



# Combined Sewer Overflow Technology Fact Sheet Chlorine Disinfection

## DESCRIPTION

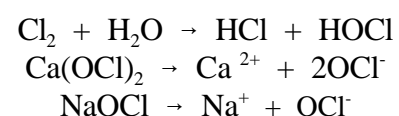
Combined sewer overflows (CSOs) tend to occur during periods of rainfall or snowmelt, when total wastewater flows exceed the capacity of the combined sewer system (CSS) and/or treatment facilities. When this occurs, the CSS is designed to overflow directly to surface water bodies, such as lakes, rivers, estuaries, or coastal waters. These overflows can be a major source of water pollution in communities served by CSSs.

CSOs typically discharge a variable mixture of raw sewage, watershed runoff pollutants, and scoured materials that build up in the collection system during dry weather periods. These discharges contain pollutants that may adversely impact the receiving water body. These pollutants range from suspended solids, pathogenic microorganisms, viruses, and cysts, to chemical and floatable materials. Dermal contact with the discharge or ingestion of water or contaminated shellfish may result in health risks.

Consistent with the U.S. Environmental Protection Agency (EPA) 1994 CSO Control Policy, cities with CSSs are implementing controls that will provide for attainment of water quality standards that protect the beneficial use of streams and other receiving water bodies. To help meet site-specific bacterial water quality standards, pathogenic bacteria in the CSO discharge will most likely require inactivation or destruction. The process of selective inactivation and/or destruction of pathogenic microorganisms is known as disinfection.

CSO disinfection occurs through the reduction of solids and through the oxidation or radiation of pathogens. Physical reduction of bacteria in CSOs is accomplished through sedimentation, flotation and filtration, while common chemical oxidizing agents include chlorine, bromine and hydrogen peroxide or their compounds. In addition to chemical oxidants, there are several alternative disinfectants, such as ultraviolet light (UV) radiation and ozonation. These are further described in the EPA CSO Technology Fact Sheet 832-F-99-020, Alternative Disinfectants for Treating CSOs. The remainder of this fact sheet focuses on chlorine as a CSO disinfectant.

Chlorine may be applied to a CSO in either a gaseous form ( $\text{Cl}_2$ ) or as an ionized solid [ $\text{Ca}(\text{OCl})_2$ ,  $\text{NaOCl}$ ]. Each compound reacts in water to produce the disinfectants  $\text{HOCl}$  (hypochlorous acid) and  $\text{OCl}^-$  (hypochlorite ion) as illustrated in Figure 1. Together, these compounds contribute to what is known as the CSO's free residual chlorine concentration. As chlorine is added to the CSO, it reacts with ammonia and organic matter to form chloramines and chloro-organic compounds. The addition of more chlorine oxidizes some of the chloro-organic compounds and chloramines, resulting in the conversion of monochloramines to dichloramines and trichloramines.



**FIGURE 1 COMMON REACTIONS OF  
CHLORINE PRODUCTS**

As more chlorine is added, the residual chloramines and chloro-organic compounds are reduced to a minimum value and free chlorine residuals result. The point at which the formation of residual chlorine compounds occurs is known as the "breakpoint." Thus, the term "breakpoint chlorination" describes the process whereby sufficient chlorine is added to the CSO to obtain a free chlorine residual. If sufficient chlorine cannot be added to achieve the breakpoint reaction and thus ensure that disinfection of the CSO is occurring through saturation with chlorine, care should be taken to ensure that disinfection is occurring through extended chlorine contact time with the CSO (see discussion of the relationship of disinfection dose vs. contact time below).

Various theories have been put forth to explain the germicidal effects of chlorine. These include oxidizing the germ cells, altering cell permeability, altering cell protoplasm, inhibiting enzyme activity, and damaging the cell DNA and RNA. Chlorine appears to react strongly with lipids in the cell membrane, and membranes having high lipid concentrations appear to be more susceptible to destruction. For this reason, viruses, cysts, and ova are more resistant to disinfectants than are bacteria.

The predominant disinfection mechanism will depend on the microorganism in question, the wastewater characteristics, and the chlorine compound used. When the physical parameters controlling the chlorination process are held constant, the germicidal effects of chlorine as measured by bacterial survival depend primarily on dosage (and form) and the contact time. It has been found that increasing either dosage or contact time, while simultaneously decreasing the other, can achieve approximately the same degree of disinfection. When breakpoint chlorination is practiced properly, the bactericidal effect is considered good and viricidal effect is considered moderate.

## **APPLICABILITY**

The selection of a disinfection method for a specific CSO outfall depends on many factors, including: the quality of the wastewater being discharged; any potential toxic effects; the ease of operation and

maintenance; and any regulations governing residual standards.

As discussed above, the disinfection capability of a system is heavily dependant on the contact time between the chlorine and bacteria. Because suspended solids can inhibit the disinfecting agent from reacting with the bacteria, disinfection is usually used in conjunction with an additional technology that specifically reduces the suspended solids in solution.

## **DESIGN CRITERIA**

CSO disinfection systems must be designed to handle variable pollutant loadings and large fluctuations in flow. Because CSOs are intermittent and are characterized by short durations and relatively large flow rates relative to base sewage flow, bacterial and organic loadings from the collection system may vary greatly, both within and between storm events. Loadings can be extremely variable from the beginning to the end of a wet weather event. The beginning of a CSO event will typically exhibit high solids and bacterial loadings as the system is flushed. The concentration of pollutants will typically trail off as the storm event continues. Loadings will also be affected by the characteristics of the watershed, the dynamics of the collection system, the antecedent dry weather conditions, and the regional rainfall rate. A CSO disinfection system should be designed with site-specific loading characteristics in mind, and should be capable of handling a large first-flush pollutant load.

The intended or designated use of the receiving water body may also affect the disinfection process design. For example, the presence of sensitive aquatic species may limit the allowable residual disinfectant concentrations in the receiving water, thereby limiting the amount of disinfectant that can be added to the CSO.

An additional baseline consideration for the successful design of a CSO disinfection process is solids reduction. Since bacteria embedded in particulate matter can be shielded from the disinfectant, solids must be removed from the CSO to ensure effective disinfection. Therefore, even if

the water quality requirements for the receiving water body do not dictate the need for solids reduction, the disinfection process itself may require it.

After these general considerations are resolved, the designer can begin to evaluate specific disinfection processes to determine which potential processes may be most appropriate. Generally, disinfection processes can be broken into “high rate” processes and extended detention processes. High rate processes using breakpoint chlorination (described above) are often chosen over extended-detention systems because the cost differences between the systems are minor (the two systems have similar capital costs, but the high rate systems often incur additional O&M costs for chemicals and power), and the decreased retention time characteristic of the high rate processes makes them more attractive.

In order to design a breakpoint chlorination system, it may be necessary to determine the amount of time that the chlorine must be in contact with the CSO to achieve the desired disinfection. This “contact time,” or CT, relationship should be developed for treatment of the design CSO event for a significant antecedent dry weather period. This will likely provide worst case conditions for determining vessel size and disinfectant supply rate.

The reactor should be designed for as close to ideal plug flow as possible and should include effective initial mixing of the chlorine solution. Strong initial mixing is critical in high rate disinfection processes where contact times are short. Mixing occurs through mechanical means (mixers, pumps, spargers) or through the utilization of the energy available in the storm water gradient (hydraulic jumps, flumes, high velocity segments).

As discussed above, control of the chlorine disinfection process for CSOs is complicated because of the highly variable nature of the flow. Measurement of the CSO flow rate is therefore critical in determining the rate at which to add disinfectant. Often a combination of weirs or flumes (for lower flows) and open channel flow measurement (for high flows) is required to cover the varying flow rates. Sonic devices, bubblers, and

pressure-type level sensors have all been used in conjunction with flumes, weirs and open channels to measure CSO rates and volumes. In addition, because CSO chlorine disinfection will typically include short contact times (one to ten minutes), be applied to relatively dirty water, and operate intermittently, the use of feedback systems and chlorine residual analyzers to pace the chemical feed is difficult. Membrane and probe type chlorine monitors have been used, but neither has been proven to date to be effective and reliable.

A flow-paced control system with a fixed chlorination feed concentration has been found to be simpler and more reliable than feedback-based systems, although flow-paced systems will require some trial and error adjustment after installation to develop proper dosage-to-flow relationships. Chlorine feed rate is based on the required dosage and the flow rate.

The flow-paced system may result in higher chlorine residual concentrations relative to feedback-based systems. While these higher residual concentrations may be more effective at inactivation of viruses, spores and cysts, these residuals and their various chlorinated byproducts can have an adverse impact on the quality of the receiving waters. Although chlorine dissipates rapidly downstream of the application point, in some cases it may be necessary to dechlorinate the disinfected effluent to protect the receiving water bodies. Gaseous sulfur dioxide or liquid sodium bisulfite can be used for this purpose and dechlorination is achieved at almost instantaneous contact times. Control system difficulties similar to those described for the flow-paced chlorination system can lead to overdosing of dechlorination chemicals.

Several chlorine forms can be used to provide disinfection. When choosing a form of chlorine for a specific application, consideration should be given to safety, stability, availability, deodorizing ability, corrosiveness, solubility and ability to respond instantaneously to initiation and rate changes.

Because of concerns over accidental releases in developed areas or from unstaffed facilities, gaseous chlorine is not utilized as frequently in CSO applications as is liquid chlorine. However, gaseous

chlorine may be appropriate for use in CSO treatment facilities that are located at Wastewater Treatment Plants (WWTPs) because the chlorine application can be carefully monitored. Gaseous chlorine-based systems will require evaporator equipment and potable water, and possibly chemical scrubbing facilities.

The most common forms of chlorine used in CSO applications are chlorine gas, sodium hypochlorite, and calcium hypochlorite. The following paragraphs describe these compounds in more detail.

Liquid forms of chlorine appear to be the most appropriate choice for wet weather treatment because they are comparatively easy to handle relative to other forms of chlorine, such as gaseous chlorine. In general, liquid chlorine will be applied from on-site chemical storage tanks using metering pumps. Because of potential problems in delivering liquid chlorine to remote sites after suppliers' hours, chlorine should be stored on-site. The chlorination system should have adequate on-site storage capacity to feed the design dosage for the design overflow event. Extra volume may also be stored to allow for chemical degradation. Feed equipment should be sized to deliver the required dose under peak flow conditions. Consideration of the time required to replenish chlorine should be factored into sizing of storage tanks.

#### **Chlorine gas:**

Gaseous chlorine ( $\text{Cl}_2$ ) is relatively inexpensive and has the lowest production and operating costs for large continuous disinfection operations. It is a stable compound which may be stored for an extended period of time, but only as a liquefied gas under high pressure. Storage containers vary in size from 150 pound cylinders to 55 ton tank cars. The size of the storage containers used at any given site will be dependent upon the facility design as well as the anticipated treatment capabilities of the system. Because chlorine gas is hazardous, it should not be stored in areas accessed by the public and any transportation of the gas should be continuously monitored. Chlorine gas is extremely toxic and corrosive and because it is such a strong oxidant, it reacts with almost any organic material found in

wastewater. Organics, ammonia, and phenolic compounds will often react with the chlorine before it has a chance to react with pathogens. For example, chlorine reacts with ammonia to form chloramines and phenols to form chlorophenols. Chloramines and chlorophenols are referred to as combined chlorine residuals and together with free chlorine residuals constitute the total residual chlorine (TRC). Therefore, use of chlorine gas should be closely monitored to ensure its effectiveness as a disinfectant.

#### **Sodium hypochlorite:**

Chlorine may also be supplied as sodium hypochlorite ( $\text{NaOCl}$ ), otherwise known as liquid bleach. Sodium hypochlorite can be generated from sodium hydroxide and chlorine, or it can be generated electrolytically from brine. Sodium hypochlorite can be manufactured on site, or it can be purchased in liquid form generally containing 3 to 15 percent available chlorine. Decay of the original product will occur as a result of exposure to light, an increase in temperature, or because of concentration of the compound. Product decay occurs more rapidly at higher concentrations; therefore sodium hypochlorite is typically stored as a 5 percent solution of available chlorine. Sodium hypochlorite should be stored at temperatures below 85 degrees Fahrenheit in a corrosion-resistant tank. Sodium hypochlorite is the most expensive of the three forms of chlorine compounds. It produces a free chlorine residual, and forms chloramines and chlorophenols. Sodium hypochlorite is safer to handle than gaseous chlorine, and can be generated and stored on site.

#### **Calcium hypochlorite:**

Chlorine may be supplied in the form of calcium hypochlorite,  $\text{Ca}(\text{OCl})_2$ , in either wet or dry form. High grade calcium hypochlorite contains at least 70 percent available chlorine, and is readily soluble in water. It is a strong oxidizer and is extremely hazardous. Calcium hypochlorite tends to be unstable and therefore should be stored in a dry place inside a corrosion-resistant container in order to reduce product breakdown. Like chlorine gas and sodium hypochlorite, calcium hypochlorite breaks down into free chlorine residuals and will

react to form chloramines and chlorophenols. Calcium hypochlorite is more expensive than chlorine gas and will degenerate as a result of storage. Calcium hypochlorite also crystallizes and can clog pipes, pumps, and valves.

## ADVANTAGES AND DISADVANTAGES

A long record of historical data has shown that chlorine is the best and most successful means of disinfecting water. Clean drinking water is a global necessity and the residual addition of chlorine to water in controlled amounts prevents the spread of life-threatening diseases and the growth of living organisms.

However, chlorine disinfection also has its disadvantages. Numerous toxicity studies have shown adverse effects due to chlorination (Rein, 1992; Hall, 1981; Ward, 1978). Any discharge of chlorinated effluent into a receiving water body may involve some release of chlorine residuals and chlorine byproducts. Free chlorine and combined chlorine residuals are toxic to aquatic life at certain concentrations. The lethal effects of free chlorine are more rapid and occur at lower concentrations than chloramines. Chlorine will also react with organic material to form trace amounts of chlorinated hydrocarbons called trihalomethanes (THMs). THMs are suspected as being carcinogens and are strictly monitored in drinking water.

Environmental variables affecting the toxicity of residual chlorine include pH and temperature of the receiving water. Due to increases in available free chlorine, toxicity increases with decreasing pH. Toxicity also tends to increase with increasing temperature. Mean acute toxicity values for several species are given in Table 1.

Intermittent discharges of total residual chlorine have been recommended not to exceed 0.2 milligrams per liter for a period of 2 hours per day where more resistant species of fish are known to persist, or 0.04 milligrams per liter for a period of 2 hours per day for trout or salmon (Brungs, 1973). In addition, chlorine may inadvertently enhance the growth of pathogenic microorganisms in receiving waters, since chlorine breaks large protein molecules into small proteins, peptides, and other

**TABLE 1 ACUTE VALUES FOR CHLORINE TOXICITY**

Species	Mean Acute Value ( g/l)
<b>Freshwater</b>	
Daphnia magna	27.66
Fathead minnow	105.2
Brook trout	117.4
Bluegill	245.8
<b>Saltwater:</b>	
Menidia	37
Mysid	162

Source: U.S. EPA, 1985.

amino acids that can be more readily used by coliform bacteria.

Using chlorine as a disinfectant does have certain health and safety limitations that should be evaluated before implementing any CSO plan. The transport of chlorine can pose serious hazards and in some states, transport of chlorine is severely restricted. Some of the health risks include:

- Irritation of mucous membranes, respiratory tract and eyes.
- Prolonged exposure to the gas may cause coughing, gagging, and may result in pulmonary edema and death.
- Gaseous chlorine has a tendency to hydrolyze in the presence of moisture, forming hydrochloric acid, which irritates the eyes and skin.
- Liquid chlorine removes body heat, freezing exposed skin.
- It should be noted, however, that sodium hypochlorite is considered to be safe for storage and handling in systems for remote disinfection of CSOs, and there is currently no definitive scientific evidence that the intermittent use of chlorine for CSO disinfection poses a significant environmental risk.

## PERFORMANCE

The performance of a CSO disinfection system depends on its ability to kill bacteria, viruses, and other pathogenic organisms. In CSOs with low suspended solids concentrations, pathogens are killed with a quick dose of disinfectant. However, when suspended solids concentrations in the CSO are high, the disinfection process is controlled by two different mechanisms. The initial disinfection phase kills individual and small clumps of bacteria. The majority of the bacterial kill occurs in this step; however, residual bacteria entrapped in solids are usually not affected. The amount of bacteria remaining in the CSO after the initial disinfectant dose is a function of the concentration of suspended solids and their particle sizes. If low levels of bacteria are required to meet the treatment objectives, the disinfection process may require a higher level of solids removal, longer contact times, or larger disinfectant dosages to kill these remaining bacteria. The first two of these options will require larger treatment vessels.

Disinfection performance is often assessed through changes in concentrations of indicator organisms (primarily fecal and total coliform) over time. This assessment is often made using mathematical equations that predict future concentrations of indicator organisms based on system-specific variables. For example, the Collins model predicts the reduction in bacterial concentration as a function of chlorine residual concentrations and system contact time according to the following equation:

$$Y_t = Y_o (1 + 0.23CT)^{-3}$$

where:

$Y_t$  = bacterial concentration after time T (MPN/100ml)

$Y_o$  = original bacterial concentration (MPN/100ml)

C = chlorine residual concentration after time T (mg/l)

T = contact time (min)

At lower values of CT, a modified model (Collins-Selleck) was developed to define the relationship between  $Y_t/Y_o$  and CT. Several other factors, including the chlorine dose, contact time, flow characteristics, and mixing intensity, also influence the effectiveness of chlorine disinfection.

As described above, the effectiveness of chlorine in disinfecting CSOs is usually measured in terms of its effect on reducing fecal coliform or total coliform bacteria. Table 2 presents the results of several studies that evaluated the effectiveness of chlorine gas in reducing pathogens from CSOs and simulated CSOs.

## OPERATION AND MAINTENANCE

Maintenance for a CSO treatment facility is typically performed similarly to maintenance performed at a batch operation. Properly designed facilities will operate automatically; however, after a storm event, most facilities will require maintenance to remove residuals (screenings, floatables & grit) and to check and replenish chemical supplies. Maintenance of disinfection equipment can occur during the post-event visit and includes the following:

- All copper tubing from lines and fittings must be checked routinely. The lines can be checked for corrosion by bending them; if the lines give off a screeching noise when they are bent, they are corroded and the tubing must be replaced.
- Tubing and vessels should be checked routinely for moisture accumulation or metal discoloration, both of which are signs of incipient leak development.
- Evaporator vessels should be inspected for sludge accumulation either every year or after every 200 tons of chlorine use. Piping and connections to the evaporator should be inspected every six months.

**TABLE 2 SUMMARY OF Cl<sub>2</sub> DISINFECTION DATA FROM STUDY LOCATIONS**

Location	Dosage Cl <sub>2</sub>	Total Coliform Reduction	Fecal Coliform Reduction	Other	Contact Time
Philadelphia <sup>1</sup>	5 mg/l	before: 1,000,000 units/100 ml after: 5-10 units/100 ml	before: 1,000,000 units/100 ml after: 5-10 units/100 ml		
Philadelphia <sup>1</sup>	2.6 mg/l	99.9% reduction			3 min.
Philadelphia <sup>2</sup>	5 mg/l		<200 units/100 ml		4 min.
Grosse Point Woods, Michigan <sup>3</sup>	8.0-10.8 mg/l	4 log reduction	4 log reduction		6 min.
Grosse Point Woods, Michigan <sup>3</sup>	1-5 mg/l	3-4 log reduction	3-4 log reduction		2 min.
Lake Onondaga, New York <sup>4</sup>	25 mg/l	1000 units/100 ml	200 units/100 ml	200/100 ml fecal strep 5 log reduction poliovirus & Sabin K-1 5 log reduction coliphage	2 min.
Lake Onondaga, New York <sup>4</sup>	25 mg/l			200 units/100 ml Fecal Strep	2 min.
Lake Onondaga, New York <sup>4</sup>	16 mg/l	1000 units/100 ml			
Lake Onondaga, New York <sup>5</sup>	0-24 mg/l 12 mg/l 12 mg/l		1-6 log reduction 3-4 log reduction to 200 units/100 mg/l 2-4 log reduction to 200 units/100 mg/l	5-9.8 mg/l Cl <sub>2</sub> residual 5-8 mg/l Cl <sub>2</sub> residual	1 min. 1 min. 1 min.

1. U.S. EPA, 1973.

2. U.S. EPA, 1974.

3. Rouge River National Wet Weather Demonstration Project, 1999.

4. U.S. EPA, 1975.

5. U.S. EPA, 1979.

- The chlorine gas filter should be inspected and the filter element should be replaced every six months. At this time, the sediment trap should also be washed and dried, and lead gaskets should be replaced.
- Chlorine pressure reducing valves should be cleaned with isopropyl alcohol or trichloroethylene. Spring valves should be replaced every two to five years.
- Ejectors should be cleaned every six months.
- Booster pumps should follow regular pump maintenance schedules.
- To prevent any health threats, the facility using chlorine should provide:
  - Adequate ventilation.
  - Safety equipment.
  - Eye wash fountains and deluge showers.
  - Emergency respiratory protection.

- Emergency kits.
- Information and telephone numbers on the Chlorine Institute and the Chlorine Emergency Plan response team.
- Employee training for safe operations.
- Material Safety Data Sheets.

Finally, using chlorine in CSO applications may present serious hazards. As mentioned previously, chlorine is extremely corrosive. The following recommendations do not cover every aspect of chlorine safety, but should be considered when designing a CSO chlorination facility:

- Facilities housing chlorine require heavy ventilation at floor level, since chlorine gas is heavier than air. Ventilation should provide at least 60 air changes per hour.
- Chlorine leakage detection equipment should be located near chlorinating equipment.
- An emergency scrubbing system may be installed to neutralize any leaking chlorine.
- All storage and chlorinator equipment should be separated from the rest of the facility.
- Chlorine storage tanks should not be exposed to direct sunlight to avoid overheating.

## COSTS

Costs for designing a CSO treatment facility are highly variable, and will depend on the number of CSOs to be treated, the drainage area being served, the anticipated fluctuation in flow rates, and the sensitivity of the surrounding areas (residential or habitat). Costs for a treatment facility may include the following: planning costs, capital costs for construction of the facility, chemical costs, and yearly maintenance costs. The designer may reduce capital costs by using one vessel or basin for both suspended solids reduction and disinfection. As

most vendors typically base costs on flow conditions, it is not practical to provide generalized cost estimates for a chlorination system in this fact sheet. Chemical costs will fluctuate based on current market prices. Chlorine gas delivered in a 2000 pound cylinder currently sells for \$0.57 per pound. A 25 percent solution of sodium hypochlorite currently sells for \$2.58 per pound. Calcium hypochlorite can be purchased for \$1.29 per pound. All chemicals delivered in containers require a deposit which will vary depending on the vendor. Table 3 summarizes some of the typical costs that can be encountered by systems with specific peak design flows.

**TABLE 3 COST PROJECTIONS FOR CSO  
DISINFECTION PILOT STUDY, SPRING  
CREEK AWPCP UPGRADE**

	Peak Design Flow (cfs)		
	1,250	2,500	5,000
Capital Costs	\$854,000	\$979,000	\$1,142,000
Annualized Capital Costs	\$87,000	\$100,000	\$116,000
Annual O&M Cost	\$239,000	\$239,000	\$239,000
Total Annualized Costs	\$326,000	\$339,000	\$355,000

Source: NYDEP, 1997.

### Notes:

1. Costs are present worth in 1997 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 at 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%.



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