The Effect of Ozone Demand on Mass Transfer Efficiency and It's Importance to In-Line Ozone Contactor Design

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ABSTRACT

For disinfection purposes, the ***Dissolved Ozone*** *concentration (mg/l) times* ***the Contact Time*** *(minutes), also known as the* ***CT Value****, are critical. In order to achieve a high* ***CT Value****, either high dissolved ozone concentrations for short* ***Contact Times****, or low ozone concentrations for long* ***Contact Times*** *can be employed. Long* ***Contact Times*** *can only be facilitated by large volume contacting systems, which have large footprints and require large capital investments. Therefore, high* ***Dissolved Ozone*** *concentrations are advantageous. The new high concentration ozone generators are ideal for achieving high dissolved ozone concentrations.*

Mass Transfer Efficiency *(****MTE****) and* ***Ozone Demand*** *are critical factors in* ***In-Line Contactor*** *system design. The* ***MTE*** *is the percentage of the applied Ozone that actually goes into solution under a given set of operating conditions.* ***Ozone Demand*** *is the amount of ozone consumed by oxidizable material in the water. Both the* ***MTE*** *and* ***Ozone Demand*** *must be taken into account for prediction of* ***Dissolved Ozone*** *concentration, and hence* ***CT Value****, during* ***In-Line Contacting*** *system design.*

Presented in this paper is a computer program that facilitates the design of ***In-Line Contactors*** *which utilize side stream ozone injection via* ***High Efficiency Venturi's*** *and* ***Radial Mixing Nozzles****. <u>The predicted transfer efficiencies are based on extensive empirical test results</u>. The effect of* ***Ozone Demand*** *on both the* ***MTE*** *and the resulting* ***Dissolved Ozone*** *concentration are automatically calculated by the program.*

The derivation of the mathematical equation utilized to predict the effect of ***Ozone Demand*** *on the* ***Mass Transfer Efficiency*** *is presented.*

Introduction:

Side stream injection of ozone for purposes of in-line contacting affords advantages of small footprint, and high mass transfer and energy efficiency.

For disinfection purposes, a **CT Value** (ozone concentration x contact time) will be specified. In order to achieve the specified **CT Value** the dissolved ozone residual must be known. The dissolved ozone residual is affected by the **Mass Transfer Efficiency** and the **Ozone Demand.**

The **Mass Transfer Efficiency** of a side stream injection system that utilizes high efficiency venturis and mixing nozzles has been studied in detail (2,3). The data collected has been used to develop a spreadsheet that facilitates in-line contactor design. The spreadsheet uses empirical **Ozone Demand** data, contactor vessel volume and ozone generator output values to calculate the dissolved ozone residual and **CT Value**. In addition, the proper venturi injector(s) is specified, and based on operating cost data the overall cost of operation is calculated. **Table 1** is an example of this spreadsheet.

In-Line Contacting with Side Stream Injection:

The process of In-Line Contacting with Side Stream Injection is achieved by taking a portion of the main flow and boosting it to a higher pressure to operate a High Efficiency Venturi Injector(s). The High Efficiency Injector(s) aspirates the ozone gas from the ozone generator and dynamically/violently mixes it with the side stream flow.

The resulting, thoroughly mixed, ozone gas/water mixture is then discharged at high velocity through specially designed nozzles back into the main flow. The rate at which the maximum Mass Transfer Efficiency is achieved in the main flow is a function of the mixing efficiency of the side stream ozone gas/water mixture with the main flow. The high exit velocity of the nozzles produces a mixing eductor effect and extremely rapid mixing of the side stream with the main flow. The result is maximum Mass Transfer Efficiency within a very short time.

Figures 1 & 2 depict the thorough mixing of the side stream and main flows in the test apparatus used in the Mass Transfer Efficiency testing.

Figure 1

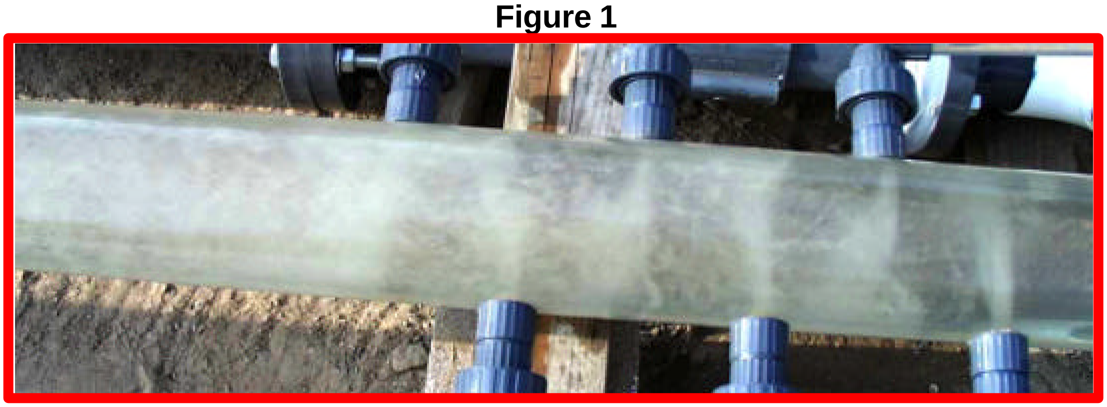
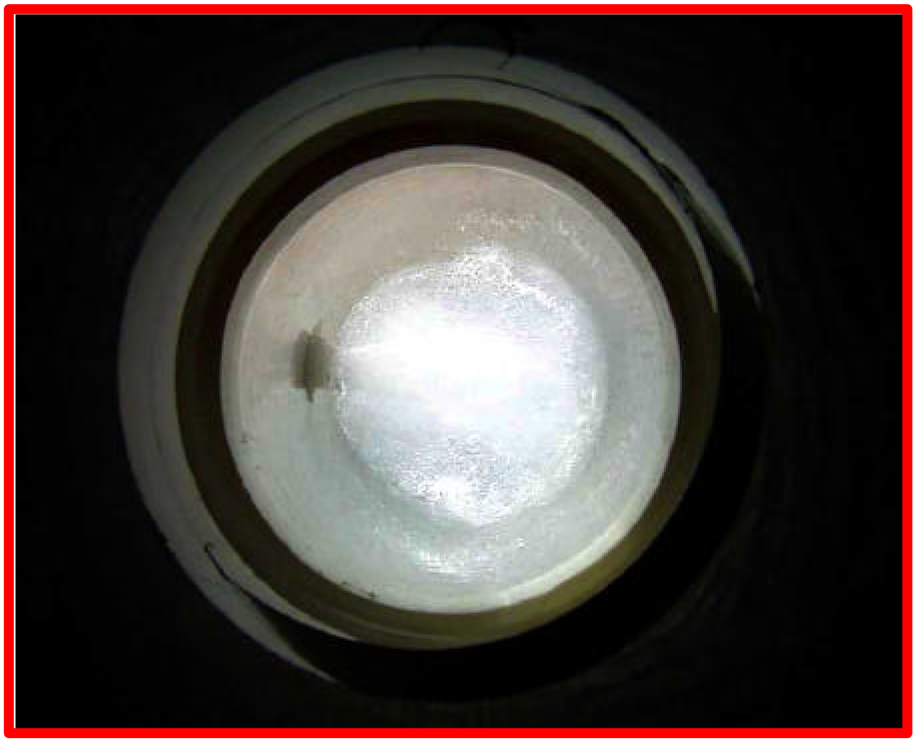


Figure 2



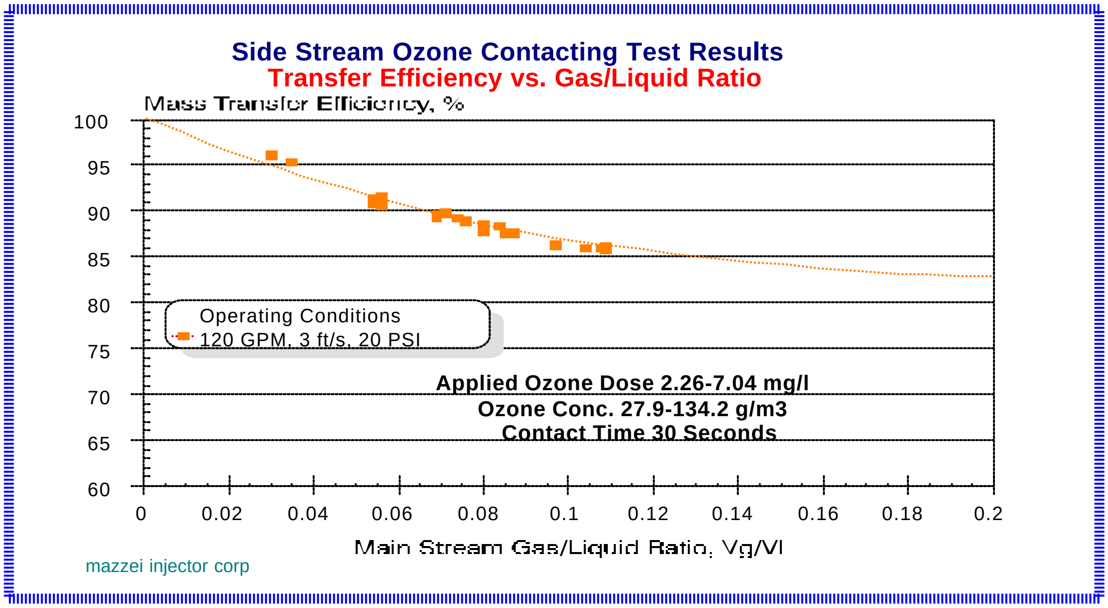
Mass Transfer Efficiency:

Mass Transfer Efficiency is defined as the portion of applied ozone that goes into solution in the water. The **MTE** is calculated from the mass of applied ozone and the mass of ozone in the off gas as follows (2,3):

$$\mathbf{MTE} = \frac{((\text{O3 Conc. in} \times \text{Gas Vol. in}) - (\text{O3 Conc. out} \times \text{Gas Vol. out}))}{(\text{O3 Con in} \times \text{Gas Vol. in})} \times 100$$

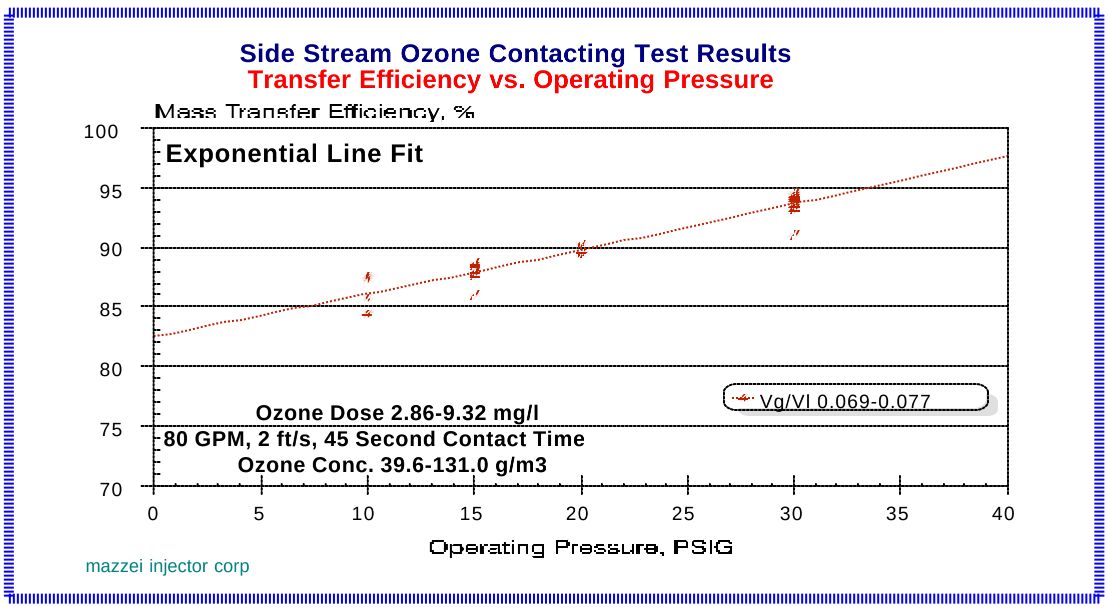
Operating parameters that affect **MTE** are water temperature, gas/liquid ratio (**Vg/Vl**) and contactor pressure (1,2,3). Ozone is more soluble in cold water than hot water. Low **Vg/Vl**'s promote high mass transfer efficiency, while high **Vg/Vl**'s result in low mass transfer efficiency (2,3). High concentration ozone generators facilitate low **Vg/Vl**'s even at high-applied ozone doses. **Figure 3** demonstrates the affect of gas/liquid ratio on **MTE**.

Figure 3



High contactor operating pressures force more ozone into solution resulting in increased **MTE** (1,2,3). **Figure 4** demonstrates the affect of contactor pressure on the **MTE**.

Figure 4



Ozone Demand:

Ozone demand is the amount of ozone consumed by oxidizable material in the water. Some factors that affect ozone demand are temperature, pH, alkalinity, and organic content etc (1). The ozone demand for a water must be determined empirically. For use in the system design spreadsheet, the ozone demand determined by experimentation must be expressed a ratio of ozone consumed to applied ozone. The units are:

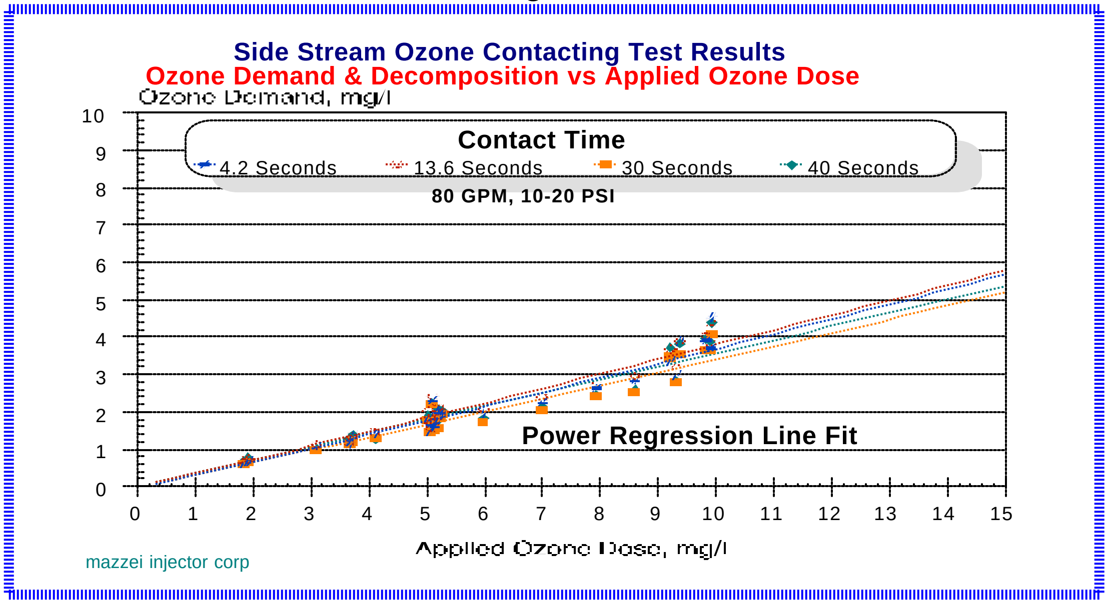
Ozone Demand (mg/l)/Applied Ozone (mg/l).

Figure 5 demonstrates the ozone demand relative to applied dose for the well water used in the mass transfer testing (3).

The slope of the ozone demand curve for the well water used in the Mass Transfer testing was 0.36/1. This value was used in the system design spreadsheet to correct the **Observed MTE** back to what the **MTE** would have been if there were no demand in the test water.

It must be noted that this **Observed MTE** is not the same as the mass transfer efficiency that would be calculated from the mass of dissolved ozone after the demand has been met, divided by the mass of applied ozone.

Figure 5



Ozone Demand & Mass Transfer Efficiency:

The mathematical formula for correction of the **No-demand MTE (ND MTE)** to the **Observed MTE (Ob MTE)** under a given set of operating conditions follows:

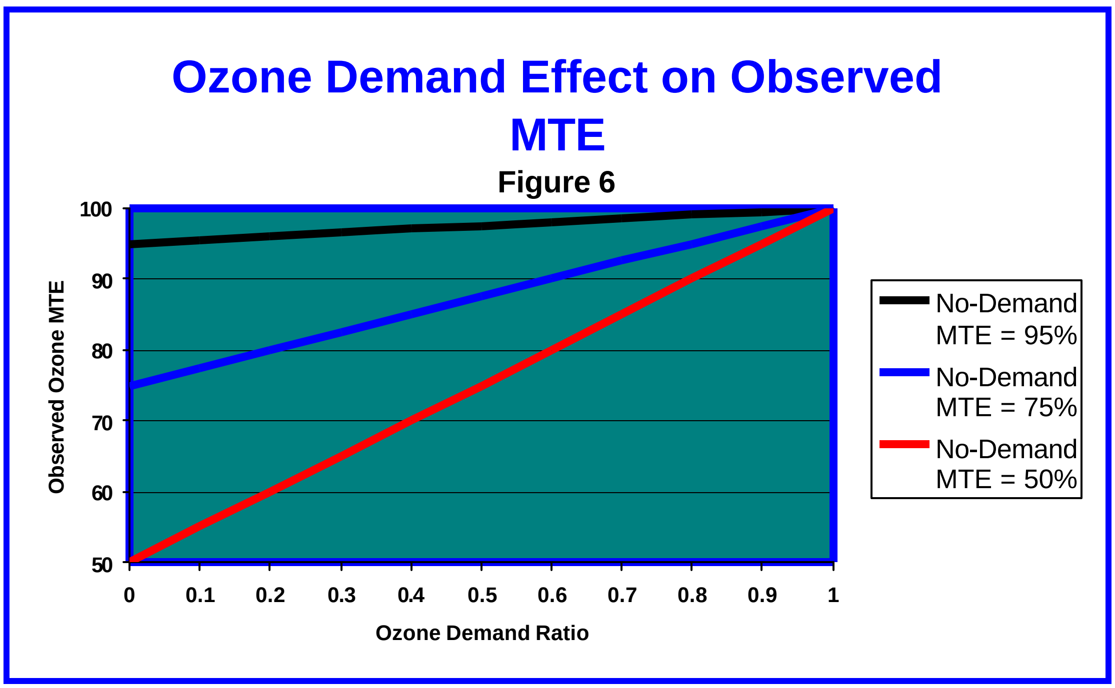
$$\text{Ob MTE} = \frac{(1-(\text{Applied Dose} \times (1-\text{Demand Ratio}) \times (1-\text{ND MTE})) \times 100}{\text{Applied Dose}}$$

The Applied Dose Factors Cancel Leaving:

Observed MTE =(1-((1-Demand Ratio) x (1-No Demand MTE))) x 100

The **Observed MTE** is used for calculation of ozone residual and **CT Value** during system design.

Figure 4 shows that the ozone demand has a relatively greater effect on the **Observed MTE** when the **No-Demand MTE** is low as compared to when it is high. In addition, it makes sense that if the demand is 100% then all of the applied ozone will have been consumed, and 100% of nothing will have to be transferred.



It must be noted that the **Observed MTE** is not the same as the mass transfer efficiency that could be calculated from the mass of dissolved ozone (after the demand has been met) divided by the mass of applied ozone. Mass transfer efficiency calculated from the dissolved ozone residual will always be less due to the ozone demand.

Contactor System Design Program:

Following are instructions on the use of the "**In-line Ozone Contactor with Side Stream Injection**" spreadsheet. **Table 1** is an example of the actual spreadsheet, which can be referred to while working through the instructions.

Operating Parameters Section:

The following values must be entered.

Main Flow Volume:

The Main Flow Volume is the total volume of water with which the ozone is to be contacted. Units are GPM.

Contactor Operating Pressure:

The Contactor Operating Pressure is the pressure in the main flow contactor conduit. Units are PSI.

Applied Ozone Dose:

The Applied Ozone Dose is the dose of ozone required to meet the ozone residual for the specified **CT Value** after the ozone demand and mass transfer efficiency have been met. Units are mg/l. This value is typically determined empirically by pilot testing.

Ozone Gas Concentration:

The Ozone Gas Concentration is the concentration of ozone in weight percent in the feed from the ozone generator.

Expected Ozone Demand Ratio:

The Ozone Demand Ratio is the amount of ozone that will be consumed by the ozone demand of the water. The value to be entered is the ratio of ozone consumed relative to the applied ozone dose. This value is a ratio, not an absolute mass of ozone consumed. For example, if 2.0 mg/l of ozone are applied, and after the demand of the water has been met, the residual is 1.0 mg/l, the demand ratio is 1.0/2.0 or 0.5. **This value must be determined empirically by pilot testing**.

Contactor Volume:

The Contactor Volume is the volume of the main flow-contacting conduit or tank. This value is used to calculate the contact time and hence **CT Value**.

Calculations Section:

The spreadsheet calculates the following values from the values entered in the Operating Parameters section.

Required Ozone Injection Rate:

The Required Ozone Injection Rate is the mass of ozone in units of Pounds/hour that must be injected to achieve the specified Applied Ozone Dose. This value along with the ozone demand must be determined empirically.

Required Ozone Gas Flow:

The Required Ozone Gas Flow is the volume of ozone gas in units of SCFM that must be injected. This value is calculated from the Required Ozone Injection Rate and the Ozone Gas Concentration from the ozone generator.

Calculated Gas/Liquid Ratio:

The volumetric Gas/Liquid Ratio (**Vg/Vl**) calculated from the Required Ozone Gas Flow and the Main Flow Volume (in units of CFM). The **Vg/Vl** value is used along with the Contactor Operating Pressure to determine the Mass Transfer Efficiency.

Mass Transfer Efficiency, **MTE**:

Mass Transfer Efficiency is calculated from the Contactor Operating Pressure, Volumetric Gas/Liquid Ratio and the Ozone Demand Ratio. This is the ratio of the mass of ozone in the off gas relative to the mass of ozone in the feed from the ozone generator.

Calculated Ozone Residual:

The Calculated Ozone Residual is the calculated dissolved ozone residual after the Ozone Demand has been met, minus the ozone in the off gas.

Contact Time:

The Contact Time (residence time) is based on the Main Flow Volume and the Contactor Volume.

CT Value:

The CT Value is the Concentration x Contact Time used for prediction of disinfection effectiveness calculated form the Contact Time and Calculated Ozone Residual Values.

Injector Selection Section:

In the this section, an appropriate injector(s) will be suggested to meet the side stream injection requirements dictated by the Required Ozone Gas Flow and contactor operating pressure conditions. The injector(s) suggestion is for the minimum required to inject the Required Ozone Gas Flow. The ozone mass transfer testing documented that the percent side stream has relatively little affect on the MTE (3). However, it is suggested that the minimum percent side stream be about 10%.

Ozone Gas Pressure @ Injector:

The Ozone Gas Pressure is the pressure of the ozone gas from the ozone generator that is available at the suction port of the injector(s). Head losses in the conduit from the generator to the injector must be taken into account. Units are gauge pressure, PSIG. Pressures less than one atmosphere absolute are entered in units of negative gauge pressure. For example, if the Ozone Gas Pressure were 0.5 atmospheres absolute (or 15" Hg vacuum), the value entered would be –7.35 PSI ((14.7*0.5)-14.7).

Number of Injectors to be used:

The number of injector to be used in the side stream injection system is specified. From this value and the Ozone Gas Pressure, the Required Suction Capacity Per Injector is calculated. The Required Suction Capacity Per Injector in units of actual CFM (ACFM). If a value > 10.5 CFM/Injector is displayed, the injector specification is invalid and a greater number of injectors must be specified.

Once a valid Required Suction Per Injector has been displayed, the injector(s) Model is specified. The Boost Pressure Required (pressure added to the Contactor Operating Pressure for injector operation), Total Side Stream volume and Percent Side Stream are calculated.

Pump Requirement:

Pumping power requirements (Water Horsepower, WHP and Brake Horsepower, BHP) are calculated for the Boost Pressure Required, Total Side Stream Volume and Pump Efficiency Values.

Operating Costs:

The Total Operating Cost for the side stream injection system is estimated from the costs for operating the ozone generator and the side stream pumping requirements.

CONCLUSIONS:

The effects of operating parameters for in-line ozone contacting systems, which use High Efficiency Venturi Injectors and Nozzles for side stream injection, have been studied in detail (2,3). Calculation techniques that take into account the key operating parameters that effect contactor design (Operating Pressure, Gas/Liquid Ratio and Ozone Demand) have been used to develop a useful computer program for contactor system design.

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Key Words

Ozone, In-Line Contacting, Side Stream Injection, Mass Transfer Efficiency, MTE, Applied Ozone Dose, Gas/Liquid Ratio, Vg/Vl, System Pressure, Ozone Demand, Contact Time, Gas/Liquid Interface, Flow Velocity,

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Side Stream Ozone Injection For In-Line Contacting

Prepared For: **Project:** **Purpose For Ozonation:** **Date: 5/31/00**	**Table 1** **Example Ozone Contactor System Design** **Values In Shades Cells Must be Entered**

Operating Parameter	Units	Value	Comments
Main Flow Volume	**GPM**	**695**	1 MGD
Contactor Operating Pressure	**PSIG**	**15**	Pressure in the Main Flow Conduit
Applied Ozone Dose	**mg/l**	**8**	Specified By pilot testing
Ozone Gas Concentration	**wt %**	**10**	
Expected Ozone Demand Ratio, mg/l/mg/l		**0.36**	**mg/l Demand/mg/l applied: Determined Empirically**
Contactor Volume	**Gal**	**1500**	Volume of the main flow conduit or tank
Calculations			
Required Ozone Injection Rate	**#/hour**	**2.78**	From the Applied Dose & Main Flow values
Required Ozone Gas Flow	**SCFM**	**5.51**	From O3 #/hr & wt% O3 Generator output
Calculated Gas/Liquid Ratio	**Vg/Vl**	**0.06**	Gas Flow SCFM/Main Flow ft3/min
Mass Transfer Efficiency, MTE	**%**	**91.0**	Ozone Off-Gas/Ozone Feed
Calculated Ozone Residual	**mg/l**	**4.40**	Applied Dose - O3 Demand & off gas O3
Contact Time	**min**	**2.16**	Contactor Volume/Main Flow Volume
CT Value, Conc. x Time, mg/l x min		**9.50**	
Injector Selection			
Ozone Gas Pressure @ Injector	**PSIG**	**12.00**	Enter Sub-Atmospheric Pressures As -PSI
Number of Injectors to be used		**1**	
Required Suction Per Injector	**CFM**	**1.67**	Corrected for Pressure, Invalid if > 10.5 CFM
Specified Injector(s)	**Model**	**1583**	
Boost Pressure Required	**PSIG**	**45.0**	Pressure added to the Main Flow Pressure
Side Stream Volume Per Injector	**GPM**	**33**	
Total Side Stream Volume	**GPM**	**33**	
Percent Side Stream	**%**	**4.8**	
Pump Requirement			
Water Horsepower Required	**WHP**	**0.9**	
Pump Efficiency	**%**	**70**	
Brake Horsepower Required	**BHP**	**1.3**	
Operating Costs			
Unit Ozone Generation Cost	**$/#**	**0.700**	Dependent on O3 Generator & Operating Conditions
Cost For Ozone	**$/Day**	**46.7**	
Unit Electricity Cost	**$/kWh**	**0.08**	
Side Stream Pumping Cost	**$/Day**	**1.8**	
Total Operating Cost	**$/Day**	**48.5**	

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