Disinfection

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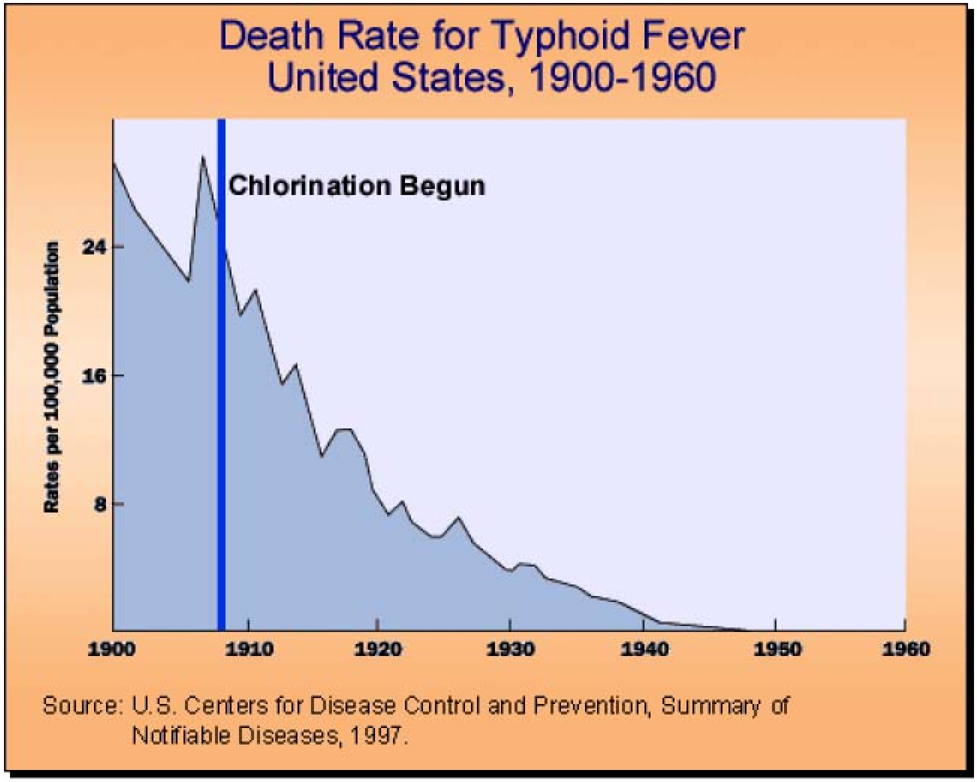
Objectives and means of disinfection

- Destruction or inactivation of pathogenic organisms

- Disinfection can be done by:
  - chemical means- chlorine, ozone,
  - non-chemical means- heat, UV irradiation



Mechanisms of pathogen inactivation

- Destruction of cellular structure
- Interference with metabolic activities and protein synthesis
  - In water treatment combinations of these mechanisms play role

Microorganisms

- Microorganisms of concern include:

Type	Size, µm
Viruses	0.01 to 0.1
Bacteria	0.1 to 5
Cryptosporidium oocysts	3 to 5
Giardia cysts	6 to 10
Protozoan	10 to 25
Algae	5 to 100

- Indicator organisms are often used to assess the presence or absence of pathogens
- Common indicator organisms are coliforms- E-coli

Disinfection kinetics

- Chick's law
- Best described by first order reaction

$$\frac{dN}{dt} = -k * N \rightarrow \ln\left(\frac{N}{N_0}\right) = -k * t$$

number of micro-organisms destroyed per unit of time is proportional to the number of organisms

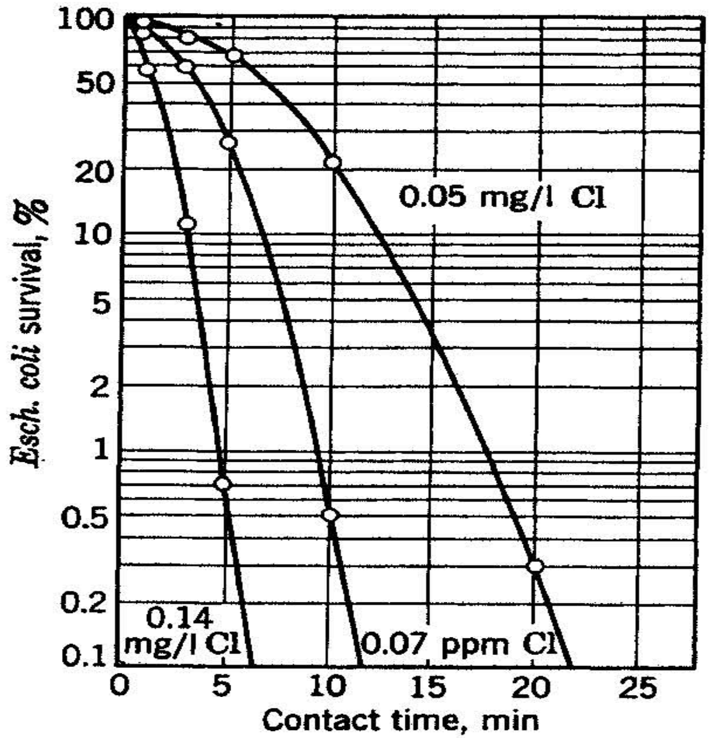
- $N/N_0 = e^{-k.t}$ → reduction factor (R)

- Where
  - N = concentration of organisms (N/m^3)
  - No = initial concentration of organisms (N/m^3)
  - t = time
  - k = rate constant- this depends on disinfectant concentration, organism and temperature

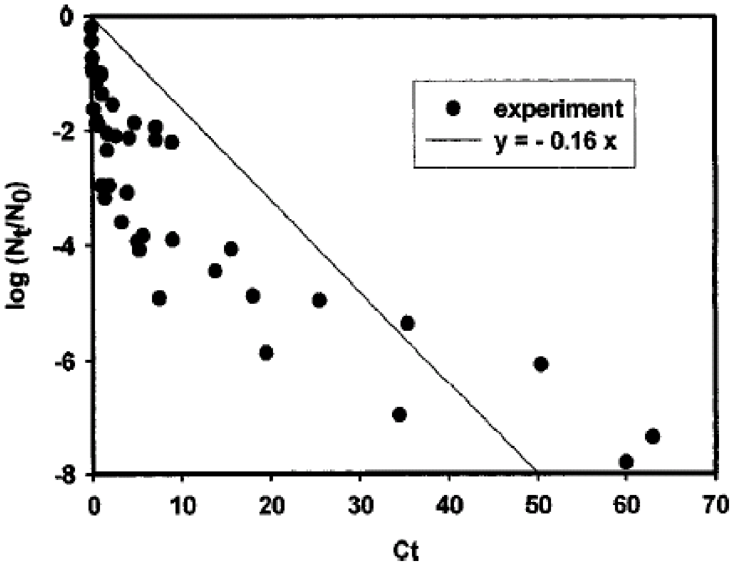
Disinfection kinetics

- Chick-Watson model
  - Relates the rate constant of inactivation, k, to the disinfectant concentration, C.
  - $k = k'C^b$ b is coefficient of dilution

$\ln (N/N_0) = k'C^b t$



Source: Faust and Aly, 1998



Relationship between log survival ratio and and Ct.(Lee and Nam, 2002)

Removal of microorganisms during water treatment

Significant removal of microorganisms is achievable by processes other than disinfection.

USEPA- Surface Water Treatment Rule (SWTR) –gives log removal credits to other processes

Treatment	Log removal	
	Giardia	Viruses
SWTR	3.0 (99.9%)	4.0 (99.99%)
Conventional treatment	2.5	2.0
Direct filtration	2.0	1.5
Slow sand filtration	2.0	2.0
Membrane processes	3-4	3-4*

* using Ultrafiltration

Factors affecting disinfection

- Turbidity (particulates can shield micro organisms); turbidity should not exceed 0.5 NTU;
- Organic matter and ammonia (they react with disinfectants);
- pH (may change chemical form of disinfectant e.g. HOC / OCl^-);
- Temperature (diffusion and reaction rate);
- Disinfectant dose and contact time

Primary and secondary disinfection

Primary disinfection: Commonly achieved by combination of filtration and chemical oxidation

Secondary or post disinfection: Maintaining residual disinfectant in the distribution system in order to control re-growth

Residual chlorine requirements at consumers points

	WHO	USEPA	NL
Residual concentration, mg/L	0.2	0.25	0.0

Re-growth

Main cause

- Availability of AOC and nutrient in the distribution system

Main effects

- Formation of taste and odour under anaerobic conditions
- Growth of macro-organisms e.g. worms;
- Corrosion

Control mechanisms

- Effective treatment to produce biostable water;
- Ensuring sufficient residual disinfectant in the network

Common disinfection chemicals

Chlorine compounds- Cl_2,	Can be found in liquefied gas, solution or solid forms
Ozone (O_3)	produced on site
Chlorine dioxide (ClO_2)	produced on site
Chloramine (eg. NH_2Cl)	formed by addition of ammonium and chlorine to the water
Potassium permanganate $(KMnO_4)^-$	a violet solid
Silver (Ag^+)	in ceramic filters

Strength and stability of disinfectants

Disinfectant	**Power**	**Stability**
OCl^- (hypochlorite)	Weak	Decomposes slowly
HOCl (Hypochlorous acid)	Strong	Decomposes slowly
NH_2Cl (Monochloramine)	Very weak	Very stable
ClO_2	Strong	(Very) stable
O_3	Very strong	Very unstable
$KMnO_3$	Weak	Unstable

Which disinfectants are suitable for post disinfection?

Effectiveness of disinfectants

- Disinfectants can be compared in terms of CT value
  - C is disinfectant dosage, mg/L
  - T contact time. min

Disinfectant	Unit	Inactivation 1-log	2-log	3-log	4-log
Bacteria					
Chlorine (free)	mg·min/L	0.1–0.2	0.4–0.8	1.5–3	10–12
Chloramine	mg·min/L	4–6	12–20	30–75	200–250
Chlorine dioxide	mg·min/L	2–4	8–10	20–30	50–70
Ozone	mg·min/L		3–4		
Virus					
Chlorine (free)	mg·min/L		2.5–3.5	4–5	6–7
Chloramine	mg·min/L		300–400	500–800	200–1200
Chlorine dioxide	mg·min/L		2–4	6–12	12–20
Ozone	mg·min/L		0.3–0.5	0.5–0.9	0.6–1.0
Protozoan cysts					
Chlorine (free)	mg·min/L	20–30	35–45	70–80	
Chloramine	mg·min/L	400–650	700–1000	1100–2000	
Chlorine dioxide	mg·min/L	7–9	14–16	20–25	
Ozone	mg·min/L	0.2–0.4	0.5–0.9	0.7–1.4	

Chlorine

Chlorine is the most commonly used and low cost disinfectant. It is available in four different forms:

Compound	**Form**	**% Chlorine**
Chlorine(Cl_2)	Liquefied gas	100
Sodium hypochlorite solution (NaOCl)	Solution	10 to 15
Bleaching powder ($CaOCl_2$)	Solid	25 to 35
High test hypochlorite $Ca(OCl)_2$	Solid	70

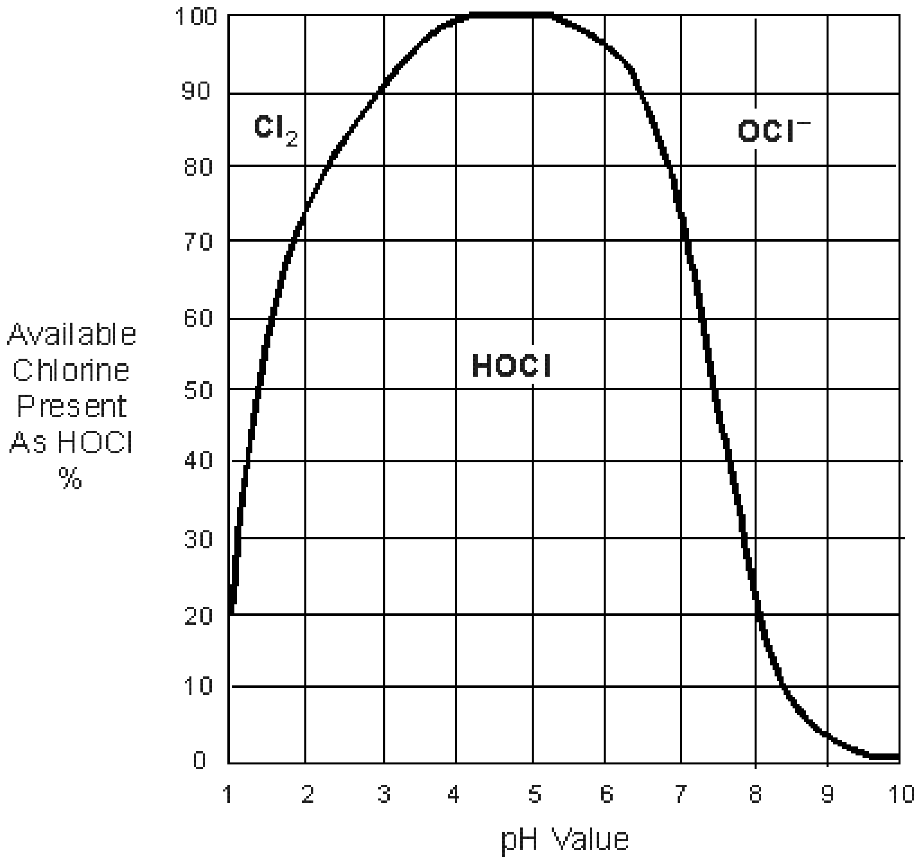
Dissociation of chlorine

Chlorine dissolves in water & at normal pH it yields HOCl and OCl^-

$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$

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

Sodium hypochlorite, Bleaching powder, High Test Hypochlorite also form HOCl and OCl^-



Note that above pH 4, Cl_2 does not exist

Break point chlorination

Break point chlorination is the addition of sufficient chlorine to produce free available chlorine

HOCl and OCl- react with ammonium to form:

- monochloramine;
- dichloramine;
- trichloramine or oxidize it to N_2

sum of HOCl and OCl^-	=	Free available chlorine
Sum of mono-, di- and tri- chloramines	=	Combined available chlorine
Sum of free and combined chlorine	=	Total available chlorine

All forms are expressed as mg Cl_2/l.

Break point chlorination

Summary of the reactions:

I. $2NH_4^+ + 2Cl_2 \rightarrow 2NH_2Cl + 4H^+ + 2Cl^-$

1 mg NH_4^+ requires 4 mg Cl_2

II. $2NH_2Cl + 2Cl_2 \rightarrow 2NHCl_2 + 2H^+ + 2Cl^-$

III. $2NHCl_2 \rightarrow N_2 + Cl_2 + 2H^+ + 2Cl^-$ formed Cl_2 reacts with remaining NH_4

IV. $2NH_4^+ + 3Cl_2 \rightarrow N_2 + 8H^+ + 6Cl^-$

The overall reaction is known as:

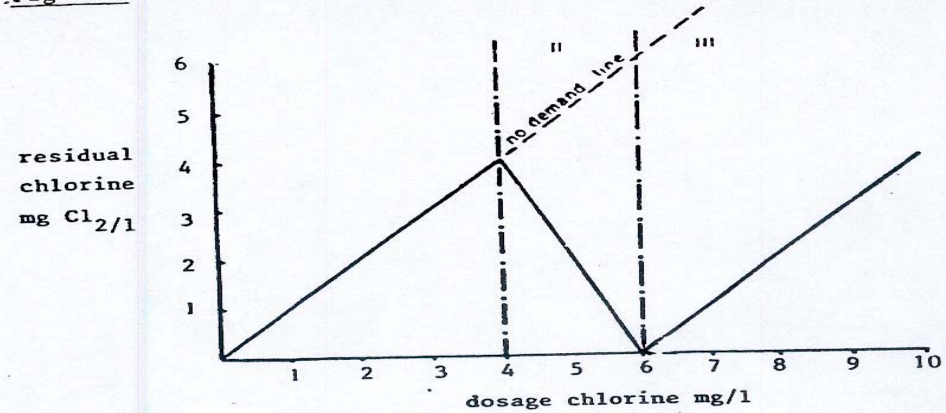
" Breakpoint Chlorination "

In general 6 mg Cl_2 is required per mg NH_4^+

In practice more chlorine is required due to presence of organic matter

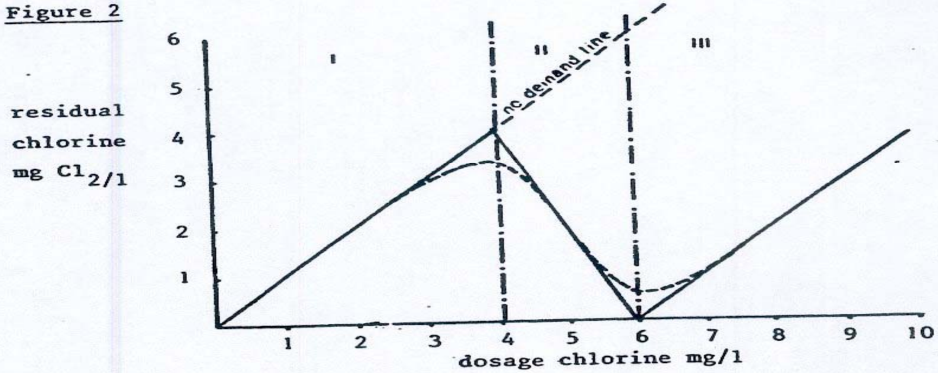
Break point chlorination

Figure 1



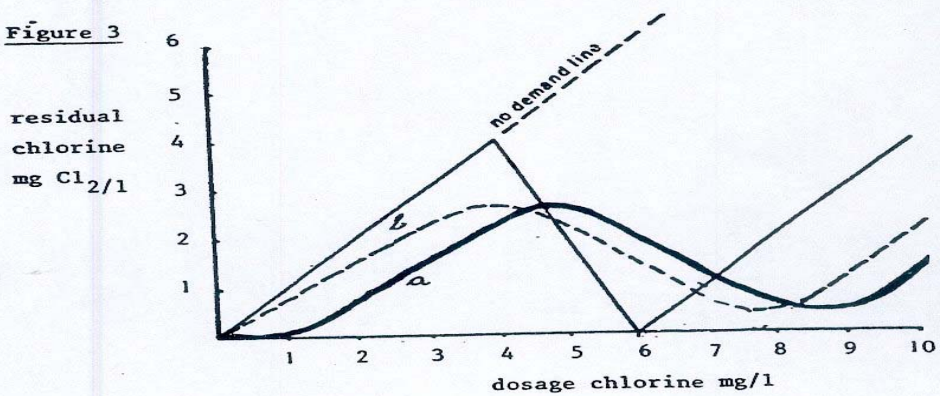
Hypothetical graph for 1 mg NH_4^+/l

Figure 2



Breakpoint graph for 1 mg NH_4^+/l

Figure 3



Breakpoint graph for 1 mg NH_4^+/l with organic matte

Disinfection by products (DBPs)

- DBPs are produced by the reaction of disinfectants and
  - mainly organic compounds (NOM)
  - bromide ion

- Most common DBPs include:
  - Trihalomethanes (THMs)
  - Haloaceticacids (HAAs)
  - Bromate
  - Chlorite

Guidelines for DBPs

DBPs	Maximum contaminant level (μg/L)			
	WHO (1993)	USEPA (2006)	EU	
Bromoform	100	0*		
Dibromochloromethane	100	60*		
Bromodichloromethane	60	0*		
Chloroform	200	70*		
TTHM	50	80	100	
HAA5**		60		
Bromate		10 (Average value)	10	
Chlorite		1mg/L		

* Maximum contaminant levels goals

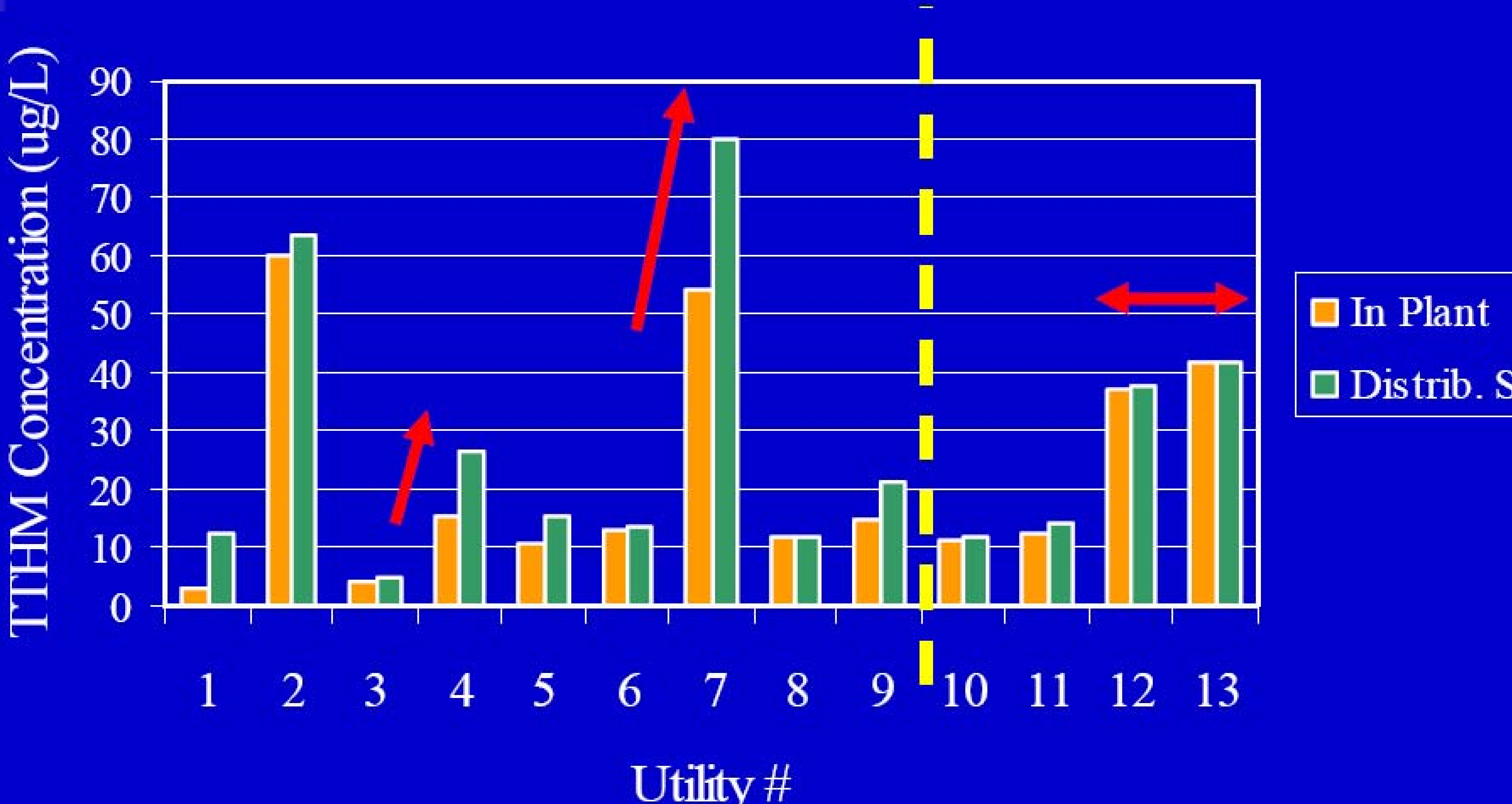
** HAA5: Sum of five HAAs,

Factors affecting DBPs formation

Water quality:	**Operational parameters**
Type and concentration of precursors NOM, bromide	Disinfectant type and dose
pH	Contact time (water age)
Temperature	
Ammonia concentration	

Chlorine vs. Chloramines

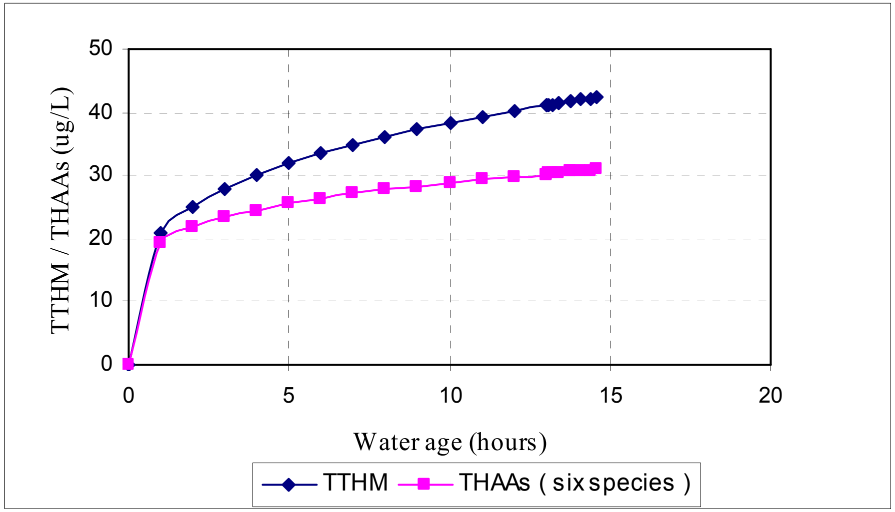
Ontario (Canada) Survey



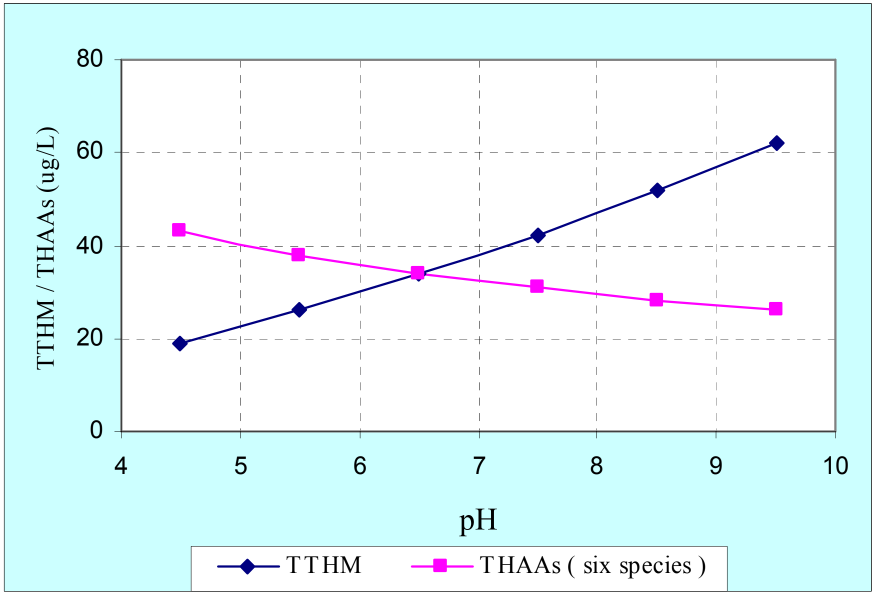
Utility 1-9 (chlorine) Utility 10-13 (chloramines)

Factors affecting DBPs formation

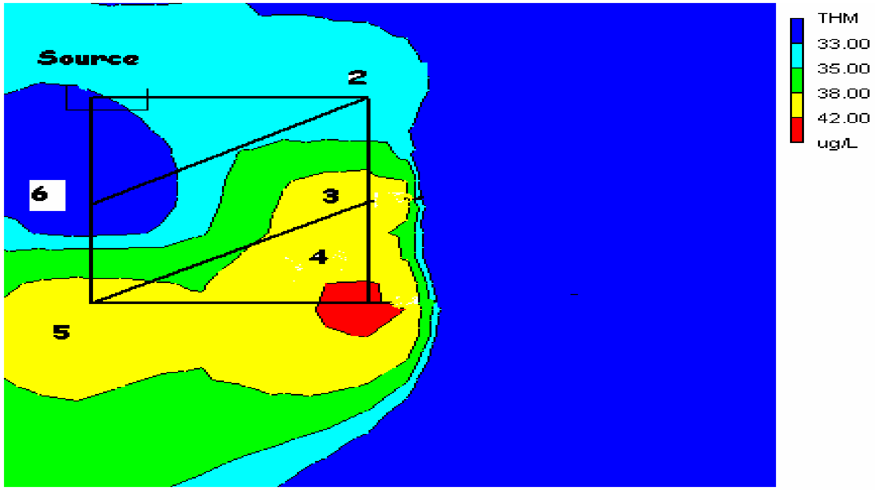
Time



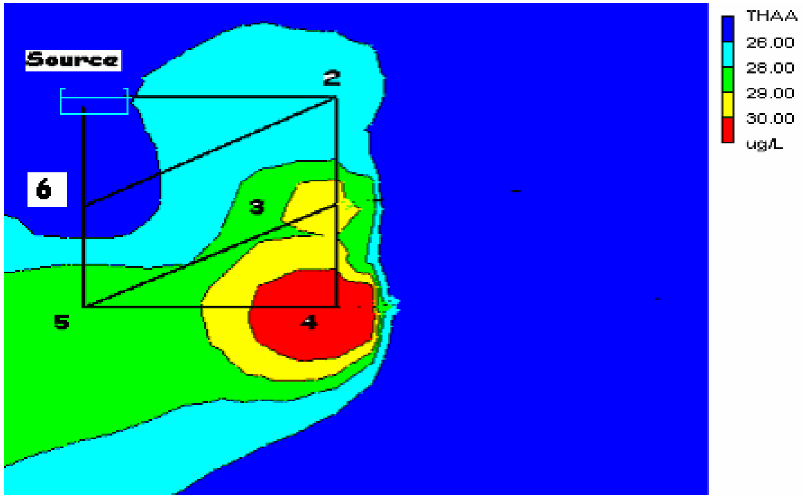
pH



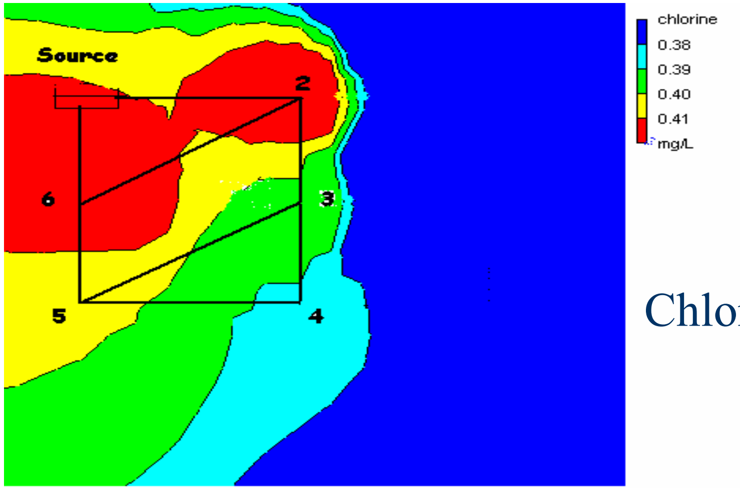
Isopleths of DBPs and chlorine residual in distribution networks



TTHM



THAA

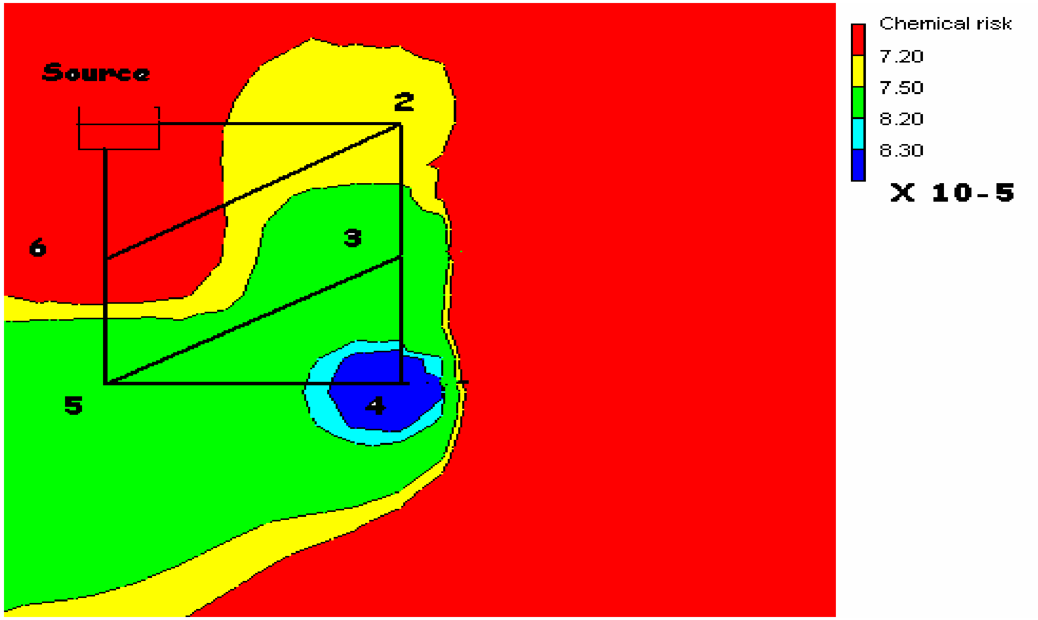


Chlorine residual

Chemical risks

DBPs	**Chemical risk factors (per µg/L)**
$CHCl_3$	$1.7x10^{-7}$
$CHBrCl_2$	$1.7x10^{-6}$
$CHBr_2Cl$	$2.4\ x10^{-6}$
$CHBr_3$	$2.5\ x10^{-7}$
DCAA	$3.0\ x10^{-6}$
TCAA	$2.4\ x10^{-6}$

Risk from BrO_3^- is much higher - a shift to H_2O_2-UV is envisaged

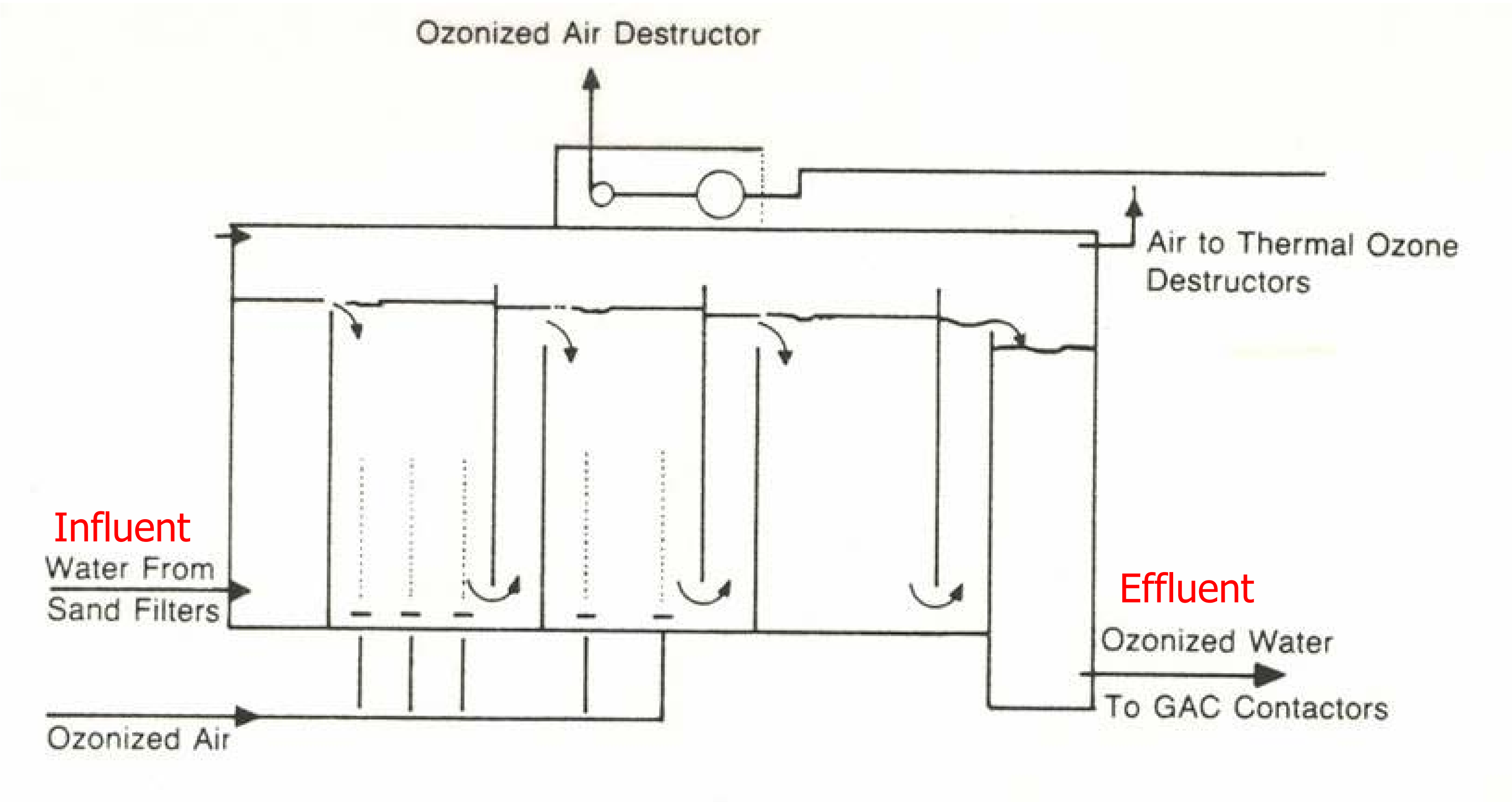


Total chemical risks for DBPs formations

Advanced disinfection

- Ozonation
  - More effective than chlorine, but expensive
  - Not much DBPs compared to chlorine
  - Ozone reacts with organic matter to form biodegradable DOC
    - $DOC + O_3 \rightarrow BDOC + O_2$
    - BDOC include: Aldehydes, Carboxylic Acids, etc.

Ozonation process



Ozone disinfection by products

- Ozone can directly or indirectly react with bromide to form ozone DBPs including bromate ion (BrO_3^-)

- In the presence of NOM, non-halogenated DBPs are formed
  These compounds are more easily assimilable (AOC) by bacteria than NOM,

- If both NOM and bromide are present, ozonation forms hypobromous acid, resulting in the formation of brominated organohalogen compounds (e.g. bromoform).

A Potential Consequence of using ozone

- Creation of Biodegradable Organic Matter (BOM) from Natural Organic Matter (NOM)
- This results in
  - Transformation of Rapid Sand Filter (RSF) into Biological Sand Filter (BSF) with Biofilm
  - Transformation of Granular Activated Carbon (GAC) into Biological Activated carbon (BAC) with Biofilm

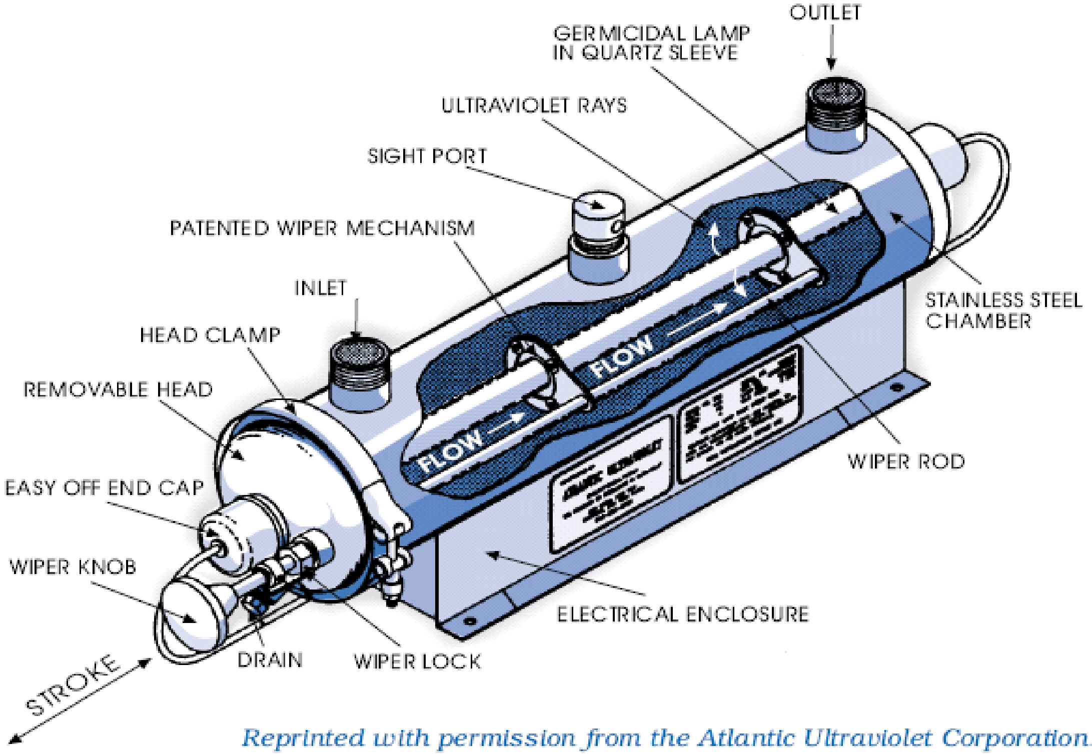
UV disinfection

- Very effective with up to 99 % removal- Viruses requires higher UV dosage
- Penetrates the cell wall and destroys DNA
- No residual disinfectant
- Requires good water quality

UV disinfection

- High tech using UV lamps

Closed Vessel Ultraviolet Reactor



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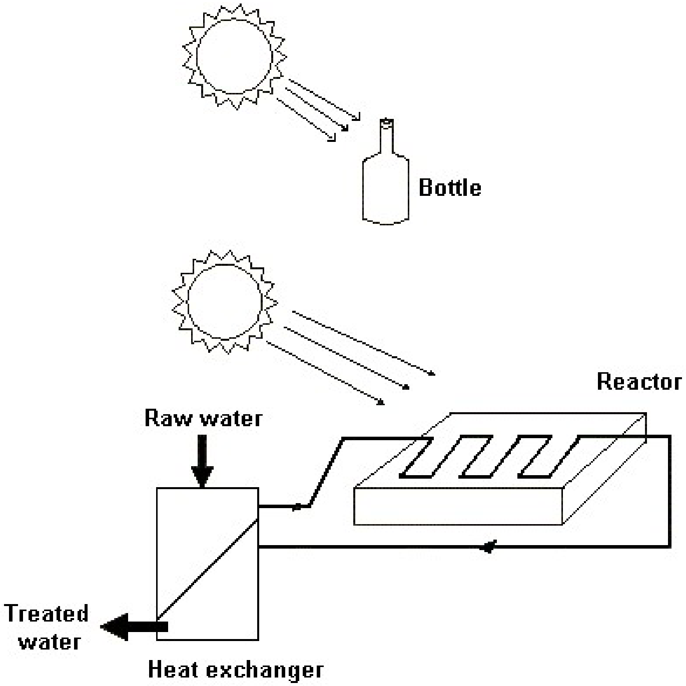
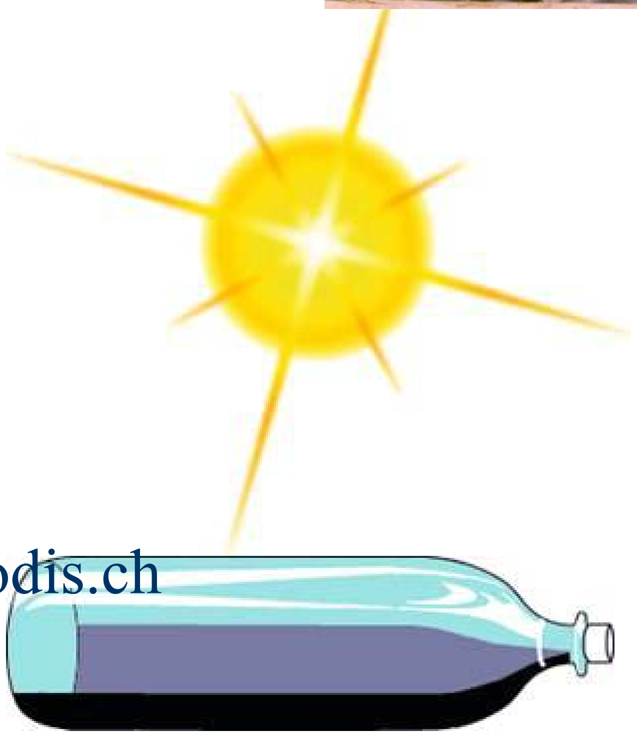
UV disinfection

- Low tech using solar energy (SODIS)



www.sodis.ch



Disinfection experience in the Netherlands and elsewhere

- Philosophical approach
  - North America:
    - Remove NOM before Cl_2
    - DOC as a contaminant
  - Central Europe:
    - Biostability
    - Limit biodegradable NOM (BOM) and eliminate Cl_2
    - BDOC (or AOC) as a contaminant

Practice in USA

- Chemical Disinfectants Employed
  - Chlorine
  - Chloramines
  - Ozone
  - Chlorine Dioxide

Practice in Europe

- Southern Europe and UK
  - Chlorine with Distribution System Residual
- Central Europe (e.g., Berlin, Amsterdam, Zurich, Vienna)
  - No Distribution System Residual!
- Some parts of Europe (e.g., Paris)
  - Low Cl_2 levels in distribution system- use booster chlorination

Thank you

Conventional water treatment