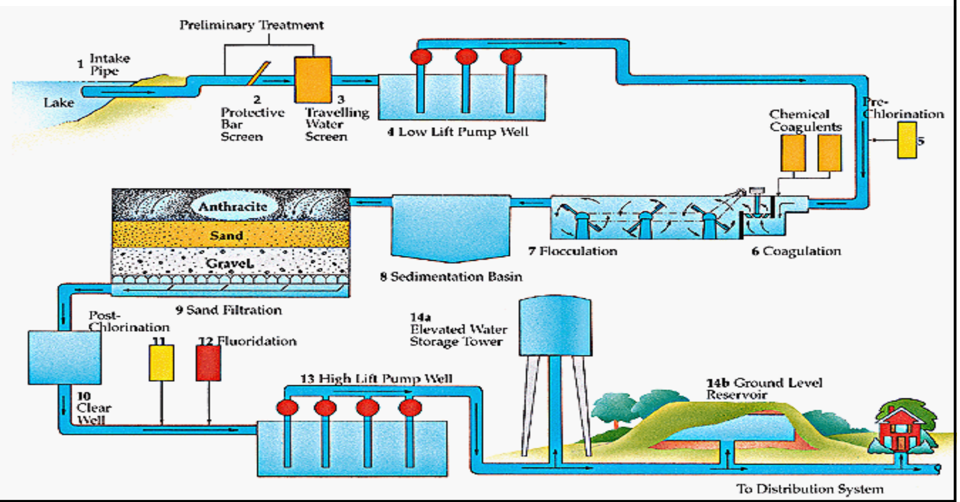
CE 370

Disinfection

1

Location in the Treatment Plant

- After the water has been filtered, it is disinfected. Disinfection follows filtration.



Overview of the Process

- The purpose of disinfecting drinking water is to destroy organisms that cause diseases in man.
- Most pathogenic bacteria are removed from water in varying degrees during the different treatment processes (coagulation, sedimentation, and filtration).
- Disinfection is used to ensure satisfactory removal of pathogens from potable water.

3

Disinfection Rate

- Disinfection rate by a chemical agent obeys Chick's Law:

$$-\frac{dN}{dt} = kN$$

  - *dN/dt* = rate of cell destruction (number / time)
  - *k* = rate constant
  - *N* = number of living cells remaining at time t
- *k* depends on:
  - Microorganisms species
  - Disinfectant nature
  - Disinfectant concentration
  - Environmental factors (pH and temperature)

4

Disinfection Rate

- Another empirical equation is:

$$C^n t_c = K$$

  - C = concentration of disinfectant at time t = 0
  - t_c = time of contact required to kill a given percentage of the microbes
  - K, n = exponential constants
- n depends on the nature of disinfectant
  - If $n > 1$, then disinfection greatly depends on the concentration of the disinfectant
  - If $n < 1$, then disinfection greatly depends on the time of contact
- K depends on type of microorganism and environmental factors such as pH and temperature

5

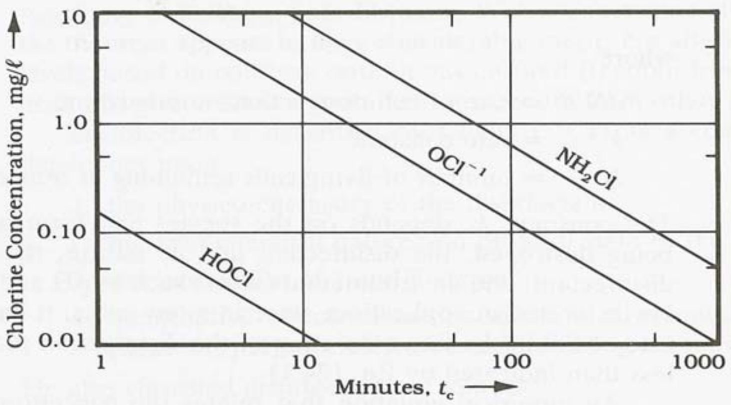


FIGURE 24.1 *Concentration versus Contact Time for 99% Kill of* **E. coli** *by Various Forms of Chlorine at 2°C to 6°C*

Adapted from "Influence of pH and Temperature on the Survival of Coliforms and Enteric Pathogens When Exposed to Free Chlorine" by C. T. Butterfield, E. Wattie, S. Megregian, and C. W. Chambers in *U.S. Public Health Reports* 58 (1943):1837.

6

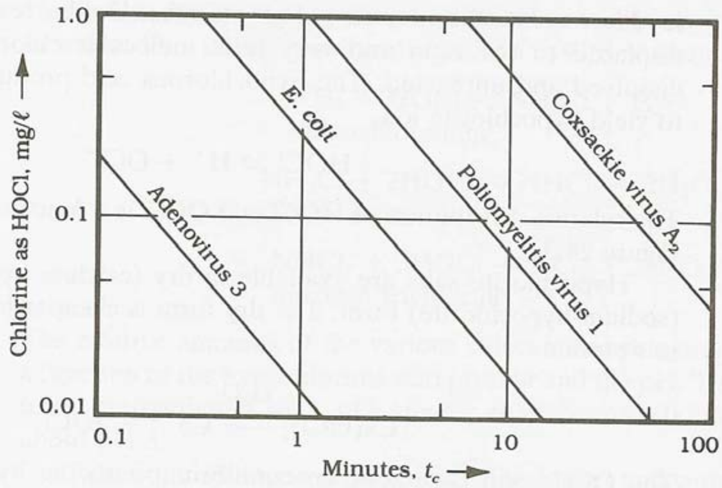


FIGURE 24.2 ***Concentration versus Contact Time for 99% Kill of* E. coli *and Three Enteric Viruses by HOCl at 0°C to 6°C***
Adapted from "The Virus Hazard in Water Supplies" by G. Berg in *Journal of New England Water Works Association* 78 (1964):79. Reprinted by permission.

Disinfection Methods

- Chlorination
- Chlorine dioxide
- Ozonation
- UV irradiation
- High pH
- Other halogens (iodine and bromine)

Chlorination

- Chlorine is widely used
  - Effective at low concentration
  - Cheap
  - Forms residual if applied in sufficient dosages
- Chlorine is applied as:
  - Gas (most common), Cl_2
  - Hypochlorite, $Ca(OCl)_2$
- Chlorine is a strong oxidizing agent
  - It oxidizes enzymes of microbial cells that are necessary for metabolic processes, thus, inactivating (destroying) the microbial cells.

9

Chlorination Reaction

- Chlorine gas reacts with water to form
  - Hypochlorous acid (HOCl)
  - Hydrochloric acid (HCl)

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

- Hypochlorous acid dissociates to hypochlorite ion

$$HOCl \leftrightarrow H^+ + OCl^-$$

- The dissociation of the HOCl is a function of pH

10

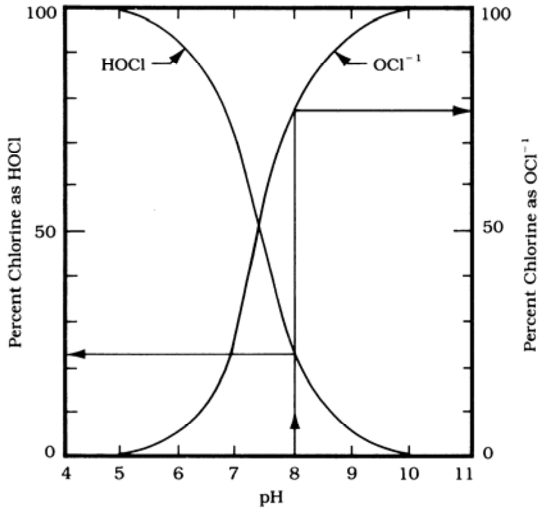


FIGURE 24.3 ***Relative Amounts of Chlorine as HOCl and OCl^{-1} at 20°C versus pH***

Adapted from "Behavior of Chlorine as a Disinfectant" by G. M. Fair *et al.*, *Journal of the American Water Works Association* 40, no. 10 (October 1948):1051. By permission. Copyright 1948, the American Water Works Association.

11

Chlorination Reaction

- Hypochlorite salts
  - Are available in dry form
  - They should be dissolved in water

$$Ca(OCl)_2 \xrightarrow{H_2O} Ca^{+2} + 2OCl^-$$

  - OCl^{-1} seeks equilibrium with H^+ ion
  - Therefore, acid may be needed to be added

$$HOCl \leftrightarrow H^+ + OCl^-$$

- Hypochlorous acid is more effective disinfectant than hypochlorite ions

12

Chlorination Reaction

- Reaction with ammonia

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O$$
$$monochloramine$$
$$NH_2Cl + 2HOCl \rightarrow NHCl_2 + 2H_2O$$
$$dichloramine$$
$$NHCl_2 + 3HOCl \rightarrow NCl_3 + 3H_2O$$
$$nitrogen - trichloride$$

- At pH > 6.0, the monochloramine predominates
- At pH about 5.0, the dichloramine predominates
- Chloramines are effective against bacteria but not viruses

13

Chlorination Reaction

- Reaction with organics
  - Reaction with phenol produces chlorophenols
    - Chlorophenols impart undesirable taste and odor to water
  - Reaction with humic substances produces trihalomethanes
    - Chloroform ($CHCl_3$)
    - Bromodichloromethane ($CHCl_2Br$)
    - Dibromochloromethane ($CHClBr_2$)

These compounds are carcinogenic and, therefore, are limited by drinking water regulations to a total of 0.1 mg/l.

14

Dosages, Demand and Residuals

- Dosage: the amount of chlorine added
- Demand: the amount of chlorine needed to oxidize materials (reaction)
- Residual: the amount of chlorine remaining after oxidation.
  - Residual = Dosage – Demand
- The relationship among them is shown in the next figure.

15

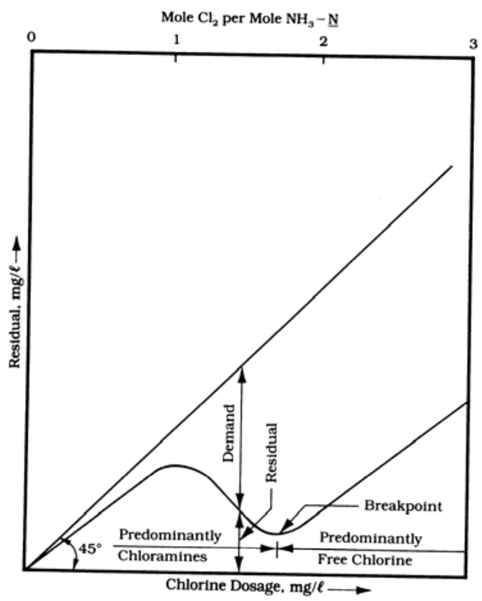


FIGURE 24.5 *Chlorine Dosages, Demands, and Residuals*
Adapted from *Chemistry for Environmental Engineers* by C. N. Sawyer and P. L. McCarty. Copyright © 1978 by McGraw-Hill, Inc. Reprinted by permission.

16

Dosages, Demand and Residuals

- Effect of Contact time
  - When increased, more microorganisms are killed
  - When increased, the demand increases
  - When increased, the amount of chlorinated by-products increase (if precursors are available)
- Free chlorine residuals
  - Chlorine gas + hypochlorous acid + hypochlorite ion
- Combined chlorine residuals
  - Chloramines + other chlorine reactive forms
- Free chlorine residuals are faster acting than combined residuals
- Free chlorine residuals have greater disinfecting capacity than combined residuals (especially for viruses)

17

Dechlorination

- Chlorinated effluents can have negative impacts on receiving environment (toxic to fish and aquatic life)
- Methods used for dechlorination include:
  - Chemical additions:
    - Sulfur dioxide (most common), Sodium sulfite, Sodium bisulfite, Sodium thiosulfate, Hydrogen peroxide, and ammonia.
  - Activated carbon adsorption:
    - Well established in the dechlorination process
    - Requires long contact times
    - It has limited use due to its high cost
    - It can be used for dechlorination and removal of organic compounds at the same time

18

Dechlorination; Sulfur Dioxide (SO_2)

- When SO_2 is added it reacts with water to form a weak solution of sulfurous acid (H_2SO_3).
- Sulfurous acid dissociates as follows:

$$H_2SO_3 \Leftrightarrow H^+ + HSO_3^-$$
$$HSO_3^- \Leftrightarrow H^+ + SO_3^{-2}$$

- Free and combined chlorine forms react readily with sulfite ion (SO_3^{-2}) as follows:

$$SO_3^{-2} + HOCl \rightarrow SO_4^{-2} + Cl^- + H^+$$
$$SO_3^{-2} + NH_2Cl + H_2O \rightarrow SO_4^{-2} + Cl^- + NH_4^+$$

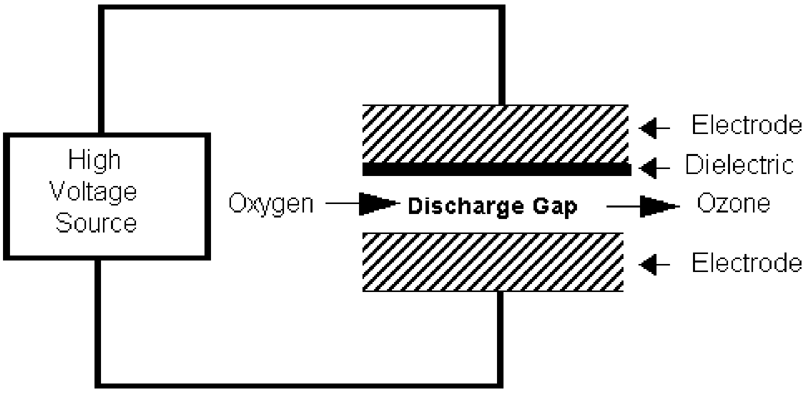
  - Required mass ratio of sulfur dioxide to chlorine is 1.1:1

19

Ozonation

- General characteristics of ozone
  - O_3
  - Powerful oxidant
  - More powerful than hypochlorous acid
  - Unstable in aqueous solutions
  - Has a half-life of 20 to 30 minutes in distilled water
  - Widely used in drinking water treatment
  - Is produced on-site and can not be stored
- Ozone production
  1. Air is refrigerated to remove moisture (-40 to -60° C)
  2. Air is dried through desiccants (silica gel and activated alumina)
  3. Air is passed between oppositely charged plates

20


High Voltage Source
Oxygen
Discharge Gap
Ozone
Electrode
Dielectric
Electrode

21

22

Ozonation Performance

- Primary Advantages to Ozone
  - Ozone is effective over a wide pH range and rapidly reacts with bacteria, viruses, and protozoan.
  - Has stronger germicidal properties then chlorination. Has a very strong oxidizing power with a short reaction time.
  - The treatment process does not add chemicals to the water.
  - Ozone can eliminate a wide variety of inorganic. Ozone removes metals (iron, manganese, zinc, copper, etc.) by precipitation.
  - Oxidizes organic contaminants.

Ozonation Performance

- Disadvantages to Ozone
  - High equipment and operational cost and it may be more difficult to find professional proficient in ozone treatment and system maintenance.
  - Ozonation provides no germicidal or disinfection residual to inhibit or prevent regrowth.
  - Ozonation by-products are still being evaluated and it is possible that some by-products by be carcinogenic.
  - System may require pretreatment for hardness reduction or the additional of polyphosphate to prevent formation of carbonate scale.
  - Ozone is less soluble in water, compared to chlorine, and therefore special mixing techniques are needed.

25

Current Research Trends

- Identification of byproducts of the reaction of ozone with organic materials
- Ozone reaction with pesticides may produce a more toxic material

26

Chlorine Dioxide (ClO_2)

- ClO_2 was originally used to remove taste and odor from water
- General characteristics of ClO_2
  - More powerful oxidant than chlorine
  - Does not react with water
  - Can be easily removed from water by aeration
  - Readily decomposed by exposure to UV radiation
  - Does not react with ammonia
  - Maintains a stable residual

27

Methods of Preparing ClO_2

- Acid and sodium chlorite

$$NaClO_2 + HCl \rightarrow ClO_2 + NaCl + H^+$$

- Chlorine gas and sodium chlorite (excess chlorine)

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$
$$HOCl + HCl + 2NaClO_2 \rightarrow 2ClO_2 + 2NaCl + H_2O$$

- Sodium hypochlorite and sodium chlorite

$$2NaClO_2 + NaOCl + 2HCl \rightarrow 2ClO_2 + 3NaCl + H_2$$

28

Applications of ClO_2 Disinfection

- ClO_2 has longer lasting residual than HOCl
- In wastewater, ClO_2 use is limited to phenolic wastes and the control of sulfide in wastewater collection systems
- ClO_2 does not produce measurable amounts of THMs (trihalomethanes) or TOXs (total organic halogens)
- Cost of equipment and sodium chlorite are high

29

Ultraviolet (UV) Irradiation

- Can disinfect both water and wastewater. However, its use in drinking water disinfection is limited to small installations such as aboard ships because it does not produce residual.
- In wastewater treatment, and when compared to chlorination and Ozonation, UV was found
  - More effective
  - More economical
- UV irradiation is gaining prominence.

30

Ultraviolet (UV) Irradiation

31

Advantages and Disadvantages of UV

- Advantages (in wastewater treatment)
  - Effective in pathogen inactivation
  - Ability to achieve disinfection goals
  - Viable applications to wide range of wastewater qualities
  - Cost effective
  - Relative simplicity
- Disadvantages (in water treatment)
  - Lack of residuals

32

High pH Treatment

- Lime can destruct bacteria at high pH values
  - In this case, no residual will remain after neutralization
- Studies showed that
  - higher removal of viruses was obtained with higher pH values
  - Optimum pH in the range of 11.2 to 11.3
  - Optimum contact time in the range of 1.56 to 2.40 hours
  - Complete destruction of viruses was obtained at pH of 11.0 and contact time of 5.0 hours and 10 minutes
- The process requires an additional residual disinfectant (minimum amount)
- High pH treatment can also remove ammonia and phosphorous
- Recarbonation of the treated water might be needed before discharge

33