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Research Summary

CSO Disinfection Pilot Study: Spring Creek CSO Storage Facility Upgrade

by

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Notice

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Foreword

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Lee A. Mulkey, Acting Director
National Risk Management Research Laboratory

Abstract

This Research Summary presents the results of a pilot-scale disinfection study performed for the New York City Department of Environmental Protection and the U.S. Environmental Protection Agency (US EPA) under a contract No. 7C-R394-NTLX to Camp Dresser & McKee of Woodbury, New York. The main objective of the pilot study was to demonstrate alternatives to hypochlorite disinfection for application to the Spring Creek facility and potentially to other combined sewer overflow (CSO) facilities. The pilot testing was divided into two phases. Phase I was performed from December 1996 through March 1997, and Phase II was performed from August through November 1999. US EPA provided technical assistance to the entire study. Phase I evaluated treatment performance of five technologies: ultraviolet (UV) irradiation; ozonation (O_3); chlorine dioxide (ClO_2) disinfection; chlorination/dechlorination (Cl_2/deCl_2); and electron beam irradiation (E-Beam). The fifth technology, E-Beam was evaluated during supplemental Phase I pilot testing sponsored by the New York Power Authority and the Electric Power Research Institute. Based on the results from Phase I, Phase II provided additional evaluation of technologies that had shown potential for CSO applications. These were UV, ClO_2, and Cl_2/deCl_2. This Research Summary concentrates on these three technologies, but the overall results of both phases for each technology along with the cost are also discussed.

Generally, all tested disinfection technologies, with the exception of E-beam, were able to achieve targeted bacterial reductions of 3 to 4 logs. Chlorination/dechlorination, ClO_2, and O_3 at the doses tested were able to provide these levels of disinfection over the full range of wastewater quality tested. To date, ozonation was not found to be cost effective for CSO applications. While ClO_2 was superior in effectiveness and similar in cost to Cl_2/deCl_2, the generation technology for ClO_2 which avoids the need for gaseous Cl_2 needs further development. Because an effective Cl_2-gas-free process of ClO_2 generation has not been proven to be reliable and, because Cl_2 gas cannot be transported within New York City, disinfection with ClO_2 cannot be recommended for use within New York City at this time.

The Spring Creek facility upgrade construction was scheduled for the Fall of 2002. The upgraded Spring Creek facility will continue to use sodium hypochlorite for disinfection, with provisions to add dechlorination at a later date. Improvements will be made to increase disinfectant flash mixing and to automate hypochlorite feed and residual control. While the decision to continue the use of hypochlorination for the upgraded facility was based upon the Phase I study, it is recognized that the overall pilot results (Phases I and II) will be used to guide decisions at other CSO facilities.

CONTENTS

List of Acronyms

AOC - assimilable organic compounds
APWA - American Public Works Association
BMP - best management practice
BOD - biochemical oxygen demand
BOD_5 - five-day biochemical oxygen demand
Cl^- - chloride
Cl_2 - chlorine
ClO_2 - chlorine dioxide
ClO_2^- - chlorite
ClO_3^- - chlorate
COD - chemical oxygen demand
deCl_2 - dechlorination
DNA - deoxyribonucleic acid
DO - dissolved oxygen
$NaClO_2$ - sodium chlorite
NPDES - National Pollutant Discharge Elimination System
NRMRL - National Risk Management Research Laboratory
NYCDEP - New York City Department of Environmental Protection
O_2 - oxygen
O_3 - ozone
ORD - Office of Research and Development
PAH - polycyclic aromatic hydrocarbon
POTW - Publically Owned Treatment Works
SS - suspended solids
SSO - sanitary sewer overflow
SW - stormwater
TCOD - total COD
THM - trihalomethane
US EPA - United States Environmental Protection Agency
UV - ultraviolet
UWMB - Urban Watershed Management Branch
WSWRD - Water Supply and Water Resources Division
WWF - wet weather flow
WWTP - wastewater treatment plant

Acknowledgments

Camp Dresser & McKee (CDM) of Woodbury, NY, was contracted by the New York City Department of Environmental Protection (NYCDEP) to provide engineering design services for the upgrade to the Spring Creek CSO Storage Facility. This Research Summary is based on the original study reports prepared by CDM and CDM's subcontractor, Moffa & Associates (currently Brown & Caldwell) of Syracuse, NY (CDM, 1997 and 1999).

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Technical review was provided by Shirley E. Clark, Ph.D., P.E. Assistant Professor, School of Science, Engineering and Technology, Penn State, Harrisburg, PA.

Editorial review was provided by Laura Panos of the Environmental Careers Organization.

1. INTRODUCTION

Camp Dresser & McKee (CDM) of Woodbury, NY, was contracted by the New York City Department of Environmental Protection (NYCDEP) to provide engineering design services for the upgrade to the Spring Creek CSO Storage Facility. These services included a pilot study to evaluate the following disinfection technologies for treatment of combined sewer overflows (CSOs): ultraviolet (UV) irradiation; ozonation (O_3); chlorine dioxide (ClO_2) disinfection; chlorination/dechlorination (Cl_2/$deCl_2$); and electron beam irradiation (E-Beam). The pilot testing was divided into two phases. Phase I, from December 1996 through March 1997, evaluated performance of all five technologies listed above. The E-Beam was evaluated during supplemental Phase I pilot testing sponsored by the New York Power Authority (NYPA) and the Electric Power Research Institute. The E-Beam technology did not appear to be feasible for CSO disinfection, thus, the study results for this technology are not being discussed in this Summary. Phase II of the pilot testing, from August through November 1999, evaluated technologies which had been found promising for CSO disinfection during the first phase. Thus, Phase II further investigated UV, ClO_2, and Cl_2/$deCl_2$ under additional wet-weather conditions. This Research Summary is based on the original study reports prepared by CDM and CDM's subcontractor, Moffa & Associates (currently Brown & Caldwell) of Syracuse, NY (CDM, 1997 and 1999). Because the original reports were prepared for internal use and were made not readily available to the Public, the authors believe that this summary will provide means to distribute the information to the Public.

Chlorine has traditionally been used to provide disinfection due to its low cost. Since the 1970s, growing awareness of the adverse environmental impacts associated with the byproducts of chlorination has led to increasingly restrictive residual Cl_2 requirements. While the current State Pollution Discharge Elimination System permit for Spring Creek allows a maximum total residual Cl_2 effluent limit of 2.0 mg/L, it is expected that more restrictive effluent limits, consistent with the water quality standard, will be required in the future. As a result of the impending restriction on the Total Residual Chlorine (TRC) in the effluent, dechlorination ($deCl_2$) was considered for disinfection of CSO at the Spring Creek and at other CSO facilities. In addition, a need to minimize environmental risks, chemical demands, and contact times that are required using conventional Cl_2/$deCl_2$ has fostered a strong interest in alternative disinfection technologies for CSO. However, there is minimal data available on the effectiveness of alternative disinfectants for the treatment of CSO. This pilot study was conducted to provide the needed performance data on the alternative disinfection technologies for their possible future use at the Spring Creek or elsewhere.

2. DESIGN AND OPERATION OF THE PILOT STUDY

As mentioned previously, the objectives of the pilot study were to provide: (1) a basis for selection of a disinfection technology for use at the Spring Creek CSO Storage Facility, (2) full-scale design criteria for application at the Spring Creek CSO Storage Facility; and (3) treatment performance data to guide selection of disinfection technologies for other CSO facilities. The location for both phases of the pilot study was a designated area at the 26th Ward Wastewater

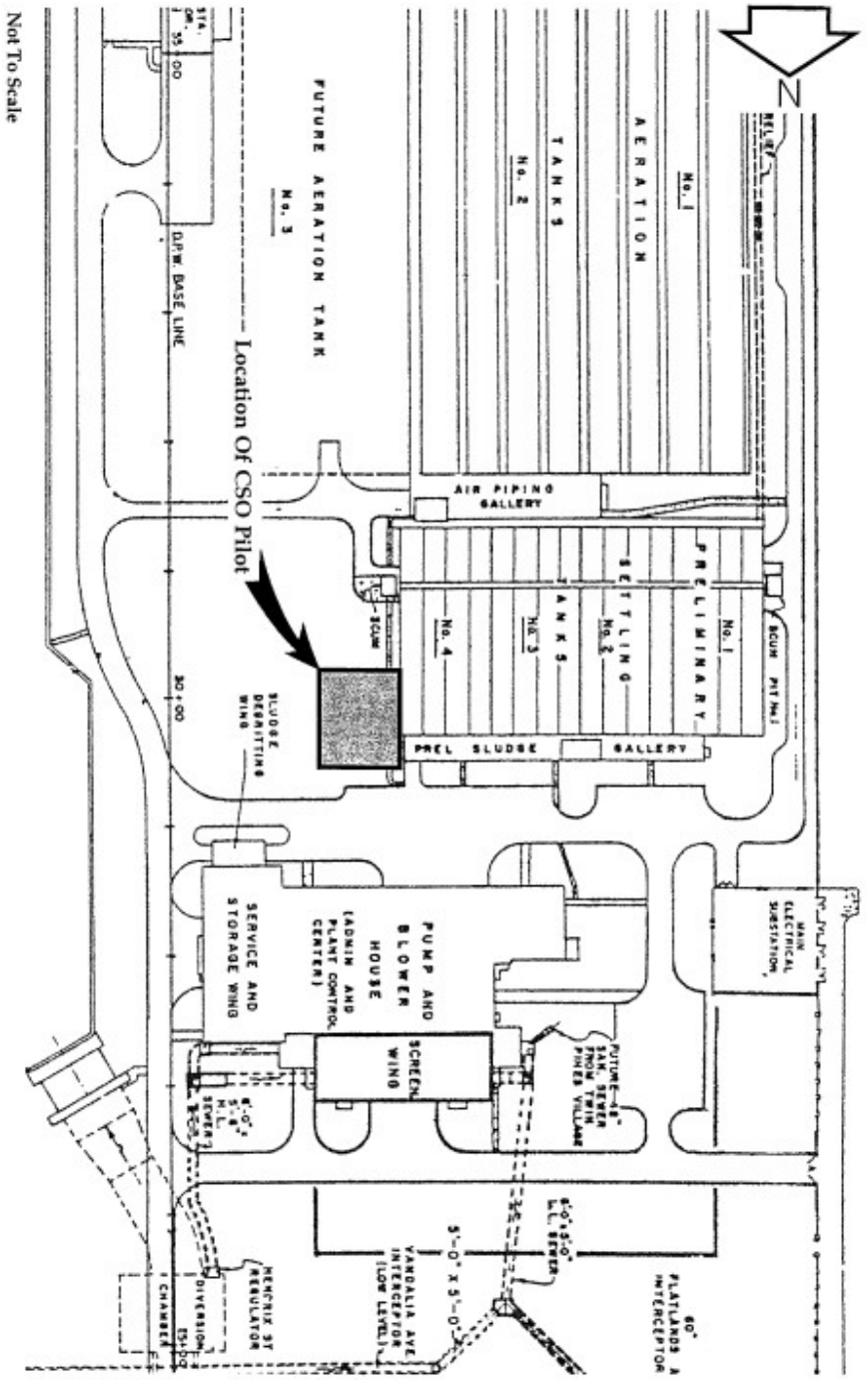
Pollution Control Plant (WPCP) rather than the CSO Storage Facility due to space and logistical constraints. In addition, the 26th Ward site was able to provide a continuous supply of wastewater regardless of weather conditions and the 26th Ward primary effluent was representative of the range of wastewater quality found in the effluent from the Spring Creek CSO Storage Facility (CDM, 1997). However, it is important to indicate that the characteristics of wastewater in Phase I and Phase II were not the same. Figure 1 presents the schematic of the CSO Pilot location.

Operation of the Phase I pilot units occurred over the period of December 17, 1996 to March 26, 1997. The 16 main test runs included a combination of 4 actual wet-weather and 12 simulated wet-weather events. During Phase I, the UV, O_3, ClO_2, and Cl_2/deCl_2 pilots were operated in parallel for a total of 16 test runs. Testing of the units in parallel allowed comparison of disinfection efficiency of each technology on wastewater of identical quality. During testing, the operating conditions of each pilot unit were held constant over the duration of the test run. Flowrates, detention times, disinfectant dose, and mixing conditions were varied between test runs. The purpose of these test runs was to evaluate the performance of each technology over a range of operating conditions and over a range of wastewater quality typical of CSOs. Wastewater flow to the pilot facility was supplied from the primary settling tank effluent channel. Each pilot unit received flow from the common header. The flowrate to each pilot unit was manually controlled using in-line magnetic flowmeters and throttling valves. Treated pilot effluent was discharged directly into the 26th Ward plant recycle line through an existing manhole adjacent to the pilot facility. Figure 2 presents the pilot system flow schematic. Each pilot system was subjected to the same wastewater, in order to compare the performance of each pilot system directly against the other.

Operation of the Phase II pilot units occurred over the period of August 25, 1999 to October 21, 1999. The same pilot location and source wastewater were used as in Phase I. During Phase II, the UV, ClO_2, and Cl_2/deCl_2 pilots were operated in parallel over eight test events. Although these technologies had been investigated in Phases I and II, the tested units were from different manufacturers. The operating conditions of each pilot unit were held constant over the duration of the test run. Flowrates, detention times, disinfectant dose, and mixing conditions were varied between test runs. Phase II pilot study supplemented the Phase I results and performed additional research on the selected three technologies. The Phase II data was compiled with the Phase I data to evaluate the treatment performance over the full range of wastewater quality experienced. Ultimately, the Phase I and Phase II results were used to make recommendations and develop design criteria for full-scale CSO disinfection in New York City. This Research Summary concentrates on discussion of these results.

In Phase II, the three pilot units were located side-by-side for concurrent operation alongside primary settling tank no. 4. This location provided a constant supply of wastewater and ready access to the primary settling tank effluent channel. The three pilot technologies were tested at various dosages, contact times and flowrates over a large range of wastewater

Figure 1. CSO pilot location at the 26th Ward WPCP.



conditions. Eight test runs were performed; four during wet-weather conditions and four during dry-weather conditions. The target dosages were designed to develop an appropriate dose-response relationship for each technology and to supplement the Phase I results. As the analytical results from prior test runs were received, the dosages and operating conditions for subsequent test runs were adjusted and modified to achieve the desired range of bacteria kills. The actual chemical dosages and pilot unit operating conditions used during Phase II are provided in Table 1. This table illustrates the flowrate, disinfection dose and detention times which were provided for each event and for each individual pilot unit.

The objectives of the entire study were limited to the relative comparison of alternative disinfection technologies and the evaluation of basic design parameters (e.g., dose, mixing configuration, contact time) for application to CSO. Optimization of other detailed design parameters and simulation of full-scale process configurations for use at the Spring Creek facility were beyond the scope of this effort. Additionally, the small size of the pilot units as compared to actual CSO flowrates, did not lend the pilot results to the determination of factors such as full-scale operational complexity and safety concerns, system constructability and size/ structural constraints, and technology cost effectiveness. This information can be determined from available full-scale facilities, but it was not within the scope of this study to do so.

3. PILOT INVESTIGATIONS

During the test runs, the pilot facilities were allowed to reach steady state conditions for a minimum of 30-min prior to initiating sampling. The UV unit was first started up on potable water in order to get an initial relative UV intensity reading on clean water. After the establishment of wastewater flow to the pilot facility, typical startup would proceed as follows: (1) balance wastewater flow to the individual pilot units, (2) restart the UV unit on wastewater, (3) startup of the Cl_2/deCl_2 and ClO_2 mixers, (4) startup and set the hypochlorite and bisulfite feed pumps to the desired dose, and finally (5) startup and set either the ClO_2 gas or liquid feed to the desired dose. Following this last step, at least 30 min were allowed to pass before beginning sampling. During each test run, samples of the common pilot influent and the treated pilot effluents were collected at various frequencies over the 2-h sampling period. In addition to offsite laboratory analyses, field monitoring of pH, temperature, dissolved oxygen (DO), oxidation/reduction potential probe (ORP), Cl_2 and ClO_2 residual were performed. Process monitoring and control parameters are summarized in Table 2.

4. PROCESSES INVESTIGATED

4.1 UV Light Disinfection

UV disinfection is accomplished by electromagnetic radiation at specific wavelengths ranging from 100 to 400 nanometers (nm) with optimum disinfection at 253.7 nm. UV radiation

Figure 2. The pilot system flow schematic**.**

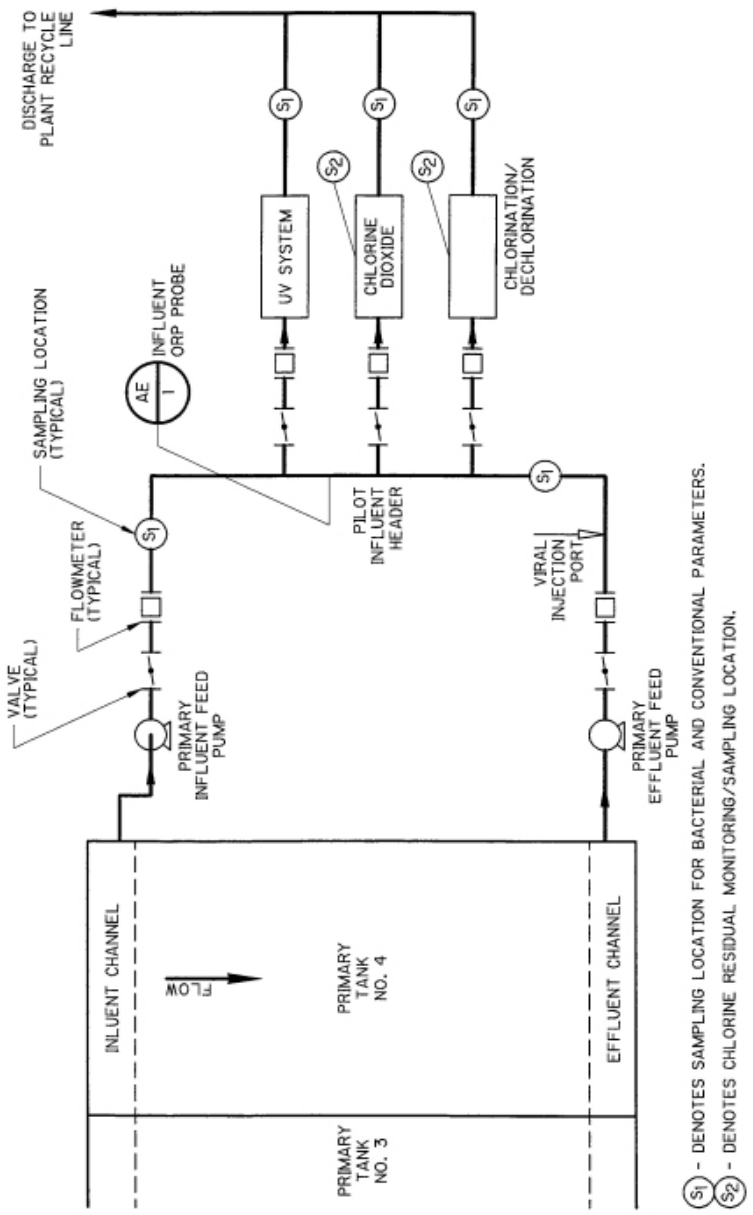


Table 1. Summary of pilot unit operating conditions during Phase II.

Alternative	*Date*	DRY-WEATHER EVENTS				WET-WEATHER EVENTS			
		Run #1	*Run #4*	*Run #7*	*Run #8*	*Run #2*	*Run #3*	*Run #5*	*Run #6*
		Viral #1	*Viral #2*	*Viral #3*	*Viral #4*				
UV	Flowrate	140	113	140	58	113	77	58	77
	Lamp Power	1	3	1	3	3	3	3	3
	UV Loading	3.6	7.1	3.6	13.8	7.1	10.4	13.8	10.4
	Average UV	32.3	36.8	35.8	37.0	33.9	27.4	36.1	25.5
	Absorbed	46.2	88.6	50.1	172.6	83.5	105.0	169.3	100.0
ClO_2	Flowrate	32	32	32	32	32	32	32	32
	Concentration	8	6	10	8	6	8	6.5	10
	Generator	CDG	UVD	UVD,	CDG	UVD	UVD	UVD	UVD
	Mixing	1 stage	2 stage	1 stage	1 stage	1 stage	2 stage	2 stage	2 stage
Cl_2/deCl_2	Flowrate	32	32	32	32	32	32	32	32
	Chlorine	18	20	24	28	20	24	28	18
	Mixing	1 stage	2 stage	1 stage	2 stage	1 stage	2 stage	1 stage	2 stage

Note:
1. Power levels 1, 2 and 3 provide lamp power outputs of 125, 160, and 200 watts UV-C per lamp, respectively.
2. Absorbed UV dose calculated using UV manufacturer's empirical equation.
3. UVD Generator used during the first hour of sampling, while the CDG Generator was used during second hour.

Table 2. Process Monitoring and Control Parameters.

Process Monitoring	Control Parameters
Influent Wastewater	Temperature
	pH
	Available Plant Wastewater Quality/Flow Data
UV Pilot Disinfection System	Wastewater Flowrate Through Pilot
	UV Dose
Chlorine Dioxide Pilot Disinfection System	Wastewater Flowrate Through Pilot
	Chlorine Dioxide Purity
	Chlorine Dioxide Dose
Chlorination/deChlorination Pilot	Wastewater Flowrate Through Pilot
	Sodium Hypochlorite Feed Concentration
	Sodium Hypochlorite Dose
	Sodium Bisulfite Dose
Ozone Pilot Disinfection System	Ozone Dose
	Wastewater Flowrate Through Pilot
E-Beam Pilot Disinfection System	Beam Current
	Wastewater Flowrate Through Pilot
	Temperature Changes
	Absorbed Dose

is the most common electromagnetic radiation technique used for disinfection. It is a physical process offering short detention times (5 to 7 sec). UV disinfection does not produce residuals or byproducts that are known to produce risk to humans or aquatic systems. Some concerns have been raised regarding the development of organism mutations, but no conclusive data exists. UV technology works on the principle that all microorganisms that contain nucleic acids are susceptible to damage through the absorption of radiation in the UV energy range. The extent of damage, mutation, or death will depend upon the organism's resistance to radiation penetration. UV disinfection is well demonstrated for water and wastewater treatment.

UV Pilot Equipment The UV pilot disinfection system was provided by Aquionics, Inc., of Erlanger, Kentucky, the same unit used during both phases. This skid mounted unit was manufactured by Berson Milieutechniek of Nuenen, Holland. The unit was a medium pressure, high intensity UV unit. The unit was housed inside a trailer to provide a barrier to climatic condition. A process flow diagram of the UV pilot unit is provided in Figure 3.

The stainless steel reaction chamber was fitted with four high intensity mercury vapor lamps which were mounted for protection inside four quartz sleeves. Wastewater flowed through the unit in a horizontal, parallel-flow configuration. A quartz window was provided on the
chamber wall through which UV intensity was monitored by a UV sensor. The bulbs were fitted

with a mechanical wiper type automatic cleaning mechanism, mounted on a worm gear drive. The wiper removed deposits of materials from both the quartz sleeves and quartz window. The wiping frequency was set to once every 10 min throughout the pilot testing. A panel display indicated the wipe count. The effluent pipe from the reaction chamber was installed in such a way that it could be removed for inspection of the UV lamps.

UV Pilot Operation The UV pilot unit was operated at a constant flowrate and lamp intensity throughout a sampling event. The flowrate and lamp power levels were varied between tests. Flowrate to the unit varied from 58 gal/min to 140 gal/min and was controlled manually using a flowmeter and throttling valve located at the influent side of the UV pilot. Lamp intensity was also controlled manually by adjusting the power level of the UV lamps to one of three preset power levels. Power levels 1, 2 and 3 provided lamp power outputs of 125, 160 and 200 w UV-C per lamp, respectively. Treated UV effluent samples were collected from a sample port installed on the effluent discharge pipe and were analyzed for indicator bacteria (total coliform, fecal coliform, *Escherichia coli*, and enterococcus), UV transmissivity, particle size, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), halogenated aromatic amines (HAAs,) Whole Effluent Toxicity (WET), and Microtox. All samples, except for the particle size samples, were discrete (grab) samples. The particle size sample was a composite sample made up of discrete samples taken at 15-min intervals over the duration of the test run. Absorbed dosage was also measured once per test event via a collimated beam test. The analytical results of the samples are summarized in Table 3.

The UV pilot unit was found to be the simplest unit to operate, requiring minimal operator attention. As was the case with Phase I, the wiper mechanism periodically became jammed by rags or other bulk material in the wastewater. The jammed wipers were fixed easily by resetting the wiper fault condition and reversing wiper direction. At the end of the pilot operations, the quartz sleeves showed signs of slight reddish discoloration, possibly due to iron deposits, at the ends of the sleeves. In addition, a slight transparent film was present over the entire length of sleeve. In a full scale system this would likely necessitate periodic chemical cleaning of the quartz sleeves.

4.2 Chlorine Dioxide

Chlorine dioxide has proven its capabilities as an outstanding bactericide and viricide. It is ten times more soluble in water than Cl_2. In contrast to Cl_2, ClO_2 does not react with ammonia and other nitrogenous compounds to form chlorinated organics, and its disinfection efficiency is high over a wide pH range. Due to its instability, ClO_2 must be generated on-site on an as needed basis. It may be generated on-site by: acid/sodium chlorate generation; acid/sodium chlorite generation; chlorine/sodium chlorite generation (solution generators, gas-solid generators); and UV radiation/sodium chlorite generation. A recent advance involving UV radiation of sodium chlorite ($NaClO_2$) has emerged as a new and innovative technology for ClO_2 generation.

Chlorine dioxide is produced by this method through the disassociation of chlorite, a process that requires very little energy in the generation process. The primary benefit of this generation method compared to classical ClO_2 generation methods is that Cl_2 gas is not used in the

generation process. In Phase I, the Cl_2 (gas) - $NaClO_2$ (solid) generation process was used. During Phase II, the UV-chlorite generation process was intended to be used throughout the testing. However, due to operational problems with the UV-chlorite pilot generator, the backup gas-solid type generator was used.

Typically for wastewater treatment, aqueous disinfectants such as sodium hypochlorite and ClO_2 are injected into wastewater using a diffuser arrangement, without providing additional mixing. However, studies on CSO disinfection performed for the US EPA in Philadelphia, Syracuse, and Rochester demonstrated that disinfection performance could be significantly increased and required contact times reduced by providing mixing at high velocity gradients (G) (e.g., high-rate mixing) (US EPA 1978a and 1978b). These studies showed that values of GT (G x contact time [T]) between 10,000 and 100,000 provided effective disinfection at contact times of less than 5 min. Additionally, recent studies and operations experience with disinfection of secondary effluent have shown that high-energy mechanical mixing can improve chemical performance and minimize effluent residuals. Based upon this information, high-rate mixing was selected for use in the pilot testing.

Chlorine Dioxide Pilot Equipment This pilot system consisted of two main components: the contact tank system and the ClO_2 generator. The contact tank system included separate flash mix tank, contact tank and weir tank. The contact tank system was identical for the ClO_2 and Cl_2/deCl_2 pilots. Two separate ClO_2 generators were used as part of the pilot study. Ultra Violet Dioxide, Inc., (UVD) of Syracuse, New York, manufactured the first generator, which produced a ClO_2 liquid using an innovative UV-chlorite process. The second generator, which produced a ClO_2 gas using the Cl_2 (gas)/chlorite (solid) process, was manufactured by CDG Technology, Inc., (CDG) of Bethlehem, Pennsylvania. Because the UVD system is a new technology, the system manufactured by CDG, used during Phase I was available as a backup system and was used during Test Runs No. 1, 7 and 8.

UVD Pilot Equipment The UVD ClO_2 generator generates ClO_2 by passing an aqueous $NaClO_2$ solution through a UV reactor. The ClO_2 gas is then stripped out of the $NaClO_2$/ClO_2 solution and sparked into water producing an aqueous ClO_2 feedstock. Liquid ClO_2 product, strength between 864 mg/L and 2,300 mg/L ClO_2 was generated up to a week prior to testing. The ClO_2 product was then stored in a product tank, which was cooled to retard degradation. The product strength was then measured prior to testing. Based on the measured product strength and the desired dose, the ClO_2 product was metered into the wastewater flash mix tank.

Several difficulties were encountered in the operation of the UVD generator. Most of the difficulties can be attributed to the fact that the unit was still an early prototype. Chlorine dioxide could only be prepared on a batch basis and operator attention was required throughout the generation process. During test runs 2 through 6, volumes of gas in the product pump suction line would periodically air bind the product metering pump, potentially decreasing the

Figure 3. A process flow diagram of the UV pilot unit.

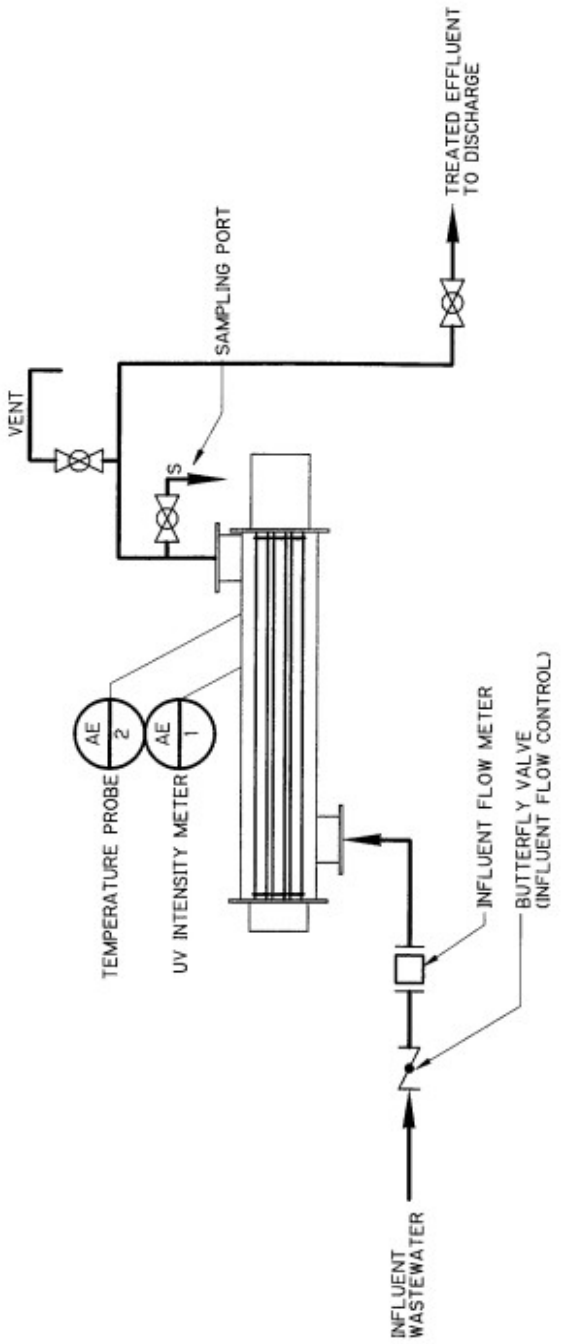


Table 3. UV pilot sample parameter table.

	Total Number of Samples	Analytical Reference Method	Sample Preservation [1]	Maximum Holding Times [2]	Container
Conventional Parameters					
SS	76	EPA-160.2	cool to 4° C	7 d	2-L poly (A)
VSS	26	EPA-160.4	cool to 4° C	7 d	2-L poly (A)
Settleable Solids	26	SM 20-2540 F	cool to 4° C	48 h	2-L poly (A)
BOD	26	EPA-405.1	cool to 4° C	48 h	1-L poly (B)
Soluble BOD	26	EPA-405.1	cool to 4° C	48 h	1-L poly (B)
TKN	76	EPA-351.2	cool to 4° C, H_2SO_4 to pH<2	28 d	500-mL poly (C)
Ammonia	76	EPA-350.1		28 d	500-mL poly (C)
COD	26	EPA-410.1/410.2	cool to 4° C, H_2SO_4 to pH<2	28 d	500-mL poly (C)
TOC	26	EPA-415.1	cool to 4° C, H_2SO_4 to pH<2	28 d	500-mL poly (C)
Iron (total)	26	EPA-200.7		6 months	250-mL poly
Bacterial Parameters					
T. Coliform	152	SM 20-9222 B [3]	cool to 4° C, 10 mg $Na_2S_2O_3$	6 h [4]	250-mL Whirl Pack (D)
F. Coliform	656	SM 20-9222 D [3]			250-mL Whirl Pack (D)
Escherichia coli	488	SM 20-9222 G [3]	cool to 4° C, 10 mg $Na_2S_2O_3$	6 h [4]	250-mL Whirl Pack (D)
Enterococcus	152	SM 20-9230 C		6 h [4]	250-mL Whirl Pack (D)
Target Organic DBPs					
VOCs	80	EPA-624 / NYSDEC ASP	cool to 4° C	7 d	2 x 40-mL vials
SVOCs	72	EPA-625 / NYSDEC ASP	cool to 4° C	5 d extraction, 40 d analysis	4 x 1-L amber
HAAs	68	EPA-552.2	cool to 4° C, ammonium chloride	7 d	250-mL amber
Other					

	Total Number of Samples	Analytical Reference Method	Sample Preservation [1]	Maximum Holding Times [2]	Container
UV Transmissivity (unfiltered)	76	NA	cool to 4° C	NA	250-mL poly (E)
UV Transmissivity (filtered) [5]	76	NA	cool to 4° C	NA	250-mL poly (E)
UV Collimated Beam	9	EPA-625.1/86.021	cool to 4° C	14 d	3 x 1-L poly
Particle Size	9	SM 20-2560	cool to 4° C, 0.25 mL 10% NaOCl	14 d	500-mL poly
Chlorate	93	EPA-300 D	purge w/N_2 gas (for samples with ClO_2), 50 mg/L EDA, cool to 4° C, protect from light	28 d	250-mL poly (F)
Chlorite	93	EPA-300 D		14 d	250-mL poly (F)
Whole Effluent Toxicity	34	EPA 600/4-90/027F	keep cool, protect from light	48 h	5 x 1-gal poly
Viral	101	NA	cool to 4° C, 10 mg $Na_2S_2O_3$	1 month	4 x 1-L poly
Chlorine Residual (total and free)	NA	HACH DPD Method	NA	NA	NA
Chlorine Residual (amperometric titration)	NA	SM 20-4500-CID	NA	NA	NA
Chlorine Dioxide Residual	NA	gas diffusion FIA and HACH Chlorophenol Red Method	NA	30 min	NA
Chlorine Dioxide Residual	NA	direct measurement	NA	NA	NA
Microtox	NA	SM 20-8050, ASTM D5660-96	NA	NA	NA

Note: 1. Samples were preserved immediately upon sample collection; 2. Unless otherwise noted, all holding times are from the time of sample collection; 3. For all 9222 methods, mastication of samples must be completed prior to analysis; 4. A maximum holding time of 6 hrs for all bacterial samples was a goal. At no time did holding times exceed 10 h; 5. Filtered UV transmissivity samples were filtered at the laboratory using a 0.45 un filter. A. These parameters were combined in the same 2-L polyethylene container; B. These parameters were combined in the same 1-L polyethylene container; C. These parameters were combined in the same 500-mL polyethylene container; D. These parameters were combined in the same sterilized 250-mL swirl container; E. These parameters were combined in the same 250-mL polyethylene container; F. These parameters were combined in the same 250-mL polyethylene container.

disinfectant feed rate. Also, due to leaking fittings/valves, the $NaClO_2$ solution leaked into the ClO_2 product tank, resulting in a feedstock contaminated with up to 7,500 mg/L of chlorite. The maximum strength of ClO_2 produced was 2,300 mg/L.

CDG Pilot Equipment Because the UVD system was a new technology, the CDG ClO_2 generation system used during Phase I had been used as a backup system. In this system, ClO_2 gas was generated by passing a humidified 4% Cl_2 gas in nitrogen blend through a packed column of solid $NaClO_2$. A rapid reaction between the Cl_2 gas and the $NaClO_2$ results in a ClO_2 gas. The CDG unit was used to produce ClO_2 during pilot test runs no. 1 and 8, and for half of pilot test run no. 7. In the contact tank system, wastewater flowed into the flash mix tank where ClO_2 was mixed with the wastewater using a ½-hp, Series 32F, Gas Mastrrr, high-rate, chemical induction mixer. After the flash mix tank, the wastewater was directed into the contact tank. The contact tank was subdivided into 2 sections, one with corrugated longitudinal baffles and one with flat longitudinal baffles. Each section received equal flow, which was controlled by the adjustable v-notch weir plate located in the weir tank. The corrugated baffles were designed to provide a headloss of 1-in. H_2O. The actual headloss was found to be approximately 0.75-in. H_2O. This provided a gradient G for the corrugated baffled section of 303 s^{-1}. In addition the contact tanks also had a second mixer located at a contact time of 0.5 min to evaluate the performance of single-stage versus two-stage mixing. For the mixing configuration used during each test event and the design conditions of the contact tank system please refer to the original CDM report (CDM, 1999).

Chlorine Dioxide Pilot Operation The ClO_2 pilot system was operated at a constant flowrate and chemical dose throughout each sampling event. Flash mixing and the addition of disinfectant into the wastewater stream was performed in all test runs using the high-rate chemical induction mixer in the flash mix tank. The corrugated and flat baffled tank sections were operated for all 8 test runs, and samples were collected at three different contact times (2.7, 5 and 8 min) in each section to measure treatment performance. The majority of the sampling was performed at the 5-min sample port in the flat baffled section, to be consistent with the Phase I test conditions. Samples for bacterial parameters, target organic DBPs, chlorate, chlorite, WET and microtox were collected at the 5-min sampling location. Process monitoring for TRC and ORP was performed at a detention time of approximately nine minutes on the flat baffled section only. Monitoring for pH and ClO_2 was performed at the effluent of the weir tank. Bacterial samples for fecal coliform and *Escherichia coli* were also collected at the 2.7-min and 8-min contact times in both the baffled and unbaffled sections to correlate inactivation against contact time. The analytical results are summarized in the Results section.

Because of questions on the accuracy of the UVD ClO_2 product strength measurements, pilot test runs no. 2 through 7 may have been underdosed with ClO_2. Without accurately knowing the ClO_2 product strength, a reliable relationship between applied dose and toxicity could not be established. In order to make this correlation an additional test was performed. Using the ClO_2 product from the CDG system, wastewater was dosed with five different known dosages of ClO_2 (4, 6, 8, 10, and 12 mg/L ClO_2).

4.3 Chlorination/Dechlorination

Chlorine has been the most widely used disinfectant for wastewater and potable water in the United States due to its low cost, reliable disinfection capabilities, and adequate supply. Generally, bacteria are more susceptible to Cl_2 than viruses. The disinfection effectiveness of Cl_2 is largely a function of the chemical form of the disinfecting species. Chlorine is applied to the waste stream in molecular (Cl_2) or hypochlorite (OCl^-) form. Chlorine is available in many forms including Cl_2 gas and Cl_2 products such as sodium and calcium hypochlorite. Liquid sodium hypochlorite has become widely used for wastewater disinfection due to its reliability and ease of handling. Sodium hypochlorite can be purchased in bulk forms of 10 to 15% of available Cl_2 or can be manufactured on site. Sodium hypochlorite has limited shelf-life and is subject to loss of available Cl_2 content by decay to Cl_2 gas. Sufficient mixing, contact time, and dosages are necessary to maximize the use of Cl_2 disinfection.

Dechlorination may be accomplished through injection of a solution of sodium bisulfite ($NaHSO_3$) or sulfur dioxide (SO_2) gas into the process flow, following the chlorination process. Figure 4 presents Cl_2/deCl_2 pilot unit flow schematic. The deCl_2 process is nearly an instantaneous process. A potential problem with deCl_2 is the possible depletion of dissolved oxygen by excess sulfite ion.

Chlorination/Dechlorination Pilot Equipment The Cl_2/deCl_2 pilot unit mixing configuration and sampling program was generally identical to that of the ClO_2 system, with the exception of deCl_2. In this pilot system an 8 to 15% solution of sodium hypochlorite was introduced, using a chemical metering pump, through the vacuum port on the ½-hp Gas Mastrrr chemical induction mixer. Dechlorination was performed in the weir tank downstream of the flow control weirs by injecting a 38% sodium bisulfite to the waste stream near the impeller of a small propeller mixer to provide for deCl_2 of both free and combined Cl_2 residual. Dosages of OCl^- and $NaHSO_3$ were controlled manually by adjusting the pump stroke/frequency. The pilot system included residual instrumentation for continuous monitoring of DO, total residual Cl_2, deCl_2 residual and ORP. The Cl_2 and ClO_2 contact tanks were both identical in design.

Chlorination/Dechlorination Pilot Operations Operations of the Cl_2/de Cl_2 pilot were similar to the ClO_2 pilot. The Cl_2/de Cl_2 pilot system was operated at a constant flowrate and chemical dose throughout each sampling event. Flash mixing and the addition of disinfectant into the wastewater stream were performed in all test runs using the high-rate chemical induction mixer in the flash mix tank. The corrugated and flat baffled tank section were operated for all 8 test runs, and samples were collected from three different contact times (2.7, 5, and 8 min) in each section to measure treatment performance. The majority of the sampling was performed at the 5-min sample port in the flat baffled section, to be consistent with the Phase I test conditions. Samples for bacterial parameters, target organic disinfection byproducts (DBPs), chlorate, chlorite, WET, and Microtox were collected at the 5-min sampling location. Process monitoring for TRC and ORP was performed at approximately nine minutes on the flat baffled section only. Monitoring of the deCl_2 effluent was performed by measuring the DO and the free residual Cl_2 at the effluent of the deCl_2 tank. Bacterial samples for fecal coliform and *Escherichia coli* were also collected at the 2.7-min and 8-min contact times in both the baffled and unbaffled sections

to correlate inactivation against contact time. The analytical results can be found in the Results section.

4.4 Ozone

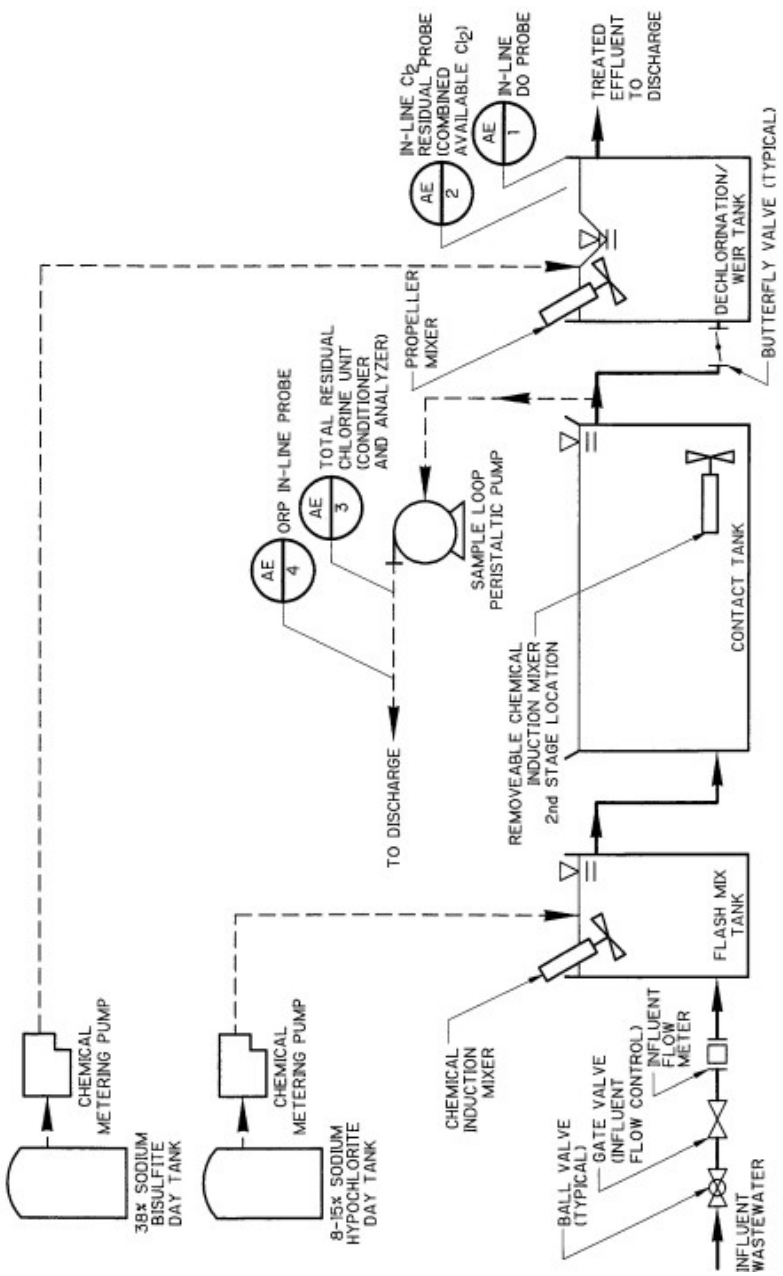
Ozone is a chemical oxidizing agent that has been widely used for disinfection of drinking water systems and bleaching in the pulp and paper industry. It is an extremely strong oxidant and is well established for its powerful antibacterial and antiviral properties (Wojtenko et al. 2001). Ozone is a rapid disinfectant, requiring substantially less contact time than conventional chlorination disinfection systems. Based upon research performed by the US EPA in the 1970s and early 1980s, O_3 was considered to be one of the most feasible disinfection alternatives to Cl_2; the other technology being UV radiation. However, there presently are few operating facilities using O_3 for disinfection of municipal wastewater. This may be attributable to the relatively high initial capital costs associated with O_3 generation equipment and the poor operating records of previous O_3 generators.

Ozone Equipment The ozone unit was a trailer mounted system manufactured by Aquifine Wedeco Environmental Systems, Inc., (AWES) of Valencia, California. Ozone was generated on-site and on-demand using 90% pure oxygen and a corona discharge type O_3 generator. Oxygen was supplied using an air compressor and a pressure swing adsorption oxygen generation unit. Ozone was transferred to the wastewater using a pressure booster pump and a gas eductor. Following the eductor, contact time for disinfection was provided by a baffled contact tank. The tank was sized to provide a minimum detention time of 10 min at a flow of 10 gal/min. Flow out of the tank was controlled by level sensors and an automatic valve.

Ozone Operations The O_3 pilot was operated at an approximately constant wastewater flowrate and O_3 feed gas concentration throughout each sampling event. Some variation in wastewater flowrate occurred as a result of clogging of the strainer baskets. However, this variation was generally only significant when primary influent wastewater was used as the source water. This wastewater contained large particles of solids and waste which rapidly clogged the basket screens. Several difficulties were encountered in the operation of the O_3 pilot. Some of these can be attributed to the use of the eductor mass transfer system rather than the technology itself.

The O_3 pilot could not be operated during test runs no. 1 and 2 due to a problem with a low differential pressure alarm. This may have been related to potential clogging of the booster pump impellers. The pressure transmitter alarm circuit was disconnected and the unit was successfully operated from runs no. 3 through 16. For runs no. 3 through 6, the booster pump discharge pressure was observed to be lower than required for normal operation. Lower pressures may have resulted in lower mass transfer efficiency in the eductor. During run no. 6,

Figure 4. Chlorination/dechlorination pilot unit flow schematic.



the unit was subject to numerous shutdowns during the test period due to clogging of the basket strainer and the pump impellers. Following cleaning of the booster pump, the pump discharge pressure in runs no. 7 through 16 was much improved. In these runs, the pump discharge pressure was generally in the range of 58 to 65 lb/in^2. In addition, this particular unit was subject to O_3 gas leaks. Because of the difficulties observed with the system during Phase I, the technology was found not to be feasible for CSO applications at this time. As a result, this technology was not investigated during Phase II, and this Research Summary does not discuss the ozonation study results.

5. RESULTS

5.1 Ultraviolet Irradiation

Dose-Response Relationships Scatter plots were developed for dose versus log reduction and effluent bacterial concentrations for each bacteria group. These relationships were developed to identify the dose required to achieve a range of bacterial log reductions and effluent concentrations. These dose-response relationships were generated for total coliform, fecal coliform, *Escherichia coli*, and enterococcus data. Blending was performed on the samples in order to release potentially entrained bacteria by shearing the solid particles without causing significant kills to the bacteria. Blending requirements for CSO wastewater samples were initially developed by US EPA (US EPA 1975). An example of the dose-response relationship generated for fecal coliform is presented in Figure 5. The figure shows the Phase I dose-response curve along with the Phase II scatter plot. In general, these graphs demonstrate that as UV dose increases, log reduction of bacteria also increases while the effluent mean concentration decreases.

The dose-response relationships provide two obvious trends: a tailing-off effect for UV effectiveness, and higher variability of wet weather data vs. dry weather data. Based on the dose-response relationship, it appears that as dose increases in the range of 10 to 75 mW/cm^2, log reduction of bacteria also increases. However, as dose increases above the 75 mW/cm^2 UV, effectiveness tails-off. The tailing effect in the dose-response data is more clearly shown in the collimated beam data in Figure 6. Above approximately 100 mW/cm^2, the lab collimated beam dose curve becomes asymptotic to 100 cfu/100 mL of fecal coliform. The pilot unit data follows the same trend, although more variable and with a higher asymptote.

The wet-weather runs captured during the Phase II pilot study were generally the result of large storms. Consequently, the dose-response data show much more variability for the wet-weather data than for the dry-weather data. The bacteria log reduction data for dry-weather tend to be grouped together; whereas the wet-weather data are more widespread. The variability in the wet-weather dose-response data can be attributed to the variability in the pilot influent wastewater during wet-weather events. This is likely the result of variable solids concentration and particle size, both known to significantly affect UV disinfection performance.

Table 4 summarizes the estimated range of UV doses required to achieve corresponding bacterial concentrations of 1,000 cfu/100 mL, 3-log and 4-log bacterial reductions. These targeted doses were based on the Phase II and adjusted Phase I results. The dose required to achieve the fecal coliform effluent target compares favorably with the results of Phase I, after the UV doses were recalculated. Additionally, data from both Phase I and Phase II show that the lowest effluent fecal coliform concentration achieved by UV disinfection was approximately 100 cfu/100mL.

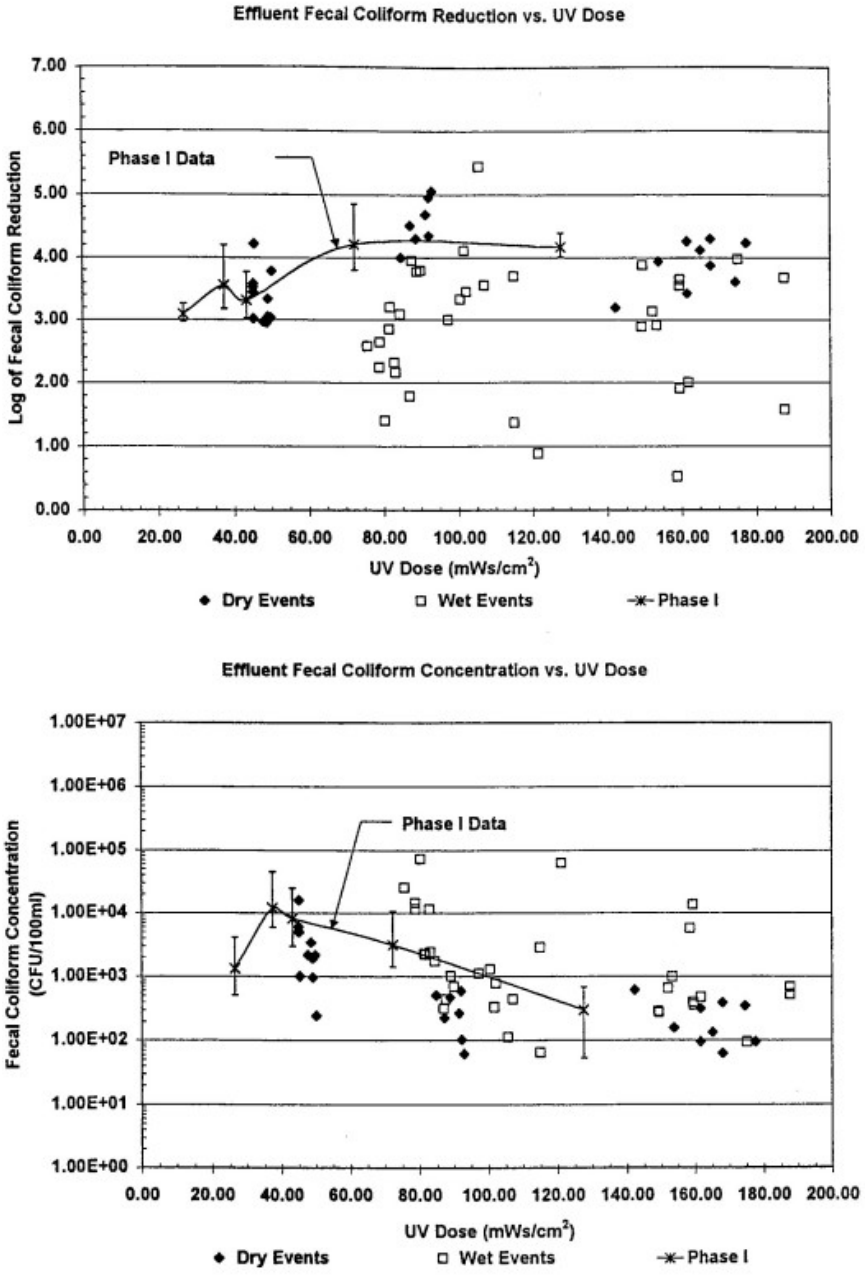
Table 4. Targeted UV dose.

Parameter	UV Dose (mWs/cm2)		
	1,000 cfu/100ml	3-log reduction	4-log reduction
Total Coliform	N/A	40	120-180
Fecal Coliform	60-120	30	60-120
Escherichia coli	40-80	30-40	75-160
Enterococcus	75	40-80	130-160

Water Quality Relationships Constituents such as suspended solids (SS) and iron absorb UV light, thus decreasing the available light intensity within the reactor, which in turn reduces the UV dose. Additionally, constituents such as SS limit the exposure of bacteria to UV radiation by shielding or harboring the bacteria from exposure to the UV light.

Plots of UV transmittance versus SS and iron concentration are presented in Figure 7. Plots of SS concentration versus log reduction and effluent fecal coliform concentration by dose are shown in Figure 8. This relationship indicates a slight trend of reduced disinfection effectiveness with increasing SS concentrations. This trend is likely the result of harbored bacteria within the solids, a phenomenon that is not accounted for when measuring UV transmittance. The phenomenon of harbored bacteria is also likely the cause of the "tailing-off" effect. Because the bacteria are entrenched in the solids they are not exposed to the UV light, and therefore are not destroyed. The relatively constant bacteria concentrations at the higher UV doses could reflect a relatively constant concentration of harbored bacteria. Besides SS, no other water quality parameters showed a positive correction to UV disinfection effectiveness. These water quality results, as they relate to UV disinfection effectiveness, were similar to the trends observed during Phase I.

Figure 5. UV dose response relationship for fecal coliform.



Viral Reductions All four viral runs clearly demonstrated that UV disinfection produced nearly complete reductions of bacteriophage. As a result, no apparent relationship between dose and phage reductions could be drawn from this data set. However, the reductions provided by UV disinfection would likely inactivate most wastewater enteroviruses at concentrations in CSOs. Table 5 presents the results of the viral disinfection by UV dose and phage reductions. Because of the small number of positive observations of naturally occurring enteroviruses in the pilot influent, the UV treatment could not be evaluated satisfactorily on the basis of the tissue cultural infectivity assays.

Disinfection Byproducts No disinfection byproducts were detected in the UV effluent with greater concentrations than in the pilot influent. UV has the distinct advantage of producing little or no byproducts that may cause a concern for toxicity. Haloacetic acids and semi-volatile and volatile organic compounds, as well as acute whole effluent toxicity were measured in the UV
effluent. These samples were used as being representative of the pilot influent because there was essentially no difference between the UV effluent and the influent.

Table 5. UV viral reductions.

Parameter Sample location	Run #1	Run #4	Run #7	Run #8
UV Dose (mWs/cm^2)	43	75	43	145
T4 & f2				
Seeded influent concentration (PFU/mL)	$1x10^3$	500	$3.7x10^5$	$3.5x10^5$
Effluent concentration (PFU/mL)	15	0	0	60
Log reduction	1.9	2.7	5.6	3.9
S2 & X174				
Seeded influent concentration (PFU/mL)	$1x10^4$	$2x10^4$	$7x10^{5*}$	$1.1x10^{6*}$
Effluent concentration (PFU/mL)	150	0	0^*	0^*
Log reduction	2.9	4.3	5.8	6.0
* ·X174 not included in these samples				

5.2 Chlorine Dioxide

The ClO_2 disinfection pilot was operated for eight runs at a controlled flow of 32 gal/min. The flowrate was held relatively constant during each run. Difficulties were encountered with the ClO_2 injection system, which are believed to have resulted in lower actual applied dosages than calculated. This became apparent when the results using the UVD system were compared against those for the CDG system at the same calculated dose. Due to these mechanical difficulties, the CDG ClO_2 generator system was used for runs 1 and 8, and part of run number 7. The above mentioned mechanical difficulties excluded the use of data collected during runs number 2, 3, 4, and part of 7, while laboratory difficulties excluded the use of the data collected during the other part of run number 7. Only data from runs number 1, 5, 6, and 8 were considered valid and were used in the data analyses. This limited the amount of data and

restricted the ClO_2 dose range tested to 6.5 mg/L to 10 mg/L.

Dose-Response Relationships Scatter plots were developed for dose versus log reduction and effluent bacteria concentrations for each bacteria group. These relationships were developed (for total coliform, fecal coliform, Escherichia coli, and enterococcus data) to identify the dose required to achieve a range of bacterial reductions and effluent concentrations. The dose versus log reduction plot for fecal coliform is shown in Figure 7. The Phase II data exhibited a high degree of variability; more so than the Phase I data. This variability is similar to the UV and Cl_2/deCl_2 results and is at least partially attributable to more variable influent wastewater quality resulting from the greater number of and more intense storm events in Phase II. The Phase II data does show an increase in bacterial log reduction between 6.5 and 8 mg/L, as would be expected, and a slight decrease between 8 and 10 mg/L. It is possible that the actual dose was less than 10 mg/L due to the malfunctioning ClO_2 injection system. Except for the total coliform data, Phase I data shows a higher degree of inactivation at a given dose than Phase II. This could be due to differences in wastewater quality between the two Phases.

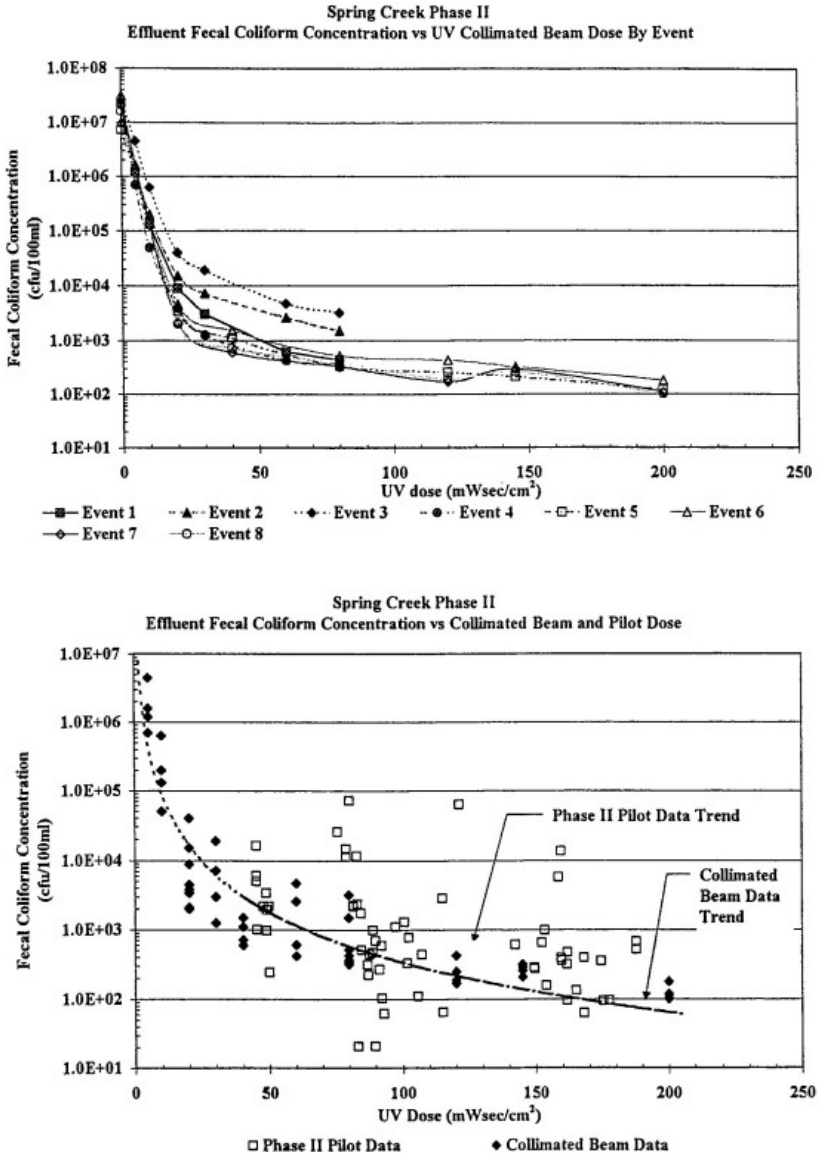
It was difficult to discern the difference between wet-weather versus dry-weather disinfection efficacies because of the way that the pilot units were operated. For instance, the CDG ClO_2 product was used during runs number 1 and 8, both dry-weather runs, and the UVD ClO_2 product was used during runs number 5 and 6, both wet-weather runs. This limited data set and its variability made it difficult to differentiate between performance during wet-weather and dry-weather events. Table 6 summarizes the estimated range of ClO_2 doses required to achieve corresponding bacterial concentrations of 1,000 cfu/100 mL, 3-log and 4-log bacterial reductions. These target doses were based on both Phase I and Phase II results. In general, the performance of the ClO_2 system was less effective during Phase II than during Phase I. For example, the Phase II results for fecal coliform reduction were approximately 0.5 log less than Phase I results at equivalent ClO_2 dose (Figure 9).

Comparisons of these pilot results with full-scale facilities cannot be done since there are presently no known facilities that use ClO_2 to disinfect CSO or municipal wastewater. However, these results are consistent with bench-scale and field pilot work previously done under US EPA funded demonstrations (US EPA 1975; US EPA 1979).

Table 6. Targeted ClO_2 doses.

Parameter	ClO_2 Dose (mg/L)		
	1,000 cfu/100mL	3-log reduction	4-log reduction
Total Coliform	N/A	9	N/A
Fecal Coliform	7	5-7	8-10
Escherichia coli	6-8	4-8	6-9
Enterococcus	6-9	6-9	>10

Figure 6. UV collimated beam results.



Water Quality Relationships Disinfection performance is dependent upon wastewater characteristics such as SS and BOD. Many constituents found in wastewater limit disinfection by either exerting a disinfectant demand or shielding bacteria from contact with the disinfectant. Suspended solids limit the exposure of the disinfectant by shielding or harboring bacteria from contact with the disinfectant.

Similar to Phase I, trends of reduced disinfection effectiveness as a result of increased concentrations of TKN, BOD, COD and TOC were not apparent. In general, the concentrations of these parameters measured during Phase I and Phase II were comparable, albeit Phase II was characterized by greater variability. Based on both Phase I and Phase II results, it does not appear that these parameters have a significant affect on ClO_2 disinfection efficiency at the concentrations measured.

In contrast to Phase I, SS concentrations appeared to affect disinfection effectiveness; as SS concentration increased disinfection effectiveness decreased. This relationship is depicted in Figure 10. During Phase II, a higher percentage of the samples had SS concentrations greater than 120 mg/L, thus offering more information regarding the effects of higher SS concentrations. These data indicate that as SS concentration increase, disinfection effectiveness decreases.

Viral Reductions For test runs no. 1 and 7, ClO_2 disinfection produced nearly complete reductions of bacteriophage. Data from the second viral run (run no. 4) was not included in this analysis because of the operational difficulties experienced with the ClO_2 disinfection system. Data from the last viral run (run number 8) showed lower phage reductions than the other runs. It is not clear why the viral reduction is lower for this test run. By comparison the mean fecal reduction during test run no. 8 was 3.0 log. Because of the relatively limited data set, no apparent relationship between dose and phage reductions could be drawn from this data set. However the reductions provided by ClO_2 disinfection would be expected to inactivate most wastewater enteroviruses at the concentrations in CSOs. Table 7 presents the results of the ClO_2 disinfection by dose and phage reductions. Because of the small number of positive observations of naturally occurring enteroviruses in the pilot influent, the ClO_2 treatment could not be evaluated satisfactorily on the basis of the tissue cultural infectivity assays.

Disinfection Byproducts The generation of toxic byproducts and disinfectant residuals has become a concern for chemical disinfectants. Byproducts from the reaction of ClO_2 with wastewater, depending upon the generation process, include chlorate ion, chlorite ion, and Cl_2. However, ClO_2 produces far fewer byproducts than Cl_2 and is a more effective disinfectant because of its superior penetration characteristics and bactericidal properties. The main byproducts of ClO_2 disinfection are chlorite ion and chlorate ion. The presence of these ions can be the result of both the ClO_2 generation process and reactions in the wastewater.

There is little data available on the toxicity of chlorite and chlorate. Only two toxicity studies relating to lethal concentrations of chlorite and chlorate were found after a search of the

Figure 7. UV transmittance versus SS and iron concentration.

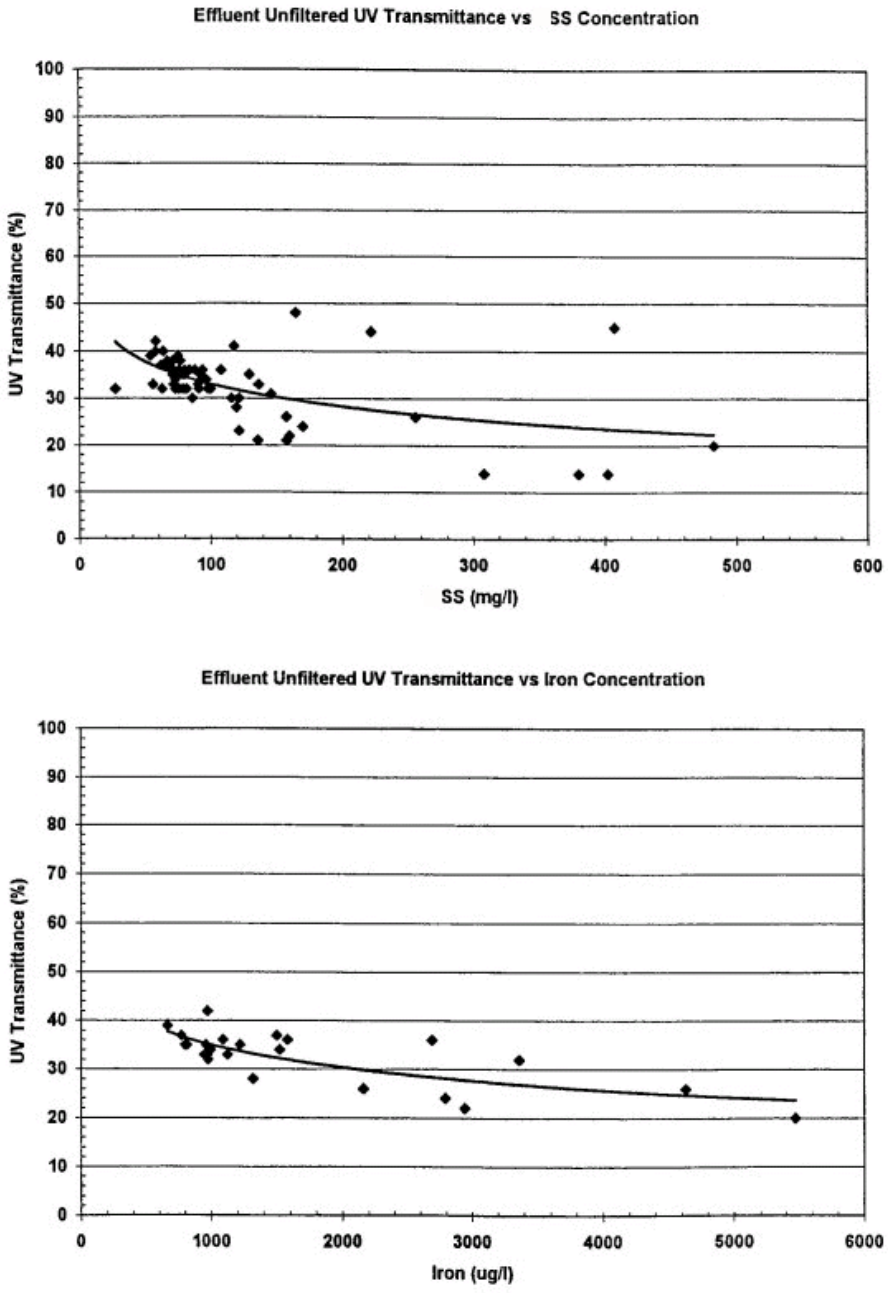
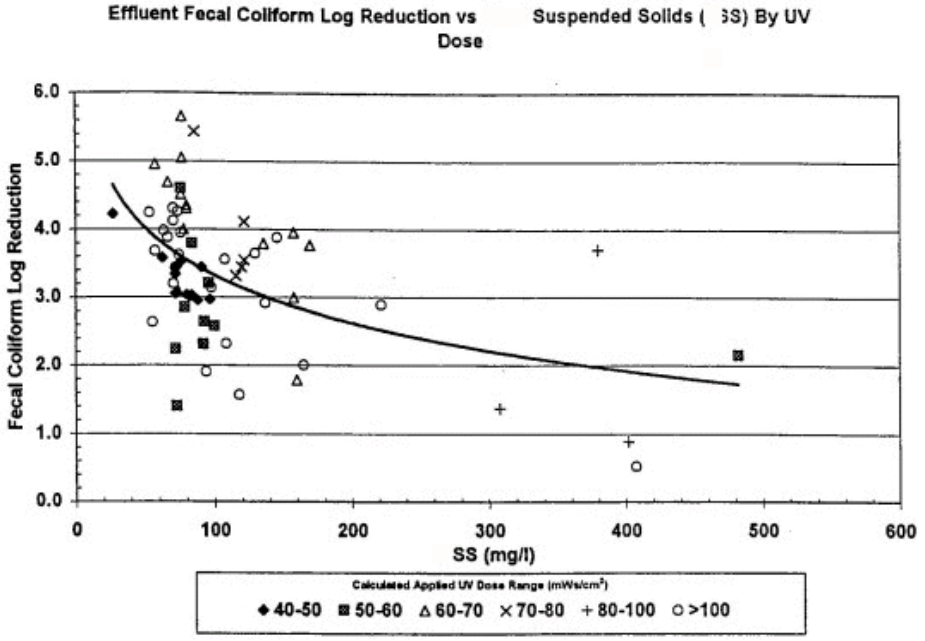
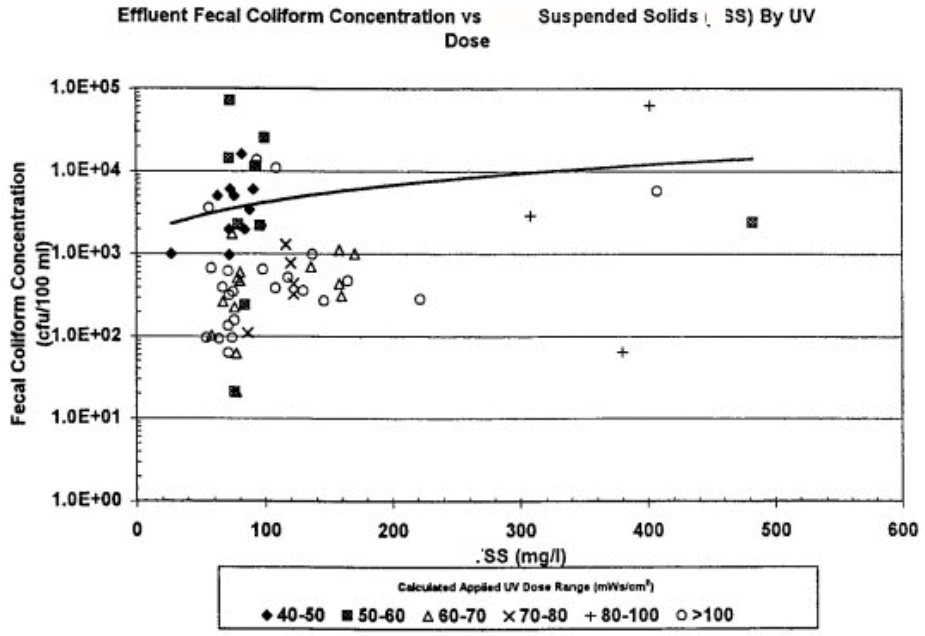


Figure 8. SS concentration versus log reduction and effluent fecal coliform concentration by dose.





US EPA's ECOTOX database. The first was a chlorate toxicity study predominately related to fresh and salt-water algae species. The second was a chlorite toxicity study by the US EPA's Office of Pesticide Programs on many fresh water species including opossum shrimp. The opossum shrimp resulted in LC_{50} values of approximately 0.6 mg/L. It is important to note that the toxicity data provided in the US EPA's ECOTOX database are from single chemical exposures, and therefore, do not reflect synergistic affects with other chemicals. Additionally, they may be the result of different experimental designs.

Residual chlorate ion and chlorite ion concentrations were evaluated to determine if there was a correlation between these residuals and ClO_2 dose, and if the concentrations of these byproducts exceed regulatory standards. The data does not show a trend of increasing chlorate or chlorite ion concentrations with increasing ClO_2 doses as was observed in Phase I. However, the Phase II data set was very limited due to the operational problems experienced with the UVD Inc. generator, and therefore, the trends observed during Phase I should be considered more reliable.

The chlorite and chlorate data from Phase I demonstrate that a relatively small amounts of chlorite and chlorate were found in the pilot effluent when using the CDG ClO_2 product. During Phase I, effluent chlorite generally ranged from 0.5 to 4 mg/L for applied CLO_2 doses of 4 to 10 mg/L. Conversely, relatively high concentrations of chlorite and chlorate were found in the pilot effluent when using the UVD ClO_2 product. This is the result of mechanical problems encountered with the UVD prototype ClO_2 generator. These mechanical problems were discussed in greater detail in the previous section. It is important to note that UVD Inc. corrected these mechanical problems after the testing was complete, and produced a ClO_2 feedstock with chlorite and chlorate concentrations of 44 and 210 mg/L, respectively. At the highest ClO_2 dose of 10 mg/L, these concentrations of feedstock would contribute approximately 0.22 and 1.1 mg/L, to the effluent chlorite and chlorate concentrations, respectively.

Total residual oxidant (as Cl_2) was also evaluated to determine if there was a correlation between TRC and ClO_2 dose, and if the concentration of TRC exceeds regulatory standards. Total residual oxidant concentrations were low; the highest observed concentration of TRC was 1.5 mg/L. It should be noted that the DPD TRC method used did not differentiate between the various oxidizing forms of chlorine and included Cl_2, ClO_2, ClO^-_2 and ClO_3.

Chlorine dioxide residual concentrations were measured to identify the lowest ClO_2 dose at which a residual would be detected. However, this relationship could not be developed due to the limited data set. Measurable residual ClO_2 concentrations were found at a dose of 8 mg/L, which corresponded to runs when the CDG ClO_2 unit was used. However, no ClO_2 residual was apparent when the UVD ClO_2 unit was used, even at a dose of 10 mg/L. Based on water quality data such as organics, it is unlikely that the ClO_2 demand explains the lack of residual when using the UVD ClO_2 unit. It is more likely that the actual ClO_2 dose using the UVD ClO_2 unit was less than 10 mg/L due to the operational problems, discussed previously.

Chlorine Dioxide Residuals Vs Dose Similar to Phase I, ORP sensors and data loggers were

installed on the effluent side of the ClO_2 contact tank. No relationship between ORP and ClO_2 residual concentrations was apparent. Conversely, a strong correlation between ORP and TRC was apparent, thus producing a n44early linear trend throughout the range of ORP and TRC values that were measured. The ORP values quickly rose and stabilized at a relatively high ORP reading (> 650 mV) and consequently the Phase I data was not suitable for developing a relationship as a process control technique. The Phase II ORP versus TRC data shows more potential for developing a relationship as a process control technique than the Phase I data. More testing is needed to determine the discrepancy between Phase I and Phase II data.

Table 7. Chlorine dioxide viral reductions.

Parameter Sample Location	Run #1	Run #7	Run #8
ClO2 Dose (mg/L)	8	10	8
T4 & f2			
Seeded influent concentration (PFU/mL)	$1x10^3$	$3.7x10^5$	$3.5x10^5$
Effluent concentration (PFU/mL)	0	0	$5x10^3$
Log reduction	3.0	5.6	1.9
MS2 & X174			
Seeded influent concentration (PFU/mL)	$1x10^4$	$7x10^5$	$1.1x10^6$
Effluent concentration (PFU/mL)	0	0	$3x10^3$
Log reduction	4.0	5.8	2.9

5.3 Chlorination/Dechlorination

The Cl_2/deCl_2 disinfection pilot was operated for 8 runs during the pilot study at a controlled flow of 32 gal/min. The pilot flowrate was held relatively constant during each run.

Dose-Response Relationships Scatter plots were developed for dose versus log reduction and effluent bacteria concentrations. These were developed for each bacterial group to identify the dose required to achieve a range of bacterial log reductions and effluent concentrations. The dose-response relationships for total coliform, fecal coliform, *Escherichia coli*, and enterococcus data had been generated. The example of one for fecal coliform is presented in Figure 11.

Similar to the UV and ClO_2 results, the Phase II Cl_2/deCl_2 data exhibited a high degree of variability. This is at least partially attributable to the more variable influent wastewater quality resulting from the greater number and more intense storm events during Phase II. The Phase II effluent bacteria concentrations for doses of 18, 20, and 24 mg/L are generally consistent with the results from Phase I, although in most cases the Phase II data exhibits a trend of poorer disinfection performance than Phase I. It is interesting to note that between doses of 24 and 28 mg/L, no further decrease in effluent bacteria concentrations is observed. In some cases an increase in effluent bacteria is apparent at the higher dose.

Figure 9. Chlorine dioxide dose versus log reduction plot for fecal coliform.

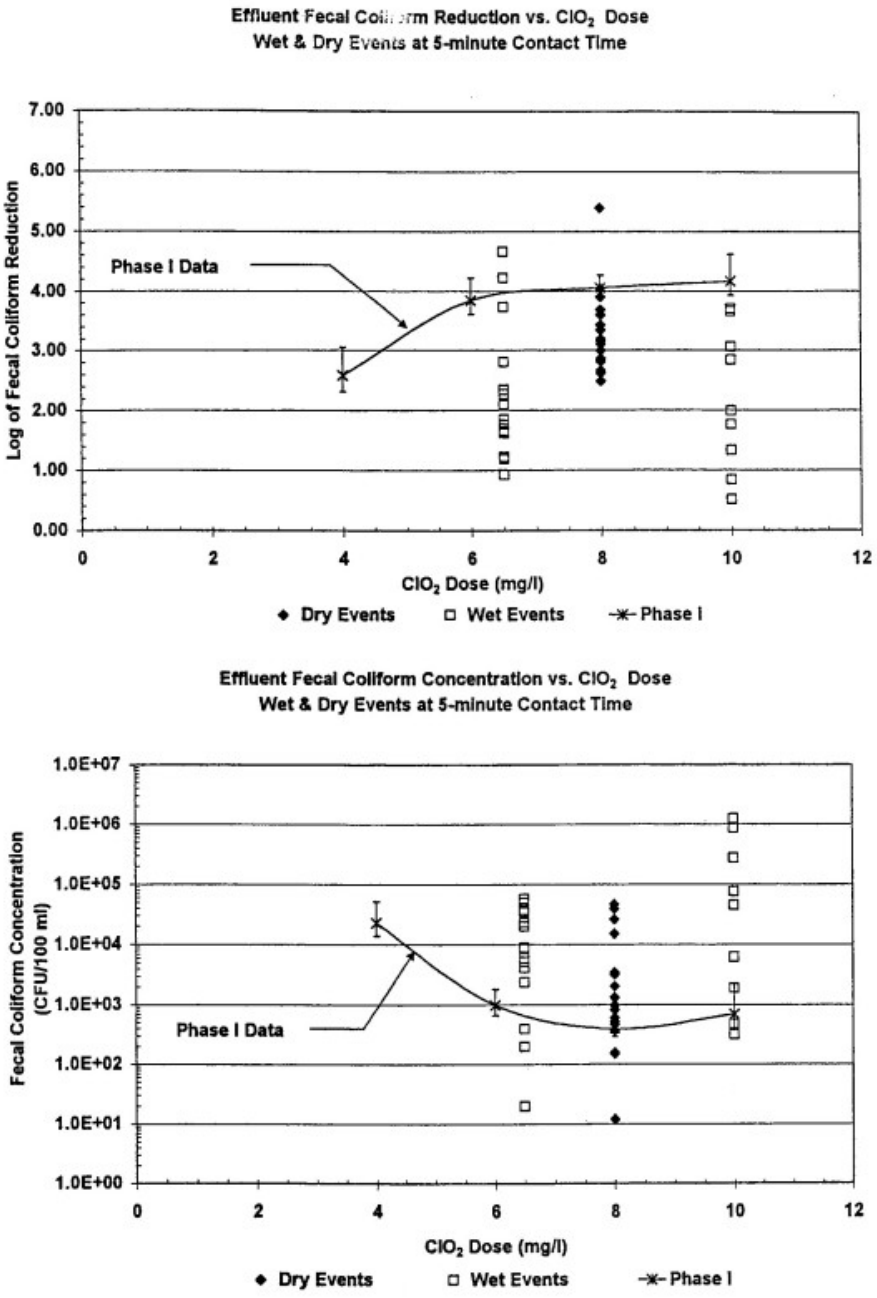
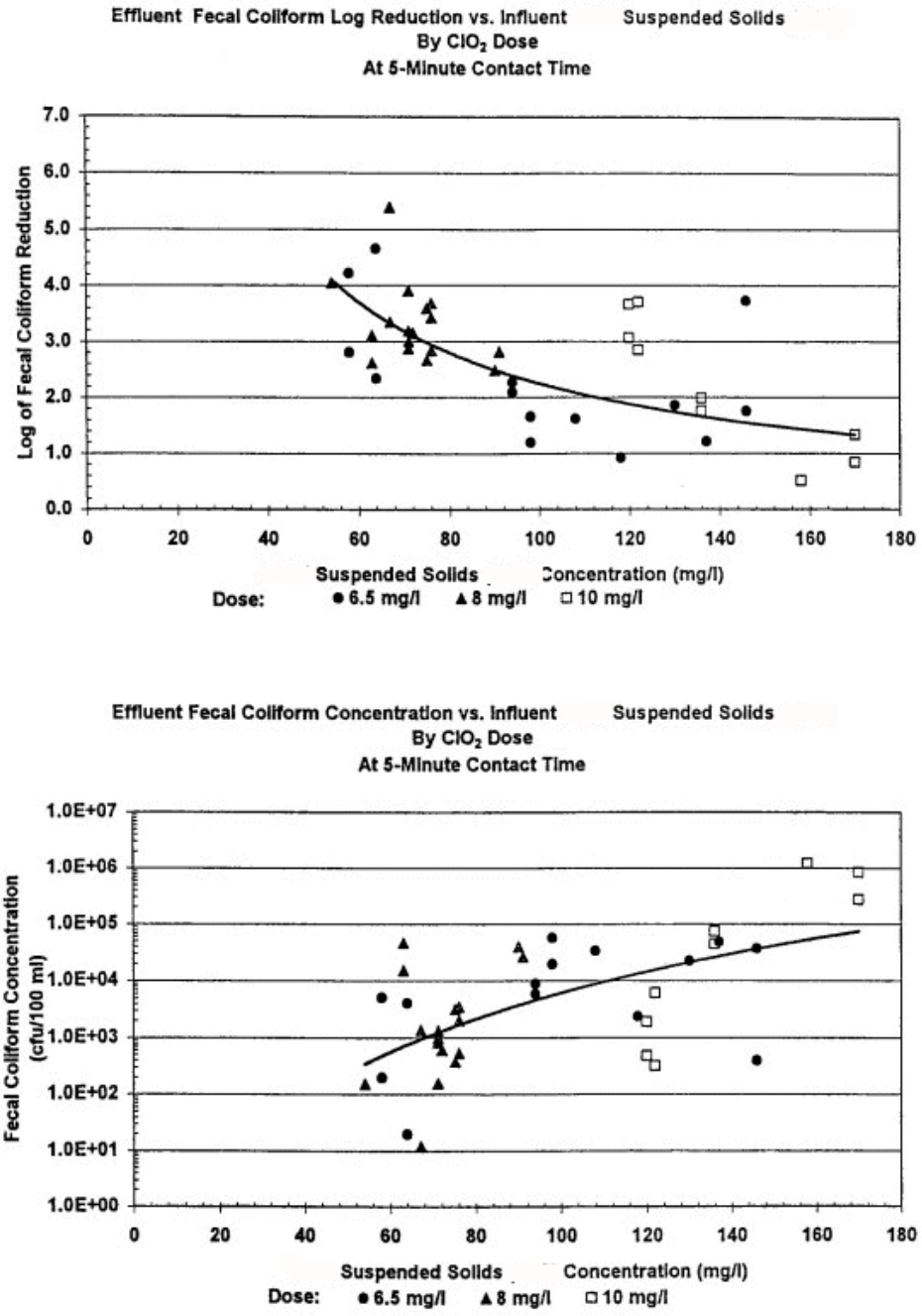


Figure 10. Chlorine dioxide fecal coliform dose response relationship for SS.



The factors which may contribute to these observations include variations in wastewater quality, pH, and temperature. Wastewater temperature, for instance, is known to significantly affect the rate of reaction of hypochlorous acid (free Cl_2) with ammonia to form monochloramine. During Phase I, the mean wastewater temperature was 11.6 ^oC, versus a temperature of 20.9 ^oC for Phase II. The colder winter temperatures would impede the formation of monochloramine, which has approximately 25 time less germicidal efficiency as free Cl_2. This effect is corroborated to some degree by the Cl_2 residual measurements during Phases I and II. As seen in Table 8, the lower doses during Phase I, when the mean water temperature was 9.3 ^oC cooler, produced significantly higher free residuals than were observed for the higher applied doses of Phase II.

The decrease in treatment performance at a dose of 28 mg/L corresponds with a change in the chlorine-ammonia chemistry. The poor performance at this dose occurred during test run no. 5, a wet weather event when the mean ammonia concentration dropped to 5.6 mg/L versus an average dry weather concentration of 13.6 mg/L. The resulting Cl:N weight ratio of 5.0 corresponds with the typical inflection in the chlorine-ammonia breakpoint curve. Beyond the break, further Cl_2 addition will actually decrease the measured residual as dichloramine and organochloramines are formed. Although dichloramine is believed to be approximately twice as germicidal as monochloramine, organochloramines are generally nongermicidal. This and other factors may partially explain the tailing effect observed at these high doses.

Table 8. Mean residual chlorine vs. applied dose for Phases I and II.

Applied Cl_2 Dose (mg/L)	***Mean Total Residual Chlorine mg/L (DPD Method)***	
	Phase I	***Phase II***
12	9.0	-
16	13.5	-
20-21	17.0	-
24-25	20.0	-
18	-	5.5
20	-	7.0
24	-	10.0
28	-	13.0

The Phase II log reduction plots also depart from the Phase I data at the applied doses of 24 and 28 mg/L. This can be attributed to the tailing effect observed in the effluent bacteria concentration plots and to the dilution of the untreated bacteria concentrations during wet weather events. The Phase II data for doses of 24 and 28 mg/L include data from wet weather events no. 3 and 5. In these events, the mean influent fecal coliform, for example, was only 1.06E+05 and 8.32E+05 respectively versus an average dry weather concentration of 4.3E+06.

So for similar treated effluent concentrations, the log reduction may be lower due to dilution of the influent.

Table 9 summarizes the estimated Cl_2 dose required to achieve corresponding bacterial concentrations of 1,000 cfu/100 mL and 3- and 4-log bacterial reductions. These doses were based on the results of Phase I and Phase II. The Phase II dose required to achieve the fecal coliform effluent target did not exactly match with the results of Phase I. The Phase II results for fecal coliform reduction were approximately 0.5 log less than the Phase I results. Similarly, the effluent fecal coliform concentration results were approximately 0.5 log greater than the Phase I results. These results are consistent with work previously done under US EPA supported efforts (US EPA 1975, US EPA 1979). Similar log reductions of bacteria resulted for the range of doses of Cl_2 tested under this pilot study.

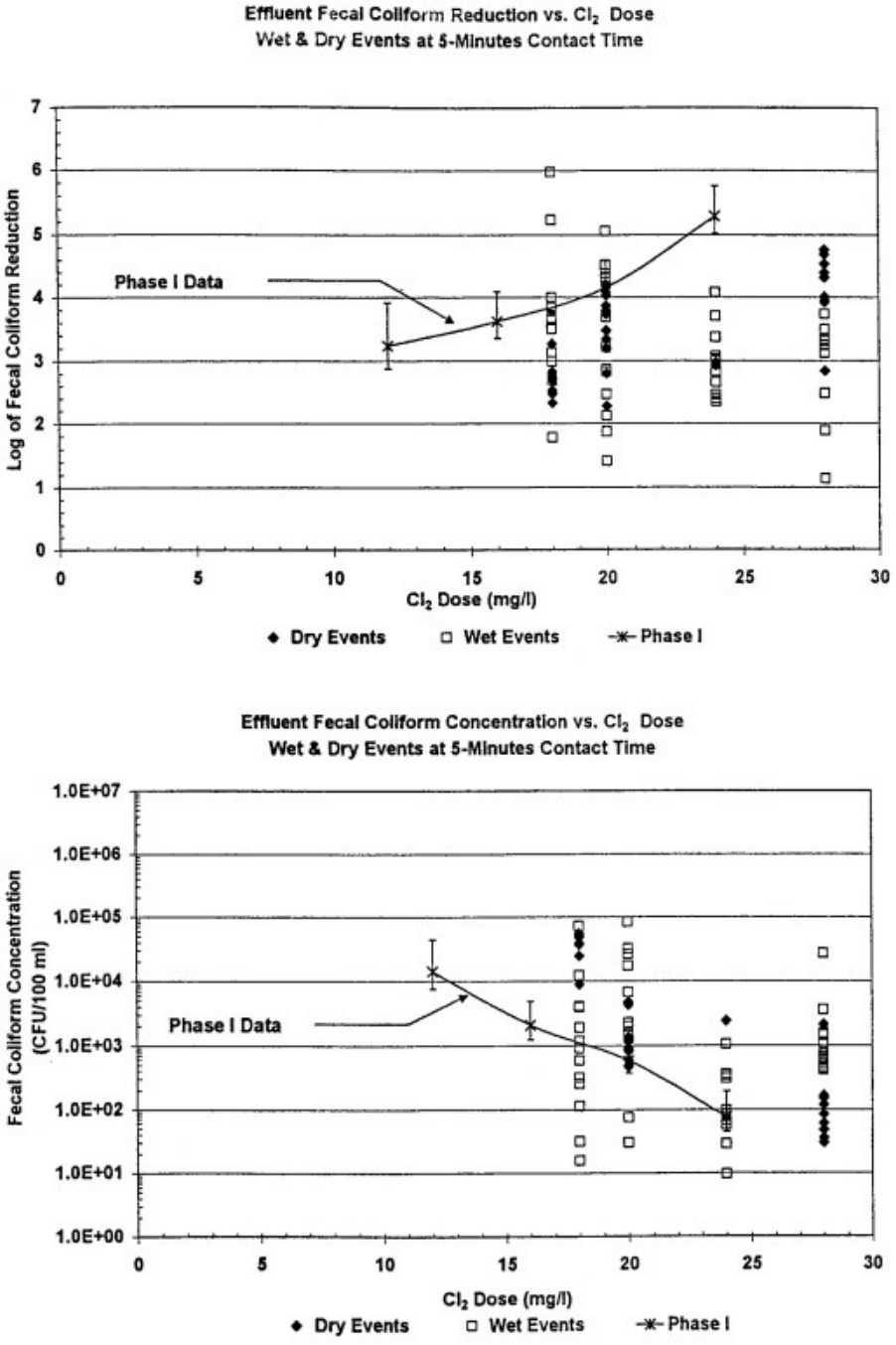
Table 9. Targeted Cl_2 doses.

Parameter	***Cl_2 Dose (mg/L)***		
	1,000 cfu/100mL	***3-log reduction***	***4-log reduction***
Total Coliform	N/A	25	N/A
Fecal Coliform	20	12	20-28
Escherichia coli	17-22	12	20-28
Enterococcus	>22-28	>22-28	N/A

Water Quality Relationships Generally, disinfection performance is dependent upon wastewater characteristics such as SS, ammonia, and BOD. Many constituents found in wastewater limit disinfection by either exerting a Cl_2 demand or shielding bacteria from contact with Cl_2. Suspended solids limit the exposure of embedded bacteria by shielding them from contact with the disinfectant. Plots of SS concentration versus log reduction and log concentration of fecal coliform for the different doses are shown in Figure 12. These relationships show that there is no apparent trend between disinfection effectiveness and SS. This is particularly evident at a dose of 24 mg/L for SS concentrations ranging from 200 to 500 mg/L.

Residual chlorate and chlorite concentrations were evaluated to determine if there was a trend between these residuals to sodium hypochlorite dose and the relative concentrations of these byproducts. Only a small percentage of the sodium hypochlorite remained in the form of chlorite, and essentially all of the sodium hypochlorite was converted into chlorate. Chlorate concentration increased with increasing dose hypochlorite concentrations. These chlorate concentrations are much higher than the chlorate concentrations measured during Phase I. In some cases the chlorate concentrations represent more than 80% of the sodium hypochlorite dose concentrations.

Figure 11. Chlorine dose-response relationships for fecal coliform data.



Oxidation-reduction potential versus Cl_2 dose and TRC relationships were developed to determine the practicality of using ORP technology to control disinfection dosing processes. ORP is not very sensitive to changes in chlorine residual at the levels required for CSO disinfection. For the range and magnitude of the TRC values measured during Phase I and Phase II for Cl_2/deCl_2, ORP probes did not appear to work effectively because of the lack of sensitivity at higher TRC values.

In general, the concentration of the haloacetic acid compounds increased after disinfection with Cl_2; however, the magnitude of this increase was very small (on the order of 10 to 50 ug/L). Bromochloroacetic acid and dichloroacetic acid were the haloacetic acid compounds with the greatest increase in concentration after disinfection. However, the absolute magnitude of these concentrations is low. The US EPA's ECOTOX database did not contain information regarding bromochloroacetic acid but did include LC_{50} results for dichloroacetic acid. The LC_{50} results for dichloroacetic acid based on freshwater fish test species was on the order of 5 mg/L. It is important to note that the toxicity data provided in the US EPA's ECOTOX database are from single chemical exposures, and therefore, do not reflect synergistic affects with other chemicals. Additionally, they may be the result of different experimental designs. A few semi-volatile and volatile organic compounds appeared to be produced during the Cl_2 disinfection process. These compounds are listed in Table 10. Again, the absolute magnitude of these concentrations is low, and it is unlikely that these compounds will exceed discharge criteria or play a role in effluent toxicity because of the very low concentrations. Over 78 haloacetic acids, and semi volatile and volatile organic compounds were measured during the Phase II pilot study. Table 12 presents only the compounds that increased after disinfection with Cl_2 for one or more runs.

5.4 Toxicity

Due to operational problems with the UV-chlorite ClO_2 generator, the ClO_2 effluent toxicity data for test runs no. 2 through 6 are not qualified. During these test events, the ClO_2 feedstock from the UV-chlorite generator was high in chlorite and the ClO_2 strength could not be determined accurately (Santos et al., 2000). This resulted in effluent wastewater chlorite concentrations as high as 55 mg/L and high chlorite likely was a significant contributor to effluent toxicity. As reported in the US EPA ECOTOX database, chlorite exhibits chronic toxicity to opossum shrimp at an LC_{50} of 0.6 mg/L. Since the high chlorite levels were due to equipment operational problems, the toxicity observed during these runs may not be indicative of ClO_2 itself or of a properly operating ClO_2 generator. To account for this, an additional ClO_2 test event (test event no. 9) was performed using the CDG Inc., Cl_2 (gas)/sodium chlorite (solid) generator.

Toxicity to opossum shrimp or sheepshead minnow in the untreated influent wastewater was observed in runs no. 1, 4, and 5 with LC_{50} values ranging from 66 to 76% (Santos et al., 2000). Somewhat higher toxicity effects were observed in the UV and Cl_2/deCl_2 effluent for runs no. 1 and 4 (LC_{50} of 39 to 52% effluent). However, when compared to the variability observed in the WET results, these values are generally within the observed influent toxicity. By comparison, results of WET analyses on field duplicate samples showed a mean relative percent

difference
(RPD) between duplicates of 24%. The WET data for runs no. 2 and 7 show a slight toxic effect for the UV and Cl_2/deCl_2 effluents compared to no toxicity on the influent wastewater. However again, the 95% confidence intervals for the data show that there may be no difference between the influent and effluent data for these samples.

In contrast to the UV and Cl_2/deCl_2 effluents, the ClO_2 effluent did show significant toxicity to opossum shrimp in runs no. 1, 2, 6, and 7 as compared to influent toxicity. LC_{50}s in these test events ranged from less than 6% effluent up to 26% effluent. This could not be attributed to influent toxicity, which had an LC_{50} of 82% effluent for run no. 1 and greater than 100% effluent for runs no. 2, 6, and 7. It is believed that the toxicity of the ClO_2 effluent observed during this test runs was at least partially due to the high chlorite levels mentioned previously. This was assessed by plotting relative toxicity (i.e., influent LC_{50} minus effluent LC_{50}) of the ClO_2 effluent versus effluent chlorite concentration. A strong correlation between chlorite concentration and effluent toxicity was observed. One anomaly is apparent in this trend; no toxicity was observed in the effluent sample with the highest chlorite concentration (55 mg/L). This data point is probably erroneous. The Cl_2 (gas)/sodium chlorite (solid) generator was used in the toxicity analyses for test event no. 9. In this test event, the effluent chlorite concentration varied from less than 0.2 mg/L up to a maximum of 5.8 mg/L, and no toxicity was observed in the WET tests up to a ClO_2 dose of 10 mg/L. Therefore, it appears the effluent toxicity observed in prior test runs was related to high chlorite concentrations resulting from an improperly operating generator.

The field microtox data may still be used to identify relative trends in toxicity within a CSO event. One can see two trends in this data. First, the influent wastewater generally shows higher mortality than the UV effluent and similar, though in some cases higher, mortality as the Cl_2/deCl_2 effluent. This indicates that the toxicity observed in these effluents is most likely associated with that of the untreated wastewater. Second, the ClO_2 effluent overall shows higher mortalities than the other two pilot units or the untreated influent wastewater.

6. COST COMPARISON

During the Phase I pilot study, conceptual level cost projections were prepared for each disinfection technology for comparison purposes, with the goal of recommending a technology for implementation at the Spring Creek CSO Storage Facility. The Phase II pilot study results served to verify the Phase I result; as such, the assumptions and approach used for the original cost comparison were applicable. Costs for each disinfection technology were prepared on a common flow basis and were prepared for a range of flow rates experienced at Spring Creek CSO Storage Facility. This approach shows the sensitivity of cost to flow rate, and allows independent comparison of technology costs at similar flow rates.

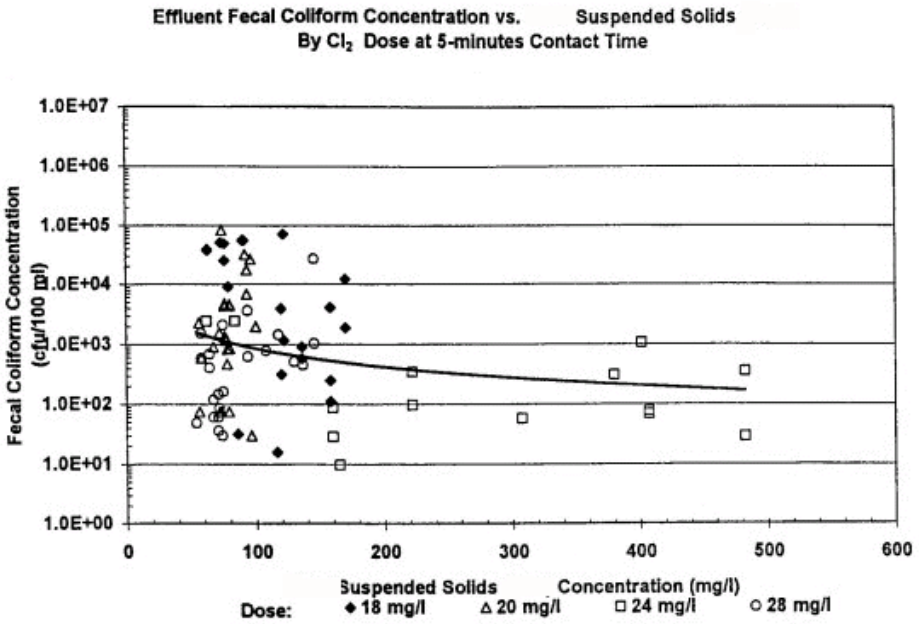
Equipment capital costs were developed for peak design flow conditions of 1,250 cfs (800 mgd), 2,500 cfs (1,600 mgd), and 5,000 cfs (3,200 mgd) for a duration of 4 hours. The 5,000 cfs flow rate represents approximately the maximum facility inflow for the 5-year storm.

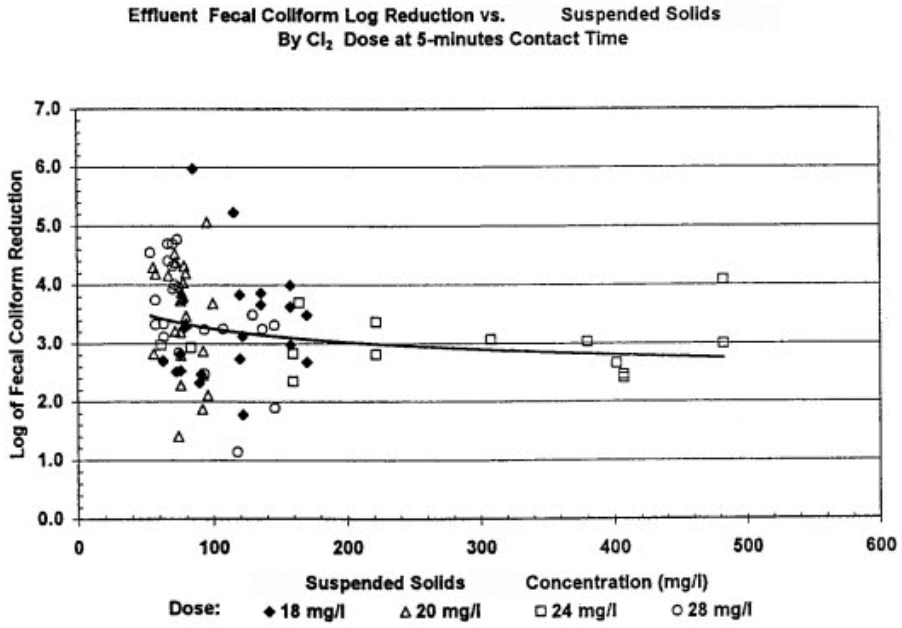
Table 10. Organic compounds concentration, chlorine effluent vs. pilot influent.

Parameter	Detection Limit (µg/l)	Concentration (µg/l)															
		Run #1		Run #2		Run #3		Run #4		Run #5		Run #6		Run #7		Run #8	
		Infl.	Eff.	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
VOCs:																	
Bromodichloromethane	10	ND	ND	ND	3.5	ND	ND	ND	10	ND	22	ND	ND	ND	11	ND	ND
Dibromochloromethane	10	ND	ND	ND	1.5	ND	ND	ND	14	ND	18	ND	ND	ND	18	ND	ND
Bromoform	10	ND	ND	ND	0.9	ND	ND	ND	12	ND	ND	ND	ND	ND	14	ND	ND
Chloroform	10	ND	ND	ND	10	ND	ND	ND	ND	ND	18	ND	ND	ND	ND	ND	ND
SVOCs:																	
4-Methylphenol	10	ND	22	ND	ND	ND	ND	ND	4	ND	ND	ND	ND	ND	ND	ND	10
Benzoic Acid	10	ND	69	ND	ND	ND	ND	3	23	ND	ND	ND	ND	ND	ND	ND	71
HAAs:																	
Bromochloroacetic acid	1	ND	ND	1	6	1	10	1	7.4	1	20	1	12	1	23	1	17
Dibromoacetic acid	1	1	1	1	1	1	11	1	1	1	4	1	3	1	9	1	6
Dichloroacetic acid	1	10	35	4	27	1	22	5	64	1	42	1	38	9	52	7	54
Monobromoacetic acid	1	1	1	1	1	24	2	1	2.6	1	2	1	1	1	1	1	1
Monochloroacetic acid	1	3	1	1	1	1	1	3	2	1	1	1	5	1	1	1	1
Trichloroacetic acid	1	17	19	7	14	2	6	9	10.4	4	13	4	8	12	13	9	13

Notes:
1. "Infl" and "Eff" denote pilot influent and ClO_2 pilot effluent, respectively.
2. ND denotes non-detected.

Figure12. Plots of SS concentration versus log reduction and log concentration of fecal coliform for the different doses.





The original design report for Spring Creek CSO Storage Facility (Greeley and Hansen, 1962) calculated a peak 5-year storm inflow of 3,750 cfs. However, this flow rate was based upon a runoff coefficient of 0.65. As identified by CDM in the Spring Creek Stabilization Study (1990), a more realistic runoff coefficient would be 0.90 - 0.95.

This would result in a peak inflow of approximately 5,000 cfs. This flow rate and selected duration are also consistent with inflows observed during the Stabilization Study. The lower flow conditions were selected at reasonable fractions of the 5-year condition. Operating costs were developed based on an estimate of approximately 40 events/year producing inflow to the Spring Creek CSO Storage Facility, at a volume of 15 million gallons (MG) treated per event. This condition was selected based upon a review of the design inflow volumes (Greeley and Hansen, 1964).

Costs were developed for UV, ozone, chlorine dioxide, and chlorination/dechlorination. Due to the limited effectiveness and high power consumption of the E-Beam pilot unit, the E-beam technology as tested was not considered feasible for CSO disinfection. By comparison, the power usage for E-beam based on the pilot unit was approximately 3.5 kW/gpm (or 2,430 kW/mgd) while the power usage for UV at 4-log reduction was 0.0325 kW/gpm (or 22.6 kW/mgd). Therefore, since the E-beam technology was not considered feasible for CSO, costs were not developed for the technology. The cost projections were developed for a 4-log reduction of fecal coliform and included the following process options:

- UV - Medium-pressure, high-intensity lamps
- Ozone - Oxygen feed ozonation with eductor or side stream venturi type mass transfer configuration
- Chlorine Dioxide - High-rate mixing, generation of ClO_2 using the chlorine (gas)/sodium chlorite (solid) process, with onsite generation of chlorine gas via the acidification of NaOCl with HCl, use of emergency gas scrubber for potential chlorine gas, and 5 minute contact time (provided by existing basins at approximately 5,000 cfs)
- Chlorination/Dechlorination - High-rate mixing, use of 15% sodium hypochlorite and 38% sodium bisulfite, and 5 minute contact time (provided by existing basins at approximately 5,000 cfs)

The cost projections are shown in Table 11. The table presents estimated capital, annual O&M, and total annualized costs. Annualized costs were prepared on the basis of a 20-year period at an 8 percent discount rate. The capital costs only include the costs for the basic process equipment associated with each technology and do not include:

- The construction of additional basin tankage or structures for contact/disinfection,
- Modifications to the existing basins,
- Building expansion to house disinfection equipment,
- Support equipment or facilities, for example: additional power supply equipment, HVAC equipment, and plumbing equipment

As shown in Table 11, chlorination/dechlorination and chlorine dioxide are significantly less costly than either UV or ozone. Due to the intermittent nature of CSOs, disinfection

technologies like chlorination and chlorine dioxide, which are less capital intensive with higher O&M costs are favored over high capital cost technologies with lower O&M costs.

It is important to note that for other CSO facilities, the cost for construction of disinfection contact tanks for the chlorination/dechlorination and chlorine dioxide alternatives would need to be considered and may make UV somewhat more attractive. It is also important to note that the cost of contact tankage for chlorine dioxide could be almost 40% less than chlorination/ dechlorination. This difference is attributed to chlorine dioxide's greater bactericidal properties and solids penetration characteristics than those of chlorination, as demonstrated during the contact time analysis performed for the Phase II contact time.

Chlorine dioxide cost projections were developed using the demonstrated chlorine (gas)/sodium chlorite (solid) process. This system was chosen as more reliable for cost projections because it is in use at a number of full-scale installations. Because the UV-chlorite chlorine dioxide generator is currently in the prototype status, costs using this technology were not developed.

7. CONCLUSIONS

7.1 Wastewater Quality

During the Phase I and Phase II pilot studies five disinfection technologies, UV, ClO_2, Cl_2, O_3, and E-Beam were piloted to determine their effectiveness in reducing bacteria levels in water representative of the CSO at the Spring Creek CSO Storage Facility. These pilots were tested during wet and dry events. In general, the pilot influent water quality was variable but representative of CSO water quality from the Spring Creek CSO Storage Facility. The variation in wastewater temperature between Phase I (mean of 11.6 ^{o}C) and Phase II (mean of 20.9 ^{o}C) is believed to have had a significant impact on the performance of Cl_2 disinfection. While the majority of CSO discharges from Spring Creek are likely to occur during the late summer and early fall months, discharges have also occurred during the winter and early spring months. Therefore, it was an added benefit to characterize the difference in performance resulting from temperature effects.

To achieve a four-log reduction of fecal coliform and fecal coliform effluent concentrations less than 1,000 colony forming units/100 mL (cfu/100 mL) required doses for UV, O_3, ClO_2, and Cl_2 of 60-80 mWs/cm^2, 24 mg/L, 8-10 mg/L, and 20-28 mg/L, respectively. The spread in disinfectant doses for each technology reflects the variation in performance between Phase I and Phase II.

Table 6-1. Cost projections.

Technology	Conceptual Level Disinfection Costs ($)											
	Chlorination/Dechlorination			Chlorine Dioxide			Ozone			UV		
Peak Design Flow (cfs)	1,250	2,500	5,000	1,250	2,500	5,000	1,250	2,500	5,000	1,250	2,500	5,000
Capital Costs	912,000	1,045,000	1,219,000	695,000	1,159,000	1,932,000	19,221,000	24,560,000	30,539,000	48,052,000	67,272,000	87,774,000
Annualized Capital Costs	93,000	107,000	124,000	70,000	119,000	196,000	1,957,000	2,502,000	3,111,000	4,894,000	6,852,000	9,592,000
Annual O&M Cost	255,000	255,000	255,000	294,000	294,000	294,000	534,000	587,000	657,000	248,000	497,000	992,000
Total Annualized Costs	348,000	362,000	379,000	364,000	413,000	490,000	2,491,000	3,089,000	3,768,000	5,142,000	7,349,000	10,584,000

Notes:

1. Costs are present worth in 2000 dollars.
2. Capital costs are based upon sizing to meet peak design flow and a 4-log reduction in fecal coliform.
3. Capital costs are for installation of Spring Creek and are for process equipment only. Costs do not Include additional contact tankage (if required) or support facilities
4. Annual operating costs are based upon an assumed typical 40 CSO events/year at a volume treated of 15 million gallons per event.
5. Annualized costs are based upon a period of 20 years at an interest rate of 8%.

7.2 Treatment Performance

Four bacteria indicators were used as a measure of the effectiveness of each of the disinfection technologies; namely total coliform, fecal coliform, Escherichia coli, and enterococcus. Kills of each of the indicators, in terms of log reduction and concentration, were related to dose for each of the disinfection technologies. Currently, there are no effluent bacteria criteria established for the Spring Creek CSO Storage Facility or for other CSO facilities. However, these targeted bacterial reductions were selected as conservative estimates of levels that could be met by the technologies and that may represent permit criteria. Generally, all the tested disinfection technologies, with the exception of E-beam, were able to effectively provide bacterial reductions of 3 to 4 logs. Chlorination/dechlorination, ClO_2, and O_3 at the doses tested were able to provide these levels of disinfection over the full range of wastewater quality tested. UV disinfection effectiveness tended to drop off at higher SS concentrations (e.g., SS greater than approximately 150 mg/L). This was attributed to lower effective penetration of UV due to harboring of bacteria in solids.

Fecal coliform and Escherichia coli exhibited similar dose-response relationships. However, total coliform and enterococcus generally required higher doses to achieve the same level of inactivation as that for fecal coliform and Escherichia coli. This was observed in all technologies except for the E-beam, where the inactivation results were inconclusive. The existing receiving water quality standards for Spring Creek and Jamaica Bay address only total and fecal coliform. However, in the future regulators may use indicator bacteria that are more specific to human waste such as Escherichia coli and enterococcus for water quality standards. In the absence of specific densities indicating health risk, this information can only be preserved for future reference at this time.

The UV and ClO_2 technologies provided nearly complete reductions of bacteriophage. However, the viral inactivation data for the ClO_2 system was limited to only two out of the four runs due to operational problems. Of the valid data considered, the effluent concentrations of bacteriophage ranged from non-detect to 60 pfu/mL. Low influent concentrations of the seeded phage limited the maximum log reduction that could be observed. The log reduction of bacteriaphage ranged from 1.9 to 6.0. Because of the low concentrations of naturally occurring enteroviruses in the pilot influent, the UV could not be evaluated satisfactorily on the basis of the tissue culture infectivity assays. However, based upon the reductions of the marginal concentrations found and upon the bacteriophage results, it is likely that theses technologies would inactivate most natural enteroviruses found in wastewater at concentrations on the order of 10^6 pfu/mL.

UV disinfection achieved 4-log bacteria reduction but at extremely high dosage levels owing to the impediments of poor water quality. UV effectiveness tended to be reduced by high SS concentrations (e.g., greater than 150 mg/L). Additionally, UV effectiveness tended not to increase at doses greater than 75 mWs/cm^2; a phenomena known as “tailing-off.”

Ozone disinfection can be accomplished but at dosage levels more than one and one-half times that of Cl_2. However, the O_3 pilot unit did not include a contactor design appropriate for

the wastewater conditions tested. Thus, the required O_3 dosages may have been less if a more applicable O_3 dissolution/contactor system were provided. An O_3 disinfection system would require contact chambers other than the tankage that presently exists at Spring Creek.

Chlorine disinfection included dechlorination to eliminate residual Cl_2. Both Cl_2/deCl_2 can be accomplished using the existing tanks at the Spring Creek CSO Storage Facility. High-rate mixing can be added to the head end of the tanks. Chlorine dioxide disinfection can be accomplished at doses on the order of 30% of the required Cl_2 dose.

Chlorination/dechlorination and ClO_2 were determined to be the most cost effective technologies for application to Spring Creek. However, neither ClO_2 generation method tested is currently feasible within New York City; the Cl_2 gas solid sodium chlorite generation method because of its use of Cl_2 gas, and the UV-sodium chlorite generation method because of its developmental status as a prototype. The capital costs for UV and O_3 were significantly more expensive than Cl_2/deCl_2 or ClO_2. For other CSO facilities that do not have existing tanks for contact time, UV could be somewhat more cost competitive.

In the case of ClO_2, there is no significant increase in disinfection performance beyond a contact time of 3 min. This is in contrast to the chlorination results, which show a greater dependence on contact time and required five minutes for comparable kills. The difference is attributed to ClO_2's greater bactericidal properties and solids penetration characteristics than those of chlorination. The results of this study confirm the optimum contact times for ClO_2 and Cl_2/deCl_2 of 3 and 5 min respectively, originally determined in the Syracuse and Rochester studies (US EPA, 1979a and 1979b). Chlorination/dechlorination and ClO_2 were determined to be the most cost effective technologies for application at this facility. Further development of the UV-chlorite ClO_2 generator is required before reliable costs for this technology can be developed.

Comparison of the dry weather performance data for single and two-stage mechanical mixing configurations for chlorine disinfection implied a slight increase in disinfection effectiveness for two-stage mixing. The wet weather data, with its higher variability, was excluded from this comparison as it appears to have obscured the effects of 2nd stage mixing. The evaluation of single versus 2-stage mixing could not be performed for the ClO_2 system due to the limited data from the field operational problems.

7.3 Disinfection Residuals and Toxicity

Selected disinfection effluent residuals and byproducts, namely ClO_2, chlorate, chlorite, TRC, volatile and semivolatile organics, haloacetic acids, were monitored to relate these residuals to disinfectant dose. UV disinfection had the distinct advantage of producing no byproducts. This is in contrast to Cl_2 and ClO_2, which produced increased levels of TRC, chlorate, chlorite and haloacetic acids in the effluent. The slightly increased haloacetic acid concentrations were considered insignificant. The increased TRC, chlorate and chlorite concentrations were directly related to increased Cl_2 and ClO_2 dose.

No additional toxicity was observed in the UV effluent as compared to the UV pilot influent. In contrast, there were occurrences where the ClO_2 effluent was considerably more toxic than the pilot influent. An attempt was made to correlate this toxicity with the specific disinfection byproducts, in particular TRC, chlorate and chlorite, but no correlation could be made. It is likely that the increased effluent toxicity is directly related to influent toxicity (i.e., influent water quality) or a synergistic effect of the disinfectant residuals, which could not be measured. Although the concentrations of TRC, chlorate and chlorite did not cause a concern for effluent toxicity, this relationship should be revisited when establishing ClO_2 dose for specific sites.

Effluent TRC was generally below 0.1 mg/L following $deCl_2$, as compared to a receiving water quality standard of 0.0075 mg/L. This value of $deCl_2$ effluent TRC reflects the practical quantitation limit of the process instrumentation used. Lower TRC values could not be quantified. Often, the $deCl_2$ effluent TRC instrumentation displayed a negative value indicating the presence of excess bisulfite. Residual Cl_2 was also monitored in the ClO_2 effluent. However, these TRC values include all oxidizing species of Cl_2 and the possible presence of free and combined Cl_2 could not be differentiated from ClO_2, ClO_2^-, and ClO_3^-.

7.4 Chlorine Dioxide Generation

The method of generating ClO_2 must be considered when selecting the appropriate disinfection process. The chlorine gas/solid sodium chlorite generation method was tested during the Phase I and Phase II pilot studies. Although this pilot unit was reliable, the use of chlorine gas (either with chlorine cylinders or with on-site Cl_2 gas generation) in this process may limit its application in residential and urban areas, including New York City. The UV-sodium chlorite solution generation method was also tested during the Phase II pilot study. This method had the distinct advantage of not using or generating chlorine gas in the generation process. However, this technology is currently in the prototype stages of development and would need to be developed as a full-scale unit to be considered further. The UV-chlorite generator from the UVD Inc., was a prototype unit.

8. SUMMARY

Pilot testing of disinfection technologies on CSO wastewater, as part of the upgrade to the Spring Creek CSO Storage Facility, was performed in two phases. Phase I was performed over 16 pilot test events from December 1996 through March 1997. This testing evaluated the performance of five high-rate disinfection technologies: UV, O_3, ClO_2, $Cl_2/deCl_2$, and E-Beam. The results from Phase I were presented in a final report dated November 1997. The purpose of the Phase II pilot testing was to address data gaps identified in the Phase I study, provide additional wet-weather data, and perform additional research that was beyond the scope of the original study. The Phase II pilot program was performed from August through November 1999 and evaluated the performance of disinfection with UV, ClO_2, and $Cl_2/deCl_2$.

Influent and effluent from each pilot unit were analyzed by a certified laboratory for

bacterial and conventional wastewater quality parameters: VOC's, SVOCs, HAAs, and toxicity. Four indicator bacteria were used as a measure of the effectiveness of each of the four disinfectant technologies: total coliform, fecal coliform, Escherichia coli, and enterococcus. Bacteria kills for each of the indicator bacteria, in terms of 3 to 4 log reduction, were related to dose for each of the four technologies.

Based upon the technologies evaluated in these pilot studies, only Cl_2/deCl_2 was recommended for CSO disinfection at the Spring Creek CSO Storage Facility and other New York City CSO facilities. While ClO_2 was superior in effectiveness and similar in cost to Cl_2/deCl_2, the generation technology for ClO_2 which avoids the need for gaseous Cl_2 needs further development. Because an effective Cl_2-gas-free process of ClO_2 generation has not been proven to be reliable and, because Cl_2 gas cannot be transported within New York City, disinfection with ClO_2 cannot be recommended for use within New York City at this time. However, the City and its engineers should remain apprized of advances in alternative disinfection technologies, such as UV-chlorite ClO_2 generation. These advances may make these technologies more effective, both in terms of cost and disinfection effectiveness.

While UV and O_3 treatment were technically viable, the study showed that, given the intermittent nature of CSO treatment and the high peak flows involved, the high capital cost of these technologies makes them cost prohibitive. Electron beam disinfection did not meet the treatment goals.

The original, detailed reports from the two studies, Phase I and Phase II, were produced in 1997 and 1999 by CDM of Woodbury, New York, and CDM's Subcontractor Moffa & Associates, a unit of Brown & Caldwell, of Syracuse, New York, for the NYCDEP and the US EPA (Urban Watershed Management Branch, Edison, New Jersey). Funding for the studies was provided by NYCDEP (NYCDEP Capital Project No. WP-225) and partial funding for Phase II only was provided by US EPA (US EPA Purchase Order No. 7C-R394-NTLX). Partial funding for Phase I only was provided by New York Power Authority (NYPA) and the Electric Power Research Institute, both of New York City, New York.

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