Integrating Ozone and UV Disinfection Processes at the Greater Vancouver Water District's Coquitlam Source

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ABSTRACT

In 2004, an engineering study was completed to investigate the ramifications of adding ultraviolet (UV) treatment to the Greater Vancouver Water District's Coquitlam source. UV would replace or supplement the existing ozone and chlorine treatment. The 2004 study found that there are clear benefits to retaining ozone. Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L: is more economical than UV alone; reduces the formation of disinfection by-products (DBPs), with trihalomethanes (THMs) meeting the USEPA standard of 80 µg/L or less; provides some reduction in HAAs to approximately 80 µg/L; and provides an additional treatment barrier for disinfection. Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L, in conjunction with UV treatment will further reduce HAA levels to the USEPA standard of 60 µg/L, has little impact on 20-year life cycle costs, but there is a significant shift from capital to operating dollars.

INTRODUCTION

The Greater Vancouver Water District (GVWD) delivers water to 18 Lower Mainland municipalities, which in turn deliver water to approximately two million people. Water is collected from three mountainous watersheds: Capilano, Seymour, and Coquitlam. The system consists of six dams and an extensive transmission system of 22 reservoirs, 15 pumping stations, and over 500 km of supply mains.

BC Hydro operates the Coquitlam Lake and dam. The GVWD has an intake tower at the south end of the lake and withdraws water in accordance with its provincial licenses and an agreement with BC Hydro. Presently the GVWD treats the Coquitlam source using ozone for primary disinfection, soda ash for corrosion control, and free chlorine for secondary disinfection.

In mid 2000, the Coquitlam ozone disinfection facility was commissioned and began treating water from the existing intake. At the time of design and construction of this facility, UV disinfection was not considered a viable technology for primary disinfection of large scale water systems. However, more recently, UV has become a viable primary disinfection option for large scale water supply systems, primarily for the inactivation of *Cryptosporidium* and *Giardia*.

While ozonation of the Coquitlam water supply provides excellent treatment for most pathogens, the GVWD recognizes that ozone may not provide adequate year-round inactivation of *Cryptosporidium*. In light of new guidelines for *Cryptosporidium* and the desire to improve water quality, the GVWD approved the addition of UV treatments as a supplement to existing ozone treatment with the approval of the Drinking Water Management Plan in September 2005. Such a change has considerable merit since it would provide a minimum 3-log inactivation of *Cryptosporidium* at all times especially during periods of low temperature water when ozone loses its effectiveness. It would also ensure compliance with future EPA regulations for *Cryptosporidium*.

In 2004 an engineering study to investigate the ramifications of adding UV treatment of the Coquitlam source was completed. A key question was whether ozone treatment should be retained when UV treatment is added, and if so, at what level. This paper is a summary of the 2004 engineering study.

EXISTING WATER SYSTEM

Coquitlam Lake currently supplies about 30% of the region's drinking water. Water is derived from a 20,000 ha mountain watershed which is closed to the public.

Water at the south end of Coquitlam Lake enters an intake tower and passes through coarse screens. It then flows through a tunnel and pipeline to an ozone treatment facility approximately 1,300 m downstream of the dam and intake.

Ozone is generated from liquid oxygen (LOX) stored in a bulk tank adjacent to the ozone facility. It is fed to a sidestream from the main flow which is then recombined with the main process flow in a long pipeline which serves as an ozone contactor. The ozone facility is designed to provide an applied ozone dose of up to 2.3 mg/L ozone at the peak hour flow of 1,200 ML/d.

At the end of the ozone pipeline contactor, the water flows to a corrosion control and chlorination facility. This facility contains four chemical feed systems: hydrogen peroxide for quenching of residual ozone, soda ash and carbon dioxide for reducing the corrosiveness of the water, and chlorine for residual disinfection (Figure 1).

WATER QUALITY

Table 1 is a summary of historic water quality data for Coquitlam Lake.

1. Units are mg/L unless otherwise noted.
2. MAC means maximum acceptable concentration, AO means aesthetic objective. There is no guideline if none shown.
3. The Canadian Drinking Water Quality Guideline for turbidity published in March 2005 allows for a waterworks system to remain unfiltered if appropriate treatment is applied and average daily source water turbidity levels measured at equal intervals, immediately prior to where the disinfectant is applied, are around 1.0 NTU but do not exceed 5.0 NTU for more than 2 days in a 12-month period.

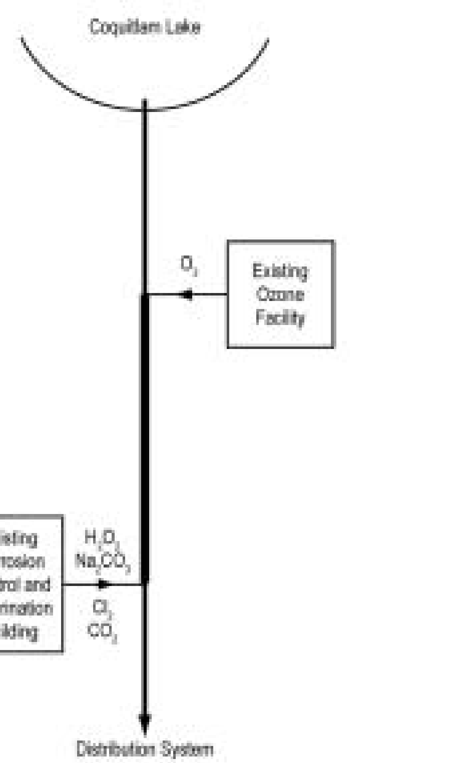


Figure 1. *Simplified Process Flow Diagram – Existing Intake*

Table 1. *Coquitlam Lake Water Quality*

Parameter[1]	Guidelines for Canadian Drinking Water Quality[2]		Mean	Min	Max	Samples	Period
	MAC	AO					
Physical							
UVT (filtered), % transmittance			86.6	75.7	93.5	382	1998 to 2004
UVT (apparent), % transmittance			85.8	74	91.4	63	2003 to 2004
Colour, tcu		15	11	4	22	260	1999 to 2004
pH		6.5-8.5	6.3	5.9	6.5	52	2003
Temperature °C		15		5	19	52	2003
Turbidity, NTU (daily average for an unfiltered source)	5[3]	5	0.58	0.17	**77**	3989	1993 to 2004
Inorganics							
Alkalinity, as $CaCO_3$			1.9	1.2	7.6	61	1999 to 2004
Calcium			0.96	0.74	1.08	65	1999 to 2004
Hardness, as $CaCO_3$			2.83	2.18	3.15	61	1999 to 2004
Iron		0.3	0.064	0.03	0.26	258	1999 to 2004
Manganese		0.05	0.007	0.003	0.01	64	1999 to 2004
Sodium		200	0.53	0.33	3.3	32	1999 to 2004
Total Dissolved Residue		500	11.8	10	13	6	2003
Organics							
Total Organic Carbon			1.8	1.2	2.8	297	1999 to 2004
Dissolved Organic Carbon			1.7	1.1	2.7	296	1999 to 2004

The lake water meets the Guidelines for Canadian Drinking Water Quality for all parameters listed in Table 1 except turbidity and pH. Occasionally, the colour and temperature are above the Aesthetic Objectives. The lake water turbidity is normally less than 1 NTU, but occasionally spikes to 5 NTU or greater after heavy rains. Current operation for the GVWD system is to take the Coquitlam source out of service before the turbidity exceeds 5 NTU and supply water to the system from the Capilano and Seymour sources.

DESIGN CONSIDERATIONS

For the 2004 engineering study, the GVWD specified that the overall treatment train should achieve 4 log (99.99%) virus inactivation and 3 log (99.9%) inactivation of *Cryptosporidium* and *Giardia lamblia*.

Based on the USEPA's UV Draft Disinfection Guidance Manual, the required UV dose for unfiltered water to achieve the 3-log inactivation of *Cryptosporidium* and *Giardia lamblia* is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV or 36 mJ/cm^2 (360 J/m^2) for low pressure high output UV. Ozone and/or chlorine treatment will achieve 4-log virus inactivation.

The average day and peak hour flows are 450 ML/d and 1,200 ML/d respectively.

OZONE EVALUATION

In considering a switch to UV treatment, the benefits of ozone needed to be assessed. Previous research has shown that ozone treatment increases the ultraviolet transmittance (UVT) (1 cm path length) of the water and may decrease disinfection by-products (DBP) formation when applying free chlorine downstream of the ozone process.

Since the Coquitlam ozone system began operation, the increase in UVT and reduction in DBPs has also been seen by the GVWD. Data on total trihalomethane (THM) levels in the water distribution system indicates that treated water from the Coquitlam source has lower THM levels than treated water from the other GVWD sources. Data for haloacetic acid (HAA) levels also seems to show lower HAA levels in treated water from the Coquitlam source.

UV Transmittance (UVT)

Normal laboratory analysis of UVT includes filtering of the sample to remove suspended materials. For the design of UV systems, what is important is the 'apparent' UVT. The apparent UVT is the actual UVT of the water passing through the UV reactor. For unfiltered water systems such as Coquitlam, it is appropriate to measure UVT without filtration of the sample.

Figure 2 shows the apparent UVT of the Coquitlam intake and treated water, from June 2003 to August 2004.

It can be seen that ozone treatment of the water has historically increased the apparent UVT value by 5 to 11%, with the greatest increases (9 to 11%) occurring when the incoming UVT was lowest (< 85%).

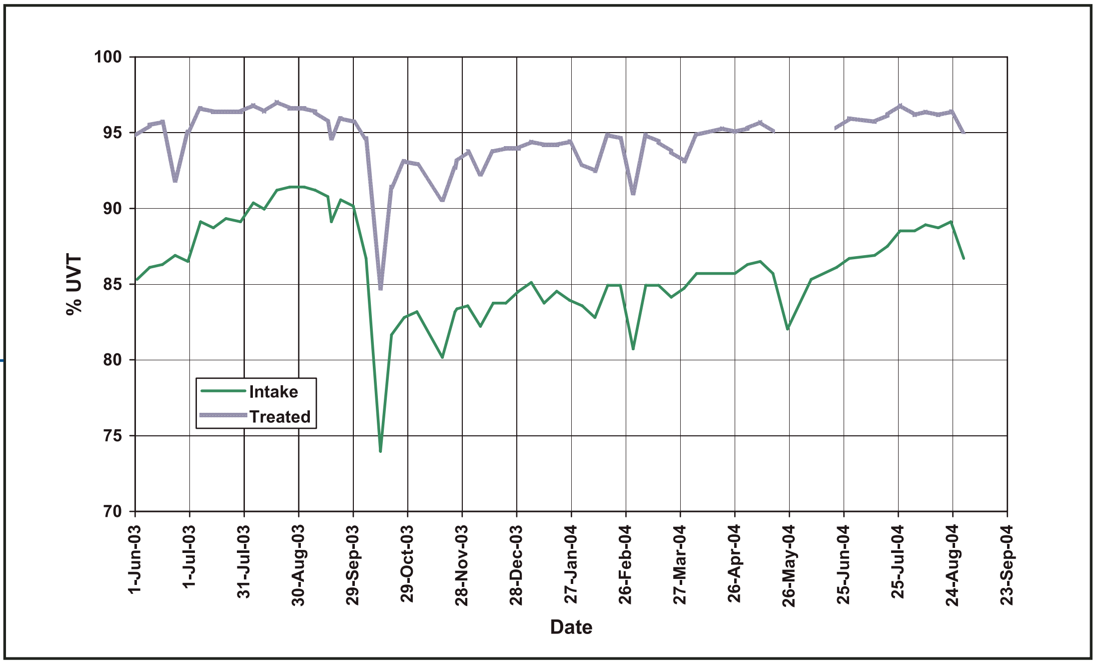


Figure 2. *Apparent UVT of Coquitlam Water (2003 – 2004)*

Figure 3 shows UVT over a longer period of time. In this plot, the UVT is the 'filtered' UVT.

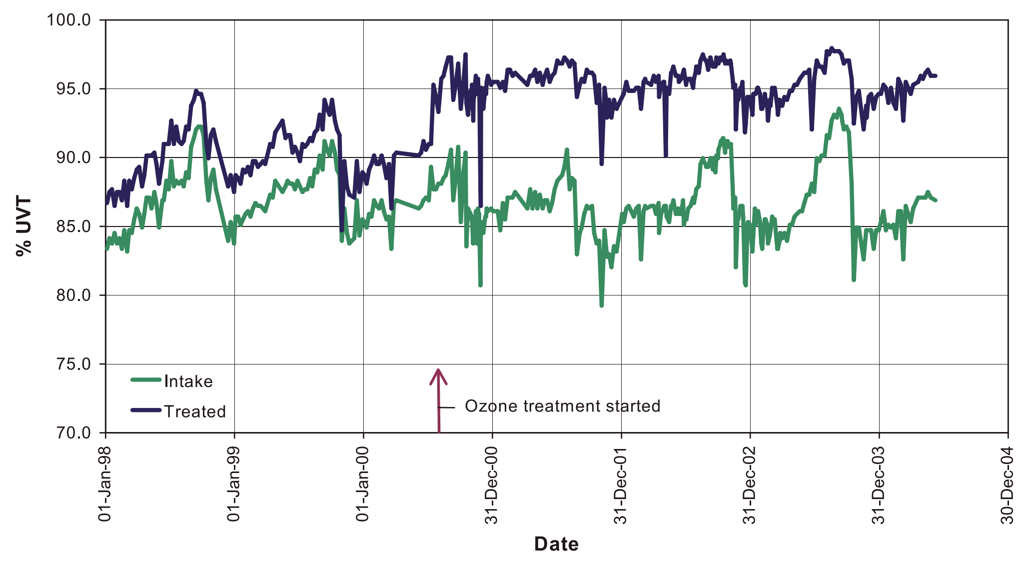


Figure 3. ***Filtered UVT of Coquitlam Water (1998 to June 2004)***

The filtered UVT of the intake water increases over the summer months then dips sharply when the fall rains commence.

For raw and treated Coquitlam water, the filtered UVT data is 0.6 to 3% higher than the apparent UVT when turbidities are low (< 2 NTU). During periods of higher turbidity (e.g. 20 October 2003, treated water turbidity 7.9 NTU), the filtered UVT was 8% higher than the apparent UVT in the treated water. The jump in treated water UVT in mid 2000 is due to the commissioning of the ozone treatment system.

From June 2003 to June 2004 the average apparent UVT for intake water was 86% and 94% for treated water. The minimum values were 74% UVT for intake water and 85% UVT for treated water (October 20, 2003).

Organics

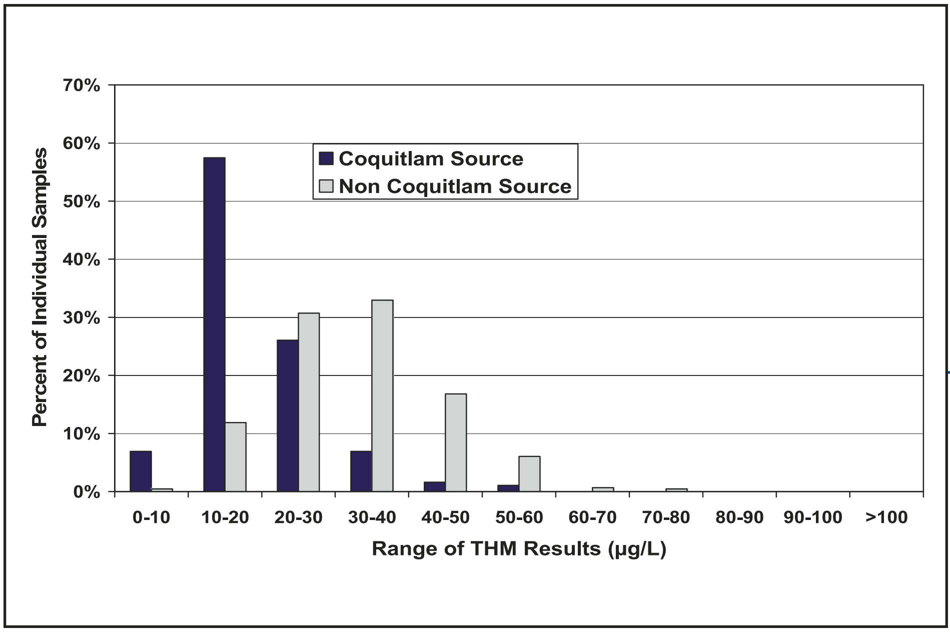
NOM in the source water can adversely affect UVT levels and can include precursors available for DBP formation after chlorination.

Currently THMs are the only DBPs with guidelines in Canada. The interim maximum acceptable concentration for total THMs is 100 μg/L as a running annual average. DBPs regulated in the U.S. include THMs and HAAs. The current USEPA maximum concentrations are 80 μg/L for total THMs and 60 μg/L for total HAAs (yearly running averages). For comparison, the European Union (EU) standard is 100 μg/L total THMs. The World Health Organization (WHO) guideline for THMs is that "the sum of the ratio of the concentration of each [THM] to its respective guideline value should not exceed 1" where the individual THM acceptable maximum concentrations are: bromodichloromethane 60 μg/L, chlorodibromomethane 100 μg/L, bromoform 100 μg/L, and chloroform 200 μg/L.

Historically in the GVWD system, the levels of THMs and HAAs have increased since the implementation of secondary disinfection in the distribution system in 1998. Figure 4 shows the level and occurrence of THMs in the distribution system. A similar comparison for HAAs in the distribution system is shown in Figure 5.

For the Coquitlam source, treatment with ozone has lowered the levels of DBPs in the distribution system in comparison to waters from non-Coquitlam sources, that is, the Capilano and Seymour watersheds or water which is a blend of these two sources.

For the period shown, the total THMs measured in Coquitlam water treated with ozone do not exceed 80 μg/L. On average the levels are 41% less than the total THMs in the system from non-Coquitlam water which has not been treated with ozone. Similarly, the total HAAs in Coquitlam water treated with ozone are, on average, 31% less than the total HAAs detected in non-Coquitlam waters in the distribution system. The maximum total HAA level measured in the distribution system in single samples of Coquitlam water treated with ozone exceeds 60 μg/L, however, the yearly running average does not exceed the USEPA standard of 60 μg/L. These observations are supported by specific laboratory testing done on Coquitlam source water for the GVWD in September 2004. The testing found that ozone treatment reduced the level of total THMs by an average of 46% and the level of total HAAs by 33%. Research conducted by the University of British Columbia on Seymour water showed total THM and HAA3 reduction of more than 50% at an ozone dose of approximately 2.5 mg/L.



Coquitlam source water has dissolved organic carbon (DOC) at an average level of 1.7 mg/L and total organic carbon (TOC) at an average level of 1.8 mg/L. Ozone treatment does not significantly change the DOC and TOC levels but likely changes the molecular structure, which can make it less reactive with free chlorine. In 2003, ozonation reduced the true colour from an average of 10 tcu to 2 tcu.

Figure 4. ***GVWD THM Data (January 2000 to June 2004)***

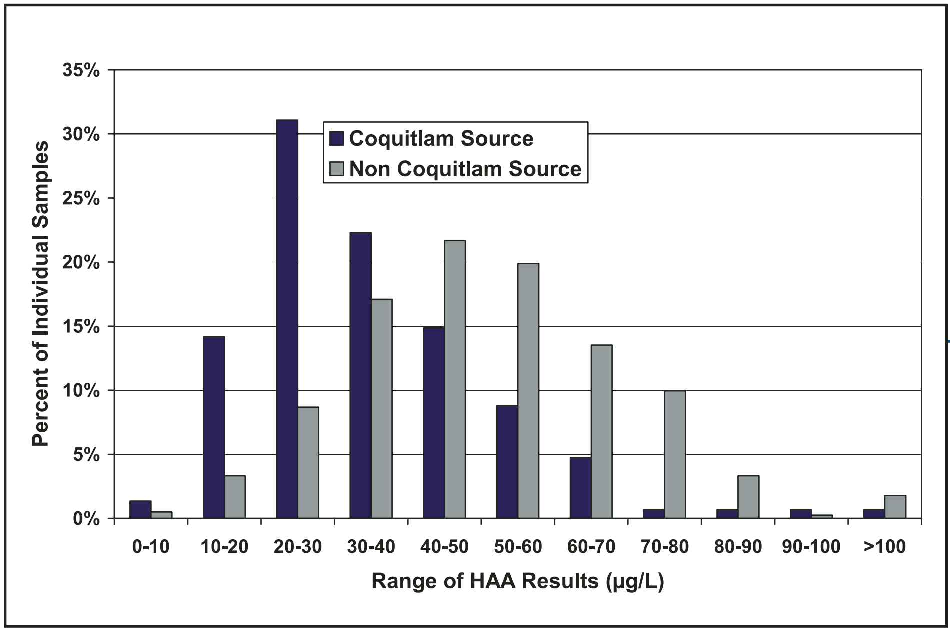


Figure 5. ***GVWD HAA Data (January 2000 to June 2004)***

TURBIDITY

Table 2 shows the historical turbidity levels for the Coquitlam source for the period 1992 to 2004.

Table 2. ***Coquitlam Turbidity Data, January 1, 1992 to December 7, 2004, Daily Grab Samples***

Turbidity (NTU)	Percentage of samples in range (%)	Cumulative Percentage less than Criteria (%)
≤ 1.0	94.8	94.8
> 1.0 – ≤ 2.0	4.0	98.8
> 2.0 – ≤ 3.0	0.6	99.4
> 3.0 – ≤ 4.0	0.2	99.6
> 4.0 – ≤ 5.0	0.2	99.8
>5.0	0.2	100.0

Turbidity measurements are less than or equal to 1 NTU for 94.8% of daily grab samples, and less than or equal to 5 NTU for 99.8% of daily grab samples collected from the existing Coquitlam intake prior to treatment (raw water).

PROCESS TESTING

To help with the ozone evaluation, testing of Coquitlam raw water was carried out in the CH2M HILL process laboratory in Corvallis, Oregon. Although this was only a snapshot based on one sample of intake water, the testing was required to quantify the effects of ozone addition at various dosages on the treated water UVT and distribution system DBP levels. Systematic testing at different ozone doses had not been carried out previously. Simulated distribution system (SDS) testing of the ozonated water for levels of THMs and HAAs present after 96 hours was also performed.

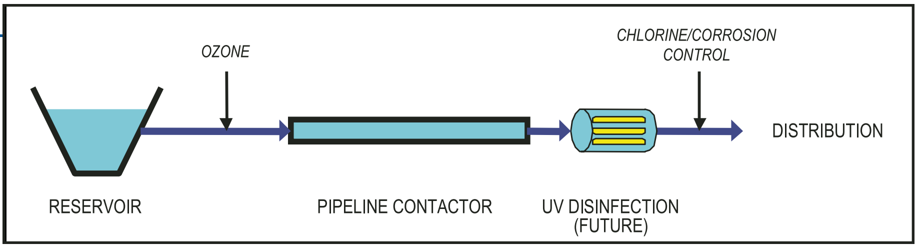


Figure 6. *Test System Simulated*

Treatment Process

Figure 6 shows the process diagram for the proposed UV disinfection system, to be added after ozonation. The test system in the process lab simulated the existing treatment system.

The pipeline contactor provides a contact time of 9.7 min at the maximum design flow of 1,200 ML/d. At a typical flow of 450 ML/d, the contactor provides a contact time of 26 min.

TEST PLAN

The scope of the testing conducted at the process lab was as follows:

- Characterize raw water as received:
  - Apparent UVT, TOC, alkalinity, hardness, pH, turbidity, SDS THMs, SDS HAAs
- Perform baseline run:
  - Simulate design dose (2.2 mg/L ozone, 26 minutes contact time)
  - Measure finished water apparent UVT, SDS THM, SDS HAAs
- Simulate ozonation at differing doses (1 run each): 0.5 mg/L, 1 mg/L, 2.2 mg/L, and 3 mg/L
  - Measure apparent UVT, SDS THM, SDS HAAs

The GVWD advised that a SDS testing time of 96 hours should be used for the Coquitlam water.

TEST RESULTS

Effect of Ozone on UVT

Figure 7 shows the effect of ozone dose on apparent UVT. The results show that for ozone doses of 0.94 to 2.84 mg/L, ozone increases the apparent UVT by 5 to 10%.

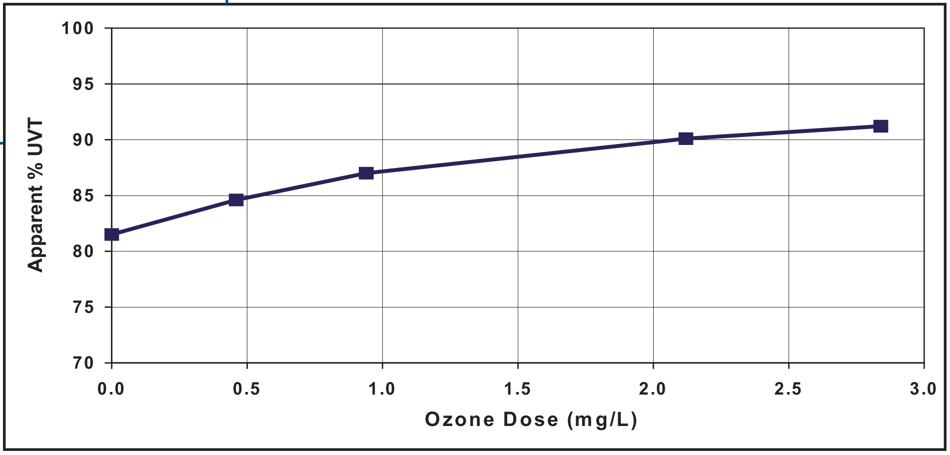


Figure 7. *Effect of Ozone Dose on UVT*

Effects of Ozone Dose on DBP Formation

Figure 8 shows the effects of ozone dose on the levels of THM and HAA formation. The results show that in comparison to non-ozonated water, for ozone doses of 0.94 to 2.84 mg/L, THMs levels decrease by 19 to 53%, and HAAs levels decrease by 20 to 51%.

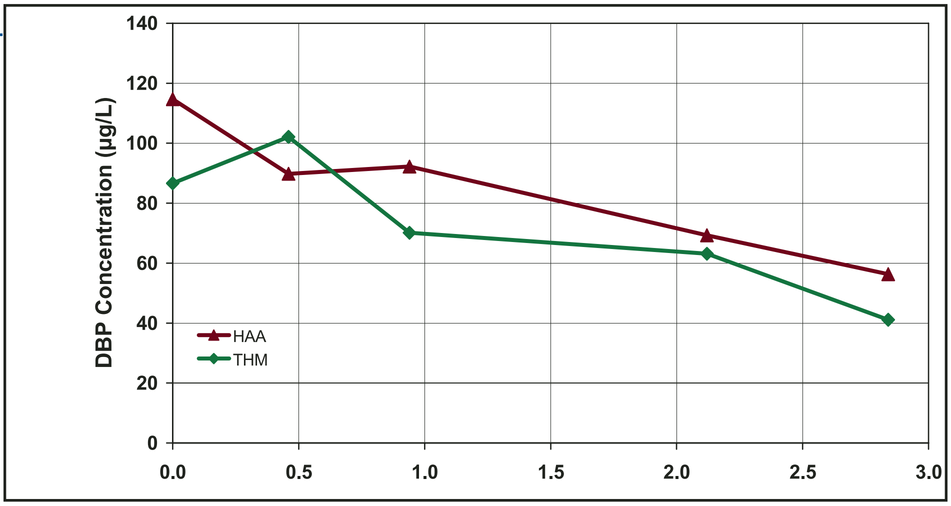


Figure 8. *Effect of Ozone on SDS DBPs*

Of note, the THM levels at an ozone dose of 0.5 mg/L are higher than with no ozone (raw water). At higher ozone doses, the THMs levels are below raw water levels and continue to decrease with an increase in ozone dose. Normally, there is a predictable and linear trend with both the levels of THM and of HAA samples from SDS testing. The 0.5 mg/L ozone sample was re-analyzed and confirmed the test results. Possibly for GVWD water, a low ozone dose creates more precursor material, and a higher ozone dose eliminates or breaks up the precursors. Another possibility is that the atypically higher turbidity Coquitlam water sample used in the test may have had higher levels of DBP precursors.

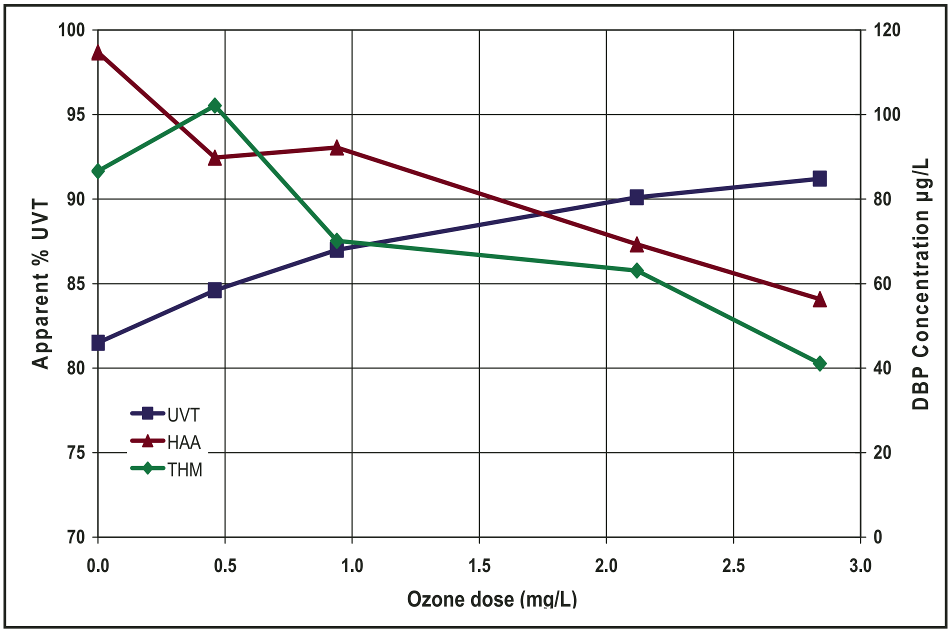


Figure 9. ***Summary of Effects of Ozone Dose on UVT and DBPs***

A summary of the effects of ozone on apparent UVT, THMs, and HAAs is presented in Figure 9.

For the sample tested, an ozone dose of 1.5 mg/L resulted in a UVT of 88% or higher and a total THM level of less than 70 μg/L which meets the USEPA standard of 80 μg/L (yearly running average). To meet the U.S. standard of 60 μg/L or less (yearly running average) for total HAA levels, an ozone dose of approximately 2.6 mg/L was required for this sample. This raised the apparent UVT to 90%. The sample tested had a turbidity of 3.5 NTU.

ECONOMICS

The cost of adding UV treatment with and without ozone pretreatment was evaluated. Table 3 shows three treatment scenarios considered.

Table 3. ***Design UVT and Ozone Dose***

Treatment Scenario	Ozone Dose (mg/L)	Apparent UVT (%)
Intake water, no ozone pretreatment	0	75
Intake water, low ozone dose	1.5	85
Intake water, higher ozone dose	2.6[1]	90

1. This is a preliminary dose based on a single laboratory test. Additional testing is required to confirm this dosage.

The raw water apparent UVT of 75% is taken as being a worst-case scenario, based on the available records. Given this incoming UVT, a low ozone dose scenario is chosen to achieve an apparent UVT of 85%. This scenario also meets the USEPA standard of 80 μg/L (yearly running average) for THMs. The higher ozone dose is to meet the USEPA standard of 60 μg/L for HAAs in the distribution system (yearly running average).

The GVWD's treatment goal for the 2004 study for Cryptosporidium and Giardia was 3-log inactivation or higher to meet the requirements of the USEPA Long Term 2 Enhanced Surface Water Treatment Rule. Based on the draft USEPA Guidance Manual for UV Disinfection, the required UV dose is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV and 36 mJ/cm^2 (360 J/m^2) for low pressure UV.

The Health Canada Turbidity Guideline which was published in March 2005 indicates that for unfiltered source waters, disinfection should reliably achieve at least 2-log reduction of *Cryptosporidium* oocysts and 3-log reduction of *Giardia lamblia* cysts. If mean source water cyst/oocyst levels are above 10/1000L, more than 2-log reduction of *Cryptosporidium* oocysts and 3-log reduction of *Giardia lamblia* cysts should be achieved. Overall inactivation should be met using a minimum of two disinfectants. Coquitlam has a mean cyst/oocyst concentration above 10/1000 L and would therefore be subject to the more stringent guideline criteria.

UV Equipment and Operating Costs

Preliminary UV equipment sizing and cost information was obtained from three vendors of validated UV equipment. A summary of this information is presented in Table 4.

Table 4. *UV Equipment Summary*

Equipment and Costs[1]	Calgon	Trojan	Wedeco
75% UVT			
Number of reactors	25	35	12
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	9	10	252
Equipment capital cost[2]	$9,140,000	$11,600,000	$8,420,000
Annual O&M cost[3]	$ 890,000	$ 940,000	$ 370,000
85% UVT			
Number of reactors	11	17	9
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	9	10	192
Equipment capital cost[2]	$4,020,000	$5,980,000	$5,150,000
Annual O&M costs[3]	$ 410,000	$ 450,000	$ 210,000
90% UVT			
Number of reactors	11	12	9
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	6	10	168
Equipment capital cost[2]	$2,820,000	$4,200,000	$4,680,000
Annual O&M costs[3]	$ 250,000	$ 310,000	$ 184,000

1. Costs in Canadian dollars, December 2004.
2. For capital costs a peak flow (1,200 MLD) was used.
3. O&M costs include power and lamp replacements at an average flow of 450 ML/d.

The data indicates that the UV costs (capital and O&M) can be reduced by approximately 40% or more by increasing the apparent UVT from 75% to 85%.

A medium pressure UV system designed for a 90% apparent UVT reduces UV costs (capital and O&M) an additional 30% in comparison to a system designed for an apparent UVT of 85%. For a low pressure system, increasing the apparent UVT from 85% to 90% reduces the capital cost by 9% and O&M costs by 14%.

Ozone Operational Costs

The major operating costs associated with producing ozone are power and liquid oxygen (LOX). Based on actual operating data for 2003, the annual operating costs of the ozone system for a dose of 1.5 mg/L and a typical flow of 450 ML/d is $600,000 per year. Increasing the ozone dose to 2.6 mg/L would increase the annual operating costs to $1,040,000.

Total UV System Life Cycle Costs

Total UV system costs are the sum of the UV equipment costs, building costs, and the UV and ozone operational costs. Table 5 shows the 20-year life cycle costs for the three UV scenarios: no ozone pretreatment, 1.5 mg/L ozone pretreatment, and 2.6 mg/L ozone pretreatment. Note that the estimates are preliminary in nature but are suitable for comparing the three treatment scenarios.

Table 5. *Summary of Estimated UV System Costs*[1]

	UV Systems Costs in $1,000's		
	Calgon Carbon	**Trojan Technologies**	**Wedeco**
75% UVT, no ozone pretreatment			
UV equipment cost (1200 ML/d)	9,140	11,600	8,420
Building area, m^2	1,816	1,989	1,213
Building cost	29,060	31,830	19,410
Total capital cost	38,200	43,430	27,830
Annual O&M cost (450 ML/d)[2]	890	940	370
NPV[3] of O&M	10,220	10,770	4,210
20-year life cycle cost	**48,420**	**54,200**	**32,040**
85% UVT, 1.5 mg/L ozone pretreatment			
UV equipment cost (1,200 ML/d)	4,020	5,980	5,150
Building area, m^2	900	1064	900
Building cost	14,400	17,020	14,400
Total capital cost	18,420	23,000	19,550
Annual O&M cost (450 ML/d)[2]	1,010	1,050	810
NPV[3] of O&M	11,570	12,090	9,290
20-year life cycle cost	**29,990**	**35,090**	**28,840**
90% UVT, 2.6 mg/L ozone pretreatment			
UV equipment cost (1,200 ML/d)	2,820	4,200	4,680
Building area, m^2	863	807	869
Building cost	13,810	12,910	13,900
Total capital cost	16,630	17,110	18,580
Annual O&M Cost (450 ML/d)[2]	1,290	1,350	1,220
NPV[3] of O&M	14,820	15,520	14,030
20-year life cycle cost	**31,450**	**32,630**	**32,610**

1. Excludes standby power and power supply.
2. O&M cost includes cost of LOX and power for UV and ozone, and UV lamp replacement, but excludes labor.
3. NPV is net present value of annual operating costs. It assumes a 6% interest rate and a 20 year life cycle.

Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L is more economical than UV alone on a 20-year life cycle cost basis. Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L in conjunction with UV treatment to meet USEPA standards for HAAs has little impact on 20-year life cycle costs, but there is a shift from capital to operating dollars.

EFFECT OF TURBIDITY ON UV INACTIVATION

A concern when designing UV treatment systems for unfiltered sources is the potential impact of turbidity events on UV disinfection.

The turbidity of Coquitlam source water grab samples collected from the existing intake is less than or equal to 1 NTU for 94.8% of grab samples, and less than or equal to 5 NTU for 99.8% of grab samples (Table 3-1). The system is usually taken off line when turbidity is greater than 5 NTU.

Figure 10. *Effect of Turbidity on UV Absorption (from 2002 AwwaRF Study)*

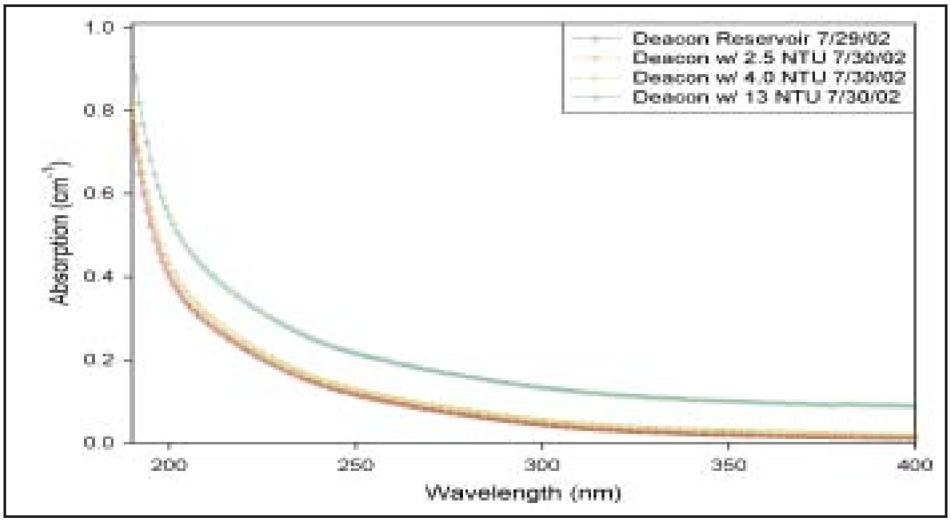


Figure 10 presents UV absorption data taken from the 2002 AwwaRF Study "UV Disinfection and DBP Characterization of an Unfiltered Water Supply". The data shows UV absorption levels for the same source water at four different turbidity levels. It shows that there is little effect on UV absorption up to a turbidity of 4 NTU. An effect can be seen at a turbidity level of 13 NTU.

Table 6 presents the effects of turbidity on UV dose taken from the same AwwaRF study.

Table 6. *Effect of Turbidity on UV Dose (2002 AwwaRF Study)*

	Challenge Test 4			Challenge Test 5			
Lamp Type and UV Dose	**3/12/02 Pre-clean**	**3/13/02 Post-clean**	**3/13/02 4.0 NTU**	**7/29/02 Post-clean**	**7/30/02 2.5 NTU**	**7/30/02 4.0 NT**	**7/30/02 13 NTU**
Medium Pressure UV							
Reduction Equivalent Dose (mJ/cm^2)	37.9	56.8	54.0	36.7	36.7	32.2	26.5
Low Pressure High Output UV							
Reduction Equivalent Dose (mJ/cm^2)	31.0	54.9	45.2	40.4	42.9	39.2	33.2

The data shows that for turbidities of up to 4 NTU there is little reduction in the effective UV dose. At 13 NTU, the turbidity reduced the UV dose by 18 to 28%. Research elsewhere for unfiltered waters shows minor UV dose effects up to a turbidity of 20 NTU, and that turbidity up to these levels does not effectively shield pathogens from UV, and UV intensity can be adjusted to compensate and achieve disinfection targets. Work done by the University of Alberta for the City of Kelowna indicates that a UV dose of 40 mJ/cm^2 (400 J/m^2) achieves 3.7 log inactivation of *Cryptosporidium* at 20 NTU compared to 4.48 log inactivation at 1 NTU.

In full-scale operation, adjustments can easily be made to compensate for the reduction in UV effectiveness. For example, reducing the plant flow by half while maintaining the full power to the UV will double the applied UV dose. Of note, the UV dose is not an issue for consumers since UV does not affect the aesthetics of the water. In contrast, doubling the chlorine dose would likely be noticed and be a concern to consumers.

In summary, the effect of turbidity on UV disinfection should not be a concern for treating Coquitlam Lake water if it continues to be operated with a maximum turbidity of 5 NTU, and even operating at 10 NTU or slightly higher should not be a concern, except flows may need to be reduced from peak design flows.

NON-MONETARY OZONE BENEFITS

Maintaining ozonation in addition to UV treatment and free chlorination will enhance the robustness of the treatment system with the multiple barrier approach to disinfection. Target disinfection organisms such as *Giardia, Cryptosporidium*, and viruses will be inactivated by two or three of the treatment methods.

UV disinfection, designed for 3-log inactivation of *Cryptosporidium*, will also provide more than 3-log inactivation of *Giardia*, and inactivate bacteria. Ozonation at doses in the 1.5 mg/L range, with 9.7 minutes contact time (ultimate capacity) will provide inactivation of bacteria, viruses, and varying levels of *Cryptosporidium* and *Giardia* inactivation depending on seasonal water temperatures. Free chlorine is very effective at virus disinfection, and, due to the long contact times in the distribution system, will also achieve a measure of *Giardia* disinfection. The synergistic effects of using three methods for disinfection may allow lower levels of free chlorine to be used, again aiding in reducing the formation of DBPs in the distribution system.

SUMMARY

The key findings are summarized as follows:

UV Transmittance

- Ozone treatment has historically increased the apparent UVT of Coquitlam water by 5 to 10%. This increase in UVT is significant since increasing the apparent UVT from 75% to 85% reduces the UV equipment and power requirements by 40% or more.
- From the historical data and initial laboratory testing done for this project, minimum apparent UVTs of 85% and 90% can be expected at ozone doses of 1.5 mg/L and 2.6 mg/L respectively.

DBPs

- Ozone reduces the level of THMs and HAAs in the distribution system.
- THM levels measured in the distribution system from Coquitlam water treated with ozone are on average 41% less than those from non-Coquitlam water which has not been treated with ozone. The maximum THM level detected in all GVWD water including Coquitlam is less than the Canadian guideline of 100 μg/L.
- HAA levels measured in the distribution system from Coquitlam water treated with ozone are on average 31% less than those from non-Coquitlam water which has not been treated with ozone. The maximum HAA level measured in the distribution system in single samples of Coquitlam water treated with ozone exceeds 60 μg/L, however the yearly running average does not exceed the USEPA standard of 60 μg/L. There is no current Canadian guideline for HAA levels.
- Based on the available laboratory data on DBP formation potential for Coquitlam source water and HAA levels measured in the system for the Seymour and Capilano sources, the yearly running average for HAAs would exceed the USEPA standard of 60 μg/L (yearly running average) if Coquitlam water was not treated with ozone.
- From the initial laboratory testing, an ozone dose of 1.5 mg/L achieved a THM level of less than 70 μg/L, which meets the USEPA standard of 80 μg/L (yearly running average) and an HAA level of approximately 80 μg/L which does not meet the USEPA requirement of 60 μg/L (yearly running average).
- From the initial laboratory testing, an ozone dose of 2.6 mg/L can be expected to achieve distribution system HAA levels of less than 60 μg/L and THM levels of less than 50 μg/L, which meets the USEPA requirements for both HAAs and THMs.

Additional Testing

Further work will be done during the UV pre-design phase.

UV Dose

The required UV dose to meet the GVWD's treatment goal of 3-log inactivation of *Cryptosporidium* and *Giardia* is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV and 36 mJ/cm^2 (360 J/m^2) for low pressure UV.

Costs

The costs of adding UV treatment to the Coquitlam source are:

Treatment Scenario	Preliminary Cost Estimates		
	Capital	O&M	Life Cycle
No ozone pretreatment, 75% UVT, THMs <100 μg/L	\$27M – \$43M	\$0.37M – \$0.94M	\$32M – \$54M
1.5 mg/L ozone pretreatment, 85% UVT, THMs ≤ 70 μg/L and some HAA reduction ≤~ 80 μg/L	\$18M – \$23M	\$0.81M – \$1.1M	\$29M – \$35M
2.6 mg/L ozone pretreatment, 90% UVT, THMs ≤ 50 μg/L, HAAs ≤ 60 μg/L	\$17M – \$19M	\$1.22M – \$1.35	\$31.5M – \$32.6M

Turbidity

- Turbidity measurements are less than or equal to 5 NTU for 99.8% of daily grab samples, collected from the existing Coquitlam intake prior to treatment (raw water).
- The effect of turbidity on UV disinfection should not be a concern if Coquitlam is operated with a maximum turbidity of 5 NTU, and even operating at 10 NTU or slightly higher should not be a concern, except flows may need to be reduced from peak design flows.

Ozone Benefits

- There are clear benefits to retaining ozone when UV treatment is added to the Coquitlam source.
- Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L:
  – is more economical than UV alone on a 20-year life cycle cost basis
  – reduces the formation of DBPs in the distribution system, with THMs meeting the USEPA standard of 80 μg/L or less (yearly running average)
  – provides some reduction in HAAs to approximately 80 μg/L
  – provides an additional treatment barrier for disinfection
  – Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L, in conjunction with UV treatment:
    - will further reduce HAA levels to USEPA standards of 60 μg/L (yearly running average)
    - has little impact on 20-year life cycle costs, but there is a significant shift from capital to operating dollars.

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