

13 Disinfection

Three basic strategies to keep microbiological contaminants out of drinking water:

1. Keeping microbiota out of water source
2. Treating water to remove contaminants
3. Maintaining safe water distribution system

Disinfection has two components:

1. Primary disinfection - inactivation of microorganisms in the water
2. Secondary disinfection - maintaining disinfecting residual in distribution system

History

Source water protection and filtration used in second half of 1800s

1880 Koch showed chlorine could inactivate bacteria

1902 First used of chlorination for disinfecting water in Belgium

1908 First use in US: Jersey City, NJ with calcium hypochlorite

1913 First use of chlorine gas - Philadelphia

1941 85% of public supplies chlorinated

mid-1970s Formation of THMs demonstrated

1980s *Giardia* identified as important pathogen
Cryptosporidium identified more recently

Disinfection methods

- 1 Free chlorine - most common
 - 2 Combined chlorine (chloramines)
 - 3 Ozone - strongest oxidant
 - 4 Chlorine dioxide
 - 5 UV light
- } chemical disinfection

Chemical disinfection kinetics

Chick's Law - Harriet Chick, 1908

documented microorganism inactivation by phenol, mercuric chloride, silver nitrate

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

N = number of organisms per volume [L^{-3}]

k = Chick's Law constant [T^{-1}]

Integrate to get:

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

N_0 = starting number of organisms

N/N_0 = "survival ratio"

Chick-Watson Model - Herbert Watson, 1908

$$C^n t = K \quad \text{achieves particular level of disinfection (i.e. } N/N_0)$$

C = concentration

n = empirical const called "coefficient of dilution"

K = constant (function of microorganisms)

If $n > 1$, disinfectant efficiency decreases with dilution - concentration is more important than time

$n < 1$, time is more important than conc.

$n = 1$, time and conc equally important

n is slope of $\log C$ vs $\log t$ plot (see pg 4)
by convention, 99% inactivation is plotted

If $n \neq 1$, then Chick-Watson model is:

$$\ln\left(\frac{N}{N_0}\right) = -\Lambda_{cw} Ct$$

Λ_{cw} = Chick-Watson coefficient
of specific lethality [L/mg·min]

Other models also exist - see MWH, 2005

Ct is specified by US EPA rules for *Giardia* and *Cryptosporidium* for different disinfectants and pH - unlike bacteria, no easy tests for *Giardia* and *Crypto*, so regulation focuses on technology (expressed as Ct) rather than monitoring

Page 5 (from MWH, 2005, p 1063) shows Ct to achieve 99.9% removal by various technologies

Note: chlorine is relatively ineffective against *Cryptosporidium* (*C. Parvum*)
UV is particularly effective against *Giardia* and *Crypto*.

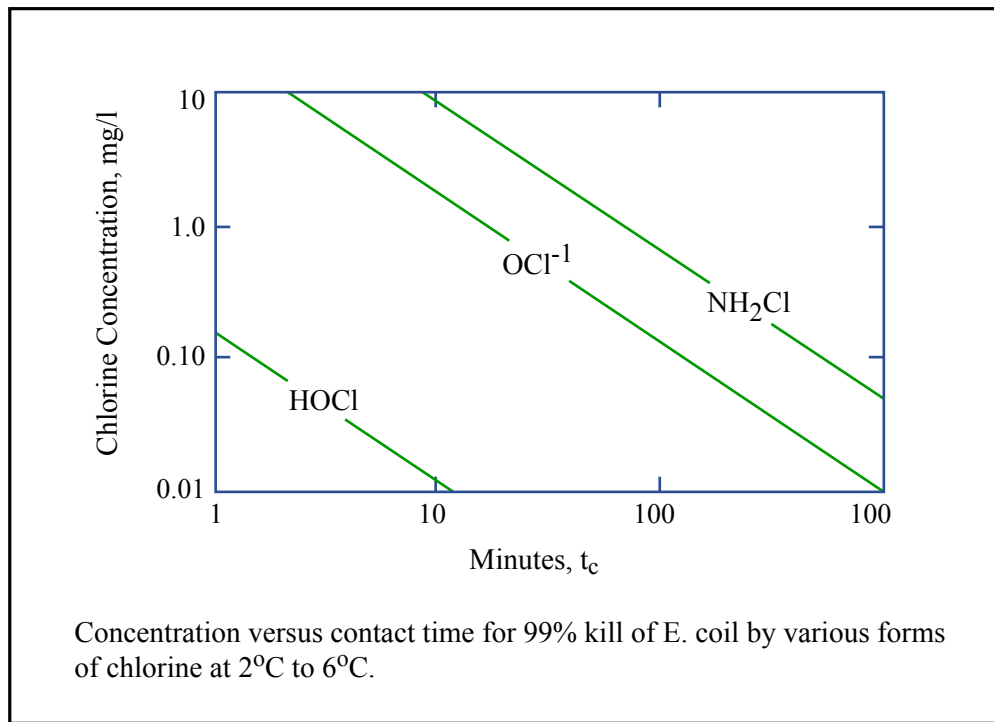


Figure by MIT OCW.

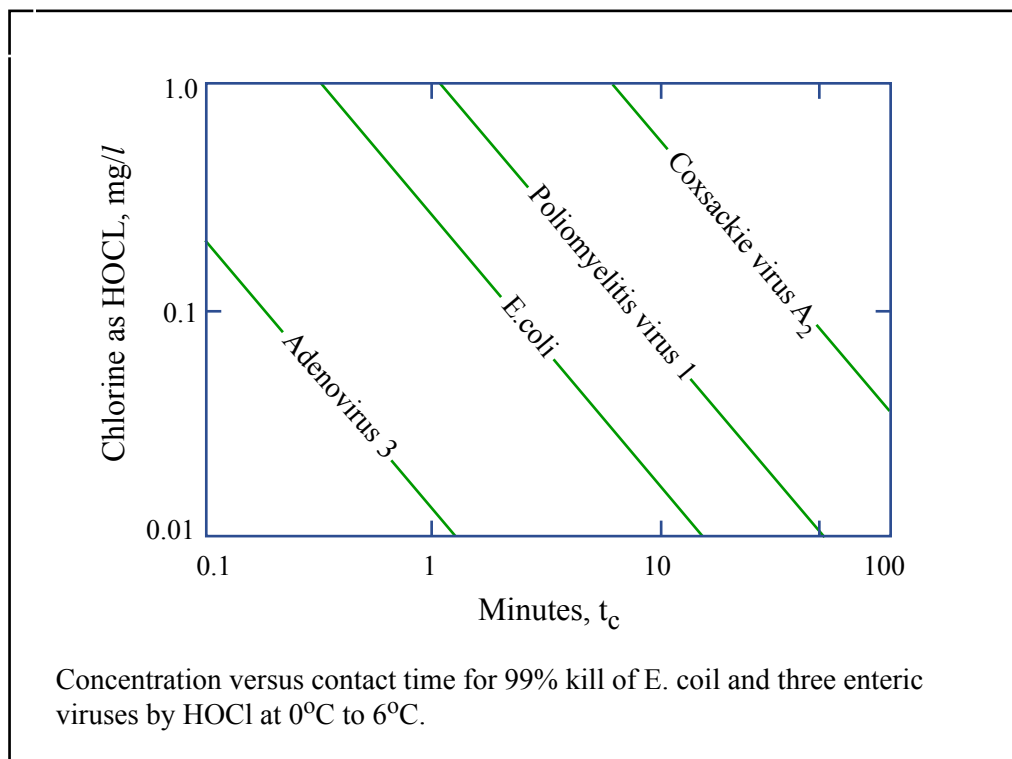
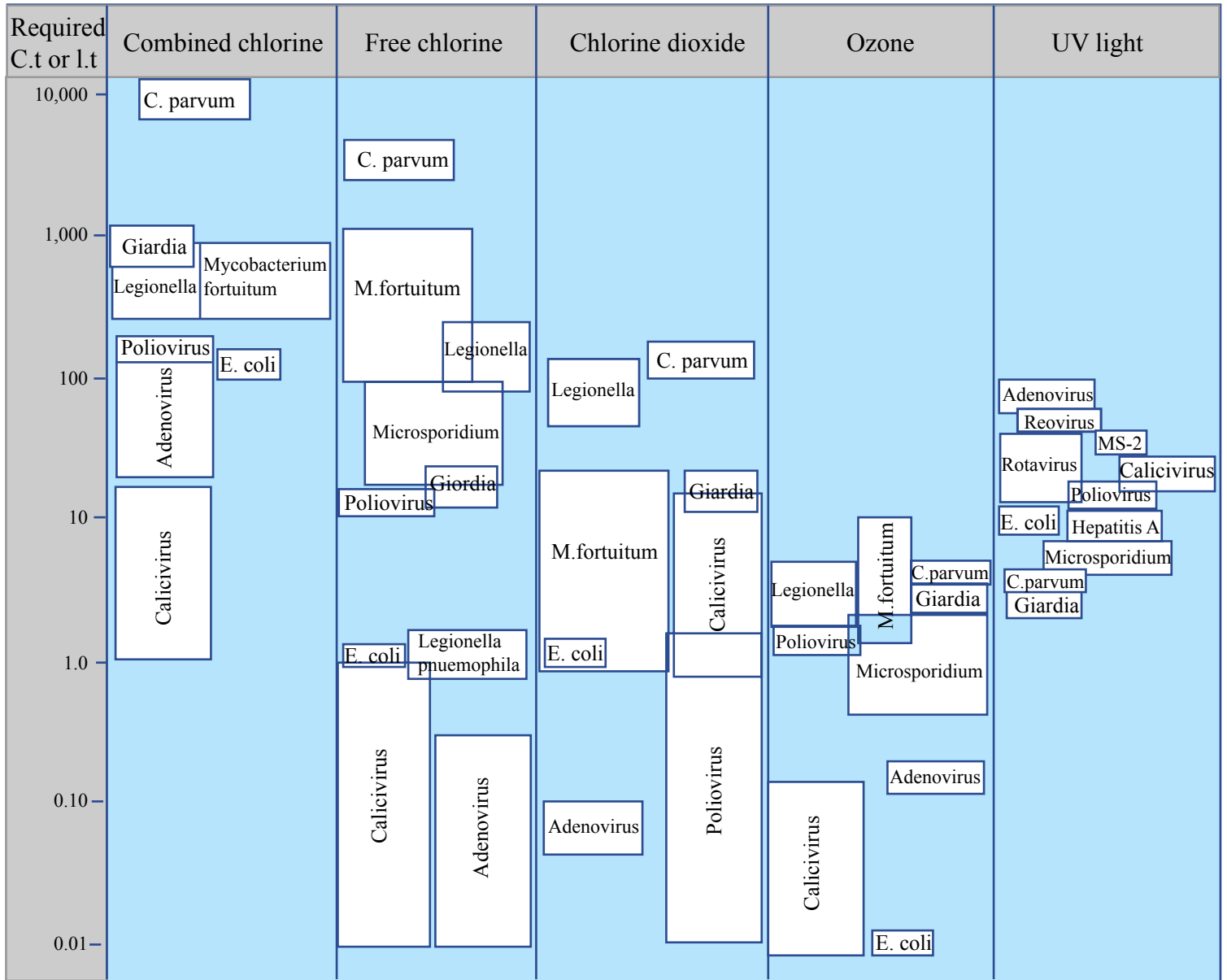


Figure by MIT OCW.



Overview of disinfection requirements for 99 percent inactivation.

Figure by MIT OCW.

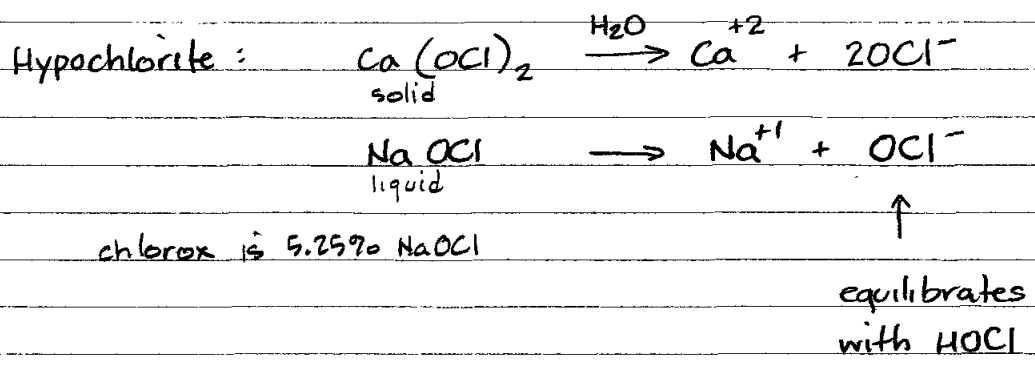
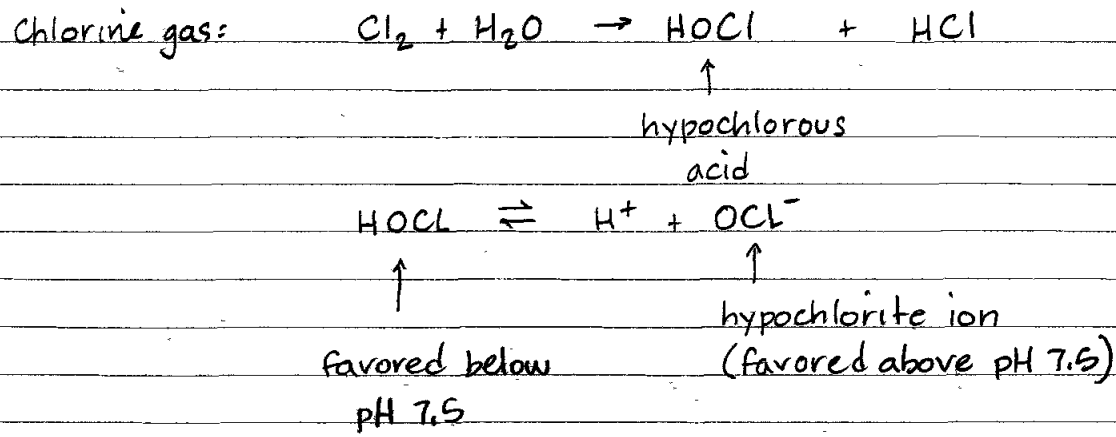
Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 1063.

Chlorine disinfection

Most widely used - effective at low conc., inexpensive, forms residual
Drawback = forms THMs

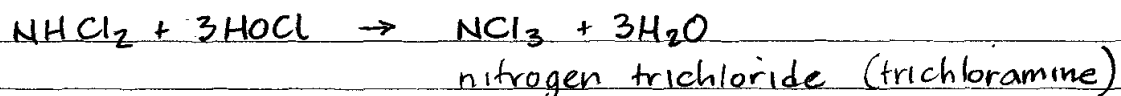
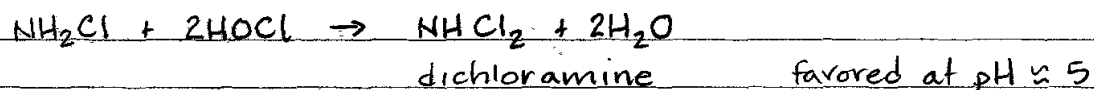
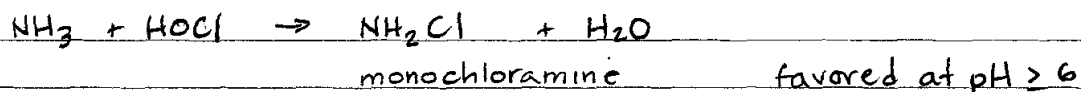
Applied as chlorine gas or hypochlorite

Acts by oxidizing enzymes of cells, preventing essential metabolic processes



HOCl is more effective disinfectant than OCl⁻ but both are excellent

HOCl reacts with ammonia =



chloramines are effective against bacteria (e.g. pipe growth)
much less effective against viruses

chloramine contributes to chlorine residual
along with residual free chlorine (HOCl + OCl⁻)
chloramines are longer lasting

Chlorine also reacts with organics

With phenol to form chlorophenols - strong taste
and odor

With NOM (natural organic matter, e.g. humic acids)
to form tri-halo methanes (THMs)

CHCl₃ chloroform

CHCl₂Br bromodichloromethane

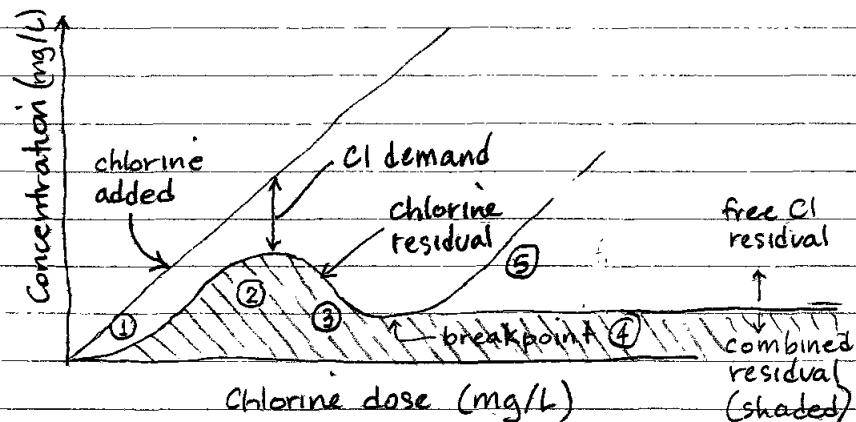
CHClBr₂ dibromochloromethane

CHBr₃ bromoform

Known as DBP - disinfection by-products
Problematic because THMs are suspected
human carcinogens

Chlorine dosage is determined so as to ensure adequate residual - known as breakpoint chlorination

Determined by lab experiments in which chlorine is added and residual is measured:



Chlorine demands =

- ① At first, inorganic reducing chems $\text{Cl}_2 \rightarrow 2\text{Cl}^-$
- ② After satisfaction of initial demand, chloramines formed, creating combined residual
- ③ With increasing Cl dosage, formation favors dichloramine over monochloramine, then trichloramine over dichloramine. Trichloramine is unstable, breaks down to N_2 and reduces chlorine residual
- ④ Low point of chlorine residual is "breakpoint"
- ⑤ Further increase in Cl adds free residual

$\text{NO}_3, \text{H}_2\text{S}, \text{Fe}^{2+}$

Desired dosage for water treatment is beyond the breakpoint

Actual breakpoint concentration varies with the water quality of the raw water - typically 4-10 mg/L

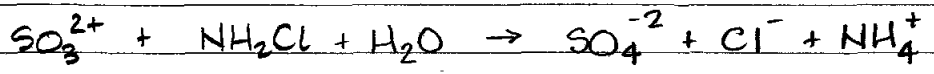
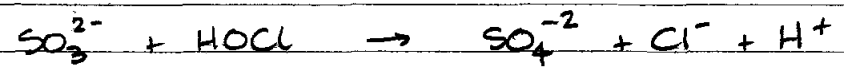
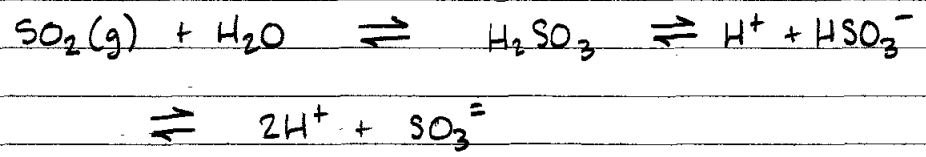
Desired residual = 0.2 mg/L at furthest point in distribution system

(Note 0.5 mg/L is generally objectionable to consumers)

Dechlorination

Chlorination is also used as a final step in wastewater treatment but here residual chlorine has adverse effects on aquatic life and is not desired

Sulfur dioxide used to remove residual Cl₂



Chlorination

Cl₂ added with proprietary chlorinators (see Fig 11.17 in VH text)

Desired Ct is best achieved in plug flow (or nearly plug flow) reactors

Typical chlorine contact chamber is serpentine chamber with baffles - see pg 10 - Figure from Droste, 1997, p. 522

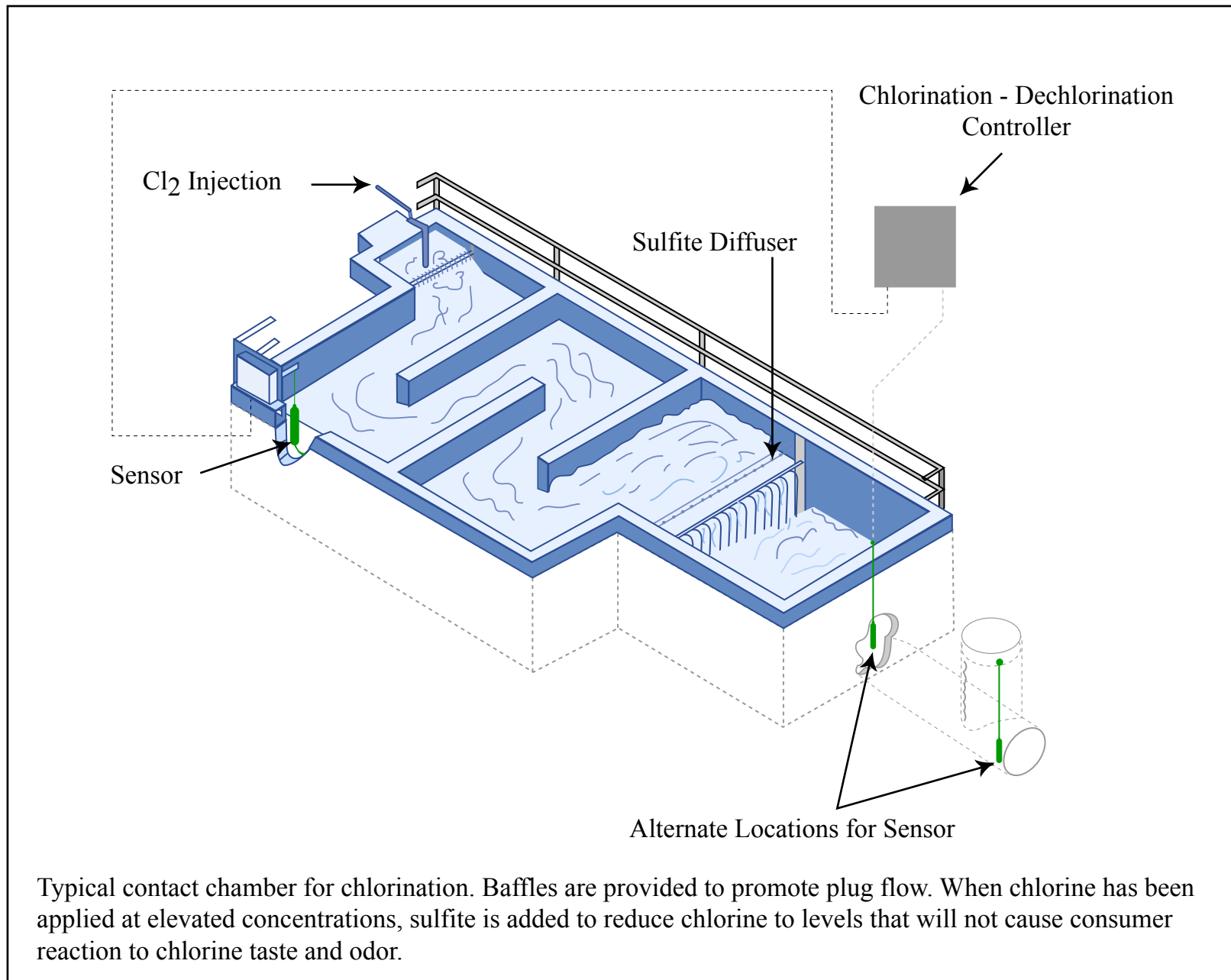


Figure by MIT OCW.

Adapted from: Binnie, C., M. Kimber, and G. Smethurst. *Basic Water Treatment*. 3rd ed. Cambridge, UK: Royal Society of Chemistry, 2002.

Ozonation

Ozone (O_3) is more powerful oxidant than HOCl

Ozone inactivates microorganisms by

1. Direct oxidation
2. Decomposition into hydroxyl radicals $HO\cdot$ which are also strong reactants

Widely used in Europe, increasingly used in US

Advantages: excellent disinfectant (including for Giardia and Cryptosporidium)
 does not form THMs, chlorophenols
 effective against taste and odor
 requires short contact time

Disadvantages: short contact-time reactors prone to short-circuiting
 more costly than Cl_2
 does not create disinfecting residual
 may produce harmful by-products
 ozone gas is potentially explosive

Ozone treatment design based on Ct, with consideration of ozone decay over time

Ozone is sparingly soluble - usually introduced as gas by fine-bubble porous diffusers in deep basins

Ozone consumption by specific water to be treated measured in lab (analogous to determining chlorine demand)

$$C_{residual} = C_{dose} - C_{demand}$$

Decay of $C_{residual}$ over time measured in lab reactors pulsed with ozone $\rightarrow C$ vs. t

Integrate C vs. t to get Ct

Ozone contactors usually introduce O_3 and get water contact in same tank (pg 13 from MWH pg 1121)

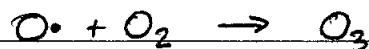
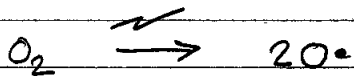
Ozone bubbled into chamber creates fully-mixed conditions

But desire plug flow to ensure Ct is achieved

Solution is to create tanks-in-series to approximate PFR

Some designs seek counter-current flow to achieve better O_3 transfer (bubble rise is slowed by counterflow of water)

Ozone is generated on-site in a corona discharge - electric arc generated by high voltage between two plates separated by air gap



(same effect as lightning storm)

Chlorine Dioxide ClO_2

stronger oxidant than Cl_2

creates long-lasting residual

effective against taste and odor

produces few by-products, however chlorate and chlorite

ions are produced but limited by regulations to non-toxic conc.

Widely used in Europe, less common in U.S.

More expensive than Cl_2

