Disinfection Practices for Water - Basic

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Agenda

- General Relationships
  - Physical and chemical interactions
  - Demand substances and byproduct formations
  - Disinfection efficiency (CT)
  - Residual maintenance and decay
- Disinfection Methods
  - Simple chemistry for the most common disinfectants
- Pathogen Destruction Mechanisms
  - Biological destruction pathways

General Relationships

- Chemical and physical relationships govern all disinfection chemistry
  - Knowledge of these relationships increases operator skills and troubleshooting abilities
  - Allows operators to control conditions that optimize disinfection practices
- Treatment processes are managed to disinfect water for consumption and to meet regulatory objectives
  - Minimum disinfectant residuals
  - CT compliance - demonstration of efficient disinfection

General Relationships

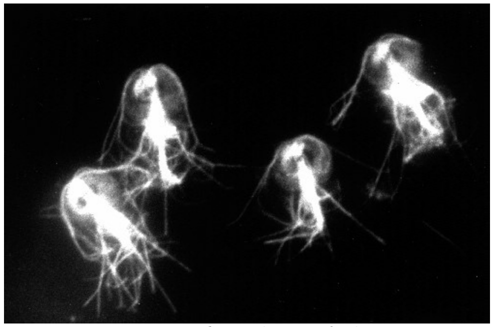
- Governing factors
  - Water pH
  - Mixing
  - Contact Time
  - Reaction Order
  - Residual concentration
  - Residual decay
  - Disinfecting power
  - Disinfection efficiency

General Relationships

Water pH

- pH alters chemical species in water
- pH affects reaction rates and conversion rates

- Most microorganisms cannot tolerate pH values above about 7.8
  - High pH destroys microbial contaminants
- Lime/soda softening destroys microbes
  - 10.2 - 84% destruction
  - 10.6 - 92.4% destruction
  - 11.2 - 99.9% destruction
  - 11.5 - 99.99% destruction



Giardia lamblia

General Relationships

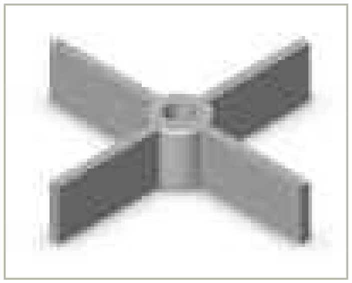
Water pH

- Chlorine more effective at low pH
  - Hypochlorous acid (HOCl) predominantly at low pH
  - Hypochlorite ion (OCl^-) predominantly at high pH
- HOCl and OCl^- relationship based on pH and temperature (discussed later)
- Monochloramine reaction - 5 to 1 Cl_2:NH_3 ratio 25°C:
  - pH 4 - 147 seconds
  - pH 7 - 0.2 seconds
  - pH 8.3 - 0.069 seconds
  - pH 12 - 33.2 seconds

General Relationships

<u>Mixing</u>

- Disinfectants often neglected with regard to mixing in water treatment
  - Injection into a pipe is most common
  - Some mixing occurs depending on pipe length and flow turbulence
  - Addition to clearwell also common - little mixing

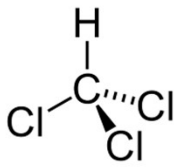


- Wastewater applications have long used mixing to disperse disinfectant
  - Mechanical mixing prior to contact historically practiced (Recommended Standards for Wastewater Works - "Ten States Standards")

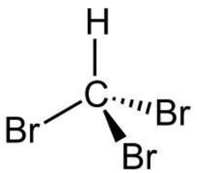
General Relationships

<u>Mixing</u>

- Proper mixing increases disinfectant residual concentration and reduces side reactions
  - Chlorine/ammonium hydroxide with mixing led to 85% monochloramine, 15% non-disinfecting chloramine
  - Chlorine/ammonium hydroxide with **<u>no</u>** mixing resulted in 45% monochloramine, 55% non-disinfecting chloramine
  - Other byproduct reactions also affected (DBP's, etc.)
- Turbulence needed for chemical dispersion (mixing energy)
- Effective mixing known to reduce byproduct concentrations from side reactions



Chloroform

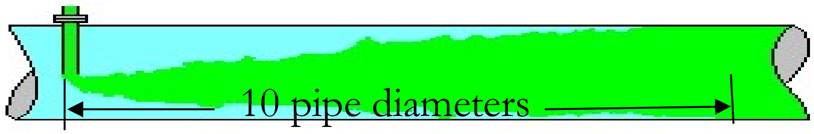


Bromoform

General Relationships

<u>Mixing</u>

- Pipe mixing optimization
  - Introduction of chemical into middle of pipe flow
  - Turbulent flow conditions
  - At least 10 pipe diameters travel length
  - Produce adequate mixing for chemical dispersion



Example 10" dia. pipe > 100" mixing zone

General Relationships

Contact Time (CT)

- Important for disinfection and microbial destruction
  - Required CT values
  - Demonstrate efficient disinfection practices
- Critical factors
  - Contact chamber design
  - Baffling factors
  - Short-circuiting affects
  - Reaction rates
  - Competing reactions

General Relationships

Contact Time (CT)

- Other important factors
  - Water temperature
  - Water pH
  - Disinfectant residual
  - Type of disinfectant
  - Production rate
  - Microbial inactivation requirements
    - Giardia
    - Viruses
    - Cryptosporidium

General Relationships

<u>Contact Time (CT)</u>

- Disinfectant application does little for disinfection
  - Demand reactions compete for disinfectant
- Persistent residuals needed for microbial destruction
  - Residuals are function of pH, demand, contact time, water temperature
  - Residuals responsible for pathogen destruction
  - Required CT values must be met
  - Large CT values often increase DBPs

General Relationships

<u>Reaction Order</u>

- Disinfectants work in specific order of reaction
  - Chemical interactions based on preference
- Inorganics react first and consume oxidation potential
  - Iron, manganese, NH_3, and other cationic metals

Iron

Manganese

General Relationships

<u>Reaction Order</u>

- Organics react next and consume oxidation potential and disinfectant
  - Taste and odor compounds and DBP precursors
  - Precursor reactions create DBPs
- Microbials react last and consume very little disinfectant
  - Destruction mechanisms presented later

Poll Question

General Relationships

Disinfecting Power

- Type of disinfectant impacts residual development and disinfection process
  - Combined chlorine -1.0 mg/L requires 60 minutes contact
  - Free chlorine - 0.2 mg/L requires 10 minutes contact
  - Chlorine dioxide - 0.25 mg/L requires 2 minutes contact
  - Ozone – 0.07 mg/L requires 0.08 minutes contact

(Based on reactions with E. Coli for 99.9% inactivation)

General Relationships

Disinfecting Power

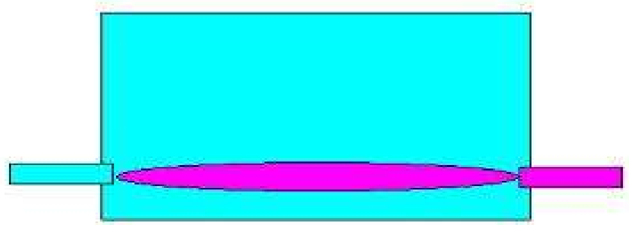
OH· (OH radical)	**24,400,000**
Ozone	18,000,000
HCO_3· (HCO_3 radical)	351,000
Hydrogen peroxide	347,000
Chlorine dioxide	263,000
Hypochlorous acid	10,000
Hypochlorite ion	100
Monochloramine	**1.0**
Fluorine	0.90
Bromine	0.63
Iodine	0.56

General Relationships

<u>Short-circuiting</u>

- Single most detrimental affect
  - Describes general flow path in basin
  - Defines stagnant areas where no disinfection occurs
  - Increases volume needed to demonstrate effective disinfection
  - Reduces process efficiency
  - Increases residuals needed for CT compliance

Water enters and fills the tank



Only small volume of tank provides treatment

General Relationships

Disinfection Byproducts

- Side reactions during disinfection create byproducts
- Byproducts have no disinfecting power
  - Organo-chloramines
  - Hydrochloric acid (HCl)
  - Hypochlorite ion (OCl^-)
  - Iron and manganese precipitates
  - Trihalomethanes (THMs)
  - Haloacetic acids (HAA5s)
  - Other DBPs

General Relationships

<u>Disinfectant Demand</u>

- Demand = Dosage - Residual
  - Dissolved gases
  - Chemical substances (ammonia, others)
  - Organic matter
  - Biological organisms
  - Inorganic matter
    - Iron, manganese, ammonia, other cationic metals
- Organic matter reacts to create DBPs
  - Organic precursors + chlorine → disinfection byproducts
  - Disinfection byproducts + time → more disinfection byproducts

General Relationships

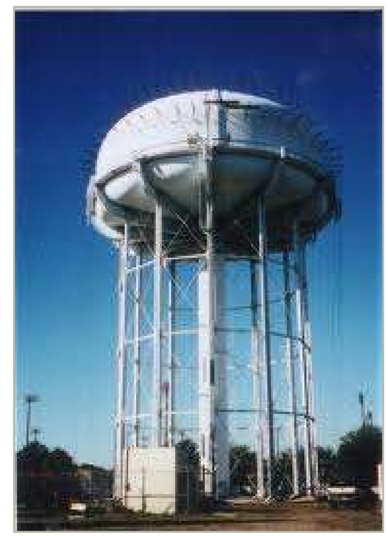
Disinfectant Demand

- Ammonia and nitrogen compounds
  - Direct reaction with many chlorine forms
- Pathogenic microorganisms
  - Most removed by coagulation and filtration processes
  - Some destroyed by chemical softening and high pH
  - Small remaining populations inactivated by disinfection

General Relationships

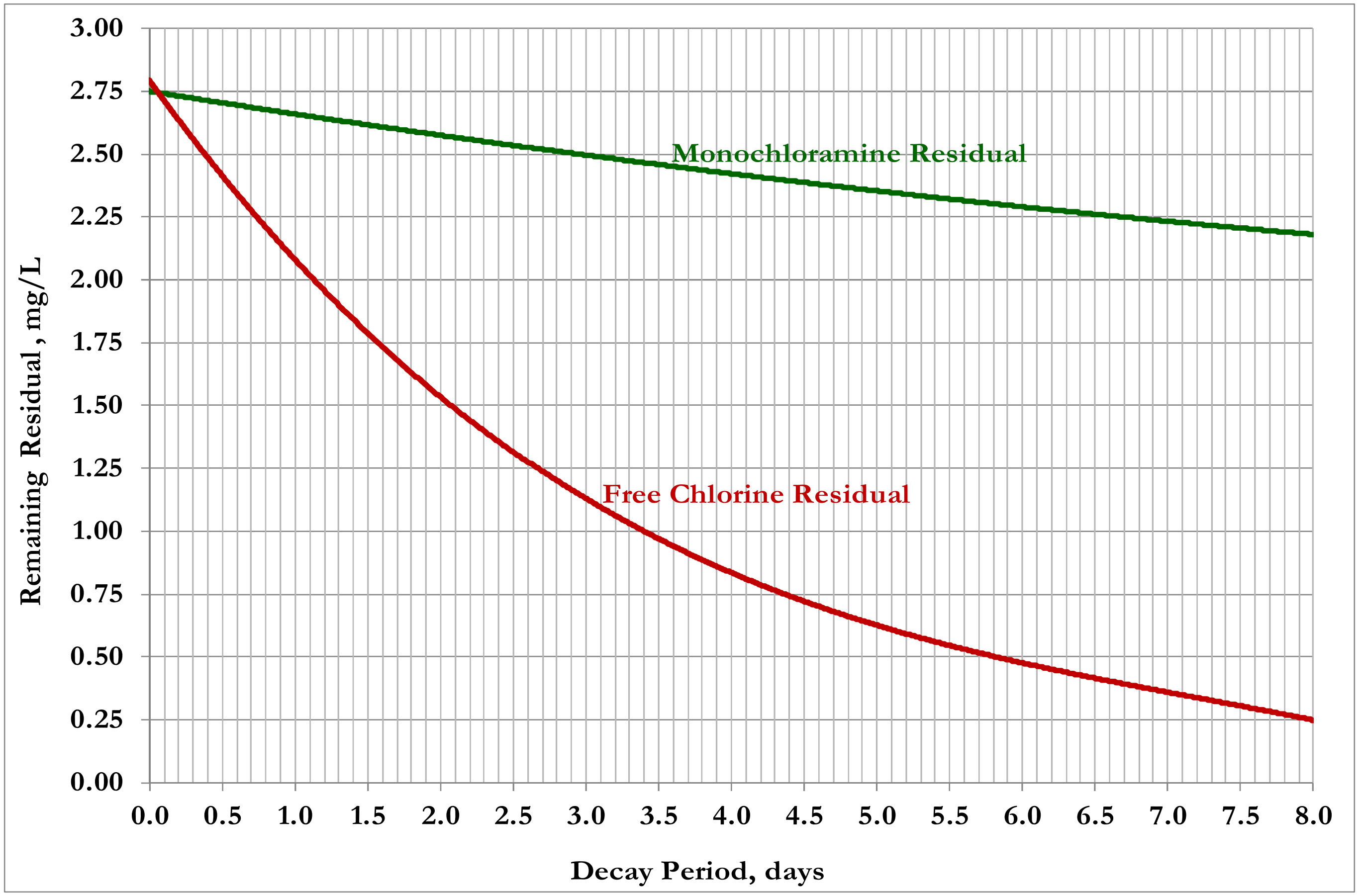
Residual Maintenance

- Essential for effective disinfection
  - Minimum residual levels regulated
  - Protection against regrowth in distribution system
  - Storage tank mixing
  - Unidirectional flushing
- Residual decay
  - Time (water age in system)
  - Temperature (especially storage tanks)
  - Introduction of demand causing substances - backpressure
  - Slime growths and/or nitrification (chloramines)
  - Backflow occurrences



General Relationships

Residual Decay Examples



Chlorine

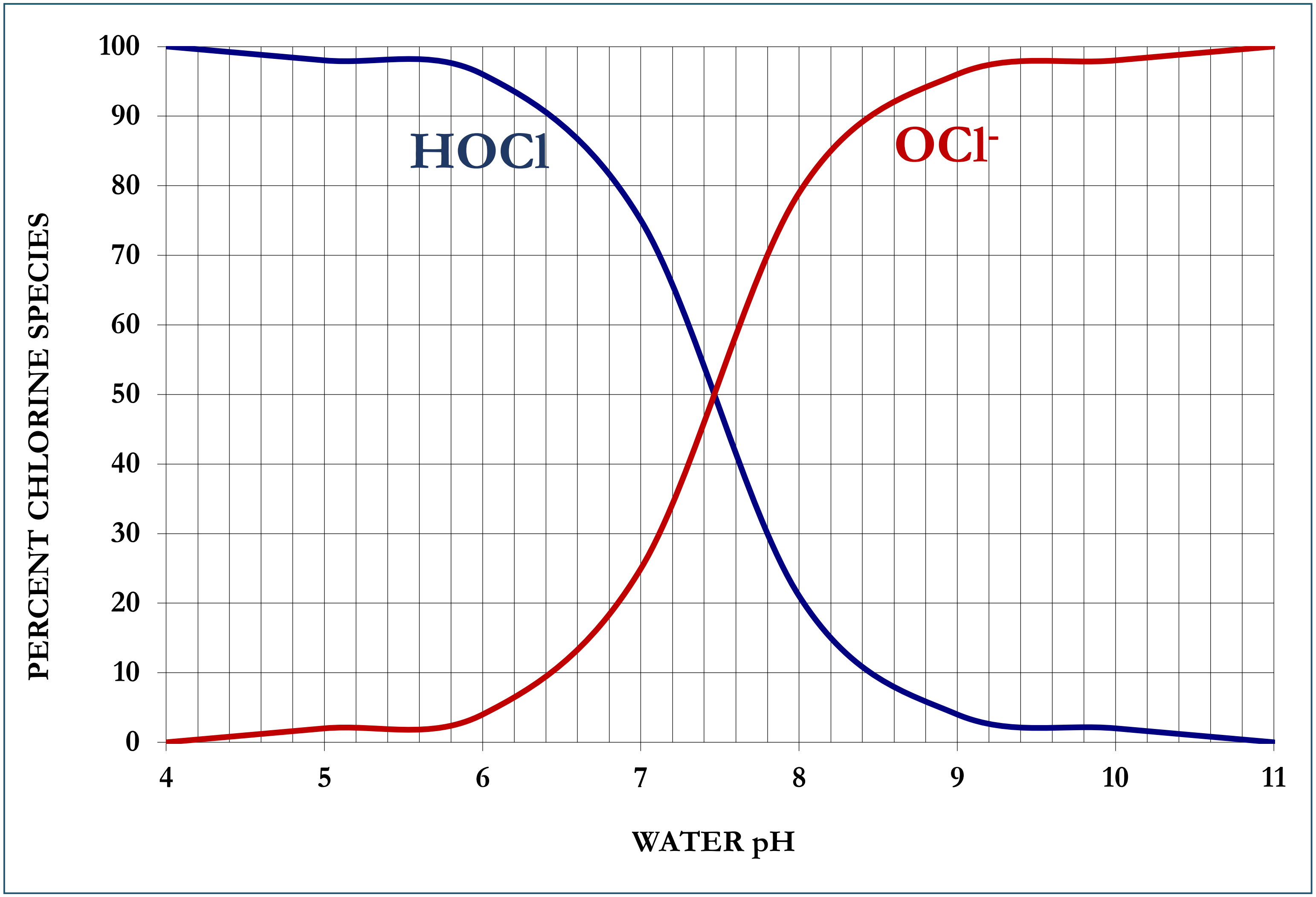
- Addition of chlorine to water produces hypochlorous acid (HOCl) and hydrochloric acid (HCl)

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

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

  - HCl has no disinfecting power - just consumes chlorine during reaction
  - HOCl in water decomposes at high pH to hypochlorite ion (OCl^-)
  - Hypochlorite ion is less powerful disinfectant
- HOCl and OCl^- relationship is pH and temperature dependent

Chlorine


HOCl
OCl-
PERCENT CHLORINE SPECIES
WATER pH
100
90
80
70
60
50
40
30
20
10
0
4
5
6
7
8
9
10
11

Chlorine

- Free chlorine
  - HOCl
  - OCl^-
- Combined chlorine
  - Monochloramine
  - Other chloramine species
  - Other non-disinfecting species

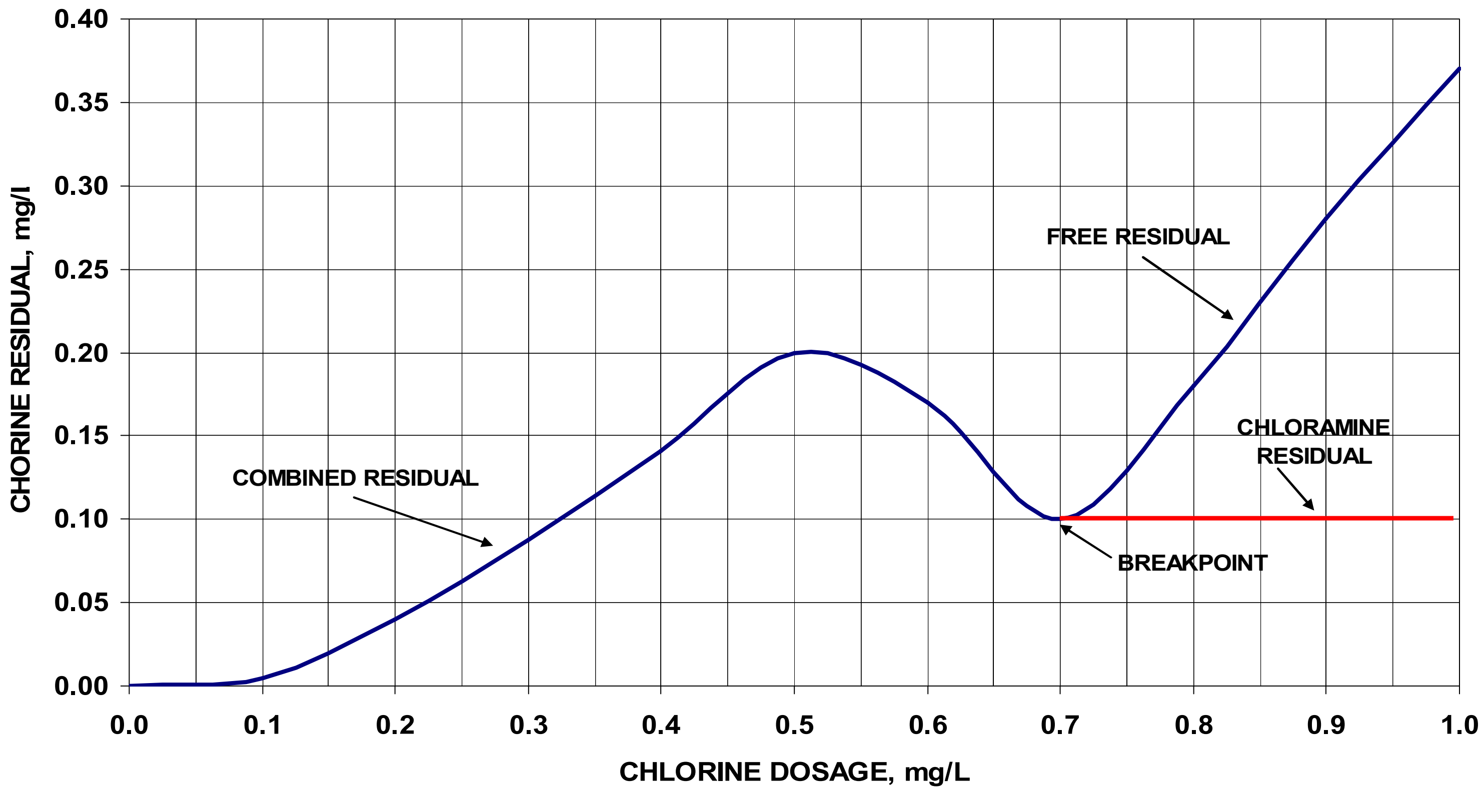
$$Cl_2 + H_2O \Rightarrow \underline{HOCl} + HCl$$

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

$$NH_4^+ \Leftrightarrow NH_3 + H^+$$

$$HOCl + NH_3 \Rightarrow \underline{NH_2Cl} + H_2O$$

Breakpoint Curve



<u>Free chlorine</u> is usually the preferred disinfectant for water treatment. To produce free chlorine, the <u>chlorine demand</u> must be satisfied. Once the demand is satisfied, further chlorine addition results in a free chlorine residual. <u>Combined chlorine</u> also is present beyond the breakpoint.

Poll Question

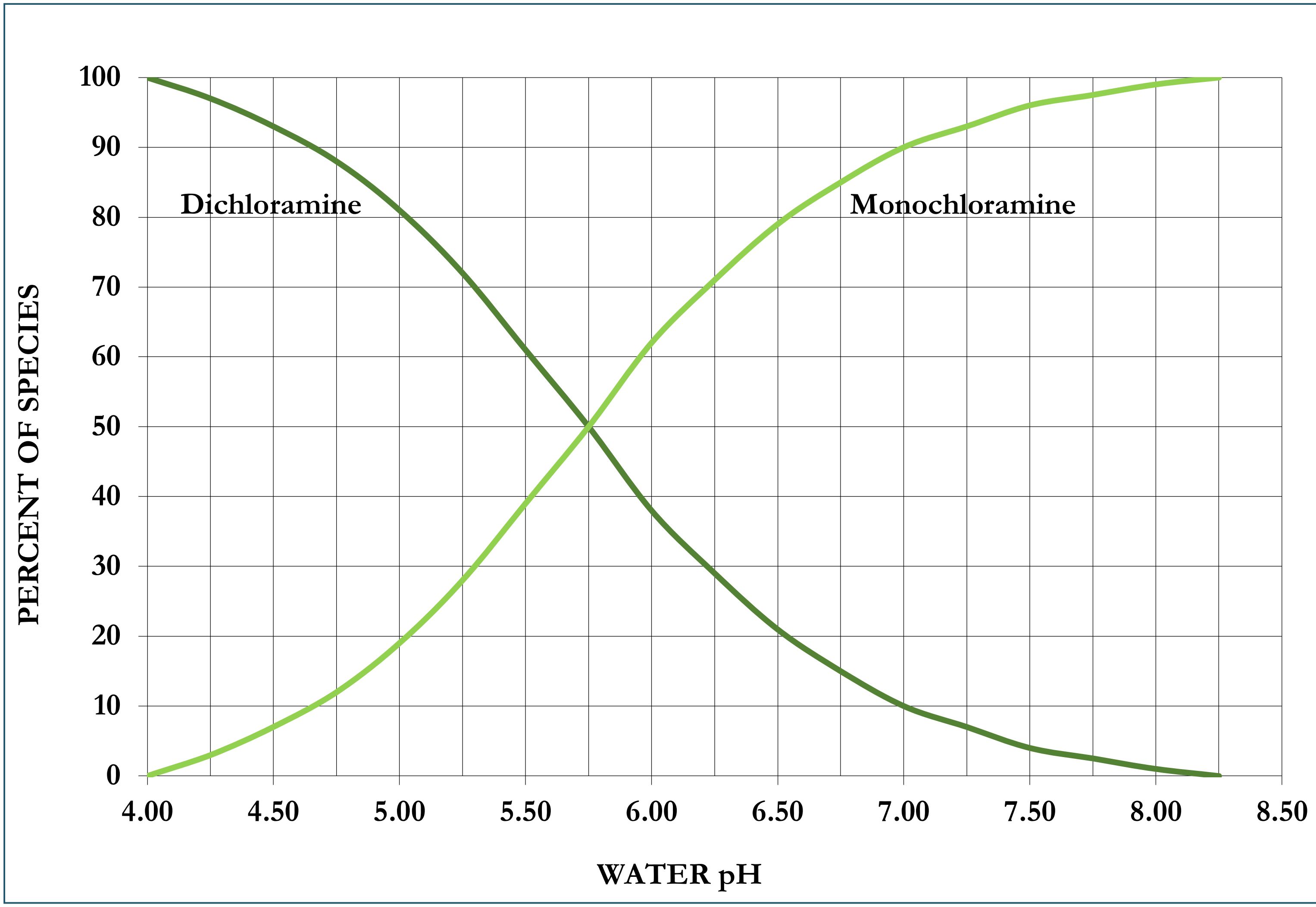
Chloramines

- Addition of ammonia to quench free chlorine creating monochloramine (odorless residual)
  - Free chlorine achieved commonly to meet CT, then add ammonia for conversion to chloramine
- Ammonia-containing compounds add ammonium ion (NH_4^+)

$$HOCl + NH_3 \Rightarrow NH_2Cl + H_2O$$

- Chlorine/ammonia ratio is important for monochloramine development
  - 3 to 5 typical, 4 maximizes monochloramine conversion
  - Chlorine/ammonia ratios greater than 7.6 to 1 can develop dichloramine residuals (odors)

Chloramines



Chloramines

- Monochloramine reverse reaction can lead to nitrification

$$NH_2Cl + H_2O \Leftrightarrow HOCl + NH_3$$

  - Nitrite development from nitrifying bacteria
  - Accompanied by increase in HPC bacteria counts and loss of residual concentrations
    - HPC counts often increases above 500 per mL

Chloramines

- High water age depletes monochloramine residual
  - Residual decay increases with organic content
  - Frequent unidirectional flushing needed
  - Storage tank turnover at least 25%
  - Storage tank mixing increases residuals
  - Booster disinfection may be needed

Chloramines

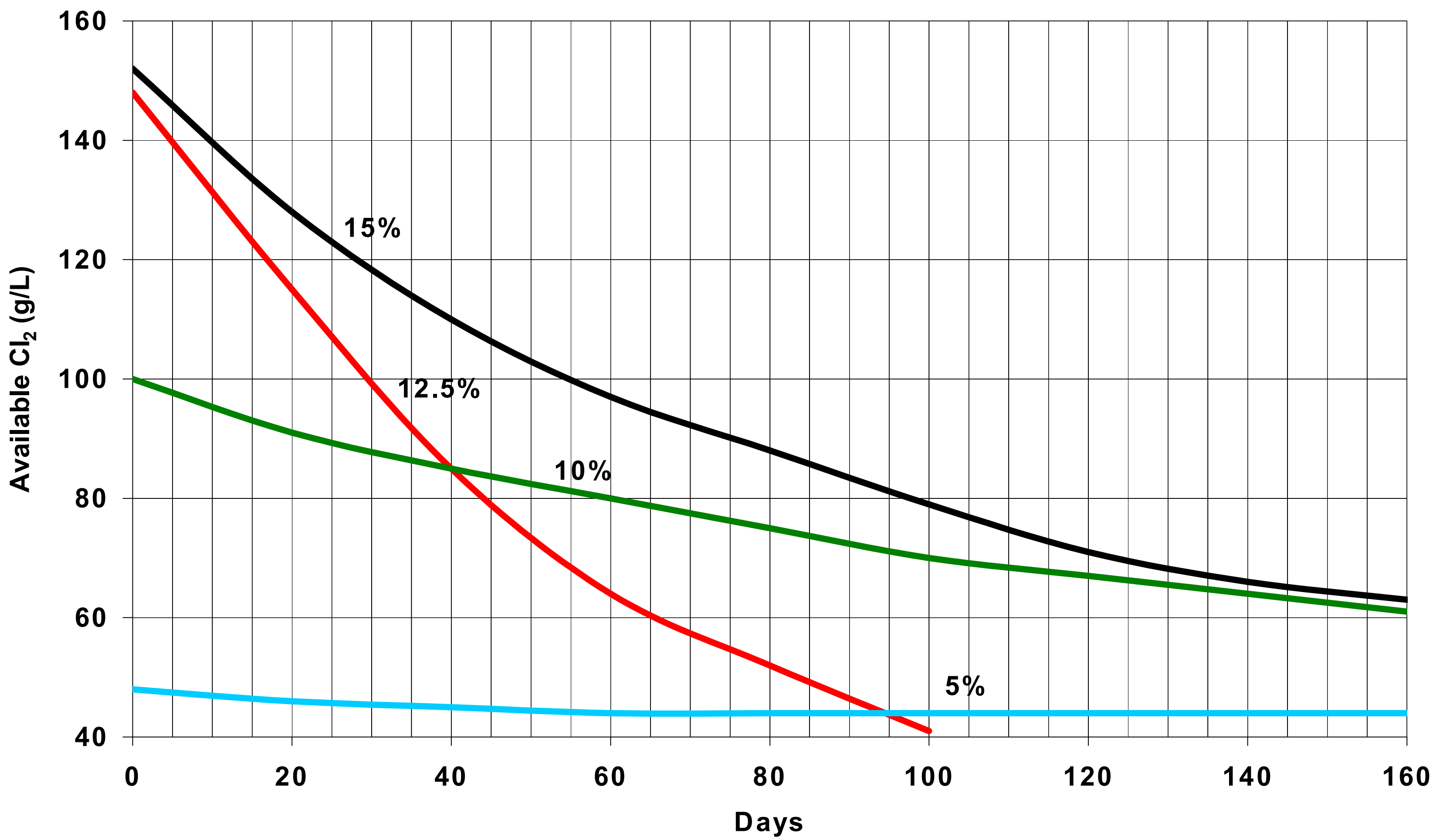
- High pH converts monochloramine to non-disinfecting compounds at pH greater than 9.5
  - Proposed hydroxylamine formation

$$NH_2Cl + OH^- \Rightarrow NH_2OH + Cl^-$$

Sodium Hypochlorite

- 1.0 pound Cl_2 plus 1.13 pounds NaOH makes 1.05 pounds NaOCl
- 12.5% commercial strength most common
- NaOH added to maintain pH>12, reduce off gassing
- On-site generation also available
  - 0.8 % and 12.5% strength
- Chlorine decay influenced by:
  - Chemical concentration
  - Heat
  - UV light
  - pH (<11 rapid decomposition)
  - Heavy metal cations

Sodium Hypochlorite



Sodium Hypochlorite

- Sodium (Na^+) does not disinfect
- Hypochlorite ion (OCl^-) is the disinfectant
  - 12.5% NaOCl solution
  - About 8.6% OCl^-
  - About 1.04 lbs/gal
- Check strength and adjust feed rate as solution decays
- NaOCl added to water reacts to make hypochlorite ion (OCl^-)
  - Reacts like chlorine gas and water
  - HOCl and OCl^- are influenced by pH and temperature (shown earlier)

$$NaOCl + H_2O \Rightarrow HOCl + OH^- + Na^+$$
$$HOCl \Leftrightarrow OCl^- + H^+$$

Sodium Hypochlorite

- Decomposition off gases oxygen and increases chlorite ion (ClO_2^-) concentration
- Off gas creates operating problems
  - Pumps
  - Valves
  - Piping
- Peristaltic pumps (hose pumps) commonly used
- Degassing pump heads strongly recommended

Chlorine Dioxide

- Chlorine gas and liquid sodium chlorite in special generator

$$2NaClO_2 + Cl_2 \Rightarrow 2ClO_2 + 2NaCl$$

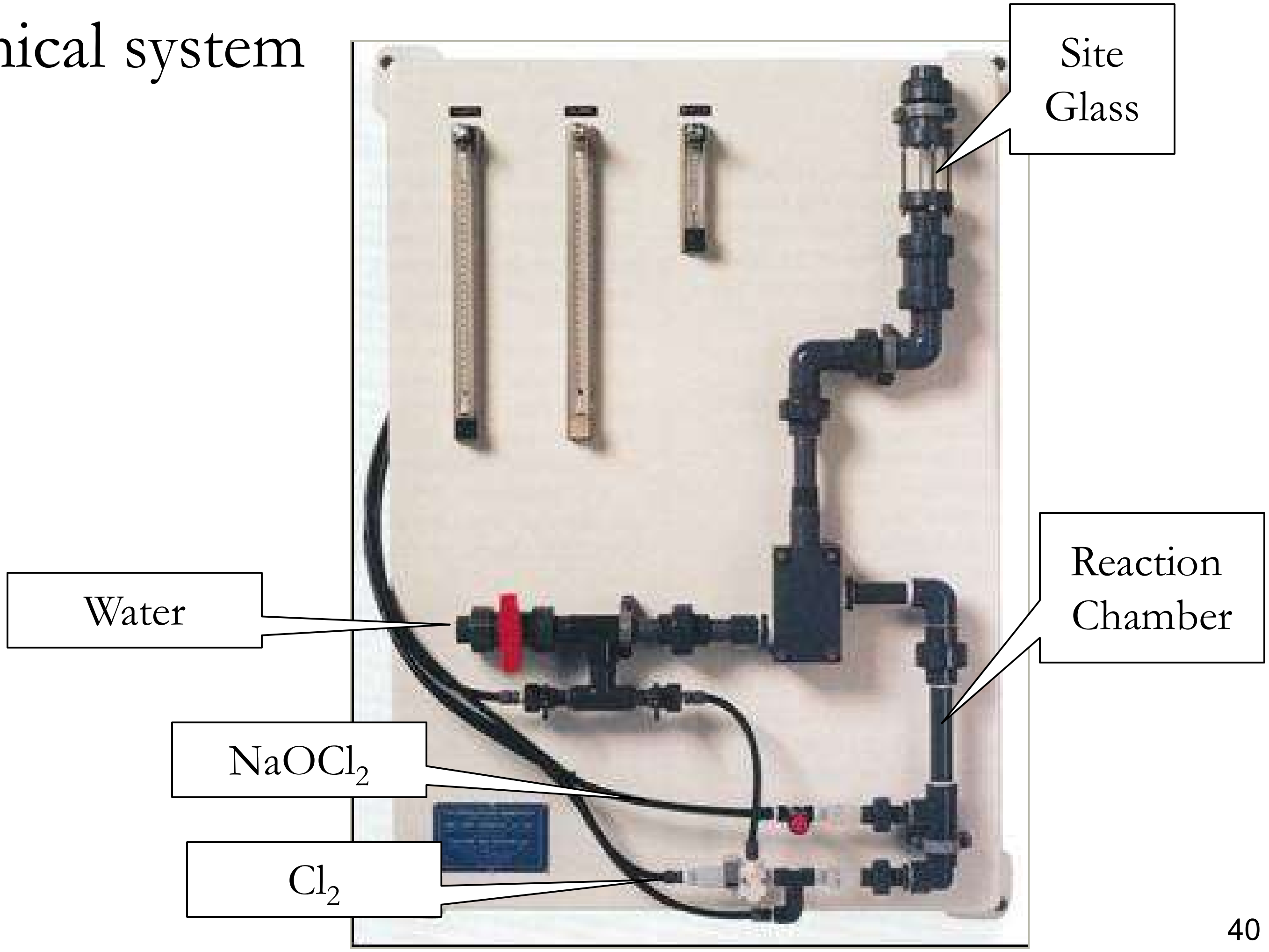
- ClO_2 concentrations 200 mg/L to 5,000 mg/L
- 95% or greater conversion common
- Sight glass confirms ClO_2 generation **neon green color**

Chlorine Dioxide

- 1 lb. Cl_2 gas plus 1.68 lbs $NaOCl_2$ makes 1 lb. ClO_2
- Byproducts from generation
  - Chlorite ClO_2^-
  - Chlorate ClO_3^-
  - Chloride Cl^-
  - NaCl (can clog generator column)

Chlorine Dioxide

- Two chemical system
  - $NaOCl_2$
  - Cl_2



Chlorine Dioxide

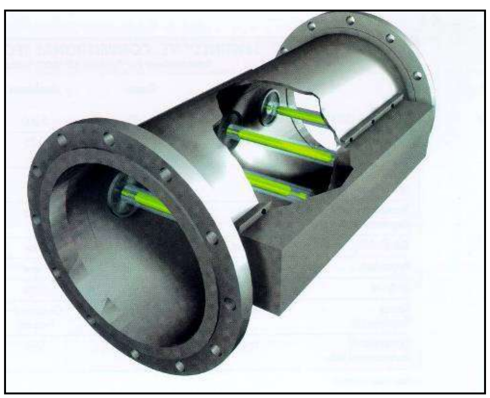
- Chlorite regulated in drinking water - 1.0 mg/L
- ClO_2 and OH^- decomposes to byproducts

$$ClO_2 + 2OH^- \Rightarrow ClO_3^- + ClO_2^- + H_2O$$

Poll Question

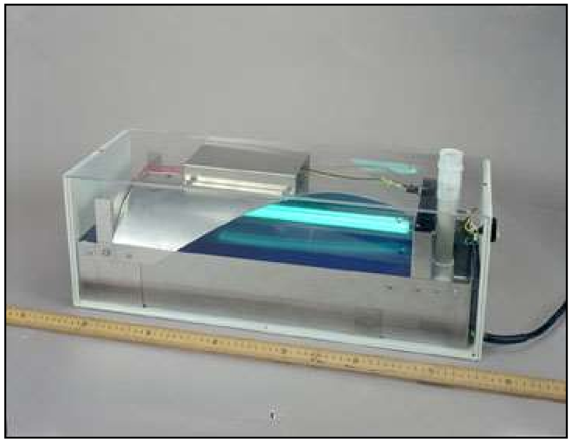
UV Disinfection

- More common in wastewater
  - Fecal coliform reductions
  - No residual destruction
- Cryptosporidium inactivation requirements show need for UV in drinking water
  - Crypto cannot be inactivated by free chlorine



UV Disinfection

- UV-C light 100 nm to 280 nm likely has germicidal properties
- Transmittance dependent on
  - Turbidity
  - Suspended solids
  - Iron, manganese
  - Hardness
  - Hydrogen sulfide (H_2S)



$$UVA = \log \frac{1}{UVT}$$

UV Disinfection

	LP	LPHO	MP
Spectra	mono	mono	poly
Power (W)	70-90	200-250	1,300-5,000
Temp, °C	40-60	100-200	600-900
Life, hours	8K-10K	8K-10K	3K-5K
No. lamps	10-15	4-8	1-6

UV Disinfection

- UV dose related to contact time and UV intensity
- Dosing is complex
  - Water quality
  - Lamp type
  - UV intensity
  - Reactor design
  - Hydraulic flow
  - Sensor performance

UV Disinfection

- No residual concentration
  - No residual destruction in wastewater
  - Post disinfectant needed for residual maintenance in water
- Critical UV design parameters
  - Field validation of reactor dosing
  - Sleeve degradation due to fouling
  - Gradual decline of lamp output with age
    - 8% reduction in output decreases UV dose 38%

UV Disinfection

E. Coli	9.6 mJ/cm^2
Hepatitis A	10.2 mJ/cm^2
Salmonella typhi	8.2 mJ/cm^2
Poliovirus	30 mJ/cm^2
Rotavirus	36 mJ/cm^2
Cryptosporidium parvum	10 mJ/cm^2
Giardia lamblia	10 mJ/cm^2

Reactor dosing much higher

Destruction Mechanisms

Free Chlorine

- HOCl penetrates cell wall
- HOCl reacts with enzymes used for glucose production
- OCl^- will not penetrate cell wall (negative charges repel)
- Reacts with nucleic acid effecting respiration in viruses leading to mortality

Chloramines

- Electrochemical reaction with enzymes within microbial cell
- Disruption of enzyme system fails to repair/grow cells
- HOCl presence in NH_2Cl may increase disinfection capability

Destruction Mechanisms

Chlorine Dioxide

- Disruption of protein synthesis
- Breakdown ability to maintain/repair cells
- pH 6.5, ClO_2 kills 99% E. coli in 60 minutes
- pH 8.5, ClO_2 kill 99% E. coli in 15 minutes
- Virus kill similar to E. coli

Destruction Mechanisms

Ozone

- Attack at bacterial cell membrane leading to rupture
- Attack of proteins in viral cell wall leading to mortality

UV Disinfection

- UV irradiation alters DNA
- Organism cannot reproduce, cannot infect

Questions

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