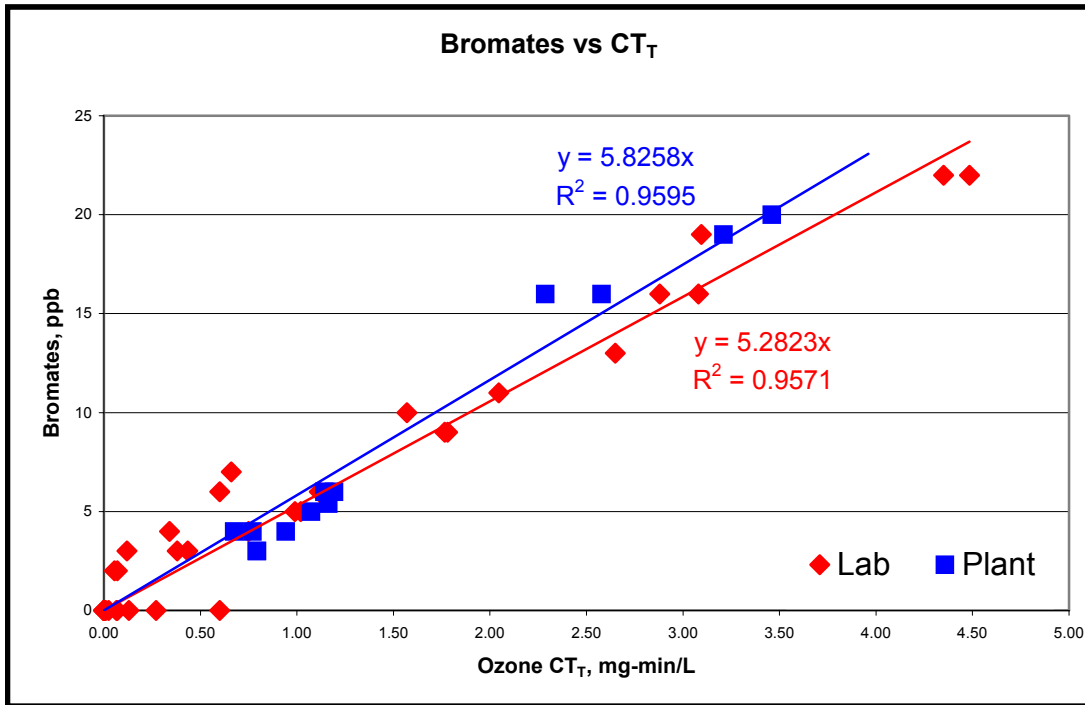
**Table 2.  $CT_T$  Values From Plant Results**

Date	Flow MGD	Theoretical Detention Time (min)	Ozone Residual (mg/L)	Bromate Conc. (ppb)	$CT_T$ (mg-min/L)
7-Mar-01	16.2	8.02	0.4	19	3.21
12-Mar-01	15.03	8.65	0.4	20	3.46
14-Mar-01	15.13	8.59	0.3	16	2.58
16-Mar-01	22.74	5.72	0.4	16	2.29
21-Mar-01	33.56	3.87	0.3	5	1.16
28-Mar-01	34.92	3.72	0.32	6	1.19
2-Apr-01	33.77	3.85	0.2	4	0.77
4-Apr-01	36.35	3.58	0.3	5	1.07
19-Apr-01	38.65	3.36	0.28	4	0.94
23-May-01	44.35	2.93	0.23	4	0.67
22-Jun-01	45.92	2.83	0.28	3	0.79
18-Jul-01	45.54	2.85	0.4	6	1.14
27-Jul-01	45.97	2.83	0.28	3	0.79

very high correlation between the bromate concentrations and the  $CT_T$  values calculated from the plant data. Figure 4 is a plot of the laboratory and full plant results on the same graph and, as shown, the two lines are essentially on top of each other. Thus, the full plant results are nearly identical to those obtained in the laboratory. Clearly then, the bromate concentration in the finished water at the plant is directly related to the product of the ozone concentration and the detention time in Cell 1 of the ozone contactor.



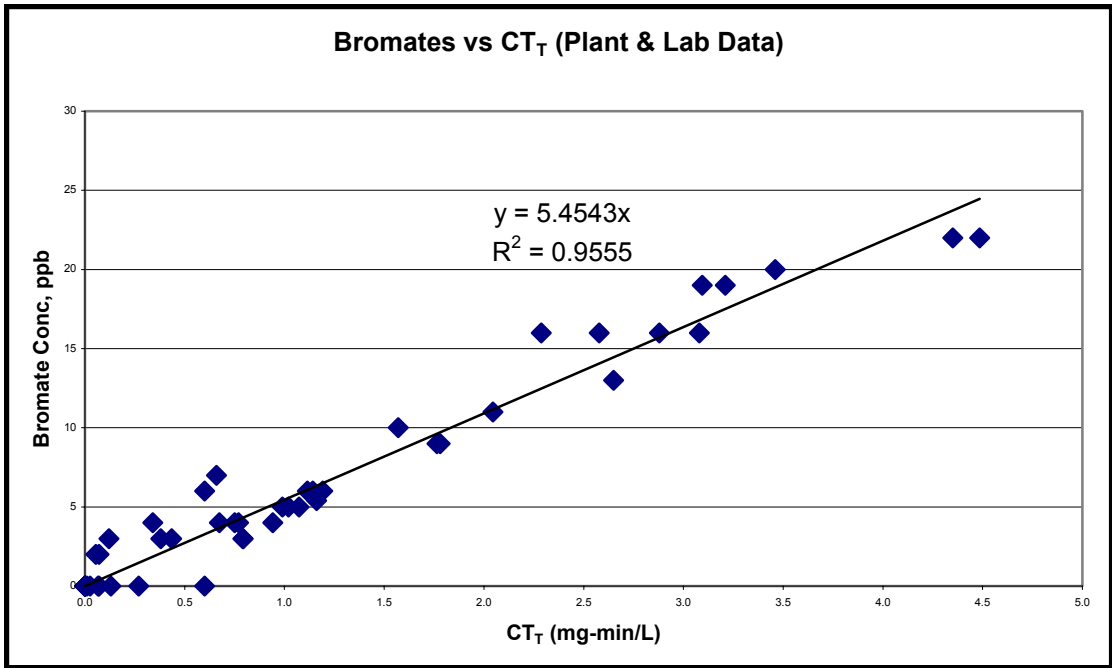
**Figure 3. Plot of Bromate Concentrations versus Plant  $CT_T$  Values**



**Figure 4. Plot of Lab and Plant Results**

Figure 5 is a least-squares regression line of the combined data from both the laboratory and plant studies. The equation of the regression line in the graph is  $Y = 5.4543x$ . This equation and the two equations generated from the separate laboratory and plant results can be used to calculate the  $CT_T$  values that would yield any specified bromate concentration in the finished water. For example, to have a bromate concentration of 5 ppb or less in the finished water, a  $CT_T$  value of 0.858 mg-min/L or less would be required (based on the equation from the plant data). At a flow rate of 40 MGD (1.75 m<sup>3</sup>/s), the detention time in the Cell 1 would be 3.25 minutes, meaning that the ozone concentration in Cell 1 should not exceed 0.26 mg/L (see Appendix B for sample calculation). Similar calculations for other flow rates using all three equations are shown in Tables 3 and 4 for bromate concentrations of 10 and 5 ppb, respectively. Obviously, similar calculations could be made for any desired bromate concentration in the finished water.

These results show that no structural, chemical, or treatment scheme modifications need to be made at the JRWTP to remain in compliance with existing or proposed changes in the allowable concentration of bromates in the finished drinking water. Since plant personnel already routinely monitor ozone (at 2-hour intervals) in Cell 1, a simple power adjustment from time-to-time is all that would be required to insure that the ozone concentration is maintained at a level that is commensurate with limiting the bromate concentration in the finished water *to any specified level for any flow rate* through the plant.



**Figure 5. Plot of Lab and Plant Results Combined**

**Table 3. Maximum Ozone Concentrations for Bromates of 10 ppb (based on  $CT_T$  value of 1.72 for plant data, 1.89 for lab data, and 1.83 for combined data)**

Flow (MGD)	Ozone Residual (mg/L)		
	Plant	Lab	Comb
10	0.13	0.15	0.14
15	0.20	0.22	0.21
20	0.26	0.29	0.28
25	0.33	0.36	0.35
30	0.40	0.44	0.42
35	0.46	0.51	0.49
40	0.53	0.58	0.56

**Table 4. Maximum Ozone Concentrations for Bromates of 5 ppb (based on  $CT_T$  value of 0.858 for plant data, 0.957 for lab data, and 0.917 for combined data)**

Flow (MGD)	Ozone Residual (mg/L)		
	Plant	Lab	Comb
10	0.07	0.07	0.07
15	0.10	0.11	0.11
20	0.13	0.15	0.14
25	0.17	0.18	0.18
30	0.20	0.22	0.21
35	0.23	0.26	0.25
40	0.26	0.29	0.28

## Economic Considerations

Ozone is generated by passing an electric charge through an oxygen-rich atmosphere and, as such, is produced in proportion to the power input to the ozonators. At the JRWTP, the ozone generated each day is represented by the following equation<sup>3</sup>:

$$\text{Ozone produced, lbs/day} = \text{kW} * 3.2$$

Where: kW = power setting at ozonator

Ozone residuals at the JRWTP are a function of several factors but, in general, an ozone concentration of 0.3 mg/L is obtained when the power input is 320 kW and the flow rate is 45 MGD (1.97 m<sup>3</sup>/s). These values indicate that under these water quality conditions, about 12% of the ozone applied to the water ends up as a residual in Cell 1. Preliminary results from on-going tests seem to indicate that there is a change of 0.1 mg/L in the ozone residual concentration for each 50 kW change in power input. Using these values and an electric power cost of \$0.061 per kW-hr, the following costs are obtained (see appendix B for calculations):

$$\begin{aligned} \text{Power cost @ 0.3 mg/L residual} &= \$468 \text{ per day} \\ &= \$14,290 / \text{mo} \end{aligned}$$

$$\text{Ozonation cost/1000 gal} = \$0.01/1000 \text{ gal}$$

$$\text{Change in cost per 0.1 mg/L residual} = \$73/\text{day}$$

In March thru July of the 2000 operating season, the average residual ozone concentration in Cell 1 at the JRWTP was 0.42 mg/L. In the same months of 2001, the average residual was 0.32 mg/L. The 0.1 mg/L difference represents a savings of \$73 per day, or about \$18,000 per operating season. Obviously, lower ozone residuals would result in even greater increased savings commensurate with the lower power levels involved.

It should be pointed out that reducing the ozone residual in Cell 1 of the ozone contactors could have a slightly adverse effect on the turbidity levels entering and leaving the GAC filters. Although such an effect is not expected to be significant (either from a plant operation or consumer health point of view), it may be worthwhile to evaluate this effect if considerable changes in ozone residuals are anticipated in future operations.

## Conclusions

Based on the results obtained in this study, the following conclusions can be made with reasonable certainty:

1. Results from both laboratory and plant data show that the bromate concentration in the finished water at the JRWTP is highly predictable and controllable based on the CT<sub>T</sub> value obtained by multiplying the residual ozone concentration (in mg/L) by the detention time in Cell 1 of the ozone contactor (in minutes).

2. The current policy of maintaining an ozone residual of 0.3 to 0.4 mg/L in Cell 1 will result in a  $CT_T$  value of 1.14 at a 40 MGD (1.75 m<sup>3</sup>/s) flow rate. This will generate a bromate concentration of about 7 ppb in the finished water. At the low flow rates that are typical at the beginning and end of the operating season, the ozone concentration would have to be reduced proportionately to limit the bromate concentration to this same value. Coincidentally, the  $CT_T$  value of 1.14 is equivalent to a disinfection CT value of 0.85 (because the  $T_{10}$  time for disinfection is about  $\frac{3}{4}$  of  $T_T$ )<sup>1</sup>. At this CT value, the JRWTP would achieve 2.5-log inactivation of *Giardia* cysts (at 15 °C) and over 4-log inactivation of viruses *in the ozone contactor alone*.
3. The bromate concentration in the finished water at the JRWTP can be limited to any concentration desired at any plant flow rate by controlling the ozone concentration in Cell 1 per the following equation:

$$Y = 5.8258x$$

Where: Y = Bromate concentration, ppb

x =  $CT_T$ , mg-min/L

C = Ozone concentration, mg/L

T = Theoretical detention time in Cell 1, minutes

4. In reducing the residual ozone concentration in Cell 1 by 0.1 mg/L as compared to last year, a savings of nearly \$18,000 will be realized in power costs in the 2001 operating season.

These results show that by following simple operating procedures (i.e. controlling the ozone concentration in the ozone contactor), the bromate concentration in the product water of a water treatment plant that employs ozone can be controlled to any level desired.

## Appendix A - Raw and Interpolated Data

**Table A1. Raw Data (Lab)**

Time (min)	Ozone Residual (mg/L)	Bromate Conc. (ppb)	Time (min)	Ozone Residual (mg/L)	Bromate Conc. (ppb)
1	0.00	0	1	0.00	0
2	0.00	0	2	0.00	0
4	0.07	0	4	0.01	0
6	0.13	0	6	0.10	3
8	0.20	0	8	0.12	4
10	0.22	5	10	0.20	7
1	0.00	0	1	0.00	0
2	0.13	0	2	0.11	2
4	0.24	3	4	0.22	3
6	0.44	6	6	0.39	5
8	0.49	11	8	0.40	9
10	0.56	19	10	0.47	13
1	0.05	0	1	0.00	0
2	0.21	0	2	0.14	2
4	0.41	4	4	0.39	6
6	0.60	9	6	0.58	10
8	0.71	16	8	0.73	16
10	0.70	22	10	0.74	22

**Table A2. Interpolated Values (to 1 minute intervals)**

Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)	Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)	Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)
1	0.000	0	1	0.050	0	1	0.000	0
2	0.000	0	2	0.210	0	2	0.110	2
<b>3</b>	<b>0.035</b>	-	<b>3</b>	<b>0.310</b>	-	<b>3</b>	<b>0.160</b>	-
4	0.070	0	4	0.410	4	4	0.220	3
<b>5</b>	<b>0.100</b>	-	<b>5</b>	<b>0.510</b>	-	<b>5</b>	<b>0.305</b>	-
6	0.130	0	6	0.600	9	6	0.390	5
<b>7</b>	<b>0.165</b>	-	<b>7</b>	<b>0.660</b>	-	<b>7</b>	<b>0.395</b>	-
8	0.200	0	8	0.710	16	8	0.400	9
<b>9</b>	<b>0.210</b>	-	<b>9</b>	<b>0.700</b>	-	<b>9</b>	<b>0.435</b>	-
10	0.220	5	10	0.700	22	10	0.470	13
1	0.000	0	1	0.000	0	1	0.000	0
2	0.130	0	2	0.000	0	2	0.140	2
<b>3</b>	<b>0.185</b>	-	<b>3</b>	<b>0.005</b>	-	<b>3</b>	<b>0.265</b>	-
4	0.240	3	4	0.010	0	4	0.390	6
<b>5</b>	<b>0.340</b>	-	<b>5</b>	<b>0.055</b>	-	<b>5</b>	<b>0.485</b>	-
6	0.440	6	6	0.100	3	6	0.580	10
<b>7</b>	<b>0.465</b>	-	<b>7</b>	<b>0.110</b>	-	<b>7</b>	<b>0.655</b>	-
8	0.490	11	8	0.120	4	8	0.730	16
<b>9</b>	<b>0.525</b>	-	<b>9</b>	<b>0.160</b>	-	<b>9</b>	<b>0.735</b>	-
10	0.560	19	10	0.200	7	10	0.740	22

\* Highlighted cells represent interpolated values

**Table A3. Interpolated Values (to 0.5 minute intervals)**

1.5 L/min Ozonation Rate					2.0 L/min Ozonation Rate				2.5 L/min Ozonation Rate			
Date	Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)	Avg. Ozone Conc. (mg/L)	Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)	Avg. Ozone Conc. (mg/L)	Time (min)	Interpolated Ozone Residual (mg/L)	Bromate Conc. (ppb)	Avg. Ozone Conc. (mg/L)
22-May-01	0.5	<b>0.000</b>	-	-	0.5	<b>0.000</b>	-	-	0.5	<b>0.000</b>	-	-
	1.0	0.000	0	0.00	1.0	0.000	0	0.00	1.0	0.050	0	0.03
	1.5	<b>0.000</b>	-	-	1.5	<b>0.065</b>	-	-	1.5	<b>0.130</b>	-	-
	2.0	0.000	0	0.00	2.0	0.130	0	0.03	2.0	0.210	0	0.07
	2.5	<b>0.018</b>	-	-	2.5	<b>0.158</b>	-	-	2.5	<b>0.260</b>	-	-
	3.0	0.035	-	-	3.0	0.185	-	-	3.0	0.310	-	-
	3.5	<b>0.053</b>	-	-	3.5	<b>0.213</b>	-	-	3.5	<b>0.360</b>	-	-
	4.0	0.070	0	0.02	4.0	0.240	3	0.11	4.0	0.410	4	0.19
	4.5	<b>0.085</b>	-	-	4.5	<b>0.290</b>	-	-	4.5	<b>0.460</b>	-	-
	5.0	0.100	-	-	5.0	0.340	-	-	5.0	0.510	-	-
	5.5	<b>0.115</b>	-	-	5.5	<b>0.390</b>	-	-	5.5	<b>0.555</b>	-	-
	6.0	0.130	0	0.05	6.0	0.440	6	0.19	6.0	0.600	9	0.29
	6.5	<b>0.148</b>	-	-	6.5	<b>0.453</b>	-	-	6.5	<b>0.630</b>	-	-
	7.0	0.165	-	-	7.0	0.465	-	-	7.0	0.660	-	-
	7.5	<b>0.183</b>	-	-	7.5	<b>0.478</b>	-	-	7.5	<b>0.685</b>	-	-
	8.0	0.200	0	0.08	8.0	0.490	11	0.26	8.0	0.710	16	0.39
8.5	<b>0.205</b>	-	-	8.5	<b>0.508</b>	-	-	8.5	<b>0.705</b>	-	-	
9.0	0.210	-	-	9.0	0.525	-	-	9.0	0.700	-	-	
9.5	<b>0.215</b>	-	-	9.5	<b>0.543</b>	-	-	9.5	<b>0.700</b>	-	-	
10.0	0.220	5	0.10	10.0	0.560	19	0.31	10.0	0.700	22	0.45	
18-Jul-01	0.5	<b>0.000</b>	-	-	0.5	<b>0.000</b>	-	-	0.5	<b>0.000</b>	-	-
	1.0	0.000	0	0.00	1.0	0.000	0	0.00	1.0	0.000	0	0.00
	1.5	<b>0.000</b>	-	-	1.5	<b>0.055</b>	-	-	1.5	<b>0.070</b>	-	-
	2.0	0.000	0	0.00	2.0	0.110	2	0.03	2.0	0.140	2	0.04
	2.5	<b>0.003</b>	-	-	2.5	<b>0.135</b>	-	-	2.5	<b>0.203</b>	-	-
	3.0	0.005	-	-	3.0	0.160	-	-	3.0	0.265	-	-
	3.5	<b>0.008</b>	-	-	3.5	<b>0.190</b>	-	-	3.5	<b>0.328</b>	-	-
	4.0	0.010	0	0.00	4.0	0.220	3	0.10	4.0	0.390	6	0.15
	4.5	<b>0.033</b>	-	-	4.5	<b>0.263</b>	-	-	4.5	<b>0.438</b>	-	-
	5.0	0.055	-	-	5.0	0.305	-	-	5.0	0.485	-	-
	5.5	<b>0.078</b>	-	-	5.5	<b>0.348</b>	-	-	5.5	<b>0.533</b>	-	-
	6.0	0.100	3	0.02	6.0	0.390	5	0.17	6.0	0.580	10	0.26
	6.5	<b>0.105</b>	-	-	6.5	<b>0.393</b>	-	-	6.5	<b>0.618</b>	-	-
	7.0	0.110	-	-	7.0	0.395	-	-	7.0	0.655	-	-
	7.5	<b>0.115</b>	-	-	7.5	<b>0.398</b>	-	-	7.5	<b>0.693</b>	-	-
	8.0	0.120	4	0.04	8.0	0.400	9	0.22	8.0	0.730	16	0.36
8.5	<b>0.140</b>	-	-	8.5	<b>0.418</b>	-	-	8.5	<b>0.733</b>	-	-	
9.0	0.160	-	-	9.0	0.435	-	-	9.0	0.735	-	-	
9.5	<b>0.180</b>	-	-	9.5	<b>0.453</b>	-	-	9.5	<b>0.738</b>	-	-	
10.0	0.200	7	0.07	10.0	0.470	13	0.27	10.0	0.740	22	0.44	

\* Highlighted cells represent interpolated values

## Appendix B

### Sample Calculations

#### Average Ozone Concentration

For 4 minute value at a rate of 2.0 L/min on 5/22/01(See Table A3 for data):

$$\begin{aligned}\text{Avg. O}_3 \text{ Conc.} &= (0.00 + 0.00 + 0.065 + 0.130 + 0.158 + 0.185 + 0.213) / 7 \\ &= 0.107 \\ &= \mathbf{0.11 \text{ mg/L}}\end{aligned}$$

#### Calculated Ozone Concentration for Specified Bromate Level

Assume flow is 40 MGD and bromate concentration is to be  $\leq 5$  ppb:

$$\begin{aligned}\text{Detention time} &= \frac{3000 \text{ ft}^3/\text{cell} * 4 \text{ cells} * 24 * 60}{40,000,000 \text{ gal/day} * 0.133 \text{ ft}^3/\text{gal}} \\ &= \mathbf{3.25 \text{ minutes}}\end{aligned}$$

CT<sub>T</sub> value for 5 ppb from plant data equation (Figure 3):

$$\begin{aligned}Y &= 5.8258x \\ 5 &= 5.8258x \\ x &= 0.858 \\ \therefore \text{CT}_T &= \mathbf{0.858}\end{aligned}$$

$$\begin{aligned}0.858 &= (\text{O}_3 \text{ Conc.}) * 3.25 \\ \text{O}_3 \text{ Conc.} &= \mathbf{0.26 \text{ mg/L}}\end{aligned}$$

#### Ozone Generation Rate

For a power setting of 320kW and Q = 45 MGD:

$$\text{Ozone generated, lbs/day} = \text{kW} * \text{factor (i.e. 3.2)}$$

$$= 320 * 3.2$$
$$= \underline{\underline{1,024 \text{ lbs/day}}}$$

### Ozone Applied

$$1024 = \text{mg/L} * 45 * 8.34$$
$$\text{O}_3 \text{ applied, mg/L} = \underline{\underline{2.7 \text{ mg/L}}}$$

### Ozone Transfer Efficiency(neglecting demand)

For average ozone residual of 0.32 mg/L:

$$\text{Overall O}_3 \text{ transfer efficiency} = (0.32/2.7) * 100$$
$$= \underline{\underline{12 \%}}$$

### Power Cost

For electricity cost of \$0.061 per kW-hr:

$$\text{Cost/day} = 320 \text{ kW} * 24 \text{ hr/day} * 0.061 \text{ \$/kW-hr}$$
$$= \underline{\underline{\$468/\text{day or } \$14,290 /\text{mo}}}$$

### Ozone Cost/1000 gal

$$\text{O}_3 \text{ Cost} = \$468/45,000$$
$$= \underline{\underline{\$0.01/1000 \text{ gal}}}$$

### Cost per 0.1mg/L O<sub>3</sub> Residual (at 50 kW for 0.1 mg/L residual)

$$\text{Cost} = 50 \text{ kW} * 24 \text{ hr/day} * 0.061 \text{ \$/kW-hr}$$
$$= \$73 /\text{day}$$
$$= \underline{\underline{\$17,800 /\text{season}}}$$

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## **References**

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