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CEE 370 Environmental Engineering Principles

Lecture #29

Water Treatment III: Disinfection, Advanced Treatment

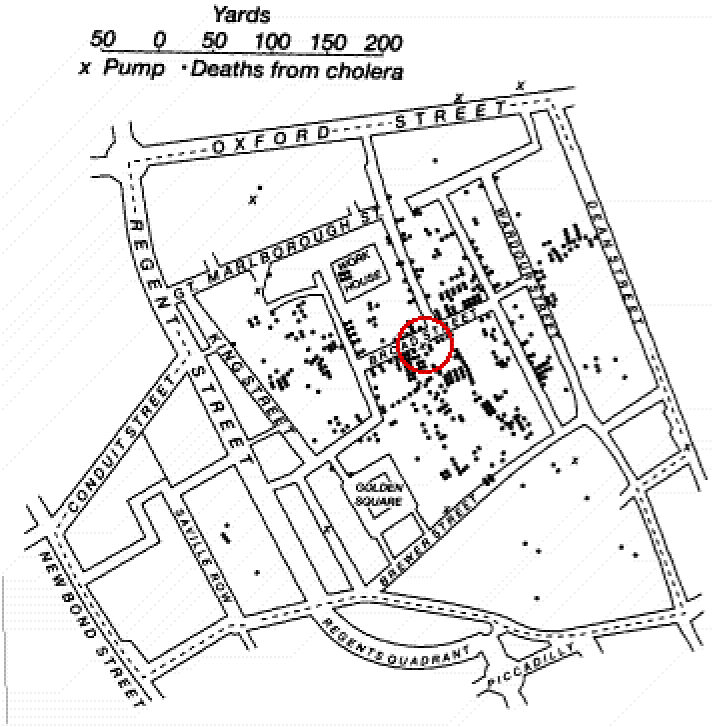
Reading: M&Z Chapter 8

Reading: Davis & Cornwall, Chapt 4-8 to 4-10

Reading: Davis & Masten, Chapter 10-7 to 10-8

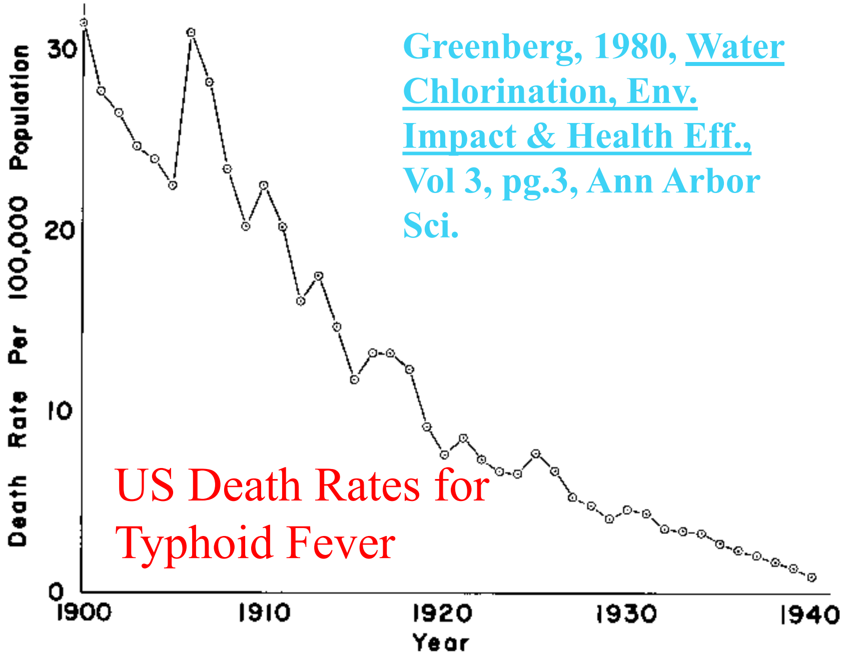
Dr. John Snow

- During an outbreak of cholera in London in 1854, John Snow plotted on a map the location of all the cases he learned of. Water in that part of London was pumped from wells located in the various neighborhoods. Snow's map revealed a close association between the density of cholera cases and a single well located Broad Street. Removing the pump hand the Broad Street well put an end to the epidemic. This despite the fact that the infectious agent that causes cholera was clearly recognized until 1905.
- John Snow's map showing cholera death London in 1854 (courtesy of The Geographical Journal). The Broad Street well is marked with an X (within the red circle).



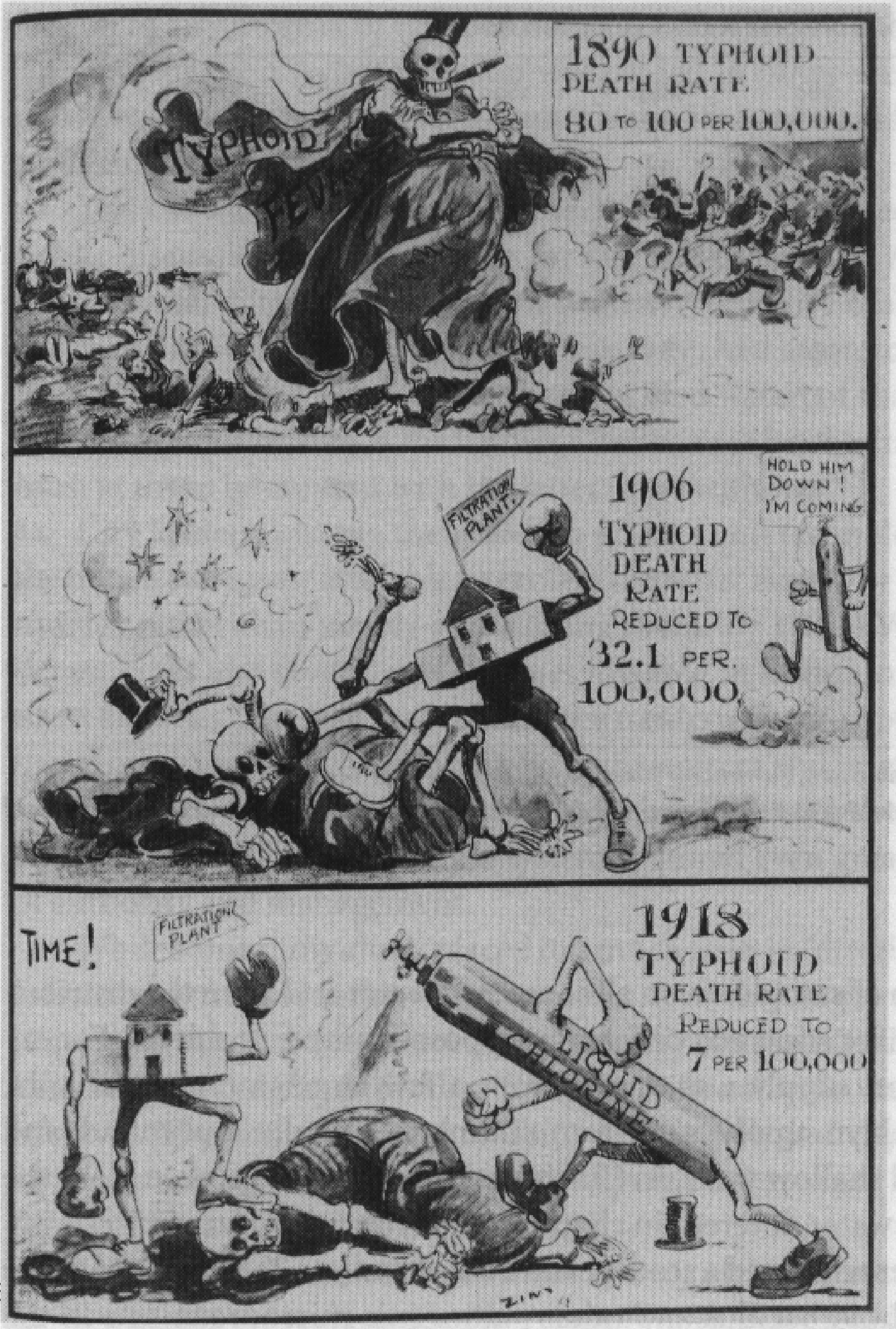
Chlorination

- 1-2 punch of filtration &



Greenberg, 1980, Water Chlorination, Env. Impact & Health Eff., Vol 3, pg.3, Ann Arbor Sci.

US Death Rates for Typhoid Fever



Melosi, 2000, The Sanitary City, John Hopkins Press

Disinfection of PWS

- One of the greatest achievements in public health during the 20th century
  - CDC
- One of the greatest engineering feats of the 20th century
  - National Academy of Engineering

Disinfection

- Kill or inactivate pathogens
  - Bacteria, viruses protozoa
- Disinfectants
  - Chlorine (Cl_2, HOCl or OCl^-)
  - Chloramines (NH_2Cl or $NHCl_2$)
  - Ozone (O_3)
  - Chlorine Dioxide (ClO_2)
  - Others: Bromine, UV light
- Primary purpose for drinking water treatment

Chick's Law

In the early 1900's Dr. Harriet Chick postulated that the death of the microorganisms was a first order process. So, for a given disinfectant and concentration:

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

This can be separated and integrated (with N = N_o at t = 0) to yield:

$$N = N_0 e^{-kt}$$

or:

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

Chick-Watson Law

- The fraction inactivated is a function of the specific lethality (λ) of the disinfectant-organism couple and the disinfectant concentration (C)

$$k = \lambda C^n \qquad \text{so} \qquad \ln\left(\frac{N}{N_0}\right) = -\lambda C^n t$$

- Many studies have found that n is in the range of 0.8 to 1.2 for most microorganisms. In engineering practice, it is usually assumed that n is unity, thus the equation becomes:

$$\ln\left(\frac{N}{N_0}\right) = -\lambda C t \qquad \text{and} \qquad k = \lambda C$$

$$\boxed{\{Ct\}_{x\log} = 2.3x/\lambda}$$

Chick-Watson II

- Use of Ct values for various "log removals" is general practice
  - Here is how Ct corresponds to specific lethality of Chick's Law (for n=1)

% Removal	"x" Log Removal	N, if N_0 = 10,000/L	Ct
90	1	1000	$2.3/\lambda$
99	2	100	$4.6/\lambda$
99.9	3	10	$6.9/\lambda$
99.99	4	1	$9.2/\lambda$

  - Model is not always accurate, but it is usually a good first approximation

Specific Lethality (λ) at 20°C

- General hierarchy
  - Disinfectants: O_3>ClO_2>HOCl>OCl^->$NHCl_2$>NH_2Cl
  - Organisms: bacteria>viruses>protozoa

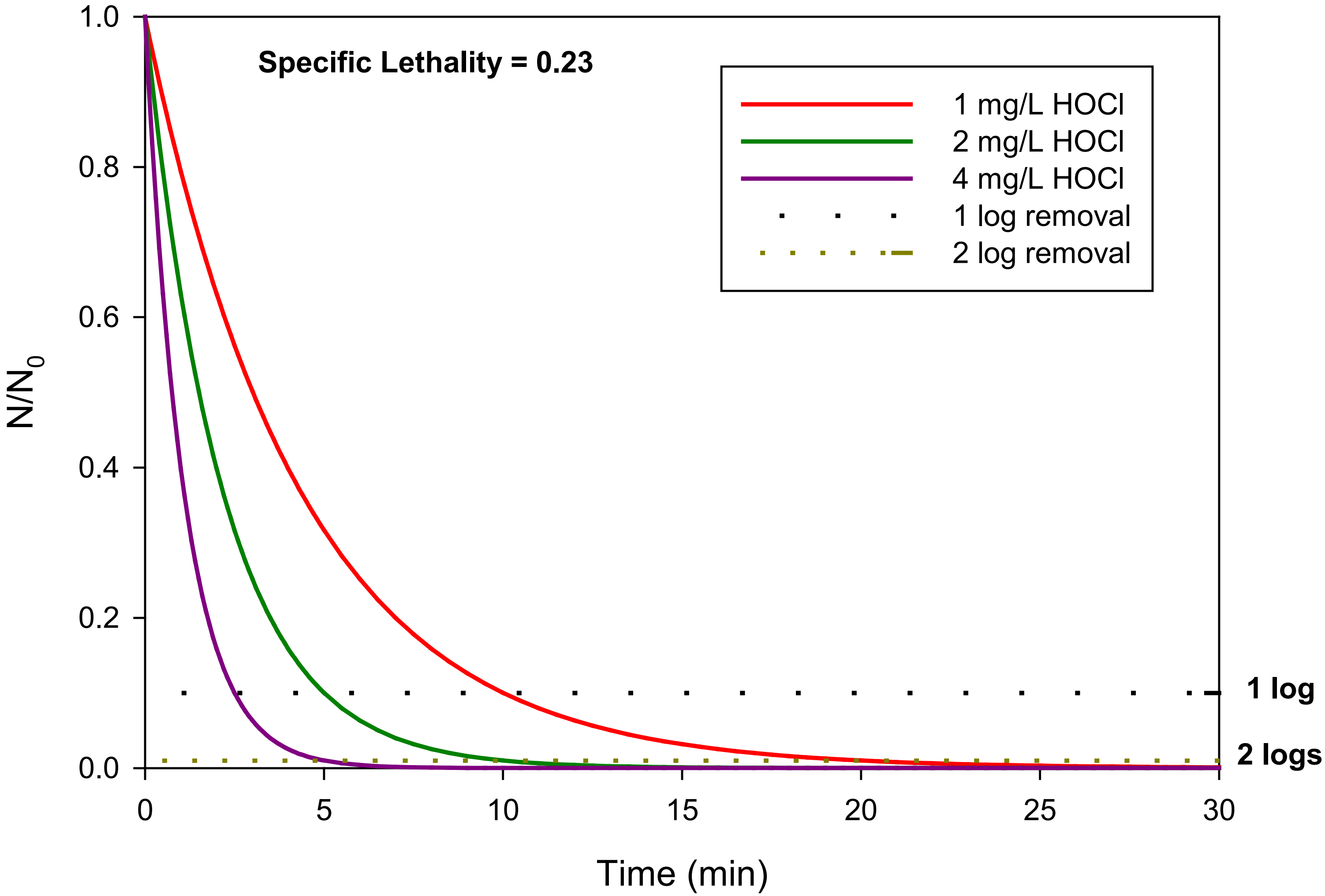
Units: L/mg-min

Some may change with pH, dose; all are affected by temperature

Disinfectant	E. coli	Poliovirus I	Entamoeba histolytica Cysts
O_3	2300	920	3.1
HOCl	120	4.6	0.23
ClO_2	16	2.4	
OCl^-	5.0	0.44	
$NHCl_2$	0.84	0.00092	
NH_2Cl	0.12	0.014	

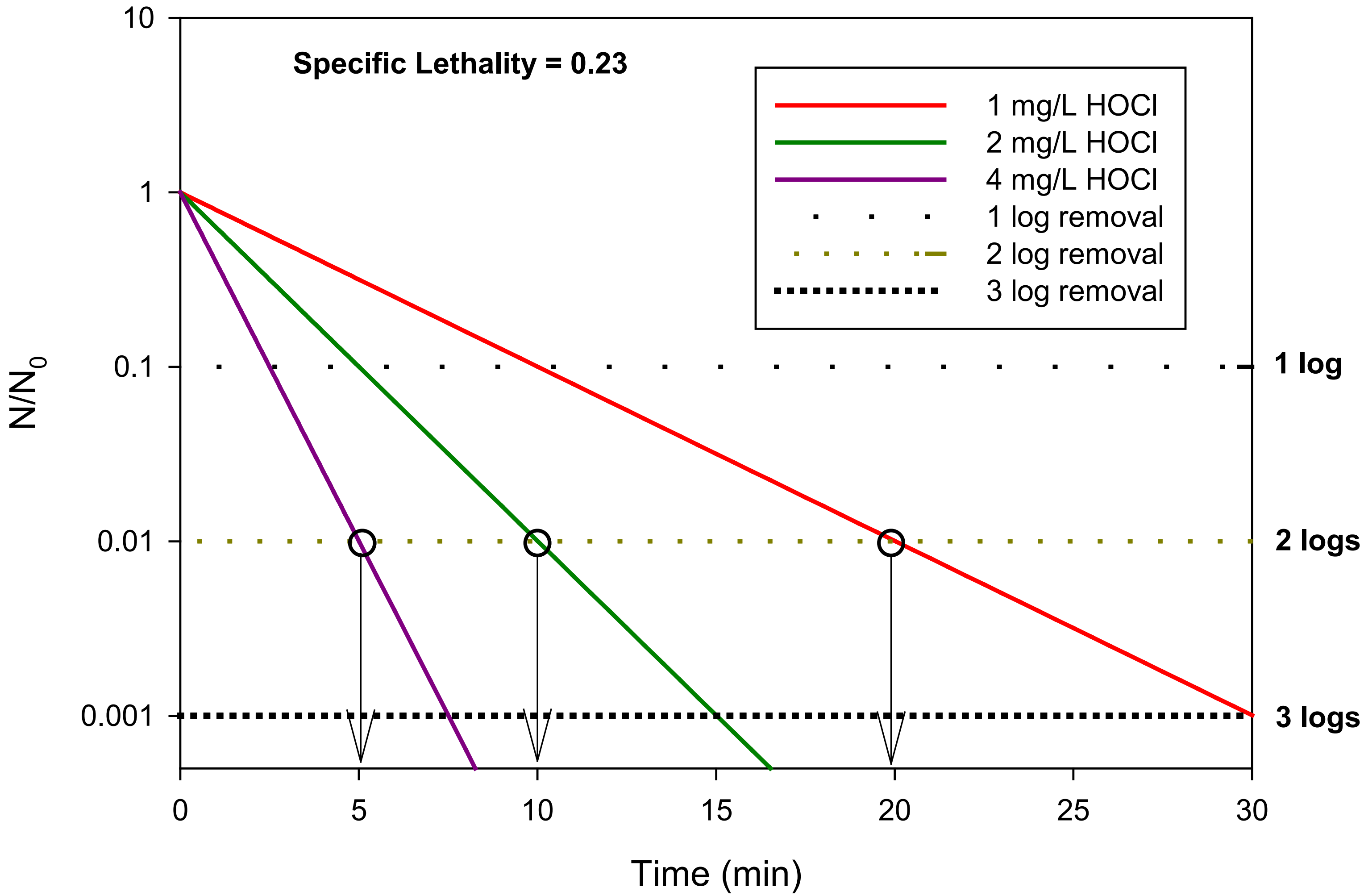
Chick-Watson Law: HOCl & Giardia

- Direct plot



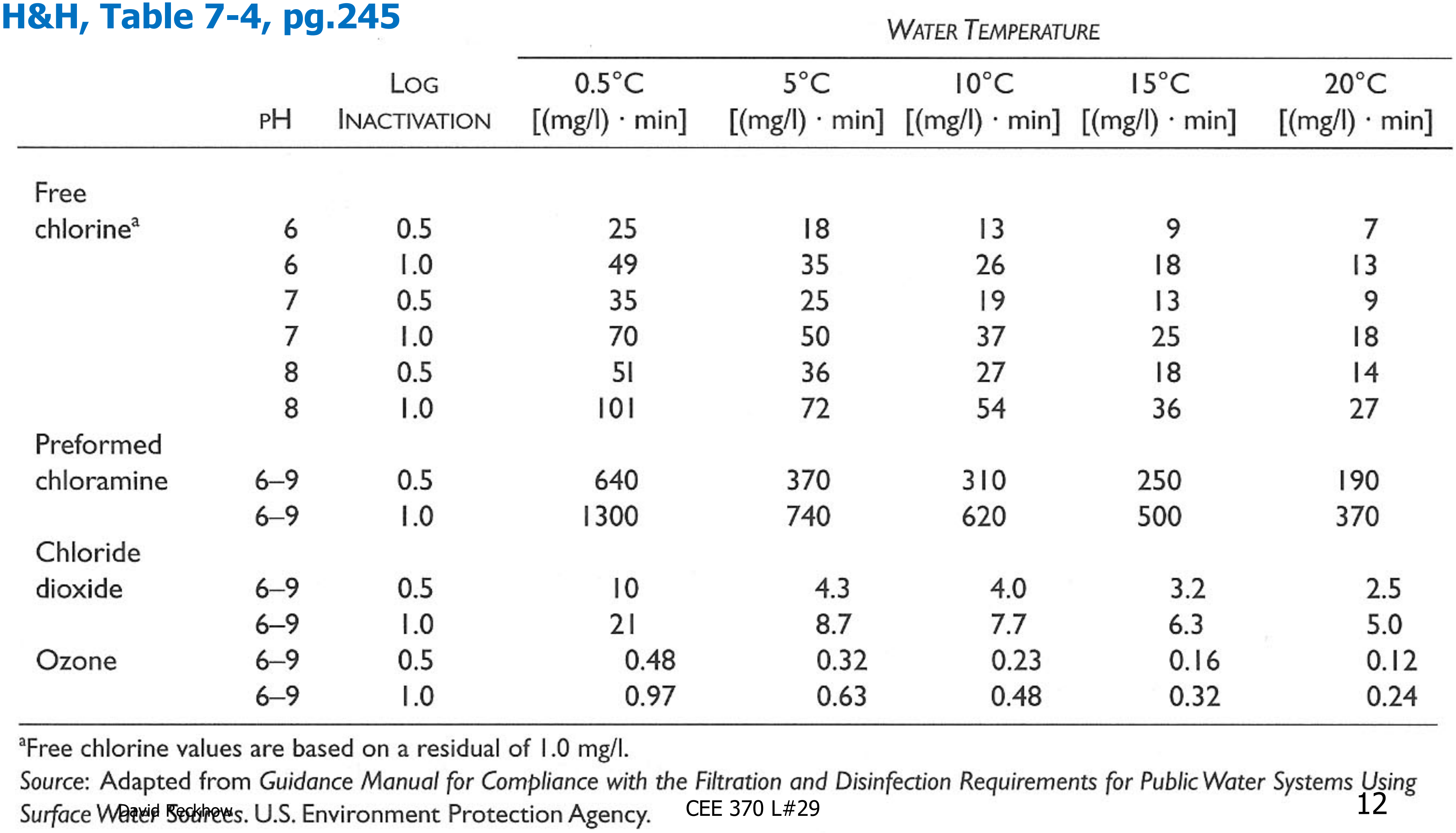
Chick-Watson Law: HOCl & Giardia

- Log plot



Ct values for *Giardia lamblia* cysts

H&H, Table 7-4, pg.245



			Water Temperature				
	pH	Log Inactivation	0.5°C [(mg/l) · min]	5°C [(mg/l) · min]	10°C [(mg/l) · min]	15°C [(mg/l) · min]	20°C [(mg/l) · min]
Free chlorine[a]	6	0.5	25	18	13	9	7
	6	1.0	49	35	26	18	13
	7	0.5	35	25	19	13	9
	7	1.0	70	50	37	25	18
	8	0.5	51	36	27	18	14
	8	1.0	101	72	54	36	27
Preformed chloramine	6–9	0.5	640	370	310	250	190
	6–9	1.0	1300	740	620	500	370
Chloride dioxide	6–9	0.5	10	4.3	4.0	3.2	2.5
	6–9	1.0	21	8.7	7.7	6.3	5.0
Ozone	6–9	0.5	0.48	0.32	0.23	0.16	0.12
	6–9	1.0	0.97	0.63	0.48	0.32	0.24

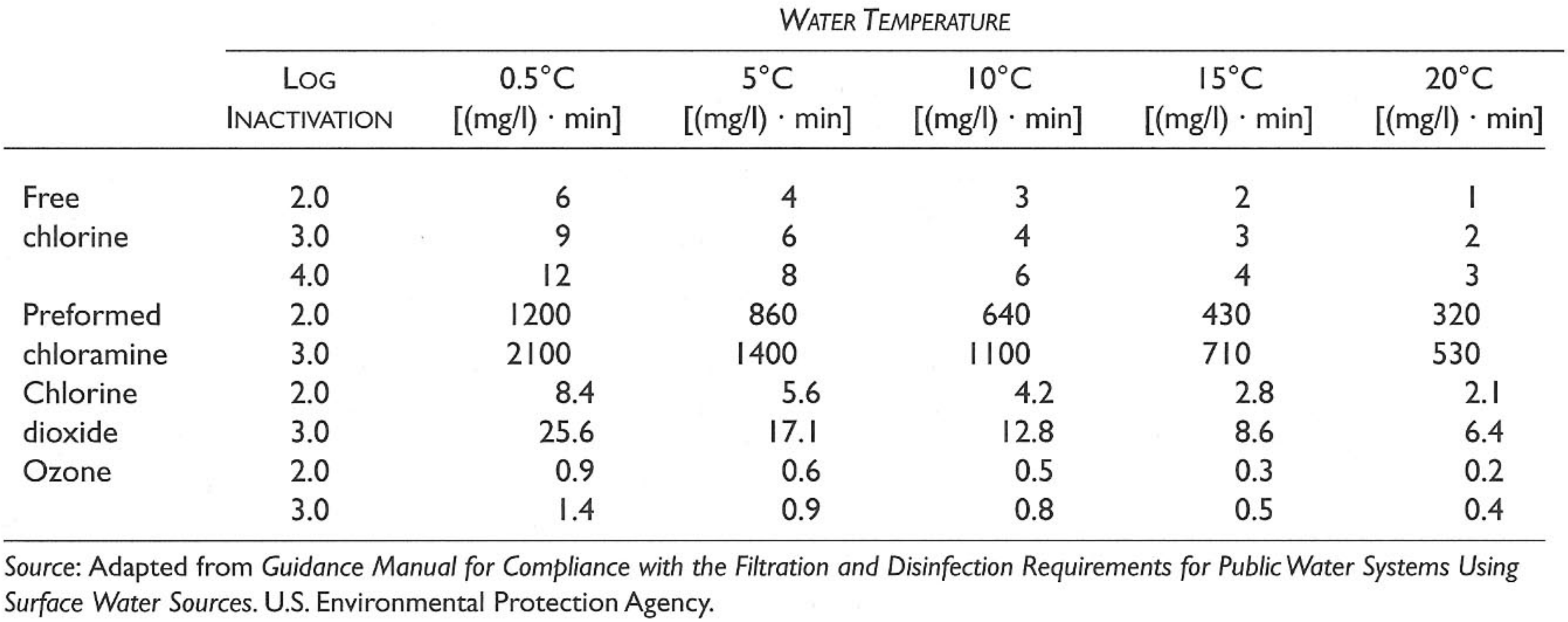
[a] Free chlorine values are based on a residual of 1.0 mg/l.

Source: Adapted from *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*. U.S. Environment Protection Agency.

Ct values for Viruses

- For Viruses at various temperatures
  - pH 6-9

H&H Table 7-5, pg 245



		WATER TEMPERATURE				
	LOG INACTIVATION	0.5°C [(mg/l) · min]	5°C [(mg/l) · min]	10°C [(mg/l) · min]	15°C [(mg/l) · min]	20°C [(mg/l) · min]
Free chlorine	2.0	6	4	3	2	1
	3.0	9	6	4	3	2
	4.0	12	8	6	4	3
Preformed chloramine	2.0	1200	860	640	430	320
	3.0	2100	1400	1100	710	530
Chlorine dioxide	2.0	8.4	5.6	4.2	2.8	2.1
	3.0	25.6	17.1	12.8	8.6	6.4
Ozone	2.0	0.9	0.6	0.5	0.3	0.2
	3.0	1.4	0.9	0.8	0.5	0.4

Source: Adapted from *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*. U.S. Environmental Protection Agency.

t_{10} concept

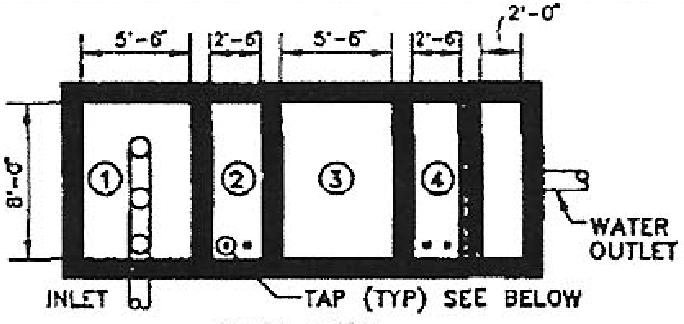
- US EPA regulatory approach
  - Use the t_{10} value
    - 90% of water has a residence time greater than t_{10}
    - 10% of water has a residence time less than t_{10}
  - A "conservative" or safe approach
    - Protection of public health
  - Value ranges from:
    - 100% of t_R for PRF
    - 10.5% of t_R for CSTR (-ln(0.9))
    - In between for all "real" reactors

Determining t_{10}

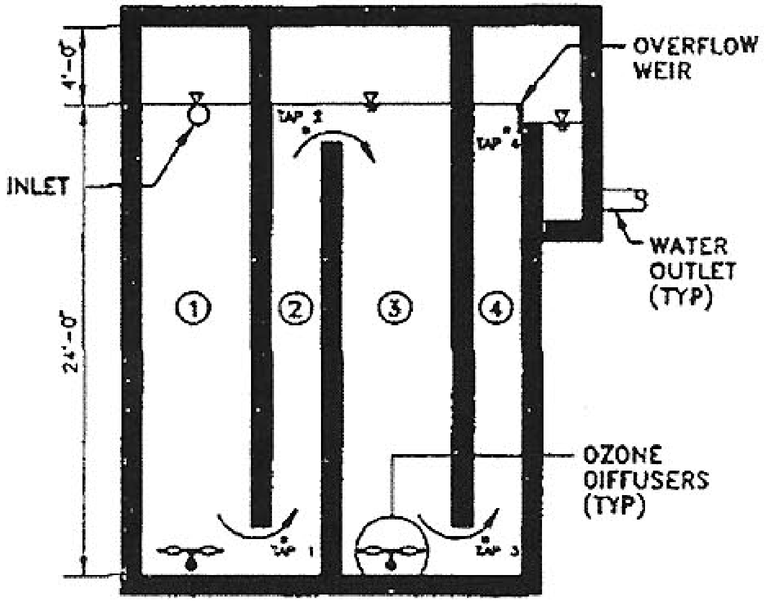
- Conduct tracer study
  - Add a conservative substance to tank inlet at a particular time
    - Fluoride is good; doesn't change, just moves with the water, non toxic
    - Can be either a pulse (slug), step-up, or step-down
  - Monitor concentration of conservative substance in tank outlet
- Data Analysis
  - Prepare graph of concentration vs time
  - Identify when concentration reaches 10% of "breakthrough" value

Case Study I: Amherst Ozone Contactor

- Four chambers
  - Under/over baffled
- Fluoride Tracer test
  - Step feed @ t=0
    - 2.4 mg/L
    - Added to inlet
    - Measure F^- at outlet v

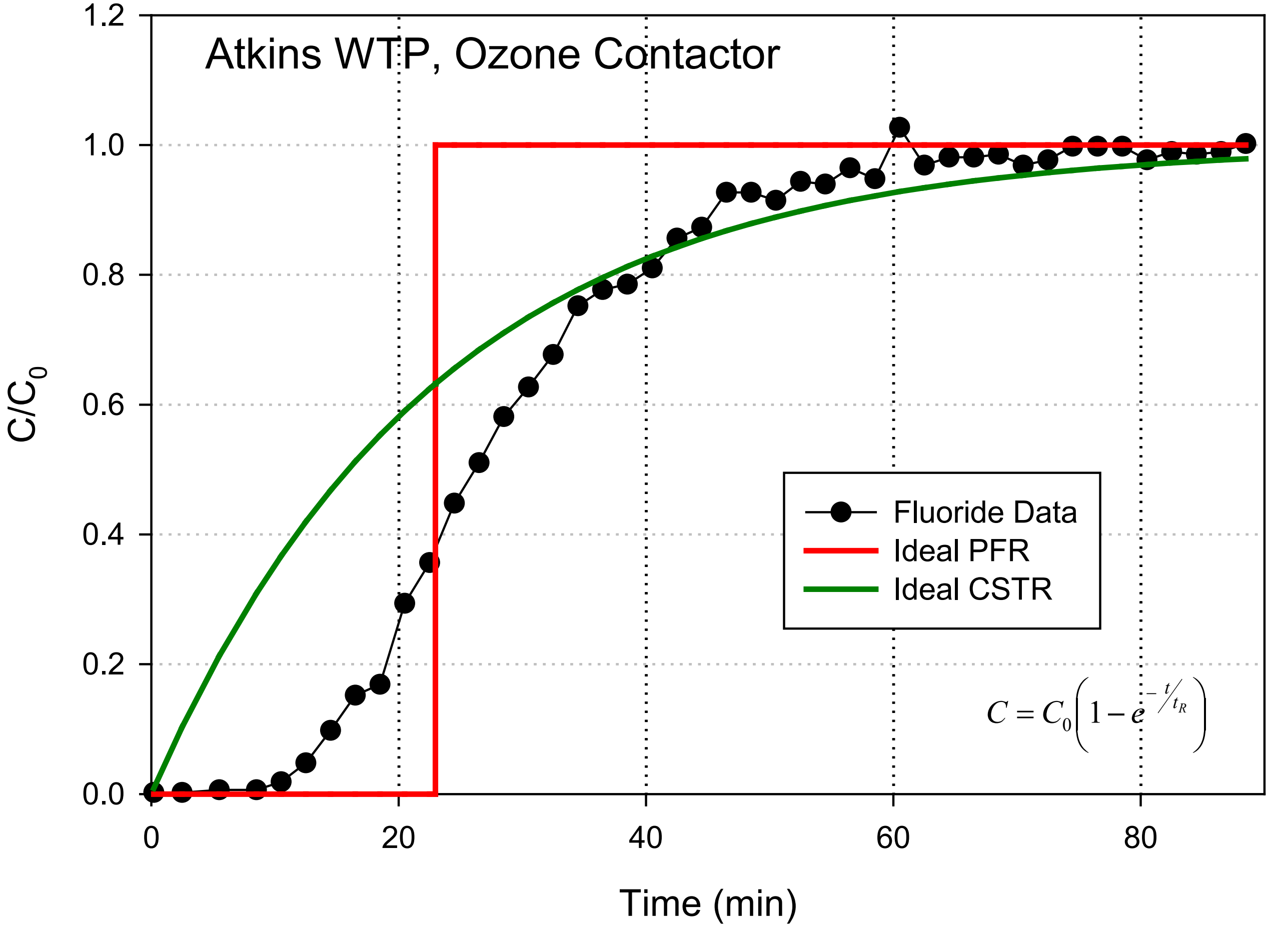


TOP VIEW



SIDE VIEW

Amherst O_3 Contactor II

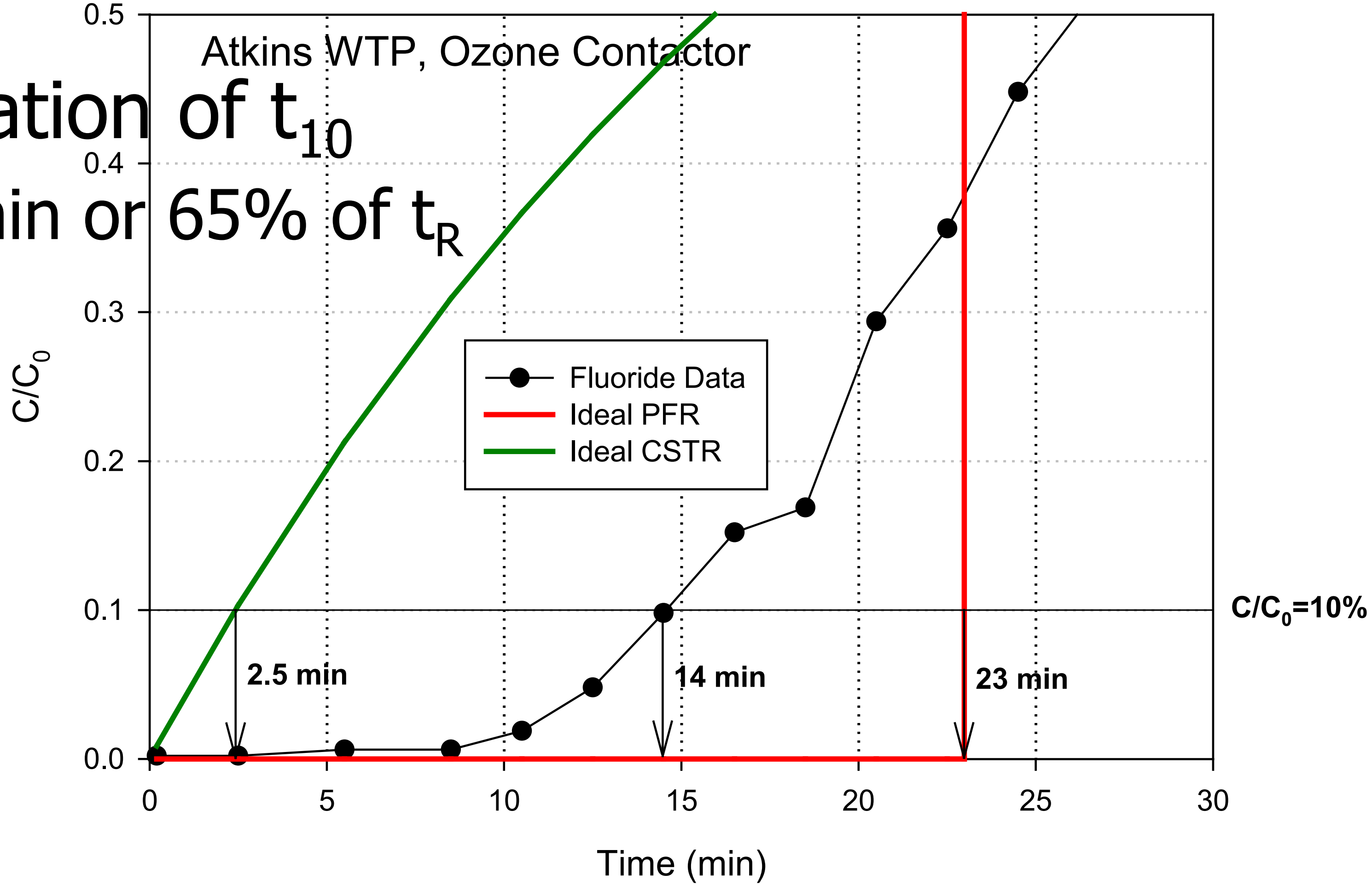


- Fluoride tracer study
  - Q=1000 gpm
  - V=22,980 gal
  - C_0=2.4 mg/L

Data from :Teefy, 1996 [AWWARF Report]

Amherst O_3 Contactor III

- Calculation of t_{10}
  - 14 min or 65% of t_R



Data from :Teefy, 1996 [AWWARF Report]

Amherst O_3 Contactor IV

- Use of t_{10} for disinfection compliance
  - Conventional treatment requires 2 log virus inactivation by disinfection
  - For ozone 0.9 mg/L – min is worst case (0.5°C, in H&H table 7-5)
  - With a t_{10} = 14 min, then we need to have 0.065 mg/L ozone residual at outlet of tank

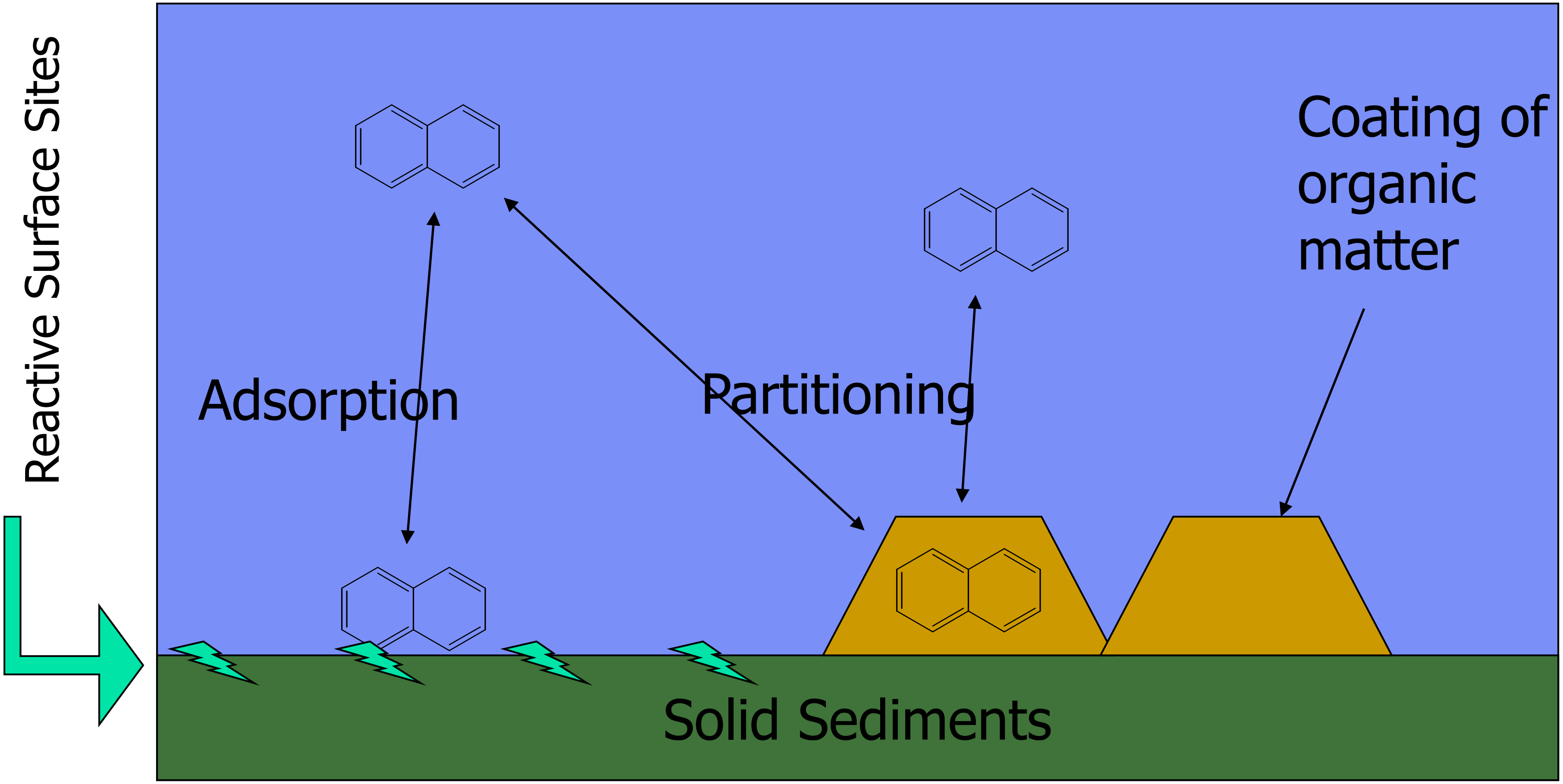
$$C_{\min} = \frac{(Ct)_{required}}{t_{10}} = \frac{0.9 \frac{mg}{L} \min}{14 \min} = 0.065 {}^{mg}\!/_{L}$$

Sorption and Ion Exchange

- Adsorption
  - The physical and/or chemical process in which a substance accumulates at a solid-liquid interface
    - Natural solids (soil, sediments, aquifer)
    - Anthropogenic (activated carbon)
- Sorption
  - The combined process of adsorption of a solute at a surface and partitioning of the solute into the organic carbon that has coated the surface of a particle

Sorption

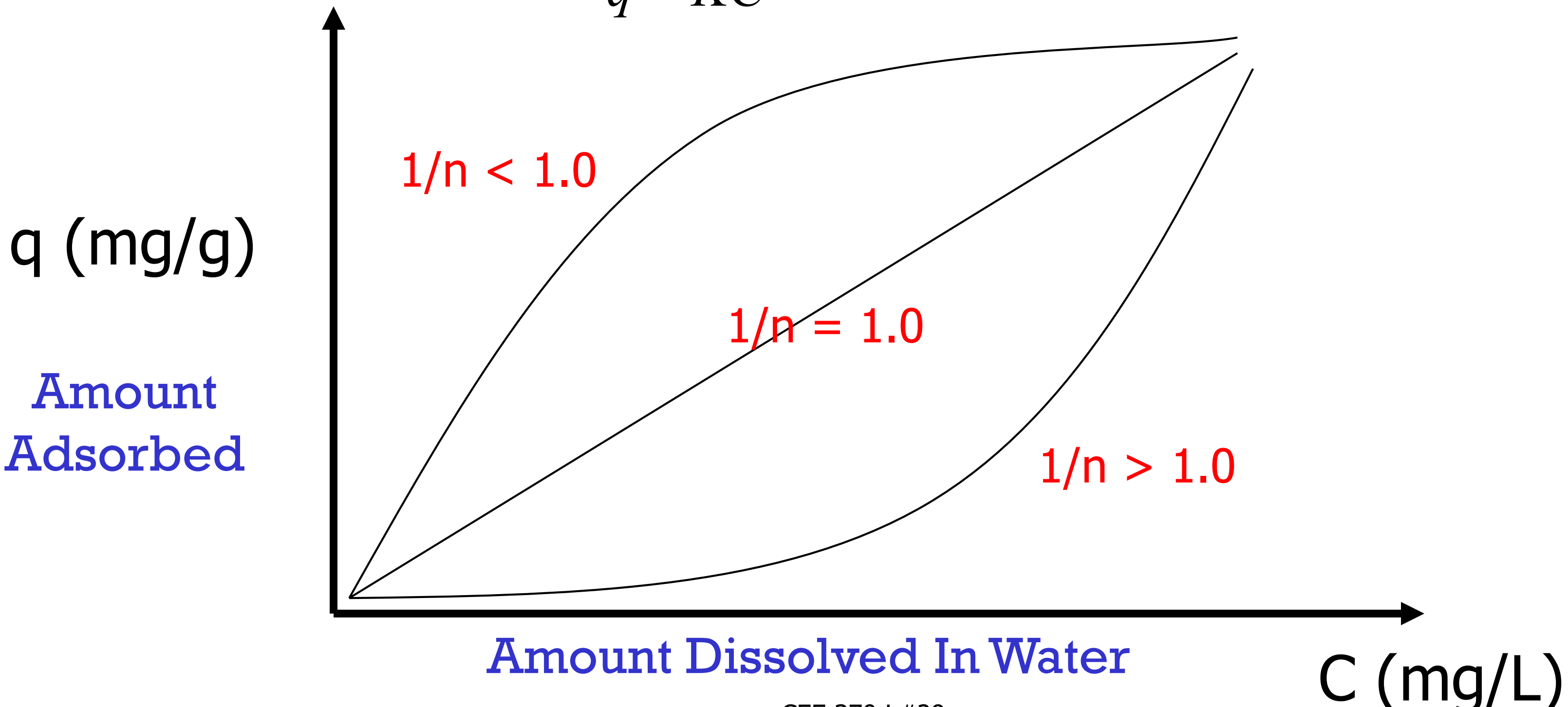
- Naphthalene: Aqueous System with Sediment



Isotherms

- Freundlich
  - Multi-layer adsorption

$$q = KC^{1/n}$$



Isotherms (cont.)

- Simple partitioning
  - When 1/n = 1.0
    - $q = KC$
  - Incorporating organic carbon layer
    - $K_{oc} = K/f_{oc}$
  - Octanol/water partition coefficients

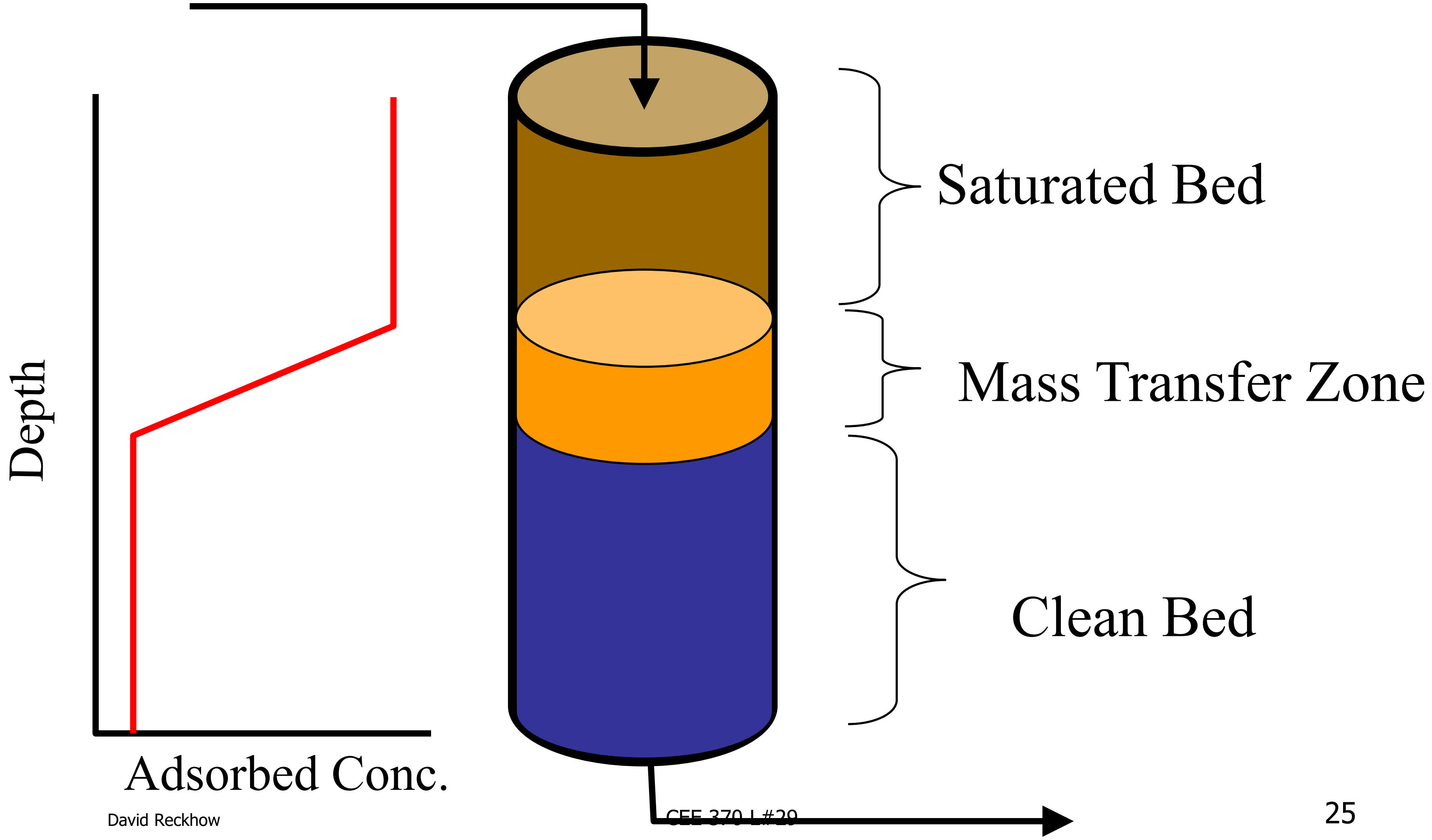
$$K_{ow} = \frac{[A]_{\text{octanol}}}{[A]_{\text{water}}}$$

- Good correlation with K_{oc}
- Relatively easy to measure

Adsorption

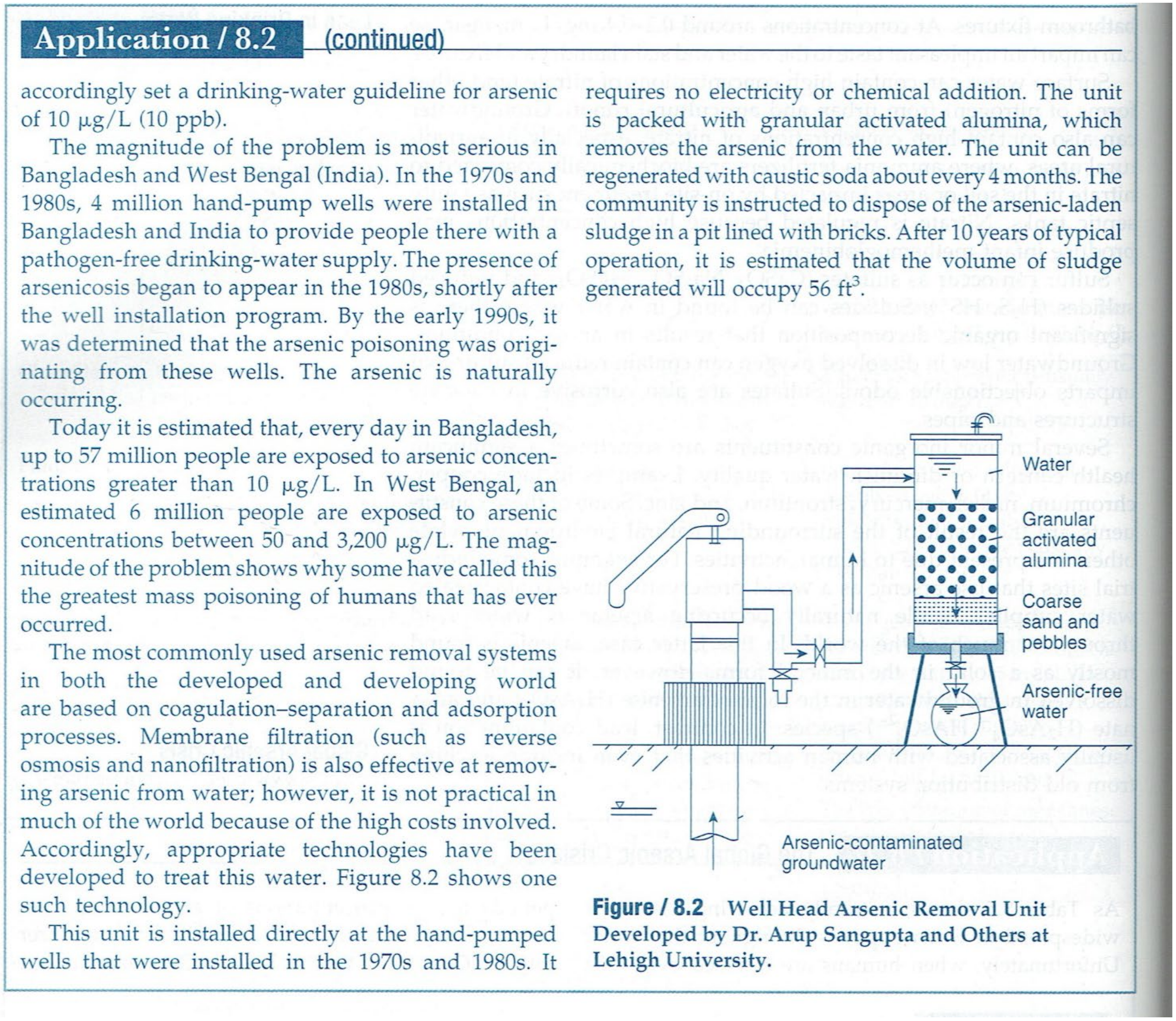
- Removal of Dissolved compounds
  - industrial solvents, pesticides
  - taste & odor compounds
  - chlorination byproducts
  - biodegradable substances (biological filtration)
    - doesn’t require regeneration
- Several Applications for activated carbon
  - granular (GAC) in a fixed bed
  - powdered (PAC) in a rapid mix
- Can be expensive when used strictly as an adsorbent

Fixed Bed Adsorber



Other Sorbents

- Activated Alumina



Application / 8.2 (continued)

accordingly set a drinking-water guideline for arsenic of 10 μg/L (10 ppb).

The magnitude of the problem is most serious in Bangladesh and West Bengal (India). In the 1970s and 1980s, 4 million hand-pump wells were installed in Bangladesh and India to provide people there with a pathogen-free drinking-water supply. The presence of arsenicosis began to appear in the 1980s, shortly after the well installation program. By the early 1990s, it was determined that the arsenic poisoning was originating from these wells. The arsenic is naturally occurring.

Today it is estimated that, every day in Bangladesh, up to 57 million people are exposed to arsenic concentrations greater than 10 μg/L. In West Bengal, an estimated 6 million people are exposed to arsenic concentrations between 50 and 3,200 μg/L. The magnitude of the problem shows why some have called this the greatest mass poisoning of humans that has ever occurred.

The most commonly used arsenic removal systems in both the developed and developing world are based on coagulation–separation and adsorption processes. Membrane filtration (such as reverse osmosis and nanofiltration) is also effective at removing arsenic from water; however, it is not practical in much of the world because of the high costs involved. Accordingly, appropriate technologies have been developed to treat this water. Figure 8.2 shows one such technology.

This unit is installed directly at the hand-pumped wells that were installed in the 1970s and 1980s. It requires no electricity or chemical addition. The unit is packed with granular activated alumina, which removes the arsenic from the water. The unit can be regenerated with caustic soda about every 4 months. The community is instructed to dispose of the arsenic-laden sludge in a pit lined with bricks. After 10 years of typical operation, it is estimated that the volume of sludge generated will occupy 56 ft^3.

Figure / 8.2 Well Head Arsenic Removal Unit Developed by Dr. Arup Sangupta and Others at Lehigh University.

Membrane Processes

Increasing Removal

Decreasing Pressure

- Reverse Osmosis (RO)
  - Demineralization, desalination
- Nanofiltration (NF)
  - softening, NOM removal
- Ultrafiltration (UF)
  - particle & pathogen removal
- Microfiltration (MF)
  - particle removal

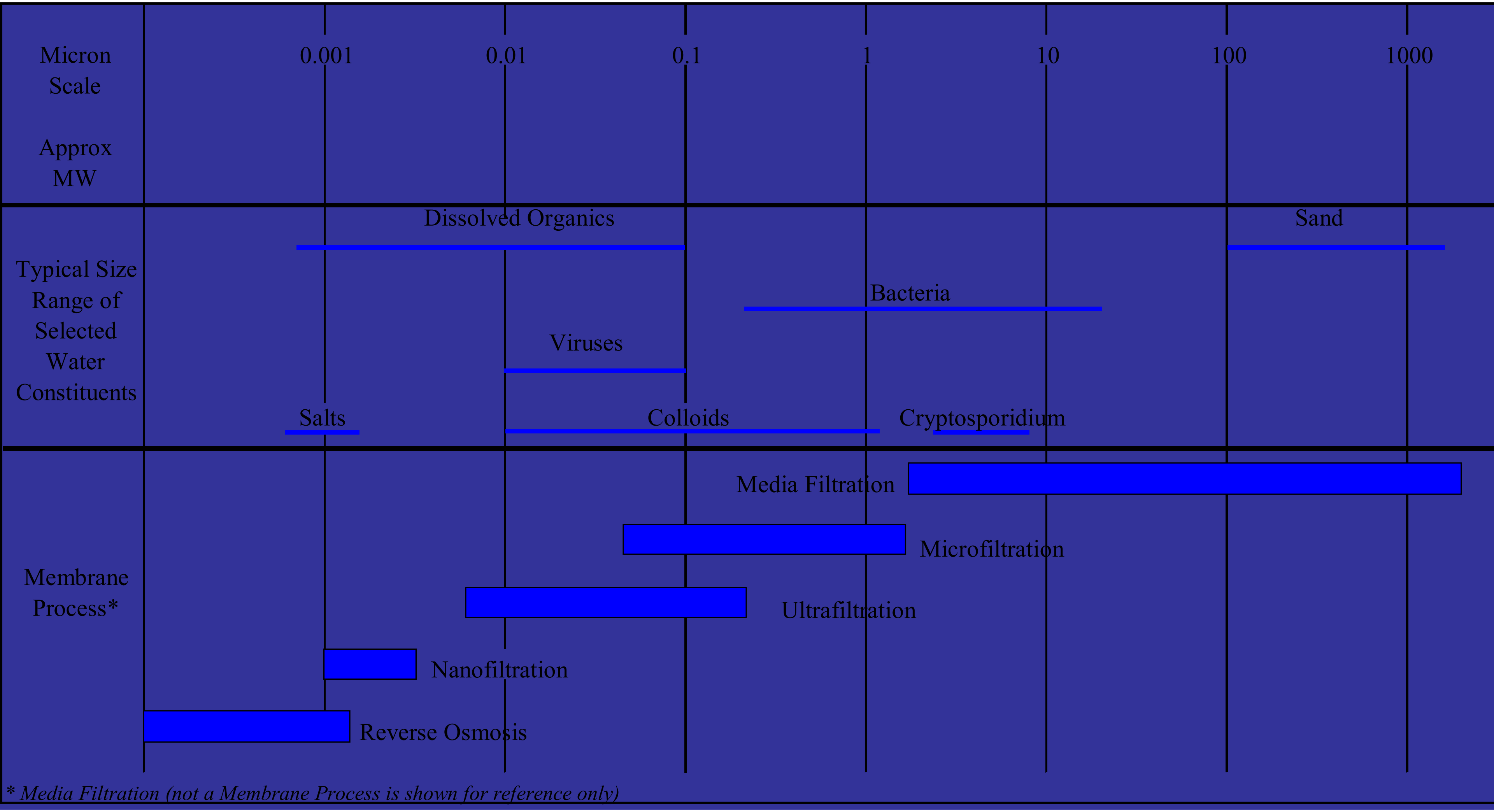
Membranes cont.

Membranes are carefully configured into:

- hollow fibers
- spiral wound
- tubular
- plates & frames

Recent advances in membrane manufacture have made this technology more practical.

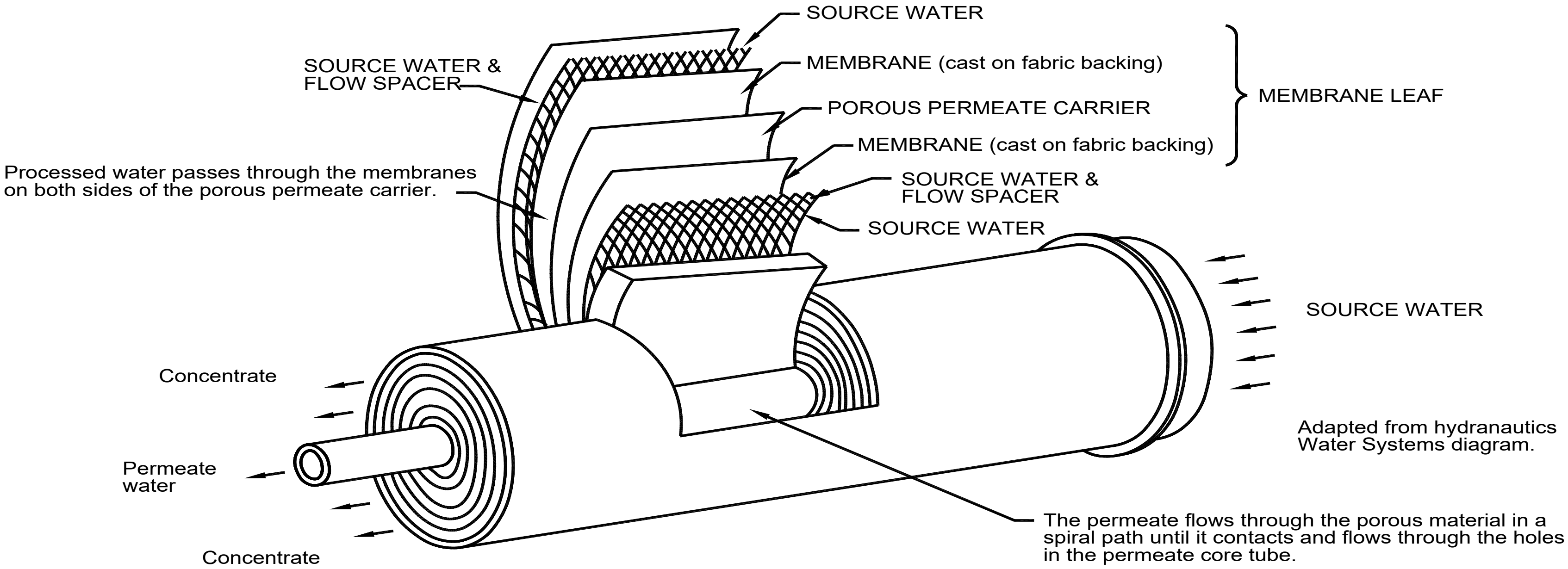
Pressure-Driven Membrane Process Application Guide



** Media Filtration (not a Membrane Process is shown for reference only)*

Typical Spiral-Wound Reverse Osmosis Membrane

Source: AWWA and ASCE, 1990.

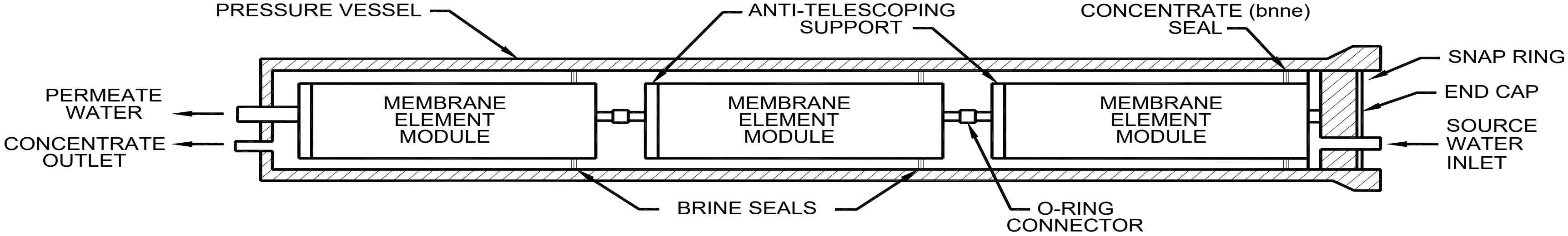


Processed water passes through the membranes on both sides of the porous permeate carrier.

The permeate flows through the porous material in a spiral path until it contacts and flows through the holes in the permeate core tube.

Adapted from hydranautics Water Systems diagram.

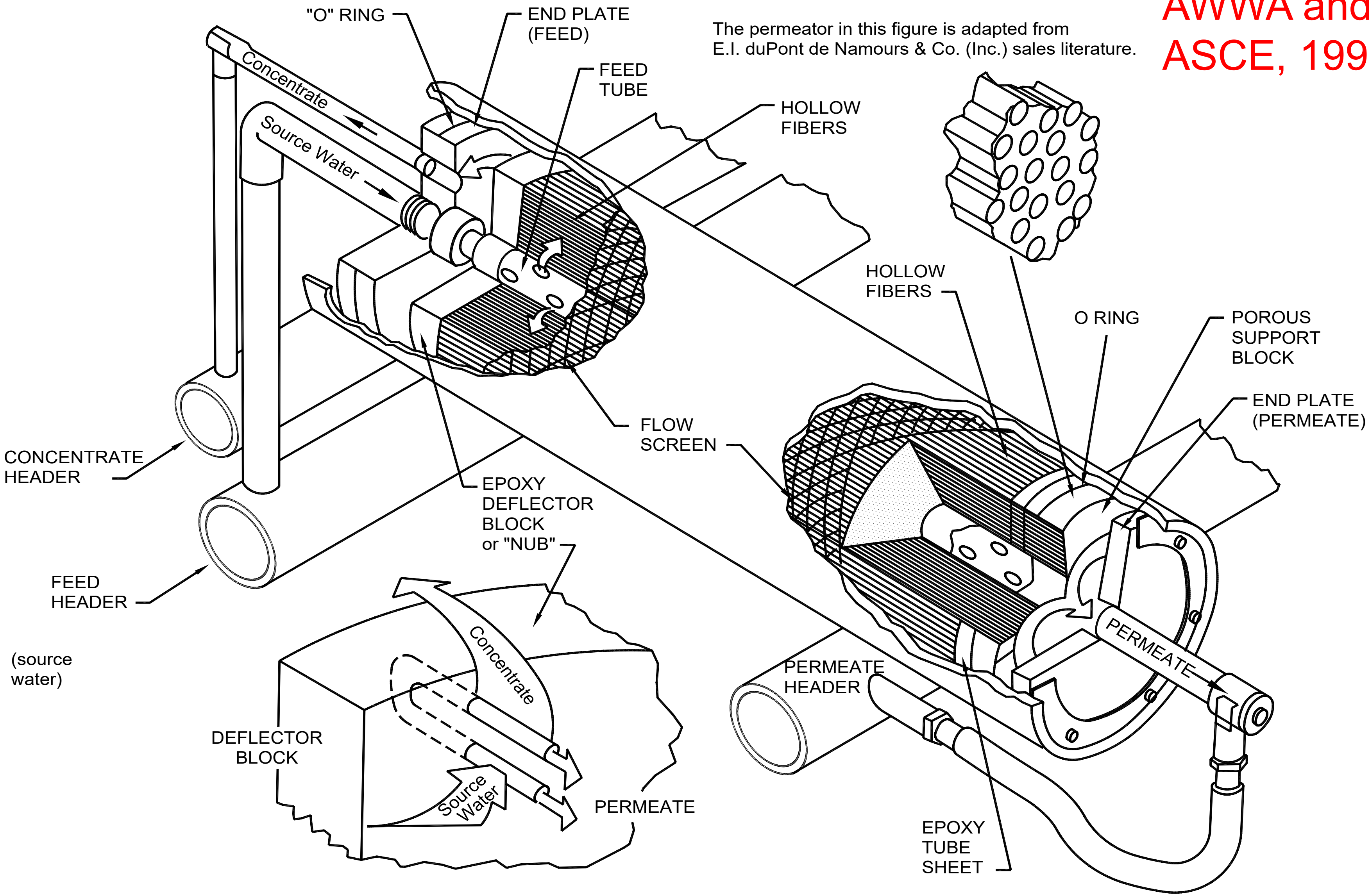
Cutaway view of a spiral membrane module



Cross section of pressure vessel with 3 membrane modules

Typical Hollow Fine-Fiber Reverse Osmosis Membrane Module

Source: AWWA and ASCE, 1990.



The permeator in this figure is adapted from
E.I. duPont de Namours & Co. (Inc.) sales literature.

RO videos

- Seven Seas Water (6:40)
  - Cartoon Style
    - https://www.youtube.com/watch?v=mZ7bgkFgqJQ
- Sydney Water (4:02)
  - Shows recovery in 3 stage system
    - https://www.youtube.com/watch?v=aVdWqbpbv_Y

Residuals

- Types
  - Settling sludge
  - Filter backwash water
  - Softening sludge
  - Reject from RO or ion exchange
  - Other
    - Contaminated air

Sludge Treatment

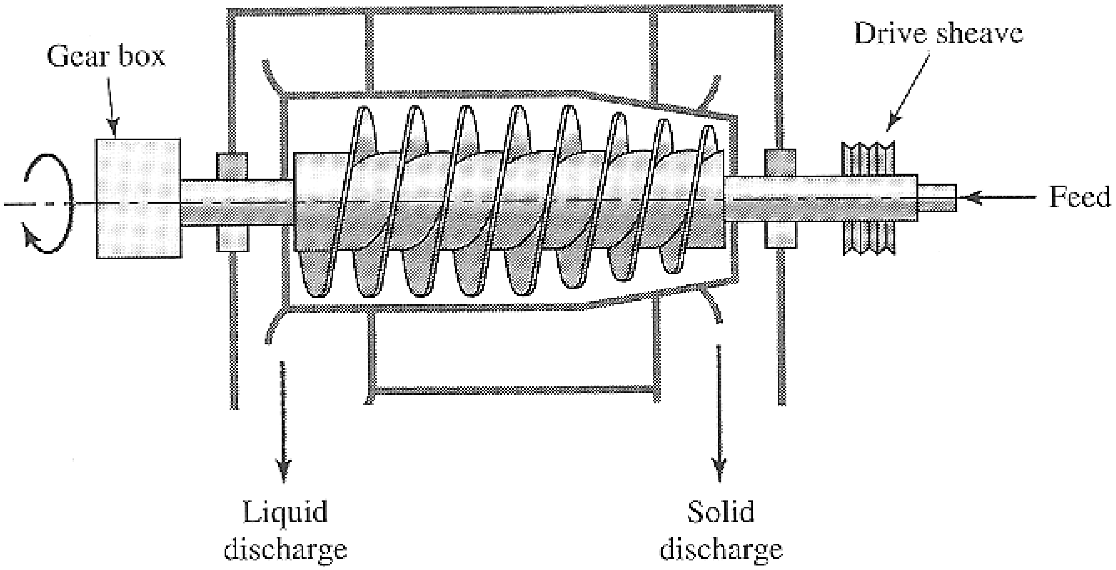
- Depends on type of sludge
- Typical process train
  - Thickening or dewatering
  - Conditioning
  - Stabilization (usually for wastewater)
  - Disposal

- Nonmechanical methods
  - Lagoons
  - Sand-drying beds
  - Freeze treatment
- Mechanical methods
  - Centrifugation
  - Vacuum filtration
  - Belt filter press
  - Plate filters

- Centrifuge

FIGURE 9–21

Solid bowl centrifuge.



Vacuum Filter

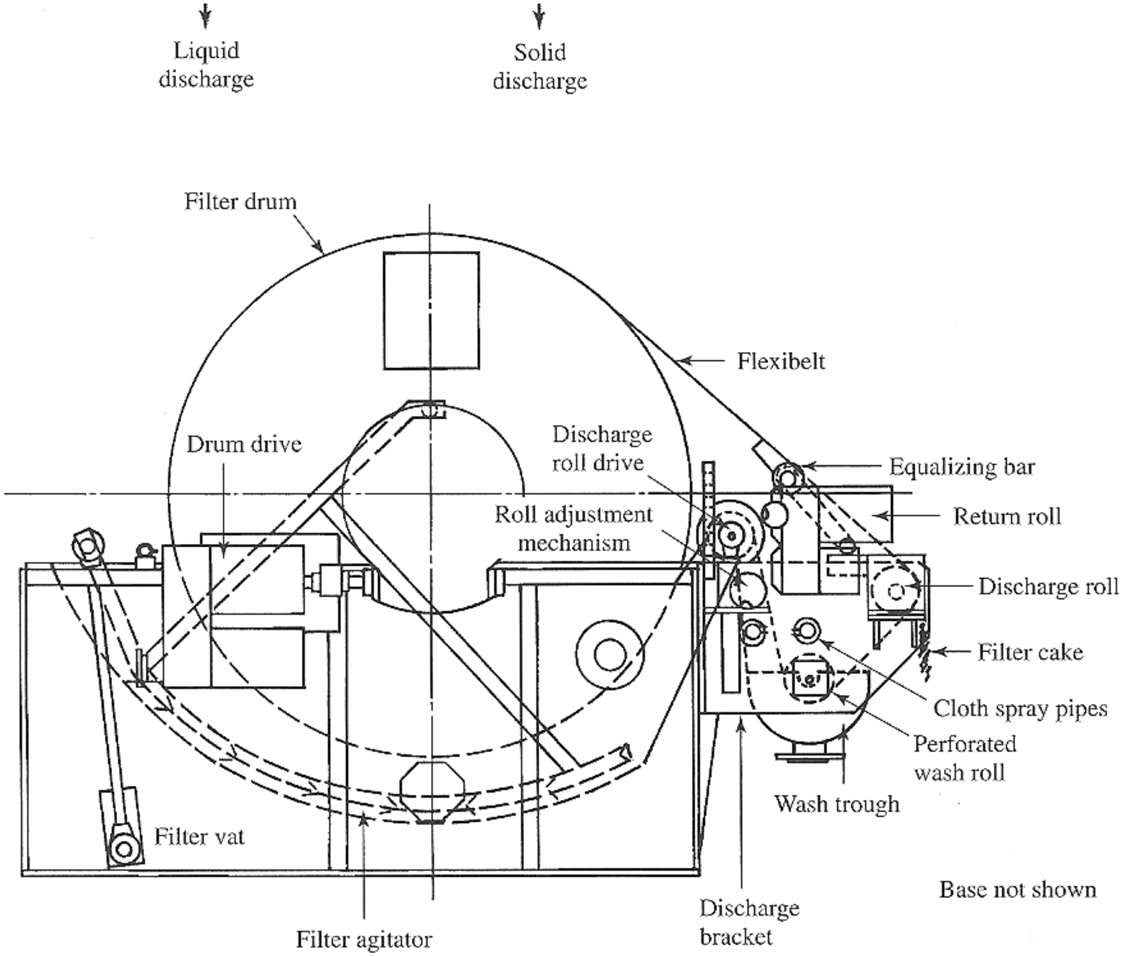


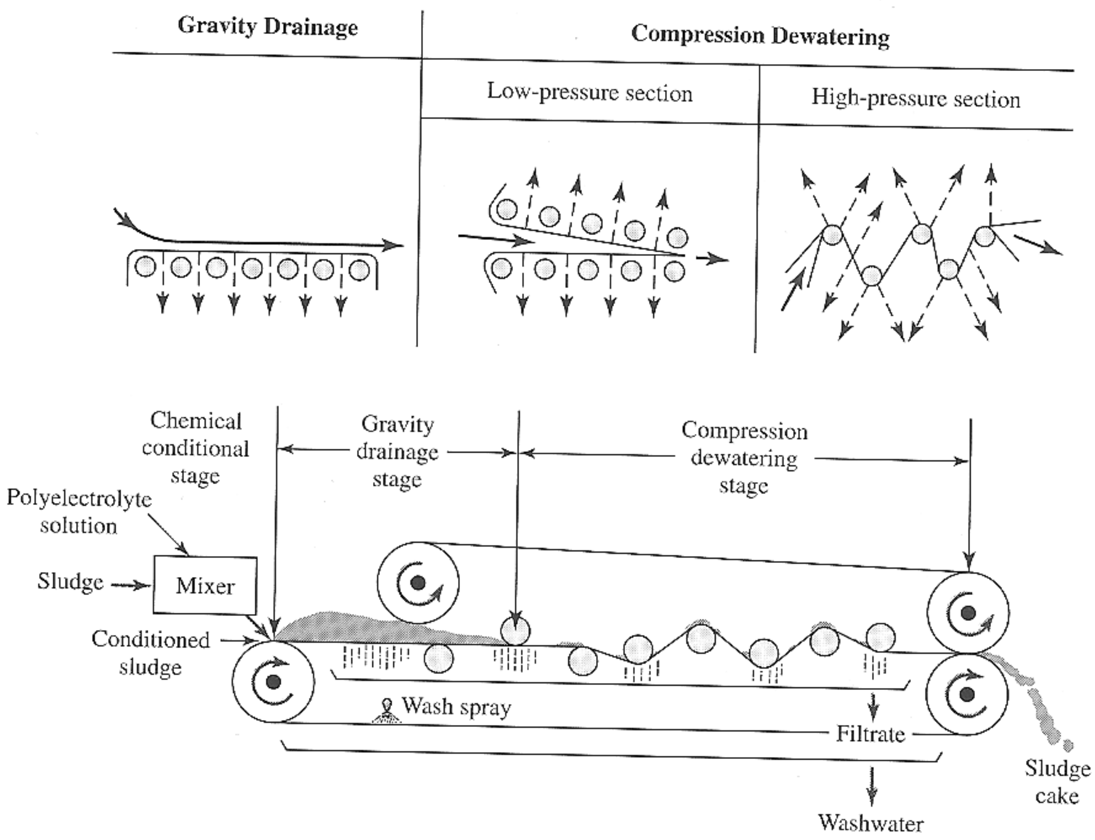
FIGURE 9–22

Vacuum filter. (*Courtesy of Komline-Sanderson Engineering Corporation.*)

Belt Filter Press

FIGURE 9–23

Continuous belt filter press. (*Source:* U.S. Environmental Protection Agency, *Process Design Manual, Sludge Treatment and Disposal,* 1979.)



- To next lecture