HONG KONG GOVERNMENT
DRAINAGE SERVICES DEPARTMENT

Agreement No. CE 49/95

Outlying Islands Sewerage - Stage I Phase I

Siu Ho Wan STW Upgrading Disinfection Pilot Plant Study

Final Report

March 2000

MAUNSELL CONSULTANTS ASIA LTD

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AGREEMENT NO. CE 49/95

OUTLYING ISLANDS SEWERAGE - STAGE 1 PHASE 1

PACKAGE B - SIU HO WAN STW UPGRADING

DISINFECTION PILOT PLANT STUDY

FINAL REPORT

Maunsell Consultants Asia Limited

Issue 1
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1. INTRODUCTION

1.1 Background

Maunsell Consultants Asia Limited was commissioned by Drainage Services Department to implement Siu Ho Wan Sewage Treatment Works (STW) Upgrading as part of the Outlying Islands Sewerage Stage 1 Phase 1 project. The STW is to be upgraded to provide chemically enhanced primary treatment (CEPT) to the wastewater mainly generated from the Tung Chung/Tai Ho New Town and surrounding areas in the Lantau Island. The treated effluent is to be discharged through an existing submarine outfall into the North Western Water Control Zone. At present, the existing facilities at Siu Ho Wan provide preliminary treatment only.

An effluent disinfection system is to be constructed at Siu Ho Wan. The purpose is to control the potential discharge of pathogens to the North Western Water Control Zone and to minimise the possible adverse impact onto the marine environment including the Chinese White Dolphins. It was considered prudent that a disinfection system was to be constructed under this STW upgrade, following the "precautionary principle" as set out by the Advisory Committee for Environment for discharges into the North Western Water Control Zone.

A desktop review was undertaken in May 1999 to assess the feasibility of using UV radiation and ozone to disinfect CEPT effluent for Siu Ho Wan. *It was decided that consideration to the other options such as chlorination was not necessary and worthwhile because of environmental, safety and other considerations.* The results of the desktop review indicated that there is only limited full-scale operating information of using UV disinfection and basically no information for using ozonation in CEPT plants. Only limited pilot- and laboratory-scale information is available to provide basis for assessing the feasibility of these disinfection options and for option comparison. It was decided that a disinfection pilot test programme should proceed to collect more site-specific data to ascertain the feasibility of the two disinfection methods for Siu Ho Wan and the basis for option comparison.

1.2 Objectives

The primary objectives of the disinfection pilot plant study are to assess the feasibility of UV and ozone disinfection and establish the appropriate design parameters for a full-scale disinfection facility to achieve the required E. Coli standards at Siu Ho Wan. The E.Coli standards are 20,000 and 300,000 per 100 mL, based on monthly geometric means and 95-percentile compliance, respectively. The results of the pilot plant study were then used as the basis to conduct a detailed comparison between the ozone and UV disinfection processes in order to select the optimum disinfection process.

Specific objectives of the pilot study include:

- To assess the influent characteristics that pertains to UV and ozone disinfection
- To develop dose-response relationship for UV and ozone disinfection under various influent conditions

- To assess the UV lamp fouling rates and required frequency of cleaning
- To assess the headloss requirements for UV option
- To conduct preliminary assessment on the possible formation of disinfection byproducts and, for UV disinfection, photoreactivation.

1.3 Overview

Figure 1.1 shows the overall schematics of the pilot plant. The study included pilot testing of both UV and ozone disinfection methods. In addition, limited sludge dewatering tests were undertaken to assess the feasibility of dewatering alum sludge using centrifuges. The disinfection pilot plant study took place from August to October 1999.

The pilot study was conducted at the Stonecutters Island Sewage Treatment Works (SCISTW). At present, the primary source of wastewater at Siu Ho Wan is generated from the Airport. Therefore, the influent characteristics are expected to vary in the future when the domestic sewage from the Tung Chung/Tai Ho New Town is collected. Also, only preliminary treatment is currently provided at Siu Ho Wan. Therefore, it is not desirable nor practical to conduct the pilot tests at Siu Ho Wan because of (1) the difference in influent characteristics and (2) the need to construct a pilot CEPT plant to generate the necessary CEPT effluent for the disinfection pilot tests.

Figure 1.2 shows the locations of the UV and ozone pilot plants at SCISTW. Treated effluent from the prototype CEPT plant was selected as the source of influent to the UV and ozone pilot plants. Different chemical coagulants, coagulant dose rates and surface overflow rates were maintained at the CEPT plant on each test day to simulate a desired effluent quality condition that may be encountered at Siu Ho Wan. The coagulants and coagulant doses were changed around 8:00 p.m. on the night before in order to ensure that the CEPT effluent became fully stabilised before the commencement of the disinfection pilot tests on the following day.

Both ferric chloride and alum were used as primary coagulants to assess the disinfection performance under different CEPT effluent conditions. In some cases, no coagulant was added to simulate high TSS conditions. In addition, controlled amount of coffee and raw sewage was added to the influent to the UV pilot plant to further reduce UV transmittance level and increase TSS level.

Ferric chloride was supplied using the existing chemical dosing system at SCISTW. Alum was supplied using a temporary alum preparation and dosing system that was built for the pilot test programme. The approximate dose levels of ferric chloride was chosen to be 5, 7.5, 10 and 15 mg/L as $FeCl_3$. The expected ferric chloride dose is 10 mg/L. The approximate dose levels of alum was 2, 4, 5 and 7.5 mg/L as Al_2O_3. The expected alum dose is 5 mg/L. An anionic polymer was added with both primary coagulants.

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A key challenge that was encountered during the pilot study was to increase the flowrate to the prototype CEPT plant such that its operation (surface overflow rate) was representative of the future design conditions. During the study period, the flowrate to the prototype CEPT tank was found to be about 30% of the design capacity even when its inlet penstock was operated at the maximum opening position. Various methods were investigated, but most of them were not found to be feasible. Temporary stoplogs were finally constructed and installed at an inlet chamber to divert adequate flows to the prototype plant.

1.4 Scope

The primary purposes of this Paper are to present the results of the pilot plant study and discuss the comparison of UV and ozone disinfection options based on the updated basis established from the pilot study.

The Paper is divided into the following sections:

- Section 1: Introduction
- Section 2: UV Pilot Tests
- Section 3: Ozone Pilot Tests
- Section 4: Sludge Dewatering Pilot Tests
- Section 5: Evaluation of Disinfection Alternatives, and
- Section 6: Conclusions and Recommendations

2. UV PILOT TESTS

2.1 Introduction

2.1.1 Overview

This purpose of this Section is to describe the UV disinfection pilot tests and discuss the test results. It is divided into the following sub-sections:

- Introduction
- Pilot Plant Equipment
- Test Method and Procedures
- Results and Discussions
- Conclusions and Recommendations

2.1.2 Objectives

The primary objectives of the UV disinfection pilot tests are to assess the feasibility of UV disinfection and establish the appropriate design parameters for a full-scale UV disinfection facility to achieve the required E. Coli standards at Siu Ho Wan. The E.Coli standards are 20,000 and 300,000 per 100 mL, based on monthly geometric means and 95-percentile compliance, respectively. The results of the pilot tests were used as the basis to conduct a detailed comparison of the ozone and UV disinfection processes to select the optimum disinfection process.

Specific objectives of the pilot tests include:

- To assess the influent characteristics that pertains to UV disinfection
- To develop dose-response relationship for UV disinfection under various influent conditions
- To assess the UV lamp fouling rates and required frequency of cleaning
- To assess the headloss requirements
- To conduct preliminary assessment on the possible formation of disinfection byproducts and photoreactivation.

2.2 UV Pilot Test Equipment

2.2.1 Selection of UV Equipment Suppliers

Because of the site constraints, the use of more compact high intensity UV systems was considered to be more appropriate for Siu Ho Wan. A preliminary review of the available information indicated that there were three potential high intensity UV equipment suppliers, namely:

- Trojan Technologies Inc.
- Aquionics Inc.
- Wedeco Inc.

The differences of these systems include both the lamp types and reactor designs. While medium pressure high intensity UV lamps are used in both Trojan and Aquionics systems, low pressure high intensity UV lamps are used in the Wedeco system. Also, their lamp orientation, array configuration and equipment design are different. One of the key requirements of the pilot unit is its similarity to the full-scale system proposed for Siu Ho Wan.

Letters were sent to these UV suppliers to invite them to submit quotations for leasing of UV pilot plant and other equipment for the disinfection pilot tests and all suppliers submitted quotations. Trojan Technologies Inc. was selected because of its lowest price. This supplier has the most experience in supplying high intensity UV equipment than the other two suppliers including the recent installations at Shek Wu Hui.

2.2.2 Pilot Plant Equipment

Figures 2.1 shows UV pilot unit supplied by Trojan Technologies Inc. The pilot unit consisted of two UV lamp banks located inside an enclosed reactor. Each lamp bank had 2 lamp modules each of two 2.8 kW medium pressure high intensity lamps. There are a total of 8 UV lamps. All the lamps were orientated horizontally and parallel to the flow direction. The lamp type and reactor configurations were identical to those proposed by the UV equipment supplier for the full-scale facility at Siu Ho Wan. In this pilot unit, cleaning of lamp sleeves was achieved manually. Flowrates to the UV pilot unit were controlled by a variable–speed submersible pump and measured by an electromagnetic flowmeter. Two side connections were made at the influent pipe to faciliate the spiking of chemicals and raw sewage, when needed.

Figure 2.2 shows the setup of the UV pilot unit at SCISTW. The pilot unit was located adjacent to the prototype CEPT plant. Treated effluent from the prototype CEPT plant was used as the source of influent to the UV unit. Chemical coagulants, coagulant dose rates and surface overflow rates were varied at the CEPT plant to simulate a range of the effluent quality conditions that may be encountered at Siu Ho Wan. Both ferric chloride and alum were used as primary coagulants to assess the UV disinfection performance under different CEPT effluent conditions. In some cases, no coagulant was added to simulate high TSS conditions. In addition, controlled amount of coffee and raw sewage was added to the influent to the UV pilot plant. Coffee is a strong UV absorbant and was used to lower the UV transmittance level. Raw sewage was used to further increase influent TSS level.

2.3 Test Methods and Procedures

2.3.1 Overview

The pilot trials took place from 6 to 29 September, 1999 and consisted of the following tests:

- Dose response tests
- Fouling tests
- Headloss analysis
- Disinfection byproducts

- Photoreactivation tests

2.3.2 Dose Response Tests

The objective of the dose response tests was to establish the relationship between the surviving E. Coli and E. Coli inactivation with UV dose levels. During these tests, the lamps were maintained under clean conditions to eliminate the impact of possible lamp fouling on disinfection efficiency. The effect of lamp fouling was analysed separately.

A total of 35 dose response runs were completed on 13 separate days. Before the commencement of each run, the lamp sleeves were cleaned. In each run, five dose response tests were conducted. Before the commencement of each run, a CEPT effluent sample was collected and analysed for unfiltered UV transmittance levels. Based on the UV transmittance levels, flowrates, number of operating lamps and lamp intensity levels were selected to give the desired UV doses. The selected UV doses were approximately 60,40,30,20 and 10mWs/cm^2. The tests were conducted in the decreasing dose levels to minimise the effects of possible sample cross-contamination.

At each UV dose level, an effluent sample was collected and analysed for E. Coli level. Influent samples were collected in the beginning and the end of each run and analysed for unfiltered UV-transmittance, suspended solids, E. Coli, particle size and total and dissolved iron levels. The unfiltered UV transmittance levels were analyzed on site using spectrophotometer and the other analysis were conducted in SGS laboratory. Collimated beam test studies were conducted in parallel using the influent samples collected at the beginning of each pilot run.

2.3.3 Fouling Tests

The objectives of the fouling tests were to assess the impact of potential reduction in UV intensity on disinfection efficiency and evaluate the required frequency of lamp cleaning. During this period, the lamps were only cleaned at the beginning of the test. Four fouling test programmes were conducted for approximately 12 hours each. During the first two test programmes, ferric chloride of 10 mg/L and anionic polymer of 0.15 mg/L were added. During the second two test programmes, alum of 5 mg/L and anionic polymer of 0.15 mg/L were added. The pilot unit was subject to a constant flowrate, which corresponded to a clean lamp UV dose of approximately 30 mWs/cm^2. The changes in effluent E.Coli and E. Coli removal was monitored at hours 0, 1,2,3,4,6,8,10 and 12. During each sampling period, influent and effluent samples were collected. The influent samples were analyzed for E. Coli, TSS, mean particle sizes, UVT (unfiltered) and iron (total and dissolved), pH and temperature, and the effluent samples for E.Coli.

2.3.4 Headloss Analysis

The objective of this test was to assess hydraulic headloss through the UV reactor under different flow conditions. The headloss through the UV reactor will be added to the expected headloss due to the inlet and outlet arrangements to calculate the total head requirement for the UV facility.

The pilot unit was operated under flowrates of 0, 10, 20, 30, 40, 50, and 60 l/s and the highest possible value. The water levels upstream and downstream of the UV reactor were measured at each flowrate. The upstream water levels were measured with a metal tape attached to one side of the influent channel of the pilot unit. The downstream water levels were measured at three locations, which were approximately at the middle and two ends of the effluent channel of the pilot unit. The headloss through the UV reactor was estimated based on the difference between the upstream and downstream water elevations.

2.3.5 Disinfection Byproduct Analysis

The objective of these analyses was to conduct a preliminary assessment on the possible formation of disinfection byproducts under the expected UV dose level. Two analyses were undertaken, one for ferric chloride-treated and one for alum-treated CEPT effluent.

During the disinfection byproduct tests, the flowrate was set to provide UV dose of approximately 90mWs/cm^2, 3 times of the design dose. Samples were taken at the upstream and downstream sides of the UV reactor when the UV lamps were turned on. After the UV lamps were turned off, a sample was taken on the downstream side. A total of two radiated and four unradiated (control) samples were collected and analysed for volatile organic compounds using GC/MS (EPA Method 5030/8260) for the regulated and unregulated compounds on the Safe Water Drinking Water Act Target compound list. The semi-volatile compounds were analyzed using a base neutral extraction with methylene chloride and GC/MS detection.

2.3.6 Photoreactivation Tests

The objective of the limited photoreactivation tests was to assess the possible regrowth of E.Coli after exposure to visible light after UV disinfection. The procedures basically followed those used in a similar study for the City of Montreal, Quebec, Canada.

The tests were undertaken using alum-treated effluent only since it has the maximum light transmittance. Samples were taken before and after the UV reactor set approximately at the design UV dose level. Effluent samples were exposed to three hours of ambient temperature in the dark to simulate maximum retention time in the submarine outfall before discharge into the receiving water followed by a one-hour exposure time suspended in the water at different depths of 10 cm, 20 cm, 40cm, 80cm and 160cm. Samples were collected and analysed for E.Coli levels.

2.4 Results and Discussions

2.4.1 Influent Characteristics

Table 2.1 shows the influent quality characteristics of the UV pilot plant during the study period. As shown in the Table, the influent characteristics covered the expected range of UV transmittance and TSS levels of the CEPT effluent from the future Siu Ho Wan STW. The UV transmittance levels ranged from 13 to 43% and TSS levels ranged from 18 to 140 mg/L. The UV transmittance levels were expected to vary with the choice of coagulants and design (adverse) levels are expected to be 20 and 35 percent for ferric chloride and alum-treated CEPT effluent. The expected average and maximum TSS levels are 50 and 120 mg/L, respectively.

Another important water quality parameter is the iron concentration. A maximum ferric chloride dose of 15 mg/L was added during runs 13 to 15 to simulate high iron conditions. However, the UV transmittance and TSS were not critical at high ferric chloride dose conditions because of the improved coagulation.

The influent E.Coli levels seemed to be consistent throughout the study period. The levels ranged from 1.8 to 9.2 x 10^7 counts per 100 mL, which are within the expected range of 10^7 to 10^8 counts per 100 mL,at Siu Ho Wan.

The available UV transmittance data of the CEPT effluent were analysed to check the appropriate level to be used in the design of the full-scale facilities. Figure 2.2a and 2.2 b show the probabilistic plots of the UV transmittance levels of the CEPT effluent at the ferric chloride dose of 10 mg/L and alum dose of 5 mg/L, respectively. Both the UV transmittance data collected during the dose response and fouling tests were used. The average and 5 percentile UV transmittance levels were estimated to be 37 and 32 percent, respectively for alum effluent. The respective levels were 32 and 29 percent for ferric chloride effluent. The alum-treated effluent was found to have a higher UV transmittance level than the ferric chloride-treated effluent. However, the difference appeared to be smaller than those obtained from other studies including the SSDS Stage 1 pilot studies.

Based on the above limited data, the use of a more conservative UV transmittance of 30 percent may be more appropriate in the design of the UV facilities for alum-treated effluent. For ferric chloride effluent, the original choice of 20 percent UV transmittance level is considered to be acceptable.

Table 2.1 – Influent Characteristics of UV Pilot Plant

Coagulant Used	**Dose Response Run Number**	**% UVT**	**TSS (mg/L)**	**Mean Particle Size (microns)**	**Influent E.Coli Levels (counts per 100 mL0**
Ferric Chloride (1)	1 to 15	13 to 35 Average 22	18 to 42 Average 31	33 to 91 Average 51	1.8 to 9.2 x 10^7
Alum (1)	16 to 26 30 to 32	24 to 43 Average 32	27 to 81 Average 47	28 to 77 Average 49	1.4 to 7.4 x 10^7
No coagulant with raw effluent blended	27 to 29 33 to 35	15 to 29 Average 24	75 to 140 Average 99	35 to 88 Average 64	1.3 to 4.3 x 10^7
Expected Effluent Quality at Siu Ho Wan					
Ferric Chloride		25 (average) 20 (minimum)	45 to 55 (average) 120 (95-percentile)		
Alum		40 (average) 35 (minimum)	Ditto		

Notes:
1. No coagulant was added in dose response runs 1 to 3 and 16 to 19.
2. Coffee was used to lower the UVT during the study. During the FeCl3 addition phase, coffee was added to lower the UVT to 15% during the first dose, 20% during the second dose and no coffee was added during the third.

2.4.2 Dose Response Tests

Figures 2.3 and 2.4 show the variations of effluent E. Coli levels and E. Coli inactivation with UV dose based on all the data collected during the pilot tests. The data included the CEPT effluent using ferric chloride, alum and no coagulants. As discussed previously, the effluent qualities encountered during the pilot study covered both the expected design TSS (120 mg/L) and UV transmittance levels (15 percent). It is apparent that the E.Coli standards of 20,000 counts and 300,000 counts should be achievable consistently under the dose levels of 30 mWs/cm^2 assumed in the previous Disinfection Option Review Paper.

The data were shown separately based on three different ranges of SS levels of less than 50 mg/L, 50 to 80 mg/L and greater than 80 mg/L. Visual inspection of Figure 2.3 indicated that the average UV dose level to achieve the required E.Coli of 20,000 counts/100 mL was about 13 mWs/cm^2 . For all data to achieve the required standard, the required UV dose level was found to be 22 mWs/cm^2.

As shown in Figure 2.3, the dose requirements to achieve the same effluent E. Coli levels appear to be higher for treated effluent with higher SS levels. It is more apparent for the dose response relationships for effluent with SS greater than 80 mg/L (shown in circles) and those for SS between 50 mg/L and 80 mg/L (in squares). The dose requirement and SS relationship is less apparent for SS lower than 50 mg/L (in diamonds) because of the significant data scattering.

Figure 2.4 shows the variations of E.Coli inactivation with UV dose. The average UV dose level to achieve 3-log E.Coli inactivation was estimated to about 13 mWs/cm^2. For all data to achieve 3-log inactivation, the required dose level became 22 mWs/cm^2. These dose requirements are similar to those achieving the required effluent E.Coli standard of 20,000 counts/100 mL.

Figures 2.5 and 2.6 show the variations of effluent E.Coli and E.Coli inactivation levels with UV dose for all the pilot test data, shown separately based on different total iron levels. Higher iron concentrations were encountered when ferric chloride was added in the CEPT process. Inspection of Figure 2.5 indicated that there was no apparent relationship between the UV dose requirements to achieve effluent E.Coli levels and iron levels. The dose requirements for effluent with different iron levels appeared to vary randomly without an apparent trend.

Figure 2.7 shows the variations of E.Coli vs. UV dose under simulated design (worst-case) influent conditions. During these test periods, TSS levels ranged from 75 to 140 mg/L and UV transmittance levels ranged from 15 to 29 percent. These conditions were achieved by using primary effluent blended with raw sewage and adding chemicals to lower the UV transmittance levels. It was found that UV dose levels of 14 and 21 mWs/cm^2 were sufficient to achieve the required standards on average and at all times, respectively. The variations of the E.Coli inactivation with UV dose is shown in Figure 2.8.

Figures 2.9 and 2.11 show the variations of effluent E.Coli with UV dose for treated effluent using ferric chloride and alum, respectively. Figure 2.10 and 2.12 show the respective variations of E.Coli inactivation with UV dose. As shown in Figures, the dose levels required to achieve the effluent E.Coli standards and 3-log E.Coli inactivation are shown in Table 2.2.

Table 2.2 UV Dose Requirements

	Influent Conditions		Average UV Dose to Achieve	
Coagulant Used	**TSS Range**	**UV Transmittance**	**E.Coli standard**	**3-log E.Coli Inactivation**
No coagulant	75 to 140	15 to 29	14	13
Ferric chloride	18 to 42	13 to 35	16	13
Alum	27 to 81	24 to 43	12	10

The data collected during this pilot study were analyzed using a mathemtical model developed by Emerick and Darby at the University of California at Davis (Emerick and Darby, 1993). In this model, the relationship between the effluent coliform density after exposure to UV light and the UV dose and water quality was stated as follows:

$$N = f\,(\text{dose})^{n}$$

Where N = Effluent coliform density, counts/100mL
f = Water quality factor
n = Empirical coefficient related to UV dose, and
Dose = Average UV reactor intensity x hydraulic retention time

The water quality factor was postulated to follow the relationship:

$$f = A\,(TSS)^{a}\,(Trans)^{b}(beta)^{c}(No)^{d}$$

Where TSS = Suspended solids concentration, mg/L
Trans = Unfiltered UV transmittance at 254 nm
Beta = Particle size distribution (PSD) coefficient
No = Influent coliform density, counts per 100mL, and
A, a, b,c,d = Empirical coefficients.

Through a multiple linear regression analysis of the water quality data and the UV disinfection performance data, statistically insignificant water quality parameters can be eliminated from the model. In this pilot study, PSD coefficients were not analyzed because of the laboratory costs and hence the parameter beta was excluded from the model. Also, there is no information to establish an appropriate design PSD coefficient at Siu Ho Wan when this parameter is included in the model. The total iron levels were also added into the model but was excluded because it was found to be statistically insignificant.

The results of the multiple linear regression analyses are as follows:

$$N = 2.0 \times 10^{11}\,(\text{dose})^{-3.39}\,(\text{Trans})^{-2.43}$$

The number of sample sets used to develop this model was 187. The squared multiple R value was found to be 0.8, showing about 80 percent variability can be accounted for using the proposed model. In this model, the influent TSS level was not found to be statistically significant. The main reason for this anomaly was probably associated with the level of disinfection required for Siu Ho Wan. The influent UV transmittance level was found to be a significant value, attributable to its effect on the performance of the disinfection reactor. Low transmittance level may increase the chance of shortcircuiting in the disinfection reactor, which in turn results in elevated levels of E.Coli in the effluent. The effect of the influent E. Coli levels was also found to be statistically insignificant and hence eliminated from the model.

Based on the model, the UV doses to meet the required effluent standards are shown in Table 2.3.

Table 2.3 Minimum UV Dose Requirements

Coagulant Used	**Influent E.Coli level., counts/100mL**	**UV Transmittance**	**E.Coli standard counts/100 mL**	**Minimum UV Dose, mWs/cm^2**
Alum	1 x10^8	30	20,000	10
Ferric chloride	1 x10^8	20	20,000	13
Alum	1 x10^8	30	300,000	5
Ferric chloride	1 x10^8	20	300,000	6

The modelling results indicated that a low dose level of less than 15 mWs/cm^2 should be sufficient to meet the required monthly and 95 percentile E.Coli standards. However, inspection of the dose response curves showed that these dose level fell before the inflection points. As such, we recommend that a dose level of at least 30 mWs/cm^2 should be used to ensure a stable disinfection condition.

2.4.3 Lamp Fouling

Quartz sleeve fouling is a unique phenomenon associated with UV disinfection whereby an accumulation of inorganic and organic solids on the quartz sleeve decreases the intensity of UV light that enters the surrounding water. This fouling rate varies with process and effluent types and may be more rapid in the presence of high concentrations of iron, calcium and magnesium ions.

During this pilot study, there were two twelve-hour fouling tests done on each type of CEPT effluent, i.e. Ferric chloride and Alum. The purpose of doing two tests was to allow for the confirmation of the first set of results.

Influent samples to the UV pilot were collected and analyzed for E. Coli, TSS, Particle size, and Iron (total and dissolved) and were taken at hours 0, 1, 2, 3, 4, 6, 8, 10 and 12. Effluent samples from the UV pilot were collected and analyzed for E. coli and UVT at the same times. Figures 2.13 and 2.14 illustrate the effect of iron and alum on relative fouling rates respectively.

The ferric chloride treated effluent shows a significant decrease in UV performance after six hours of fouling. After four hours, counts had exceeded the disinfection standard of 20,000 E. coli/100mL.The alum treated effluent shows little to no decrease in disinfection performance; i.e. effluent UV samples exceeded 6000 E. Coli/100mL during the twelve-hour period.

Figures 2.14 a to d show the response curves of ferric-chloride and alum-treated effluents projected for 2 and 3 hours after lamp cleaning. It appeared that there should not be any technical difficulty in achieving the required standards at these cleaning frequencies.

As iron is a known UV absorber, samples for both dissolved and total iron were taken throughout the study. The sampling continued even when alum was being used for checking purposes. There was no significant amount of dissolved or total iron in the effluent during the entire pilot study, even when coagulant doses of ferric chloride were increased to 15ppm.

The % of Iron associated with the TSS was calculated using the following equation:

{(Total Iron (mg/L)-Dissolved Iron (mg/L)/TSS (mg/L)} x 100% = %Fe/TSS

The results of all of the data taken during the study had a maximum of 3.5%. A level of 4% or higher is a general guideline in UV disinfection that could potentially cause poor performance. The data collected in this study with CEPT effluent shows little to no effect when ferric chloride is in use with a notable exception on the quartz sleeve-fouling rate.

Based on this study, the fouling rate for the ferric chloride treated effluent at Siu Ho Wan would be approximately four hours. The increased levels of ferric chloride (total and dissolved) is a major factor accounting for the more rapid fouling with the ferric chloride treated effluent. These results were expected. In the event that alum is used as the coagulant at Siu Ho Wan, the fouling rate would be approximately twelve hours based on this study.

2.4.4 Photoreactivation

Photochemical damage caused by UV may be repaired by some organisms. Studies show that the amount of cell damage and subsequent repair is directly related to the UV dose. The amount of repair will also depend on the dose (intensity) of photoreactivating light. For low UV doses the resulting minimal damage can be more readily repaired than for high doses where the number of damaged sites is greater (Lindenauer et al., 1994).

There are two repair mechanisms : photoreactivation and dark repair.

1. Photoreactivation is a two step process involving the formation of an enzyme dimer complex. This stage of the reaction does not require light. The next stage requires absorption of light energy (wavelength range 310 to 490nm) to convert the enzyme dimers into thymine monomers, thus resulting in a reversal of the photochemical damage.

2. Dark repair does not require light energy. It is thought to be an enzyme repair process involving the excision of dimers and may be similar to the repair of cell damage caused by non-photochemical agents. Dimer formation in cytosine is repaired by this mechanism (Jagger 1967).

In situ studies have shown that photorepair did occur, but was not significant in the receiving water body, where the number of survivors appears to be more directly related to the extent of predation and natural die-off (Whitby et al., 1993). Since visible light is required for the photorepair process, wastewater treatment systems and outfalls can be designed to take advantage of this requirement. The photochemical damage caused by UV irradiation may be repaired by some microorganisms. Often the repair is not complete and only a fraction of the microorganisms recover. Repair and recovery from sub-lethal damage has also been observed with chemicals disinfectants (Calmer, 1994).

Laboratory studies show a high rate of repair resulting in a greater increase in survivors, whereas field studies show a much poorer rate of repair indicating that environmental factors play a significant role in microbe survival.

To simulate the environmental factors that would be experienced at Siu Ho Wan, photoreactivation samples were exposed to both light and dark conditions. The samples were held at an assumed ambient water temperature of 29°C in the dark. The three hours of 'dark' would simulate the maximum length of time that wastewater would spend in the pipeline before being discharged. Samples were then exposed to light at the receiving stream temperature of 29°C, but suspended at a variety of depths in the harbor adjacent to Stonecutters to simulate the natural dispersion of effluent and natural variation in visible light intensity from the discharge pipe. Samples were suspended at 10cm, 20cm, 40cm, 80cm and 160cm. After the one-hour exposure, a reasonable assumption of time to reach the surface of the receiving stream, the samples were removed and cultured immediately. One set of samples was covered in foil so as to prevent any light exposure during the one-hour light repair period. These samples were suspended at 40cm.

Photoreactivation testing during the pilot study was done using alum treated CEPT effluent at as near to UV design dose conditions as possible (30mWs/cm^2). The UVT of the CEPT effluent at the time of testing was 60% and the TSS was 29ppm. As UV dose is a function of Average Intensity and retention time, the relatively high UVT of 60% resulted in a corresponding higher average intensity and therefore even though the pilot unit was set at its maximum allowable flow rate the minimum UV dose delivered was 45mWs/cm^2. Samples were taken before UV and seven samples were taken after UV. Each sample taken was split into two sample bottles (A and B). The control sample and one set of after UV samples were placed in a cooler with ice for three hours. The other sets of after UV samples were held in the dark followed by light exposure as described above.

Samples were cultured immediately after removal from the harbor or ice chest by Trojan Technologies Inc. on site field staff and analyzed by SGS within six hours. Once again, a comparison was made between the two methods for the enumeration of E. coli and the following equation was generated to correlate the two methods. The equation

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y=1.6667x was developed by plotting SGS vs. Trojan E. coli data followed by regression analysis. The R^2 value was 1 indicating a very good correlation. The larger variation between SGS and Trojan results could be from a further increase in dark repair time before the samples were analyzed as, even if samples were transported on ice, the ambient temperature of the sample would remain at or around 29°C. All photoreactivation data can be found in Table 2.3.

Table 2.3 - Photoreactivation Test Results

No. of Sample	Samples	Sample Treatment	Photorepair Time	Sample Depth (cm)	A sample (Trojan)	A sample (SGS-corrected)	B sample (Trojan)	B sample (SGS-corrected)	Geo Mean	Log Geo Mean	Log Increase (PR) (Scgeible, 1981)
					E. Coli (counts/1000mL)						
1	Control Before UV	Store on ice in dark	Store on ice in dark	Store on ice in dark	5100000	5099898			5099949	6.71	4.86
2 Duplicates	No Repair After UV Dose	Store on ice in dark	Store on ice in dark	Store on ice in dark	63	84	108	42	70	1.85	0.00
2 Duplicates foil wrapped	No Repair After UV Dose	3 hours, Dark ambient water temperture	Dark Repair 1 hour ambient temperature	40cm	28	42	14	48	30	1.47	-0.37
2 Duplicates	After UV dose	3 hours, Dark ambient water temperture	1 hour visible light	10cm	160	360	250	156	218	2.34	0.49
2 Duplicates	After UV dose	3 hours, Dark ambient water temperture	1 hour visible light	20cm	70	96	260	210	138	2.14	0.30
2 Duplicates	After UV dose	3 hours, Dark ambient water temperture	1 hour visible light	40cm	170	204	240	234	210	2.32	0.48
2 Duplicates	After UV dose	3 hours, Dark ambient water temperture	1 hour visible light	80cm	50	42	90	204	79	1.90	0.05
2 Duplicates	After UV dose	3 hours, Dark ambient water temperture	1 hour visible light	160cm	70	132	60	138	94	1.97	0.13

In summary, the conventional method for quantifying the amount of photoreactivation of a UV irradiated wastewater sample is calculated using the relationship:

logNpr/N = photoreactivation (Sheible, 1981)

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The maximum increase in E. coli concentration due to photoreactivation should occur at the surface of the harbor in this experiment. The results shows that there is a 0.49log increase due to photoreactivation. As the sample depth increases the log increase decreases. As such, the effect of the photoreactivation was not found to be significant, and should be well offset by natural die off etc. in actual environmental conditions.

2.4.5 Disinfection Byproducts

During the pilot study, the possible formation of disinfection byproducts was investigated. The UV pilot was set to deliver a dose that was three times the proposed design dose. The UVT at the time of testing was 46% and the dose delivered was 89.3mWs/cm^2.

Samples were taken before the UV reactor, after the UV reactor with all of the lamps on and after the UV reactor with all of the lamps off. There was no significant increase in any of the tested compounds with the exception of slight increases (i.e. when the result increase exceeds the reporting detection limit (RDL)) after UV with the lamps on for the following compounds found in Table 2.4. (Linden, 1998)

Table 2.4 - Disinfection Byproducts Testing - Results of Compounds with Slight Increases

	Alum			**Ferric Chloride**			**RDL**	**Units**
Compound	Before UV	After UV Lamps On	After UV Lamps Off	Before UV	After UV Lamps On	After UV Lamps Off		
chloroform	19	18	18	14	17	15	0.2	µg/L
bromodichloromethane	<0.9	1.9	<0.9	<0.9	2.2	<0.9	0.2	µg/L
trichloroethylene	12	10	11	22	26	24	0.2	µg/L
toluene	22	22	21	29	33	32	0.2	µg/L
m&p xylenes	3.1	2.8	2.9	4.9	6	5.2	0.2	µg/L

2.4.6 Headloss Analysis

Figure 2.15 shows the headlosses measured across the UV reactor vs. the unit flow rate. The amount of headloss at each flowrate was calculated based on the difference between the upstream and downstream water levels. Correcting the headloss at no flow condition, the relationship between the headloss of the UV reactor and the flowrate is as follows:

Headloss (mm) = 23.7 x(flowrate)^2

Based on the developed relationship, the headloss at peak flow was calculated to be 560 mm, based on an estimated lamp requirements of 720. This level of headloss was found to be comparable to the losses of other methods and considered to be acceptable.

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2.4.7 Quality Assurance

A comprehensive quality assurance programme was carried out to ensure reliability of the collected data. Except for onsite measurements such as temperature UV transmittance levels, all the analyses were sent to a laboratory approved under the Hong Kong Laboratory Accreditation Scheme (HOKLAS). About 10% extra samples were collected for duplicate E.Coli, TSS, iron analysis. Also, limited number of duplicate samples were also collected and sent to laboratory for checking UV transmittance results. In addition, the influent flowmeter was checked to be satisfactory before commencement of the pilot study and readings were recorded in presence of the MCAL engineers.

The results of the QA/QC tests are shown in the following Table 2.5 to 2.7 for E.Coli, TSS and total iron levels, respectively. Large percent differences were only found in total iron levels when the levels were low and the results were considered to be satisfactory.

Table 2.5 - QA/QC Results of E. Coli Test

Duplicate Sample No.	Date	Parameter	Duplicate Result	Corresponding Sample No.	Original Result	Percentage Difference*
A1	14-Sep	E. coli (/100mL)	340	R17-60	260	-4.82
A2	14-Sep	E. coli (/100mL)	260	R18-30	190	-5.98
A6	15-Sep	E. coli (/100mL)	290	R21-60	200	-7.01
A7	15-Sep	E. coli (/100mL)	190	R21-40	310	8.53
A8	15-Sep	E. coli (/100mL)	690	R21-30	310	-13.95
A9	15-Sep	E. coli (/100mL)	1100	R21-20	680	-7.37
A13	22-Sep	E. coli (/100mL)	110	R26-60	5	-192.06
A14	22-Sep	E. coli (/100mL)	220	R26-40	220	0.00
A15	22-Sep	E. coli (/100mL)	250	R26-30	150	-10.19
A16	22-Sep	E. coli (/100mL)	710	R26-20	780	1.41
A17	22-Sep	E. coli (/100mL)	620	R26-10	1400	11.24
A25	23-Sep	E. coli (/100mL)	64000000	FT3-Control-4	54000000	-0.95
A26	23-Sep	E. coli (/100mL)	2900	FT3-30-4	5700	7.81
A27	23-Sep	E. coli (/100mL)	44000000	FT3-Control-5	37000000	-0.99
A28	23-Sep	E. coli (/100mL)	790	FT3-30-5	2400	14.28
A29	23-Sep	E. coli (/100mL)	49000000	FT3-Control-6	53000000	0.44
A35	24-Sep	E. coli (/100mL)	380	R29-60	750	10.27
A36	24-Sep	E. coli (/100mL)	600	R29-40	580	-0.53
A37	24-Sep	E. coli (/100mL)	580	R29-30	420	-5.34
A38	24-Sep	E. coli (/100mL)	1140	R29-20	630	-9.20
A39	24-Sep	E. coli (/100mL)	5900	R29-10	5400	-1.03
A49	27-Sep	E. coli (/100mL)	160	R32-60	70	-19.46
A50	27-Sep	E. coli (/100mL)	40	R32-40	80	15.82
A51	27-Sep	E. coli (/100mL)	230	R32-30	96	-19.14
A52	27-Sep	E. coli (/100mL)	230	R32-20	110	-15.69
A53	27-Sep	E. coli (/100mL)	790	R32-10	630	-3.51
A62	29-Sep	E. coli (/100mL)	1500	R33-30	2100	4.40
A63	29-Sep	E. coli (/100mL)	1100	R33-20	2300	9.53
A64	29-Sep	E. coli (/100mL)	1200	R34-30	550	-12.36
A65	29-Sep	E. coli (/100mL)	980	R34-20	1100	1.65
A66	29-Sep	E. coli (/100mL)	490	R35-30	310	-7.98
A67	29-Sep	E. coli (/100mL)	950	R35-20	460	-11.83

* in Log scale

Table 2.6 - QA/QC Results for Total Suspended Solids (TSS) Test

QA/QC Sample No.	Date	Parameter	QA/QC Result	Corresponding Sample No	Original Result	Percentage Difference
A3	14-Sep	TSS (mg/L)	47	R18	48	2.1
A10	15-Sep	TSS (mg/L)	70	R21	46	-52.2
A18	22-Sep	TSS (mg/L)	58	R26-60	54	-7.4
A19	22-Sep	TSS (mg/L)	54	R26-40	62	12.9
A30	23-Sep	TSS (mg/L)	74	FT3-4	82	9.8
A31	23-Sep	TSS (mg/L)	75	FT3-6	66	-13.6
A40	24-Sep	TSS (mg/L)	130	R29-60	110	-18.2
A54	27-Sep	TSS (mg/L)	60	R32-60	69	13.0
A55	27-Sep	TSS (mg/L)	44	R32-30	59	25.4

Table 2.7 - QA/QC Results for Total Iron Levels Tests

QA/QC Sample No.	Date	Parameter	QA/QC Result	Corresponding Sample No	Original Result	Percentage Difference
A23	22-Sep	Fe (Total) (mg/L)	0.7	R26	0.6	-16.7
A34	23-Sep	Fe (Total) (mg/L)	0.3	FT3-8	0.3	0.0
A45	24-Sep	Fe (Total) (mg/L)	0.4	R27	0.4	0.0
A46	24-Sep	Fe (Total) (mg/L)	0.4	R28	0.4	0.0
A61	27-Sep	Fe (Total) (mg/L)	0.3	R32	0.4	25.0
A24	22-Sep	Fe (Diss.) (mg/L)	0.2	R26	0.2	0.0
A35	23-Sep	Fe (Diss.) (mg/L)	0.1	FT3-8	0.1	0.0
A47	24-Sep	Fe (Diss.) (mg/L)	0.2	R27	0.1	-100.0
A48	24-Sep	Fe (Diss.) (mg/L)	0.2	R28	0.1	-100.0
A60	27-Sep	Fe (Diss.) (mg/L)	0.2	R32	0.2	0.0

Checking the data measured on site and those in the laboratory showed that there were major differences in the UV transmittance measurements. The differences in readings might be attributable to the differences in measurement methods used in the spectrophotometers. The method adopted by Trojan has widely been used in the UV industry, although currently there is no formal standard for UV transmittance measurement. We consider that the UV transmittance method by Trojan should be used in order to ensure that reference can be made to the measurements in other plants when conducting the design of the full-scale facilities.

2.5 Conclusions and Recommendations

Based on the above analysis, we have the following conclusions and recommendations:

- The UV pilot test showed that the required E.Coli standards are achieved at practical dose levels. An UV dose levels less than 30 mWs/cm^2 was found to be sufficient to achieve the E.Coli standards of 20,000 at all times over a wide range of influent conditions

- Higher dose levels appeared to be necessary at higher TSS levels, although the trend was not apparent for some TSS ranges because of the significant data scattering.

- The collected pilot study data were found to fit well a mathematical model developed at the University of California at Davis. The disinfection model indicated that an UV dose of about 15 mWs/cm^2 should be sufficient to meet the required E.Coli standards. An UV dose of 30 mWs/cm^2 was considered to be the most appropriate to ensure stable disinfection performance and selected as the basis for the design of the full-scale facilities.

- The fouling rate was found to be acceptable. Based on this study, the fouling rate for the ferric chloride-treated effluent would be approximately four hours. In the event that alum is used as the coagulant at Siu Ho Wan, the fouling rate would be approximately twelve hours based on this study. The expected fouling rate and required frequency of cleaning should be acceptable using the UV systems with automatic wipers.

- There were no apparent increases in harmful disinfection byproducts for UV dose levels up to 3 times of the design dose.

- The limited photoreactivation tests showed that there was a maximum of 0.49log increase due to photoreactivation at the surface of the harbour under laboratory conditions. This effect should be well offset by the natural dieoff under field conditions. As the sample depth increased, the log increase was found to decrease. As such, the effect of the photoreactivation was not found to be significant.

- The headloss analyses showed that the headloss across the UV reactor should be acceptable under peak flow conditions.

3. OZONE PILOT TESTS

3.1 Introduction

This purpose of this Section is to describe the ozone disinfection pilot tests and discuss the test results. It is divided into the following sub-sections:

- Introduction
- Pilot Plant Equipment
- Test Method and Procedures
- Results and Discussions
- Conclusions and Recommendations

The ozone disinfection pilot tests were conducted by HKUST-Anjou Recherche-Trailigaz, under the supervision of E&MP Division of DSD.

3.1.1 Objectives

The primary purpose of this study was to investigate the use of ozone for the disinfection of the effluent at Siu Ho Wan STW to achieve the required E. coli standards of a monthly geometric mean of 20,000 E.coli/100 ml and a 95-percentile compliance of 300,000 E.coli/100 ml. The results of the pilot tests would be used as the basis to conduct a detailed comparison of the ozone and UV disinfection processes to select the optimum disinfection process. If ozone is selected, the design parameters established in the pilot tests will be used to design the full-scale ozone disinfection facility.

The specific objectives of the pilot study were as follows:

- to assess the influent characteristics that pertains to ozone disinfection;
- to develop the dose-response relationship for ozonation under various wastewater quality conditions, simulated by using different doses of alum and ferric chloride as coagulants;
- to assess the most appropriate applied ozone dose and transfer efficiency, at a retention time of 15 minutes for the design of the full-scale ozone disinfection facility, using either ferric chloride or alum; and
- to conduct a preliminary assessment of the possible increase in effluent five-day biochemical oxygen demand (BOD_5) and formation of disinfection byproducts under the expected ozone dose levels.

3.2 Ozone Pilot Test Equipment

3.2.1 Pilot Plant Equipment

Figures 3.1 and 3.2 show the setup and schematics of the ozone pilot plant used in this Study. The main components of the pilot plant included two ozone contact columns, an ozone generator, an ozone destruction unit, and a buffer tank. The columns were 5.5 m high and constructed using 310mm diameter polyvinyl chloride (PVC). Both columns were provided with fine bubble diffusers using Trailigaz DPP 135 porous plate diffusers. The water levels in the column were maintained at 4.5 m throughout the Study.

The ozone contact columns were of counter-current design. The gas entered the column from the bottom and rose to the top while water entered from the top and flowed down to the bottom. The first column should primarily be used as the ozone transfer column and the second for contact column (i.e no ozone transfer).

The ozone generator, a Trailigaz Ozobloc model OZC1002 supplied with pure oxygen, was housed in a dehumidified box to protect it from rain and humidity. In the original proposal by the ozone pilot test contractor, the capacity of the generator was stated to be 150 g/h. However, this figure was reduced to 100 g/h in the Final Report.

The study was also conducted at the Stonecutters Island Sewage Treatment Works, using the prototype CEPT plant. As discussed in the Section 2, various CEPT effluent qualities were generated by varying the coagulant type, coagulant dose and surface overflow rates.

The treated effluent was pumped into the buffer tank upstream of the ozone pilot unit. The wastewater was then pumped into the top of the contact column and exited from the bottom. The contact time was adjusted by varying the flow which was controlled by a valve. Ozone from the ozone generator was diffused into the column through porous diffusers located at the bottom of the column and flowed counter-current to the water. The disinfected pilot effluent was then discharged into the sewerage system, whereas the off-gas from the column was sent to the ozone destruction unit, where any remaining ozone was destroyed before discharge to the atmosphere.

Wastewater flowrate was measured by a flow meter installed before the contact column, while the ozone gas flowrate was measured by gas flow meters before the column and the gas sample port.

3.3 Test Methods and Procedures

3.3.1 Overview

The ozone pilot trials took place from 11 September to 20 October, 1999. The pilot test programme basically followed the test requirement plan prepared by MCAL before the commencement of the ozone pilot test. Some changes were made because of weather conditions and equipment problems of the temporary alum addition system. These changes were notified to DSD and MCAL. Some unnotified deviations were also identified.

During the test period from September 11 to 30, the ozone pilot tests were conducted with the UV pilot test, using the same source of effluent from the prototype CEPT plant. The test programme consisted of a total of 26 dose response tests and 2 disinfection byproduct test. Of the 26 dose response tests, 9 tests were conducted using ferric chloride-treated effluent, 13 using alum-treated effluent and 4 with primary effluent. Table 3.1 shows the test programme.

Table 3.1 Ozone Pilot Test Programme

Date		Coagulant Type	Coagulant Dose (mg/L)	Ozone Dose (mg/L)	Purpose
Sept 11	(Sat)	Ferric Chloride	10.0	25	Dose response
Sept 13	(Mon)	Ferric Chloride	10.0	20	Dose response
Sept 14	(Tue)	-	-	20	Dose response
Sept 15	(Wed)	Alum	2.0	20	Dose response
Sept 18	(Sat)	Alum	4.0	20	Dose response
Sept 21	(Tue)	-	-	40	Dose response
Sept 22	(Wed)	Alum	5.0	35	Dose response
Sept 23	(Thu)	Alum	5.0	30	Dose response
Sept 24	(Fri)	-	-	35	Dose response
Sept 27	(Mon)	Alum	7.5	30	Dose response
Sept 28	(Tue)	Alum	5.0	25	Dose response
Sept 29	(Wed)	-	-	25	Dose response
Sept 30	(Thu)	Alum	5.0	20	Dose response
Oct 2	(Sat)	Alum	7.5	35	Dose response
Oct 4	(Mon)	Alum	7.5	25	Dose response
Oct 5	(Tue)	Alum	7.5	20	Dose response
Oct 6	(Wed)	Alum	2.0	35	Dose response
Oct 7	(Thu)	Alum	2.0	35	Dose response
Oct 8	(Fri)	Ferric Chloride	10.0	35	Dose response
Oct 9	(Sat)	Ferric Chloride	15.0	35	Dose response
Oct 11	(Mon)	Ferric Chloride	15.0	25	Dose response
Oct 12	(Tue)	Ferric Chloride	15.0	20	Dose response
Oct 13	(Wed)	Ferric Chloride	5.0	35	Dose response
Oct 14	(Thu)	Ferric Chloride	5.0	35	Dose response
Oct 15	(Fri)	Ferric Chloride	5.0	25	Dose response
Oct 16	(Sat)	Ferric Chloride	10.0	37.5	Disinfection by-product
Oct 19	(Tue)	Alum	5.0	37.5	Disinfection by-product
Oct 20	(Wed)	Alum	2.0	25	Dose response

3.3.2 Dose Response Tests

The objective of these tests was to establish the relationship between the surviving E. coli and E. coli inactivation with ozone dose levels.

A test was conducted each day and a total of 26 tests were completed. The coagulant (either ferric chloride or alum) dose was set at about 8:00p.m. before the testing day to ensure that the quality of the CEPT effluent became stabilized. The flowrate was adjusted to about 1.36 m3/hr for a contact time of 15 minutes before samples were collected for analysis.

Twenty (20) effluent samples were collected every day at half-hour intervals starting from approximately 09:00a.m. to 6:30p.m.. The samples were analysed for E. coli, Total Suspended Solid (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (5 days) (BOD_5), total and dissolved iron. Sampling was scheduled during these hours in order to cover the peak times for E. coli (3:00p.m. and 5:00p.m.) and COD (10:00a.m.), which had already been determined during a previous study at Stonecutters Island STW. At least one sample volume was rejected prior to collecting each sample.

Applied ozone concentrations were monitored every half hour using a Trailigaz UVOZON on-line ozone analyser. The readings given by the on-line analyser were compared twice a day, once in the morning and again in the afternoon, to results using the iodometric titration method. The ozone concentration in the off-gas was measured twice a day using the iodometric titration method.

3.3.3 Disinfection Byproduct Analysis

This was to conduct a preliminary assessment on the possible formation of disinfection byproducts under the expected ozone dose level. A test was carried out for both ferric chloride and alum-treated CEPT effluent.

The tests were conducted with an ozone dose of 37.5 g/m^3 to CEPT wastewater treated with 5 mg/L of alum and 10 mg/L of ferric chloride. One influent and one effluent sample were collected in the afternoon on each day of testing and analysed by the EPA Methods 5030b/8260b and 8270b for volatile and semi-volatile organic compounds, respectively.

3.4 Results and Discussions

3.4.1 Influent Characteristics

Table 3.2 shows the influent characteristics of the ozone pilot plant during the study period, which were extracted from the test report prepared by the ozone pilot test contractor (HKUST et al, 1999). As shown in Table 3.2, the influent characteristics covered a wide range of TSS (14 to 85 mg/L), COD (70 to 300 mg/L) and BOD_5 levels (49 to 170 mg/L) of the CEPT effluent that may be encountered at the future Siu Ho Wan STW. However, the design (worst case) influent TSS, COD and BOD_5 levels were not achievable during the study period.

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Table 3.2

Expected and Actual CEPT effluent characteristics (extracted from HKUST et al., 1999)

Coagulant		**TSS (mg/l)**		**COD (mg/l)**		**BOD$_5$ (mg/l)**	
Type	*Dose (mg/l)*	*Expected average*	*Actual average (range)*	*Expected average*	*Actual average (range)*	*Expected average*	*Actual average (range)*
None	0	80	53 (20 – 85)	225	226 (120 – 300)	105	112 (93 – 170)
Alum	2	60	37 (14 – 74)	210	167 (70 – 240)	90	90 (71 – 110)
	5	40	51 (21 – 78)	165	175 (92 – 240)	75	85 (59 – 130)
	7.5	30	34 (19 – 52)	150	166 (100 – 210)	68	80 (52 – 110)
Ferric chloride	5	60	36 (14 – 56)	210	159 (96 – 230)	90	70 (66 – 75)
	10	40	23 (16 – 41)	165	174 (93 – 220)	75	70 (52 – 87)
	15	30	29 (14 – 56)	150	146 (97 – 190)	68	64 (49 – 81)

During the pilot study period, the CEPT effluent characteristics were found to vary appreciably on the same day because of natural variability of raw sewage characteristics and flows. The range of CEPT effluent conditions were produced from the prototype CEPT under stable operating conditions, i.e. constant chemical type and dose. Any changes in operating conditions were carried out around 8:00 p.m. at night immediately after the ozone pilot tests were completed. As such, adequate stabilization time of more than 12 hours was available in the CEPT process to ensure a new stable operating condition before the commencement of ozone pilot tests.

During the test periods from September 22 to 29, the flowrates to the prototype plant were further increased from 9:00 a.m. to 4:30 p.m. by diverting more flows from the main plant using a fourth stoplog at the inlet. The flowrate to the CEPT plant was well within its hydraulic capacity. It is important to assess the performance of the disinfection system under varying influent conditions. It should also be noted that the same source of CEPT effluent was used for both ozone and UV pilot plants.

It may be worthwhile to note the anomalies in the measured TSS levels. Figure 3.3 shows the plot of the measured effluent vs. influent TSS values. A significant scattering band of the influent and effluent TSS data was recorded. For example, at an influent TSS of 40 mg/L, the corresponding effluent TSS levels were found to vary from 15 to 55 mg/L. A number of effluent TSS levels were also measured to be higher than the corresponding influent TSS values. The differences did not seem to be able to be explained by natural variability of the influent conditions and the possible time lag of the influent and effluent samples. It was not certain regarding the reasons for such anomaly and the apparent variations in the measured TSS levels on the performance assessment of ozonation disinfection.

3.4.2 Dose Response Tests

Figures 3.4 and 3.5 show the variations of effluent E. Coli levels and E. Coli inactivation with ozone dose based on the data collected during the pilot tests. The data included the CEPT effluent using ferric chloride, alum and no coagulants. Data were discarded when obviously not representative, because either samples were taken during stabilization period of the pilot unit or had laboratory analytical problems. It was reported that the stabilization period during this pilot study was longer than the expected and more than 30 percent of the data were discarded. The exact reasons for prolonged stabilization periods could not be identified by the ozone pilot unit contractor.

The pilot test data showed that the E.Coli standards of 20,000 counts and 300,000 counts were NOT achievable consistently under the dose levels of 20 mg/L or lower, which was recommended by some ozone equipment suppliers in the previous Disinfection Option Review Paper. An ozone dose level of about 35 mg/L was found to be necessary to ensure that the required E.Coli standards of 20,000 counts/100 mL were achieved at all times. It should be noted that the influent conditions that was encountered did not cover the design worst case influent conditions (i.e. 120 mg/L TSS, 180 mg/L BOD and 360 mg/L COD).

The data were shown separately based on three different ranges of SS levels of less than 30 mg/L, 30 to 60 mg/L and 60 to 85 mg/L. As shown in Figure 3.4, the dose requirements to achieve the same effluent E. Coli levels appear to be higher for treated effluent with higher SS levels. It is more apparent for the dose response relationships for effluent with SS between 60 and 85mg/L (shown in circles) and those for SS between 30 mg/L and 60 mg/L (in square). The dose requirement and SS relationship is less apparent for SS lower than 30 mg/L (in diamond shape) because of the significant data scattering. Visual inspection of the available data showed that the approximate ozone requirements for the three ranges of TSS conditions were 35, 30 and 20 mg/L to achieve the E.Coli standards of 20,000 counts/100 mL consistently.

Figure 3.4 shows the variations of E.Coli inactivation with UV dosage. It is worthwhile to note the difference in the shape of the dose response curves for ozone and UV radiation under the test dose levels. Both curves did not follow the linear Chick's Law decay. In dose response curves for ozonation, the presence of "shoulders" or time lags until the onset of disinfection was observed. The presence of shoulders can be accounted for when multiple targets within each organism must each be damaged by independent disinfectant molecules prior to kill. Another probable reason is the presence of immediate ozone demand that must be satisfied before disinfection took place.

Figures 3.6 and 3.7 show the variations of Effluent E.Coli and E.Coli inactivation levels with ozone dose for all the pilot test data, shown separately based on different COD levels. As shown in the Figures, the ozone disinfection efficiencies were found to be lower for treated effluent with higher COD levels. The reasons were apparent because of the higher competitive demand for ozone at increasing COD levels. It is more apparent for the dose response relationships for effluent with COD between 240 and 300 mg/L (shown in circles) and those for COD between 180 mg/L and 240 mg/L (in square). The dose requirement and SS relationship is less apparent for COD lower than 180 mg/L (in diamond shape) because of the significant data scattering.

Figure 3.8 shows the variation of E.Coli vs. ozone dose under simulated design (worst-case) influent condition, based on the primary effluent samples only. During these test periods, TSS levels ranged from 2 to 85 mg/L and COD levels ranged from 180 to 300 mg/L. It is apparent that ozone dose levels of 33 and 40 mg/L were sufficient to achieve the required standards on average and at all times, respectively. The variation of the E.Coli inactivation with ozone dose is shown in Figure 3.9.

Figures 3.10 and 3.11 show the variations of effluent E.Coli with UV dose for treated effluent using ferric chloride and alum, respectively. Figures 3.12 and 3.13 show the respective variations of E.Coli inactivation with UV dose. As shown in Figures, the dose levels required to achieve the effluent E.Coli standards and 3-log E.Coli inactivation are shown in Table 3.3

Table 3.3 Ozone Requirements

	Average Ozone Dose to Achieve	
Coagulant Used	**E.Coli standard**	**3-log E.Coli Inactivation**
No coagulant	18	13
Ferric chloride	16	13
Alum	12	10

As shown in the above Table, there did not seem to be a major difference between the ozone dose requirements for either alum or ferric chloride-treated effluent. The possible reduction in ozone dose requirements when alum is used, when compared with ferric chloride-treated effluent. The possible mechanism of iron acting as scavenger for the free radicals during ozonation might have been masked by other factors.

From the above analyses, an ozone dose level of 33 mg/L was found to be necessary to meet the E.Coli standards at maximum TSS level of 85 mg/L. If a simple linear extrapolation using TSS levels is used, the minimum ozone dose requirement was estimated to be 64 mg/L at the design influent TSS level of 120 mg/L. The design ozone dose level can be selected from a lower limit of 33 mg/L and a possible upper limit of 64 mg/L. Because the highest TSS level of 85 mg/L should only be exceeded remotely at the future Siu Ho Wan STW, the mid-point of the probable design dose range should be adequate for the design of the full-scale facility. As such, we recommend that a minimum ozone dose of 40 mg/L should be used in the future design.

3.4.3 Disinfection Byproduct Tests

During the pilot study, the possible formation of disinfection byproducts was investigated. The ozone pilot was set to deliver an ozone dose of 37.5 mg/L. Higher ozone dose levels were reported to be not achievable because of the capacity constraint of the ozone generator. As such, the assessment could only be made at approximately average dose levels. Two sets of influent and effluent samples were collected, one for alum-treated and one for ferric chloride-treated effluent.

The results of the laboratory analyses indicated that there were elevated levels of bromoform, bromodichoromethane and chlorodibromomethane in the effluent samples (see Table 3.4). They are Cancer Group B carcinogens (known to cause cancer in laboratory animals) according to the U.S. EPA guidelines. Chlorodibromomethane is the most serious cancer risk, (0.6 µg/l to cause a 10^{-6} cancer risk increase) followed in order by Bromoform (4 µg /l), and Chloroform (6 µg /l). Current US and European regulations limit the concentration of these 3 chemicals with chloroform added together (total trihalomethane or TTHM levels) to 100 µg/l. There were no apparent increase in other harmful disinfection byproducts.

Table 3.4 – Disinfection Byproducts

Compound	**Concentration in alum-treated sample (µg/l)**		**Concentration in ferric chloride-treated sample (µg/l)**		**RDL (µg/l)**
	Influent	*Effluent*	*Influent*	*Effluent*	
Bromodichloromethane	< 0.9	1.8	< 0.9	1.7	0.2
Chlorodibromomethane	< 0.9	1.3	< 0.9	< 0.9	0.2
Bromoform	< 0.9	170	< 0.9	45	0.2

The major concern is the elevated levels of bromoform in effluent samples. The effluent bromoform levels were found to be 45 and 170 µg/l for CEPT effluent with alum and ferric chloride, respectively. The presence of bromoform is not unexpected because it is commonly found in other studies when the ozone is added to wastewater high in bromides. The bromide levels in the wastewater in Hong Kong are generally high because of the use of seawater for flushing. Oxidation of the bromide ion produces bromine ($HOBr/OBr^-$), which reacts with organic precursors to form bromoform and possibly other trihalomethanes (THMs). Bromodichloromethane and chlorodibromomethane are the other THMs.

3.4.4 Effect of Ozonation on Water Quality Parameters

Ozone Residuals. The residual ozone levels measured during the pilot plant study were show in Table 3.5. The residual ozone levels were found to vary between 0.02 to 0.21 mg/L. Elevated levels from 0.11 to 0.21 mg/L were encountered at high ozone levels when alum dose is high.

The effects of residual ozone appear to be varied and dependent on many factors. Although residual ozone has been shown to be toxic, it is, by comparison no more so than residual chlorine. Also, residual ozone disappears rapidly in the environment. At expected dosages, any residual ozone would be short-lived and pose few problems to the receiving water bodies.

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Table 3.5 Ozone Residual

Coagulant type	Coagulant dose (mg/l)	Ozone dose (g/m^3)	Residual O_3 (mg/l)
			Effluent
None	0	20	0.02
		25	0.02
		30	0.02
		40	0.04
Alum	2	25	0.03
		30	0.03
		35	0.06
	4	20	0.01
	5	20	0.06
		25	0.04
		30	0.02
		35	0.07
	7.5	20	0.03
		25	0.11
		30	0.21
		35	0.12
Ferric chloride	5	25	0.05
		30	0.07
		35	0.05
	10	20	0.03
		25	0.05
		30	0.04
	15	20	0.03
		25	0.05
		30	0.07

Biochemical Oxygen Demand. Figure 3.14 shows the plot of effluent BOD vs. influent BOD. There is no apparent increase in BOD levels due to ozonation based on the average values. The results indicated that possible effect of ozonation in rendering recalcitrant organic molecules more biodegradable and hence increasing the effluent BOD levels was not a major concern.

Chemical Oxygen Demand. Figure 3.15 shows the plot of effluent COD vs. influent COD. There was no apparent trend to show whether there was any increase or reduction in COD after ozonation. The data were however found to scatter significantly.

3.5 Conclusions and Recommendations

Based on the above analyses, we have the following conclusions and recommendations:

- The ozone pilot tests showed that the required E.Coli standards were achieved at elevated ozone dose levels. The ozone dose level of 20 mg/L or lower, as recommended by some ozone supplier was found to be insufficient to achieve the required E.Coli standards.

- An ozone dose level of about 35 mg/L was necessary to ensure that the required E. Coli standards of 20,000 counts/100 mL were achieved at all times, based on the collected data.
- The required ozone dose levels were also found to increase with increasing TSS levels.
- At simulated design influent conditions, minimum ozone dose levels of 35 and 40 mg/L were found to be necessary to achieve the required E.Coli standards of 20,000counts/100mL on average and at all times, respectively. A design dose level of at least 40 mg/L should be used in the design of the full-scale facility.
- Disinfection byproduct tests were conducted for both ferric chloride and alum-treated effluent at a dose level of 37.5 mg/L. Elevated levels of bromoform, bromodichloromethane and chlorodibromomethane were found in the effluent samples. They are carcinogens. The major parameter of concern is the elevated levels of bromoform in effluent samples. The effluent bromoform levels were found to be 45 and 170 µg/l for CEPT effluent with alum and ferric chloride, respectively.
- The residual ozone levels were generally low but elevated levels from 0.11 to 0.21 mg/L might also be encountered at high ozone levels.
- There appeared to be no significant changes in BOD and COD levels due to ozonation.

4. SLUDGE DEWATERING PILOT TESTS

4.1 Introduction

This purpose of this Section is to describe the sludge dewatering pilot tests and discuss the test results. It is divided into the following sub-sections:

- Introduction
- Pilot Plant Equipment
- Test Method and Procedures
- Results and Discussions
- Conclusions and Recommendations

4.1.1 Objectives

The primary objective of the sludge dewatering pilot tests was to assess the feasibility of dewatering alum sludge using centrifuges. Use of alum in the CEPT process will bring about potential significant cost savings to the UV disinfection process. The alum-treated CEPT effluent generally has a 10 to 20 percent higher in UV transmittance level when compared with the ferric chloride-treated effluent. This in turn will reduce the UV lamp requirements by 35 to 50 percent and the associated power and lamp replacement costs. However, there is limited experience of dewatering alum sludge using centrifuges, in particular to meet the stringent 30% solids content requirements. This in turn creates uncertainty regarding the feasibility of using alum and its benefits to the disinfection process.

A limited sludge dewatering test programme was conducted to investigate (1) the feasibility of using centrifuges to achieve the 30 percent solids content requirements and (2) the potential additional costs associated with the increased dewatering equipment and polymer requirements, if any. The results of the tests were used as the basis to assess the associated sludge dewatering costs when conducting detailed comparison of the UV and ozone disinfection options.

Specific objectives of the dewatering tests include:

- To assess the alum sludge characteristics that pertain to centrifuge dewatering.
- To assess the relationship between dewatered sludge dryness and centrate quality and the following control variables under various raw sludge conditions:
  - raw sludge feed rate;
  - polymer type and dosing rate; and
  - operating conditions such as centrifuge differential speed and pond depth.

4.2 Pilot Plant Equipment

One of the full-scale centrifuges at SCISTW was used in the sludge dewatering pilot study. It is a high torque solid bowl centrifuge of countercurrent flow configuration supplied by Alfa Laval, Sharples Division. The design maximum throughput of the centrifuge is about $100m^3/h$. The design cake dry solids and centrate quality are 32% and 1200 mg/L, respectively.

Figure 4.1 shows the setup of the sludge dewatering pilot plant. Chemical sludge that was generated from the prototype CEPT plant was used as the feed sludge for dewatering tests. The sludge was pumped to the sludge holding tank no 1, while the sludge from other full-scale CEPT tanks was stored separately in other tanks. During the periods when dewatering pilot tests were conducted, the dewatering process for the main plant was temporarily suspended to avoid mixing of sludges in the common sludge feed pipe.

An existing small-scale polymer preparation unit was used when the polymer for the dewatering pilot tests was different from that used in the full-scale plant. Two alternative cationic polymers: Zetag 7650 and Zetag 7651 were used, in addition to the current C495H ploymer in the full-scale plant.

4.3 Test Methods and Procedures

4.3.1 Test Programme

The dewatering pilot tests took place on 10 days, in parallel with the UV and ozone disinfection pilot plant studies. It was separated into two main phases. The first phase involved a baseline study in which ferric chloride and primary sludges were tested. It took place from September 7 to September 14.

The second phase involved testing of alum sludge. It took place on 5 days during the period from September 28 to October 20, 1999, when alum dose levels in the prototype CEPT plant ranged from 5 to 7.5 mg/L. Owing to the limited volumes of sludge generated in the prototype plant when compared with the centrifuge capacity, prior storage of sludge for 8 to 48 hours was found to be necessary.

Under both Phase 1 and Phase 2 study, one raw sludge feed rate was maintained at a constant selected level and recorded. With the assistance from the centrifuge equipment supplier, the polymer feed rate, centrifuge torque and other operating parameters were adjusted in order to achieve the highest cake dryness and the desired centrate quality. It was also decided that the dam plates of the centrifuges should be adjusted to increase the pond depths to improve centrate clarity during the alum sludge tests.

Before sludge samples were taken, adequate time of at least 15 minutes was allowed to flush out the remaining sludge in the common sludge feeder. Preliminary on-site dewatered sludge sample analyses were conducted using a Sartorius moisture analyser before the optimum operating condition was identified. When the acceptable operating condition was decided, the sludge feed rate, polymer dose level, torque, differential speed and all the relevant readings were recorded. Samples were taken on the feed sludge, dewatered sludge and centrate for analysis. The feed and dewatered sludge were analyzed for total solids and volatile solids and centrate for total suspended solids. Feed sludge and centrate samples were analyzed for total and dissolved alumimum, total and dissolved iron and alkalinity. On site measurements on the pH and temperature were carried out on the feed sludge and centrate samples.

4.4 Results and Analyses

Figures 4.2 and 4.3 show the sludge cake solids and solids recovery levels of the test centrifuge during the dewatering pilot study period. It is apparent from these Figures that it was feasible to dewater alum sludge using centrifuges to meet the 30% solids content requirements. The alum sludge was produced at alum dose levels of 5 mg/L and 7.5 mg/L , which were the expected and 1.5 times the expected dose levels, respectively. The solids contents of alum sludge cake were found to range from 33 to 42 percent, which exceeded the required 30% consistently. These solids contents were found to be similar to those for ferric chloride and primary sludges.

The solids recovery levels of the test centrifuge were found to range from 90 to 98%, when alum sludge was fed. The low solids recovery levels were encountered during initial test periods when appropriate polymer type, dose level and centrifuge operating conditions were not established. Under the subsequent operating conditions, the solids recovery levels improved to satisfactory levels and ranged from 95 to 98%. The TSS levels of centrate samples were found to range 410 and 1800 mg/L.

It is also worthwhile to note that the average solids content of alum feed sludge was 2.8%. This level was found to be similar (or slightly higher than) to that of ferric chloride sludge of 2.1%, under similar operating conditions. Therefore, the volumes of feed sludges should be similar when either alum or ferric chloride was used because both total solids mass and solids content of these sludges are similar.

The alum sludge test results were further analyzed to assess the relationship between (1) sludge cake dryness and centrate quality and (2) the control variables including raw sludge feed rate, polymer type and dosing rate and centrifuge operating conditions. It should be noted that the study was constrained by the limited volumes of alum sludge. The alum sludge characteristics were found to be consistent and are summarized as below:

Table 4.1 – Alum Sludge Characteristics

Parameters	Range	Average
Total Solids	2.0 to 3.2	2.8
Volatile Solids/Total Solids (%)	43 to 74	53
Al/TSS (%)	0.64 to 1.75	1.2
Fe/TSS (%)	0.37 to 1	0.7
PH	5.6 to 6.2	5.9
Alkalinity (as mg CaCO3)	1200 to 1300	1290

During the dewatering test period, the alum sludge was fed at 65 m^3/h and one test at 80 m^3/h. The normal feed rates of the ferric chloride sludge ranged from 70 to 80 m^3/h for the full-scale centrifuges. The conditions under the maximum feed rate of 100 m^3/h were not tested during the pilot study. It was found that the desired sludge cake and centrate quality were achieved at feed rate of 65 m^3/h, which is only 10 to 20 percent lower than the normal feed rates for ferric chloride sludge. Because of the limited data, it was not possible to decide the highest acceptable feed rates to the centrifuges when alum sludge was fed.

Figures 4.4 and 4.5 show the variations of sludge cake total solids and centrate TSS with polymer doses. During the alum sludge tests, high polymer dose up to 1.5 to 2 times of that for ferric chloride sludge were used to ensure achieving the required 30% solids with limited sludge tests. As shown in Figure 4.4, the sludge cake solids contents exceeded 33% for the range of polymer dose from 3 to 8 kg/ton dry solids and for all types of polymers. It should be noted that the apparently low solids content at polymer dose of 8 kg/ton was attributable to the changes to centrifuge operations to improve centrate clarity.

As shown in Figure 4.5, the centrate quality was found to vary with the polymer type and polymer dose. During the initial period when the polymer Zetag 7650 was used, excessive centrate TSS levels up to 3300 mg/L were found. It should be noted that the solids recovery levels of the test centrifuge still exceeded 90% during this period. The centrate quality was found to improve with the use of polymer C495H and Zetag 7651 and increasing polymer dose levels. At Zetag polymer doses from 5 to 8 kg/ton dry solids, the centrate TSS levels were found to fall within the target level 800 mg/L. From the available data, it was shown that both the sludge cake and centrate quality requirements were achieved with an appropriate polymer type at dose of 5 kg/ton dry solids. Further analyses were not possible to refine the lowest polymer dose levels because of the limited data.

During the dewatering pilot study, centrifuge operating conditions were varied to achieve the desired solids cake and centrate quality. The two key variable operating parameters included differential speed and pond depth. It was observed that due to the unique characteristics of alum sludge, the centrate clarity improved at decreasing differential speeds. Also, decreasing differential speeds reduced the solids content of the sludge cake. This unique relationship might be mainly attributable to the presence of gelatinous hydroxide particles in alum sludge. At high differential speeds, the more readily settleable materials were deposited, while the light, difficult to compact hydroxide fraction were taken away with the centrate. The result was a low solids recovery, and a high cake solids content. At decreasing differential speeds, the hydraulic residence time increased and more gelatinous hydroxide particles were also deposited. The cake solids content decreased as a result and the solids recovery increased.

Also, the centrate clarity was found to improve at greater pond depths. During the test period, the pond depths were increased from 139.5 mm to 141.2 mm by adjusting the dam plate locations. The increased depth and hence residence time were found to improve capture of the gelatinous particles in the alum sludge and hence solids recovery.

4.5 Conclusions and Recommendations

Limited sludge dewatering tests were carried out in parallel with the UV and ozone disinfection pilot study. Based on the test results, we have the following conclusions and recommendations:

- There should be no major technical difficulty to dewater alum sludge to achieve the required 30% solids content.
- A solids recovery levels of higher than 95% are achieved at the appropriate polymer type, polymer dose and centrifuge operating conditions.

- The required sludge cake solids and centrate TSS levels were achievable at the feed rate of only 10 to 20% lower than those for dewatering ferric chloride sludge. The polymer dose of 5 kg/ton dry solids was found to be sufficient.
- The optimum feed rate and polymer dose levels should be ascertained with further testing.
- Because of the presence of gelatinous hydroxide particles in alum sludge, the sludge cake solids were found to decrease and solids recovery increase with decreasing differential speeds.
- Increasing pond depths of the centrifuge was found to improve solids capture and hence centrate clarity.

5. EVALUATION OF DISINFECTION ALTERNATIVES

5.1 Introduction

The purpose of this Section is to present the cost and nonmonetary comparison between the UV and ozone disinfection options for Siu Ho Wan, based on the updated basis established during the pilot plant study. Some of the materials were extracted from the previous Disinfection Option Review Paper for easy reference.

5.2 Development of Disinfection Options

5.2.1 UV Disinfection Equipment

Table 5.1 shows the preliminary design basis for the UV disinfection facility for option evaluation purposes. We recommend that alum should be used to reduce lamp requirements and the associated power and lamp replacement costs. As discussed in Section 4, there should be no major difficulty of dewatering alum sludge to achieve the required 30 solids content. For the option comparison purposes, a low design UV transmittance level of 20% was selected to estimate lamp requirements to allow flexibility of possibly using ferric chloride in the future. It will be clear in the subsequent discussions that the conservate assumption does not affect the relative costs of the UV and ozone options. The preliminary UV equipment requirements are shown in Table 5.2.

Figure 5.1 shows the flow schematic of the UV disinfection system. Figures 5.2 to 5.5 show the proposed location plan, preliminary layout plans and hydraulic profiles for the UV disinfection facility.

Table 5.1 Preliminary Design Basis of the UV Disinfection System

Parameter	Value	Units	Basis
Influent Characteristics			
Flow	180,000 (average) 3.75 (peak)	m^3/d m^3/s	From detailed design of CEPT plant
UV transmittance (unfiltered)	20 (minimum) 25 (average)	percent	Conservative. To allow the flexibility of using ferric chloride.
TSS	120 (maximum) 50 (average)	mg/l	Based on 95 percentile basis from the provisional licensing conditions
BOD	180 (maximum) 90 (average)	mg/l	Based on 95 percentile basis from the provisional licensing conditions
Effluent Bacterial Standard			
Effluent E. Coli	20,000 (monthly geometric mean) 300,000 (95%ile on annual basis)	counts/100 ml	
UV Dosage			
	30	mWs/cm^2	

Table 5.2 Design Basis for UV Facilities

Description	Value	Units
Lamp Type	Medium Pressure High Intensity	-
Number of Channels	4	no.
Channel Dimensions	22 (L) x 2.3 (W) x 3.81 (H)	m
Minimum Submergence	1.72	m
Number of Reactor per Channel	1	no.
Number of Banks per Reactor	2	no.
Number of Modules per Bank	13	no.
Number of Lamps per Module	10	no.
Total Number of Lamps	1040	no.
Maximum Power Consumption per Lamp	2.8	kW
Total Installed Power Requirement	2912	kW

5.2.2 Ozone Disinfection Equipment

Table 5.3 shows the preliminary design basis that was used to develop the ozone equipment sizing. A low ozone dose of 30 mg/L was selected for option comparison purposes in order to avoid extrapolation of the ozone equipment quotations by the suppliers. It can be seen subsequently that the use of the low ozone dose would not affect cost comparison between the two disinfection options. It should be noted that the design ozone dose levels should be 40mg/L, as discussed in Section 3.

Table 5.4 shows the preliminary sizing requirements of the ozone disinfection equipment. Figures 5.6 to 5.9 show the flow schematics of the ozone disinfection system. It is apparent that this system requires significantly more number of process units when compared with the UV disinfection system. Figures 5.10 to 5.15 show the location plan and preliminary layout of the proposed ozone disinfection facility. The layout plans are used as the basis to assess the civil costs and land requirements for the ozone disinfection facilities. Note the area for future expansion is shown for illustration purposes. Further refinement of the process units is needed to accommodate the required flows.

The hydraulic profile is shown in Figure 5.16. The total head requirements are expected to be about 1200 mm including the losses associated with the flow splitting in the influent channel.

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Table 5.3 – Preliminary Design Basis For Ozone Disinfection Facility

Parameter	Value	Units	Basis
Influent Characteristics			
Flow	180,000 (average) 3.75 (peak)	m^3/d m^3/s	From detailed design of CEPT plant
COD	360 (maximum) 180 (average)	mg/l	
BOD	180 (maximum) 90 (average)	mg/l	Based on 95 percentile basis from the provisional licensing conditions
TSS	120 (maximum) 60 (average)	mg/l	Based on 95 percentile basis from the provisional licensing conditions
Temperature	18 (minimum) 25 (annual average) 30 (maximum)	°C	
Effluent Bacterial Standard			
Effluent E. Coli	20,000 (monthly geometric mean) 300,000 (95%ile on annual basis)	counts/100 ml	
Ozone Dosage			
Applied ozone dose levels	30	mg/l	
Retention Time	15	minutes	

Table 5.4 Design Basis for Ozone Facilities at Design Dose of 30mg/L

Description	Basis	Units
Ozone Production		
Feed Gas	Oxygen	-
Number	3	no.
Capacity, each	135	kgO_3/h
Design Ozone Dose	30	mg/l
Cooling Method	Water	-
Oxygen Production		
Method	VPSA	-
Number	1	no.
Capacity, each	4,583	kg/h
Ozone Contacting		
Contact Chamber	2	streams
Transfer Method	Fine Bubble Diffusion	
Contact Time	15	min.
Off-zone Destruction	Thermal/Catalyst	-

5.3 Cost Comparison

5.3.1 Capital Costs

The capital costs of the disinfection facilities can be broken down into E&M and civil costs. The principal component of the E&M costs is the supply of the ozone and UV disinfection equipment. For ozone systems, the equipment package includes ozone generators, water cooling units, VaPSA systems, ozone destructors and fine bubble diffusers. The UV equipment package includes the enclosed reactors, lamp modules, lamp cleaning system, system controls and module removal mechanisms. These costs are estimated based on the budgetary estimates from the disinfection equipment suppliers.

The civil costs for the ozone disinfection facility include the construction costs for the ozone disinfection complex, the VaPSA building and the foundation for the liquid oxygen facilities. The ozone disinfection complex comprises the ozone contractors in the basement and oxygen generators and associated facilities on the top floor. The civil costs for the UV disinfection facility is the UV reactor chamber which comprises the inlet chamber, UV channels and outlet chamber.

Tables 5.5 and 5.6 show the comparative capital cost estimates for UV and ozone options. It should be noted that some common items such as effluent pumping stations, pipeworks, engineering and contingency sums were not included. Also, no standby disinfection facility was assumed. As summarised in Table 5.7, the capital costs of the ozone option were estimated to be 240 percent higher than those for UV option. Both the E&M and civil costs of the UV facility were found to be significantly lower than those for ozone facility.

Table 5.5 – Capital Cost Estimates for UV Facilities

Items Description	Amount (HK$)
(1) UV system including Lamp Modules System Controls Detection System Cleaning System Automatic Level Controller Module Removal Mechanism On-line UV Transmission Monitor Standard Spare Parts	$42,800,000
(2) Weir Gates	$960,000
(3) L.V. S/Bs and MCCs	$2,188,000
(4) E & M installation	$500,000
Subtotal:	$46,400,000
Preliminaries (20%)	$9,280,000
Total:	**$55,700,000**
Civil Cost Estimates	
1) UV channel	$3,930,000
2) Control room (100 m2)	$700,000
Subtotal:	**$4,600,000**
Preliminaries (20%)	$920,000
Total:	**$5,500,000**
Total Capital Costs	**$61,200,000**

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Table 5.6 - Capital Cost Estimates for Ozone Facilities at 30mg/l Design Dose

Items Description	Amount (HK$)
E&M Cost Estimates	
(1) Ozone System including	$84,000,000
1 unit VPSA	
1 unit Compressor for VPSA	
1 unit Control Cabinet for VPSA	
3 units ozone generators operating at 9% concentration and producing each 135 kgO3/h with cooling water at 10°C	
1 set porous plate diffusers	
3 units cooling water pumps for ozone generators	
2 units dryers and filters	
2 units ozone destructors	
2 units heat exchangers	
1 set valves, pipes and cables and accessories	
1 set Ozone plant control and monitoring	
1 set on line instruments	
(2) Other main components	
Penstocks	$600,000
Crane	$600,000
Access doors to contact chamber	$2,000,000
(3) L.V. S/Bs and MCCs	$3,200,000
(4) E & M installation	$2,500,000
(5) Building services and fire service	$1,000,000
Subtotal:	$93,900,000
Preliminaries (20%)	$18,780,000
Total:	**$112,700,000**
Civil Cost Estimates	
(1) Ozone building	$26,600,000
(2) VPSA building	$2,800,000
(3) Concrete base for LOX facility	$391,000
Subtotal:	$29,800,000
Preliminaries (20%)	$5,960,000
Total:	**$35,800,000**
Total Capital Costs	**$148,500,000**

Table 5.7 – Comparative Capital Costs

Disinfection Method	Comparative Capital Costs (2) $ million
UV	61.2
Ozone	148.5

Notes: 1. Effluent pumping stations and associated pipeworks not included.
2. Engineering fees and contingency sums not included.

5.3.2 O&M Costs

The O&M costs for the UV disinfection facility can be broken down into power, parts replacement and labour costs for routine inspection and maintenance. The parts replacement costs can be further divided into lamps, ballast and quartz sleeves. The O&M costs for the ozone disinfection can also be broken down into power, cooling water, equipment maintenance and labour for inspection and maintenance. The power costs include those required for the ozone generators, off gas ozone destruction units, VaPSA (air blowers and oxygen booster compressors) and miscellaneous uses.

Tables 5.8 and 5.9 show the O&M cost estimates for UV and ozone options. A key parameter that highly affects the O&M costs of both options is unit power charges. A current electricity bill was analysed and the average power charges were calculated to be $0.8 per kWh. The power charges included electricity charges, demand charges and rebates etc. In estimating lamp replacement costs, allowance was made to include the possible additional expenses associated with lamp recycling, as discussed in the Section 5.4.

As summarised in Table 5.10, the annual O&M costs of the ozone option were estimated to be 240 percent higher than the UV option. It should be noted that the ozone facility was found to require higher power and hence incur higher power costs.

Table 5.8 - O&M Cost Estimates for UV Facilities

Items Description	Amount (HK$)
Power Costs	
Estimated System Utilization (1)	42%
Power Consumption (W/lamp)	2,800
No. of duty lamps	1,040
Unit Energy Charges/kWh	$0.80
Average Power Consumption, kW	1,223
Annual Energy Charges:	**$8,600,000**
Lamp Replacement	
Lamp Life, hours	3,000
Unit Lamp Cost[3]	$2,100
Annual Lamp Costs :	**$2,700,000**
Ballast Replacement	
Ballast Life, year	10
Unit Ballast Costs	$4,300
Annual Ballast Costs:	**$224,000**
Quartz Sleeve Replacement	
Quartz Life,year	10
Unit Quartz Costs	$1,600
Annual Quartz Costs:	**$166,000**
Labour Costs (2)	
Labour Effort, hours	2000
Hourly Rate	$100
Annual Labour Costs: **Subtotal:**	**$200,000**
Total:	**$11,900,000**

Notes: (1) Based on lamp control using both flow and UV transmittance signals.
(2) Assumed one worker working full-time.
(3) included the additional cost for the waste mercury lamp recycle/repair plan

Table 5.9 - O&M Cost Estimates for Ozone Facilities at 30 mg/l Design Dose

Items Description	Amount (HK$)
Power Costs	
Average Power Consumption, kW	3,375
Unit Energy Charges/kWh	$0.80
Annual Energy Charges: **Subtotal:**	$23,700,000
Parts Replacement (1.5% of equip. cost) Subtotal: (1)	$1,300,000
Labour Costs (1)	$1,800,000
Water Consumption Costs for Cooling	
Water Consumption, m3/d	8,100
Unit Water Consumption / m3	$0.60
Annual Water Consumption: **Subtotal:**	$1,800,000
Total:	**$28,600,000**

Note: 1. Based on estimates for ozone equipment supplier.

Table 5.10 - O&M Cost Comparison

Disinfection Method	**O&M Costs** **$ million**
UV	11.9
Ozone	28.6

5.3.3 Life-Cycle Costs

Life-cycle cost analysis are undertaken for the two options. The results of the analysis are shown in Table 5.11. The analyses are carried out based on a 15-year life cycle and an average interest rate of 4 percent.

Table 5.11 - Life-cycle Cost Analysis

Disinfection Method	**Total Life-Cost Costs** **$ million**
UV	157.3
Ozone	379.5
Notes: Based on 15-year life cycle and 4 percent interest rate.	

The UV disinfection option was found to be significantly more economical than the ozone option, in terms of life-cycle costs. When compared with the UV disinfection facility, the total life cycle costs of the ozone facilities were estimated to be more than 240 percent higher. The significant difference in costs is attributable to the significantly higher capital and O&M costs associated with the ozone option.

5.4 Nonmonetary Considerations

A detailed comparison of the two disinfection options based on nonmonetary considerations was presented in the Disinfection Option Review Paper. The factors included land requirement, schedule implications, environmental impact and safety. As summarized in Table 5.12, the UV option was considered to be more favourable in terms of nonmonetary considerations. Further discussions on the environmental impacts due to the two options are presented in the next subsections.

Table 5.12 Nonmonetary Considerations

	UV Option	**Ozone Option**
Land Requirements	Small	Large
Schedule Implications	Shorter	Longer
Environmental Impact	Pros: No toxic residual and harmful byproducts Cons: Disposal of spent UV lamps.	Pros: Increase D.O. and possibly reduce COD Cons: Toxic residuals and harmful byproducts
Safety	Low Safety Con	Similar

5.4.1 Disposal of Spent UV Lamps

A recent concern of adopting UV disinfection for Siu Ho Wan is the potential environmental impact associated with disposal of spent UV lamps. High intensity UV lamps have a design of 3000 to 9000 hours and the spent lamps will need to be disposed of. These lamps contain small amount of mercury inside their quartz sleeves. Mercury vapor and some mercury compounds are toxic and may bring about acute and chronic adverse health effects to human and animals. Exposure to mercury may occur in both occupational, i.e to landfill operators and environmental settings.

It needs to be recognized that the lamp disposal issue, if it is a problem, is much greater one for the millions of lamps that are used in office and apartment buildings. Fluorescent lamps used for lighting are mercury lamps of essentially the same design as used for germicidal application. A 40W florescent lamp contains about 50 mg of mercury while the low pressure and medium pressure high intensity lamps contain 100 and 165 mg of mercury, respectively. It is worthwhile to note that the mercury exists in liquid form, when disposed and is not hazardous because the element if ingested is poorly absorbed by the gastrointestinal tract.

Disposal of chemical wastes containing mercury and mercury compounds is regulated under the Waste Disposal Ordinance and Waste Disposal (Chemical Waste) (General) Regulation. The Waste Disposal Ordinance, enacted in 1980, along with its subsidiary regulations are the principal legislation for waste management in Hong Kong. They provide a comprehensive framework for the management of waste from the point of arising to the point of final disposal. In 1991, an amendment was made and the Waste Disposal (Chemical Waste)(General) Regulation was introduced. This regulation provides for control of chemical waste with respect to packaging, labelling, storage, collection, disposal, import and export activities. Another amendment was made in 1995 and Waste Disposal (Permits and Licences)(Forms and Fees) Regulation was introduced. This regulation introduces a permit system to control import and export of hazardous and other wastes in accordance with the requirements set out under the Basel Convention.

Under the Waste Disposal (Chemical Waste)(General) Regulation, any person produces chemical waste or causes it to be produced should register with the Environmental Protection Department as a chemical waste producer. A chemical waste producer must engage a licensed waste collector to collect the chemical waste for proper disposal. Chemical waste producers are also required to comply with the requirements of the Regulation on packaging, labelling, storage and filling out of trip tickets. Chemical waste generated from domestic source is not subject to control of this Regulation.

Currently, there is no specific requirement regarding the disposal of spent UV lamps from the existing STWs. The spent UV lamps are disposed by the STW operation staff with other domestic wastes into sanitary landfill. The total numbers of UV lamps that have been disposal are relatively small and generally in small batches. The details of the disinfection facilities in these existing STWs are shown in Table 5.13.

Table 5.13 – Existing UV Disinfection Systems in Hong Kong

STW	No. of Lamps	Lamp Types	Peak Flows	Approximate Replacement Frequency at design year
Sai Kung	264	Low pressure low intensity	24,000	Once very one to 1.5 years
Mui Wo	48	Low pressure low intensity	3,600	Once very one to 1.5 years
Sha Kau Kok	56	Low pressure low intensity	5,000	Once every one to 1.5 years
Shek Wu Hui	520	Medium pressure high intensity	240,000	Once every six to nine months

Notes: Estimated based on guaranteed lamp life of 9000 and 3000 hours and optimum system utilization.

Based on the results of the pilot tests, UV lamp requirements are estimated to be 720 at Siu Ho Wan for a design flow of 180,000 m3/d. It was calculated that an average of 73 lamps need to be disposed per month at design year. When the Siu Ho Wan STW upgrade is commissioned, the actual flow is expected to be about 30 to 40 percent of the design flowrate. The number of lamps to be disposed is calculated to be only 29 per month during initial years. Therefore, the environmental impact due to the relatively small number of spent UV lamps should not be a major concern when the spent lamps are packaged properly before transporting to landfill sites. A detailed handling procedures should be set up to minimize the possible impact onto the landfill operators and the environment.

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Discussions have been made with an UV disinfection equipment supplier regarding the feasibility of a lamp recycle/repair scheme to eliminate possible disposal problems. The scheme included the following operation:

- Collect the faulty lamps from site and pack up for shipment to the factory in Canada via sea freight
- Lamps will be repaired/disposed in their Territory
- Return of a batch of 25 UV lamps to Hong Kong via sea freight
- Provision of the new/operable lamp to the customer

The package price for a batch of 25 lamps was estimated to be $2,100 per lamp, including lamp collection and delivery. The extra costs are calculated to be $700 per lamp. The scheme is currently being investigated further by the supplier to ensure that there are no issues such as customs clearing etc. that may arise in terms of logistics of carrying out this operation.

In summary, the environmental impact due to the disposal of the spent UV lamps is not expected to be a major concern because of the relatively small number of lamps. However, a lamp repair/recycle scheme has been found to be feasible, which will eliminate possible disposal problems. The use of UV disinfection is not expected to cause any adverse environmental impacts and the incorporation of the disinfection process into the design is not considered as a material change to the original EIA Study under Section ((4) of the Environmental Impact Assessment Ordinance.

5.4.2 Water Quality Impact Due To Ozonation

A key concern with ozone is that it may cause an adverse water quality impact due to possible toxic residuals and harmful byproducts. During the pilot study, elevated levels of bromoform were found in the effluent after ozonation. The effluent bromoform levels were found to be 45 and 170 μg/l for CEPT effluent with alum and ferric chloride, respectively. The presence of bromoform is not unexpected because it is commonly found when the ozone is added to wastewater of high levels in bromides. The bromide levels in the wastewater in Hong Kong are generally high because of the use of seawater for flushing. Oxidation of the bromide ion produces bromine ($HOBr/OBr^-$), which reacts with organic precursors to form bromoform and possibly other trihalomethanes (THMs).

The four trihalomethanes (THM's) are listed as below:

Trichloromethane(chloroform)	$CHCl_3$
Dibromochloromethane	$CHClBr_2$)
Bromodichloromethane	$CHCl_2Br$
Tribromomethane (bromoform)	$CHBr_3$

They are Cancer Group B carcinogens (shown to cause cancer in laboratory animals) according to the U.S. EPA guidelines. Dibromochloromethane is the most serious cancer risk, (0.6 ug/l to cause a 10^{-6} cancer risk increase) followed in order by Bromoform (4 ug/l), and Chloroform (6 ug/l). Current US and European regulations limit the concentration of these 4 chemicals added together (total trihalomethane or TTHM levels) to 100 µg/l.

Another probable disinfection byproducts from ozonation is bromate. It is a newly regulated DBP and is a concern only for systems using ozone. A maximum contaminant level of 10 ug/l is expected. Excessive levels causes gastrointestinal, kidney, and hearing effects. It is formed when ozone is applied to water sources containing bromide ion (Br^-). This results in Br^- oxidation to first hypobromite ion (OBr^-) and eventually bromate ion (BrO_3^-).

It should be noted that these compounds are mainly regulated for drinking water potentially purposes. There are at present no standards in Hong Kong governing the discharge of these harmful compounds to North Western Water Control Zone. Nevertheless, it seems prudent to avoid it and whenever practical, in order to follow the precautionary principle which is the fundamental basis for constructing the disinfection facilities a Siu Ho Wan STW

5.5 Summary

A detailed cost comparison was undertaken for the two disinfection options, using the design basis established during the pilot plant study. Capital, O&M and life-cycle costs were estimated, after preliminary equipment sizing and layout plans for the two options were developed. The UV disinfection option was found to be significantly more economical than the ozone option, in terms of capital, O&M and life-cycle costs. Both the capital and O&M costs of ozone options were estimated to be more than 240% higher than those of UV options.

The two options were also compared based on nonmonetary considerations. The UV option was considered more favourable in terms of land requirements, schedule implications, environmental and safety. A recent concern of using UV disinfection is the disposal of spent UV lamps, which contain small amount of mercury. The concern is not considered to be major because of the small lamp quantity and can be mitigated by adopting a waste lamp recycle/repair plan, if considered necessary. The annual cost implications have been included in the cost comparison. One key concern with ozone is that it may cause an adverse water quality impact due to possible toxic residuals and harmful byproducts. Elevated levels of bromoform were found in the effluent after ozonation. It seems prudent to avoid it, whenever practical, in order to follow the precautionary principle, which is the fundamental basis for constructing the disinfection facilities at Siu Ho Wan STW.

6. CONCLUSIONS

A comprehensive disinfection pilot plant study was carried out for the Siu Ho Wan Sewage Treatment Works (STW) Upgrade. The study included detailed testing of both UV radiation and ozonation to assess their feasibility to disinfect CEPT effluent to meet the discharge standards and to obtain site specific data for option selection.

The pilot plant study took place from August to October 1999 at Stonecutters Island STW. A total of more than 700 sets of effluent and influent samples were collected for E.Coli and other water quality analyses. In parallel, limited sludge dewatering tests were conducted to assess the feasibility of dewatering alum sludge using centrifuges.

Both UV and ozone disinfection were found to be feasible in disinfecting CEPT effluent to the required E.Coli standards. The design UV and ozone dose requirements for the full-scale facilities are selected to be 30 mWs/cm^2 and 40 mg/L respectively.

Detailed cost comparison showed that UV option was significantly more economical than the ozone option, in terms of capital, O&M and life-cycle costs. UV option was also found to be more favourable when considering nonmonetary factors including land requirements, schedule implications, environmental impact and safety.

Based on both cost and nonmonetary considerations, we recommend that UV radiation should be adopted as the disinfection method for the Siu Ho Wan STW upgrade.

Our conclusions and recommendations in the individual pilot plant tests are summarized as follows:

UV Pilot Study

- The UV pilot test showed that the required E.Coli standards are achieved at practical dose levels. An UV dose levels less than 30 mWs/cm^2 was found to be sufficient to achieve the E.Coli standards of 20,000 counts/100mL over a wide range of influent conditions

- The collected pilot study data were found to fit well a mathematical model developed at the University of California at Davis. The disinfection model indicated that an UV dose of about 15 mWs/cm^2 should be sufficient to meet the required E.Coli standards. An UV dose of 30 mWs/cm^2 was considered to be the most appropriate to ensure stable disinfection performance and selected as the basis for the design of the full-scale facilities.

- The fouling rate was found to be acceptable. Based on this study, the fouling rate for the ferric chloride-treated effluent would be approximately four hours. In the event that alum is used as the coagulant at Siu Ho Wan, the fouling rate would be approximately twelve hours based on this study. The expected fouling rate and required frequency of cleaning should be acceptable using the UV systems with automatic wipers.

- There were no apparent increases in harmful disinfection byproducts for UV dose levels up to 3 times of the design dose.

- The limited photoreactivation tests showed that there was a maximum 0.49log increase due to photoreactivation at the surface of the harbour under laboratory conditions. This effect should be well offset by the natural dieoff under field conditions.

- The headloss across the UV reactor was found to be acceptable under peak flow conditions.

Ozone Pilot Study

- The ozone pilot tests showed that the required E.Coli standards were achieved at elevated ozone dose levels.

- An ozone dose level of about 35 mg/L was necessary to ensure that the required E. Coli standards of 20,000 counts/100 mL were achieved at all times, based on the collected data.

- The required ozone dose levels were also found to increase with increasing TSS levels.

- At simulated design influent conditions, a minimum ozone dose levels of 33 and 40 mg/L were needed to achieve the required E.Coli standards on average and at all times, respectively. A design dose level of at least 40 mg/L should be used in the design of the full-scale facility.

- Disinfection byproduct tests were conducted for both ferric chloride and alum-treated effluent at a dose level of 37.5 mg/L. Elevated levels of bromoform, bromodichoriomethane and chlordibromomethane were found in the effluent samples. They are carcinogens. The effluent bromoform levels were found to be 45 and 170 μg/l for CEPT effluent with alum and ferric chloride, respectively.

- The residual ozone levels were generally low but elevated levels from 0.11 to 0.21 mg/L might also be encountered at high ozone levels.

- There appeared to be no significant changes in BOD and COD levels due to ozonation.

Sludge Dewatering Tests

- There should be no significant technical difficulty to dewater alum sludge to achieve the required 30% solids content.

- The required sludge cake solids and centrate TSS levels were achievable at the feed rate of only 10 to 20% lower than those for dewatering ferric chloride sludge. The polymer dose of 5 kg/ton dry solids were found to be sufficient.

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- The optimum feed rate and polymer dose levels should be ascertained with further testing.

- Because of the presence of gelatinous hydroxide particles in alum sludge, the sludge cake solids were found to decrease and solids recovery increase with decreasing differential speeds.

- Increasing pond depths of the centrifuge was found to improve solids capture and hence centrate clarity.

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