Draft Course Handout

ENCE 3323: INTRODUCTION TO ENVIRONMENTAL ENGINEERING (4 Cr. Hrs)
SPRING 2010

Scheduled Class Timings
Class: 4:30–7:15 PM, Tuesday (GEOL/PSYCH 2025; Change Requested To Engr. Bldg.)
Lab: 1:00-3:40 PM, TH (EN 510)
Office Hours: 2:00 – 4:00 PM Tuesdays (Tentative)

Instructor:	**B. Kura, Ph.D., P.E., 828 Engineering Building** **bkura@uno.edu; Ph.: 504-280-6572**
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Course Description:

ENCE 3323 INTRODUCTION TO ENVIRONMENTAL ENGINEERING — 4 cr
Topics include: water quality, water and wastewater treatment processes, air pollution control, and solid and hazardous waste management. Laboratory provides hands-on analytical experience with various pollution parameters. Three hours of lecture and three hours of lab.

Prerequisites:

CHEM 1018 (General Chemistry), credit or registration in ENCE 3318 (Principles of Hydraulics) or credit or registration in both ENME 3720 (Fluid Mechanics) and ENME 3716 (Fluid Mechanics Lab) **[Ref: 2003-2005 Online Catalog]**

Course Objectives:

After successfully completing this course each student will be able to:

1. Calculate runoff quantities from catchment areas; estimate storage capacities required; yield from confined and unconfined wells. [More in ENCE 3318: Principles of Hydraulics, which is a required course]

2. Design water treatment units such as coagulation, softening, flocculation, sedimentation, filtration, and disinfection. [More in ENCE 4323: Water and Wastewater Treatment, which is a required course]

3. Forecast water quality within rivers and lakes with respect to dissolved oxygen and others.

4. Design wastewater treatment units, both primary and secondary treatment units. [More in ENCE 4323: Water and Wastewater Treatment, which is a required course]

5. Understand the sources of air pollution, health effects, and air quality regulations; design important particulate collection devices.

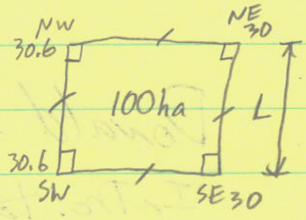
$\frac{50}{50}$

Donald Jerolleman H.W. #3 chap3(40,47,50,52,54)

3-40) 4-wells @ corners, $A = 100\,ha \left(\frac{10000\,m^2}{ha}\right)$, NE = 30m = SE

SW = 30.6m = NW

N ↑



$1000000\,m^2 = L^2$

$L = 1000\,m$

✓ 10

$$H.G. = \frac{\Delta Head}{L} = \frac{0.6}{1000} = \boxed{0.0006 \quad \text{From W to E}}$$

3-47) 28m thick, $Q_{well} = 0.00380\ m^3/s$ for 1941d drawdown = 64.05m

observation well radius = 48 m if r = 68m draw down = ?

original piez. = 94.05m above bottom, sandstone

p. 138 $K = 5.8 \times 10^{-7}\ m/s$ Useing Fig 3-31 p.144

$h_1 = 94.05 - 64.05 = 30m$

$T = KD = (5.8\times10^{-7})(28) = 1.624\times10^{-5}\ m^2/s$

$$Q = \frac{2\pi(T)(\Delta h)}{\ln\left(\frac{r_2}{r_1}\right)} \rightarrow h_2 = \ln\left(\frac{68}{48}\right)(0.00380)\left(\frac{1}{2\pi(1.624\times10^{-5})}\right) + 30m$$

$$= \underline{42.97m}$$

✓ 10

$$s_2 = 94.05 - 42.97 = \boxed{51.08m}$$

3-50) 82m thick, confined, non-pump piez. = 109.5m $Q_{pump} = 0.0280\ m^3/s$

draw down @ opser. well = 3.55m @ r = 41m,

" " " " = 1.35m @ r = 63.5m Find K

✓

$h_1 = 109.5 - 3.55 = 105.95$ $h_2 = 109.5 - 1.35 = 108.15\,m$

$$T = \frac{Q \ln\left(\frac{r_2}{r_1}\right)}{2\pi(\Delta h)} = 0.000886\ \frac{m^2}{s} = KD = K(82m) \rightarrow k = \boxed{1.08\times10^{-5}\ m/s}$$

10

3-52) 5m thick, Piez = 65m, sand/gravel, drawdown = 7m @ r = 10m

$Q = 0.020\ m^3/s$ drawdown = 2.0m @ r = ?

From p. 138 $K = 6.1 \times 10^{-4}\ m/s$

$T = KD = 0.00305\ m^2/s$

$h_1 = 65 - 2 = 63m$ $h_2 = 65 - 7 = 58m$ ✓

$$e^{\left(\ln\left(\frac{r_2}{10}\right)\right)} = e^{\left(\frac{2\pi\overset{T}{(0.00305)}\overset{\Delta h}{(5)}}{\underset{Q}{0.020}}\right)} \rightarrow \frac{r_2}{10} = 120.41$$

$$\boxed{r_2 = 1204.10\ m}$$ ✓

10

3-54) dd = 9.9m @ r = 100m $dd_{@site\,max} = 30m$

From 3-12 $K = 6.4 \times 10^{-3}$ $h_1 = 0$ $h_2 = 30 - 9.9 = 20.1$

$$Q = \frac{\pi(K)(h_2^2 - h_1^2)}{\ln\left(\frac{r_2}{r_1}\right)} = \boxed{1.36\ m^3/s}$$ ✓

↑ from example 3-12 = 0.25m

10

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Intro. to Evironmental
510

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42/50

3-3) $A_{ws} = 4000\ km^2$ $P = 102\ cm/yr$ $Q_{\substack{river\\OUT}} = 34.2\ m^3/s$

$I = 5.5 \times 10^{-7}\ cm/s$ $ET = 40\ cm/yr$

Req'd: Find Δ storage in 1 yr., ratio of R to P (runoff coefficient "C")

Solution:

$$\Delta S = P - I - ET - R$$

Conversions: $\left(\frac{cm}{yr}\right)$ $Q = 34.2\frac{m^3}{s}\left(\frac{100cm}{m}\right)^3\left(\frac{3600s}{hr}\right)\left(\frac{24hr}{d}\right)\left(\frac{365d}{yr}\right) = \overset{1.0785312}{\overset{2x}{\cancel{5.392656}}} \times 10^{15}\ cm^3/yr$

$$R = \frac{Q}{A} = \frac{Q}{4000\ km^2}\left(\frac{km}{1000m}\right)^2\left(\frac{1m}{100cm}\right)^2 = \underline{27.0\ cm/yr}$$

$$I = 5.5\times10^{-7}\frac{cm}{s}\left(\frac{3600s}{1hr}\right)\left(\frac{24hr}{d}\right)\left(\frac{365d}{yr}\right) = \underline{17.34\ cm/yr}$$

substitute

$$\Delta S = 102\frac{cm}{yr} - 17.34\frac{cm}{yr} - 40\frac{cm}{yr} - 27.0\frac{cm}{yr} = \boxed{17.66\frac{cm}{yr}}$$

Pos. ∴ increase in storage of:

$$17.66\frac{cm}{yr}\left(\frac{km}{100000cm}\right)(4000\ km^2)(1yr) = \boxed{0.7064\ km^3}$$

10

$$C = \frac{R}{P} = \frac{27.0\frac{cm}{yr}}{102\frac{cm}{yr}} = 0.265 = \boxed{26.5\%}$$

3-10) Given: Table 3-2 p. 109

Req'd: make IDF curve for 10-yr storm @ Dismal Swamp

T = avg. return period in yrs. n = # yrs in record = 45 m = rank of storm $= \frac{n+1}{T}$

T = 10 yrs. $m = \frac{46}{10} = 4.6$ rank

Durration (min)	Intinsity (mm/h) by interpolation
5	172
10	156
15	129.3
20	94
30	72.57
40	49.7
50	38.2
60	26.3

10

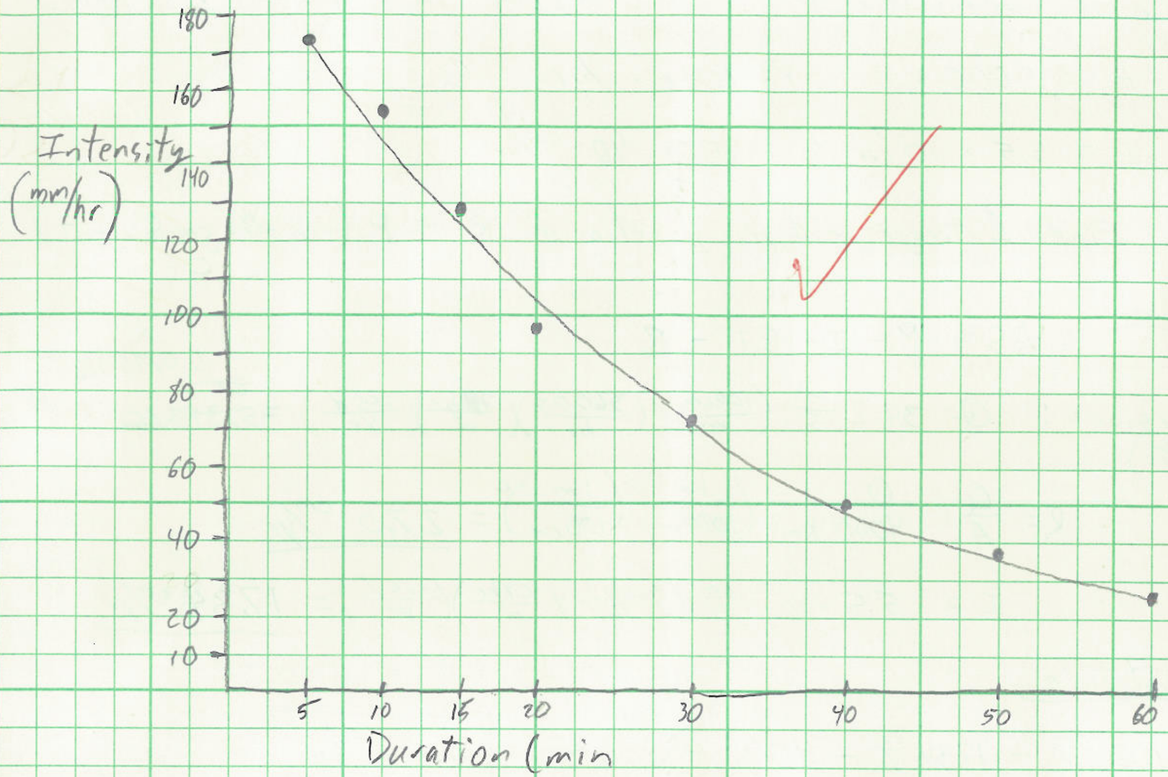
Interpolation

$$(\text{greater intinsity}) - \left[\frac{(\text{rank at}) - (\text{rank more intense})}{(\text{rank less intense}) - (\text{rank more intense})}\right]$$

$[\text{greater intensity} - \text{lesser intensity}]$

= intinsity @ needed ran

curve on rear


Intensity (mm/hr)
180
160
140
120
100
80
60
40
20
10
5
10
15
20
30
40
50
60
Duration (min

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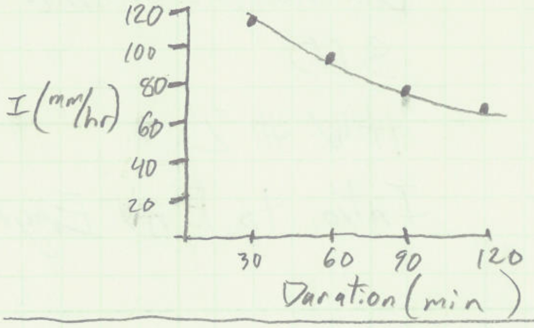
3-11) **Req'd**: IDF curve for 5 yr storm using Table shown p. 157

sol'n: $T = 5$ yrs $\quad m = \frac{1+n}{T} = \frac{11}{5} = 2.2$

Duration	Interpolation (mm/hr)		
30 min	rank between: (2, 3)	I between (122.3, 104.6)	Value: (118.76)
60 min	(2, 3)	(100.3, 82.9)	(96.82)
90 min	(2, 3)	(81.1, 64.5)	(77.78)
120 min	(2, 3)	(55.3, 39.7)	(52.18)



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3-13) See Fig P-3-13 p. 159. Using highest runoff coefficient for asphault est. time of concentration for ea. configuration & recommed one.

Solution: p. 118 Table 3-3 $C = 0.70 \rightarrow 0.95$ using highest: $\underline{C = 0.95}$

vertical layout: useing equ. 3-16 $\quad t_c = \frac{1.8(1.1-C)\sqrt{3.28D}}{\sqrt[3]{S}}$

$\underline{t_c = 7.75 \text{ min}}$

Horizontal layout: $\underline{t_c = 6.59 \text{ min}}$

$\therefore \boxed{\text{recommend horizontal layout}}$

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see Example 3-6 p. 123

3-28) using Fig P-3-23 p. 164, Find stream flow hydrograph resulting from storm in Fig P-3-28 p. 166.

Time (hr)	R.E. (cm)	DRH Ordinates 1	2	3	Compound Runoff (m³/s)
1	0.10				
2	0.20				
3	0.05				
4					
5					

?

2

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S10
HW #2
Intro. to Env. Engr

$1 \text{usgallon} = 0.133680556\ ft^3$

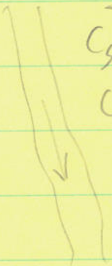
ENVIRON FEB 23

Time: 24hrs $\quad Q = 100\ m^3/d \quad V = ?$

$V = Qt = 100\ m^3$

DO – Dissolved oxygen

Dead stream



DO

$C_s = 9\ mg/L$

$C_t = 2\ mg/L$

DO

$C_s = 9\ mg/L$

$C_t = 6\ mg/L$

marginally pilluted stream

Driviy force

$9-2=7 \quad > \quad 9-6=3$

Eviron March 2 ①

Brook trout need 7.5 $\frac{mg}{L}$ DO

initial concentration $\left[\frac{mg}{L}\right]$ concentration @ time t $\left[\frac{mg}{L}\right]$

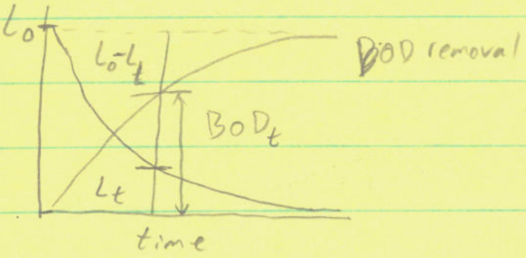
C_0 = initial concentration C_t = concentration AT TIME t K = 1^{st} order rate constant $\left(\frac{1}{t}\right)$

$$C_t = C_0 e^{-kt}$$

P.362

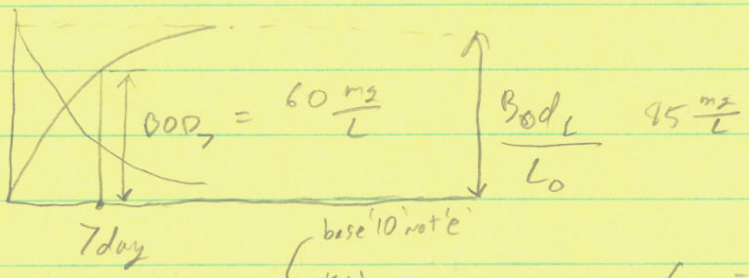
O₂ consumption

Equivalent C_xH_x removed



$$L_t = \underset{\text{initial organics}}{L_0} e^{-kt}$$

#5 BOD7 = 60 mg/L BOD$_{ultimate}$ = 85 mg/L K base 10 = ?



if see:
K = usually base 10
k = " base e

base 10 not 'e'

$$BOD_t = L_0\left(1-10^{-Kt}\right) \rightarrow 60 = 85\left(1-10^{-K(7)}\right) \rightarrow K = 0.0759 d^{-1}$$

BOD_5 = ? DO$_{initial}$ = 7 mg/L

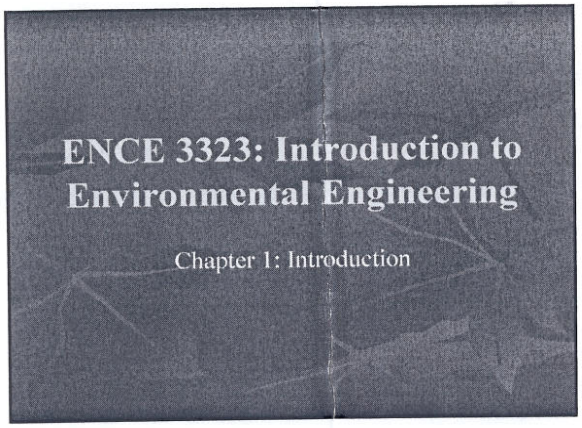
Final DO = 4 mg/L ∴ Drop of 3 mg/L

10% of sample

30 mL → actual sample → ? BOD demand

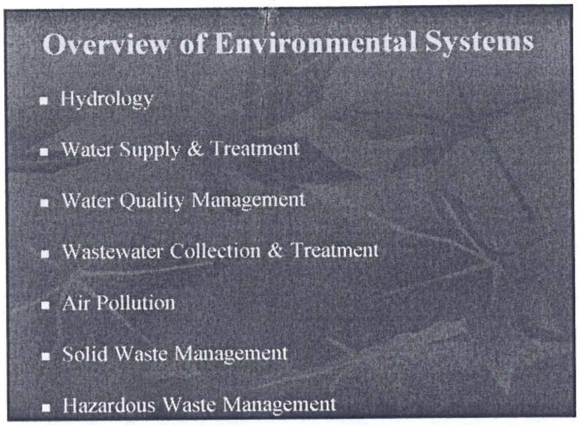
270 mL → make up water → 0 BOD demand

Actual BOD_5 value = 3 $\frac{mg}{L}$ (10) = 30 mg/L



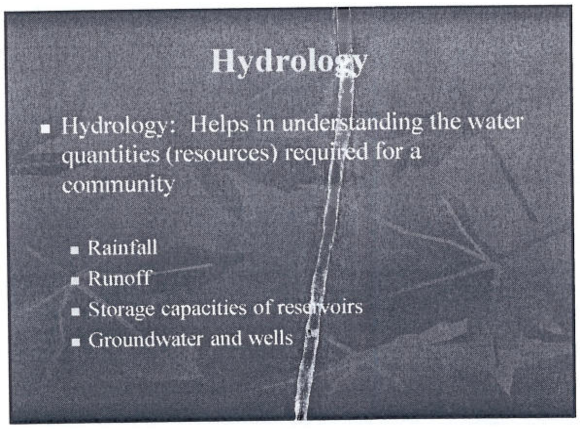
ENCE 3323: Introduction to Environmental Engineering

Chapter 1: Introduction



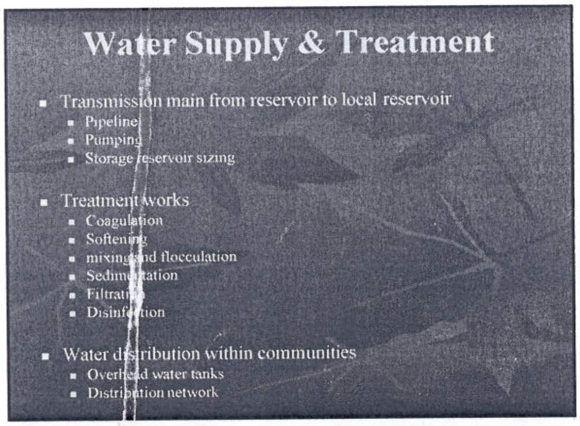
Overview of Environmental Systems

- Hydrology
- Water Supply & Treatment
- Water Quality Management
- Wastewater Collection & Treatment
- Air Pollution
- Solid Waste Management
- Hazardous Waste Management



Hydrology

- Hydrology: Helps in understanding the water quantities (resources) required for a community
  - Rainfall
  - Runoff
  - Storage capacities of reservoirs
  - Groundwater and wells



Water Supply & Treatment

- Transmission main from reservoir to local reservoir
  - Pipeline
  - Pumping
  - Storage reservoir sizing
- Treatment works
  - Coagulation
  - Softening
  - mixing and flocculation
  - Sedimentation
  - Filtration
  - Disinfection
- Water distribution within communities
  - Overhead water tanks
  - Distribution network

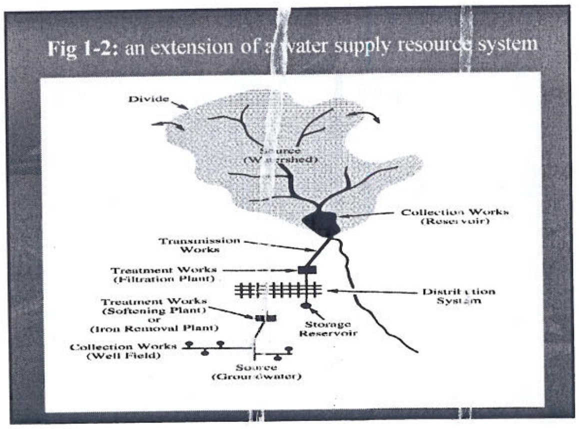
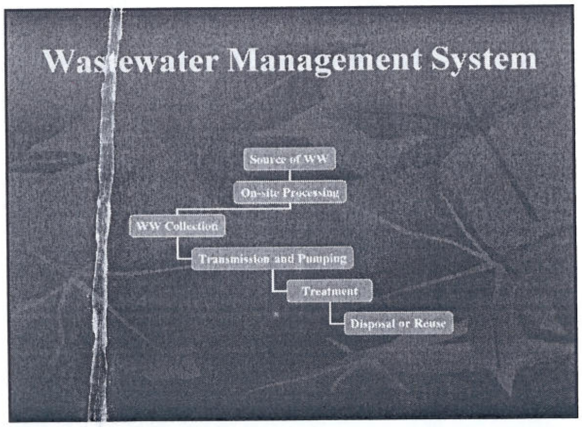


Fig 1-2: an extension of a water supply resource system



Wastewater Management System

Source of WW

On-site Processing

WW Collection

Transmission and Pumping

Treatment

Disposal or Reuse

Water Quality Management

- Water pollutants, sources, impacts on water quality, impact on water treatment, health of consumers
- Managing water quality in rivers
  - Aquatic life in water (fish) and oxygen requirements
- Managing water quality in lakes

Wastewater (WW) Collection and Treatment

- WW collection
  - Sewer network design (gravity flows)
  - Force mains
  - Pumping stations
  - Wastewater transport to suitable location for treatment
- WW treatment
  - Characteristics of wastewater
  - Pollutants in domestic WW
  - Microbiology of WW
  - Primary and secondary treatment
  - Disposal of end products (treated WW and sludge)
    - Land treatment
    - Sludge treatment
    - Sludge disposal

Air Resources Management System

- Sources
- Effects on public health and property
- Regulations
- Monitoring
- Meteorology and atmospheric dispersion of pollutants
- Control for particulates
- Control for gaseous pollutants
- Management systems (software applications)
  - For regulatory agencies (EPA, LDEQ, DOTD, Navy etc.)
  - For industries (Auto makers, shipbuilders, refineries, chemical plants etc.)

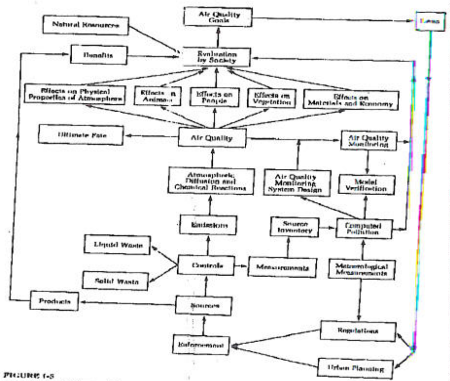
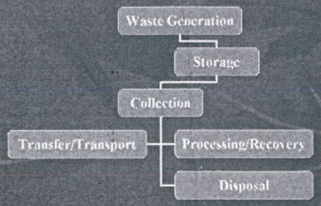


FIGURE 1-5
A simplified block diagram of an air resource management system.

Solid Waste Management

- Generation, quantities, characteristics
- Storage
- Collection
- Transfer/transport
- Processing and recovery
- Disposal

Solid Waste Management



Environmental Legislation and Regulation

- Drinking water standards
- Water pollution control
  - BPT - Best practical treatment
  - BAT - Best available treatment
  - NPDES National pollutant discharge elimination system
  - BCT - Best conventional treatment
- EPA's priority pollutant list (Table 1-6/Pg. 21)

Environmental Legislation and Regulation (Air)

- New source performance standards (NSPS) [1970]
- Title V – Comprehensive air permit system
- National ambient air quality standards (NAAQS)
- Prevention of significant deterioration (PSD)
  - For attainment areas: to prevent rapid air quality degradation

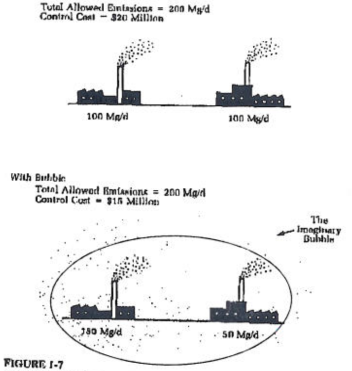


FIGURE 1-7
Illustration of bubble concept.

Environmental Legislation and Regulation (Solid Waste)

- Promote the solid waste management and resource recovery system
- Provide technical and financial assistance
- Promote national research and development program for improvements
- Provide guidelines for SW collection, transport, separation, recovery, and disposal
- Provide training grants: design, operation, and maintenance of SW disposal systems

Environmental Legislation and Regulation (Hazardous Wastes)

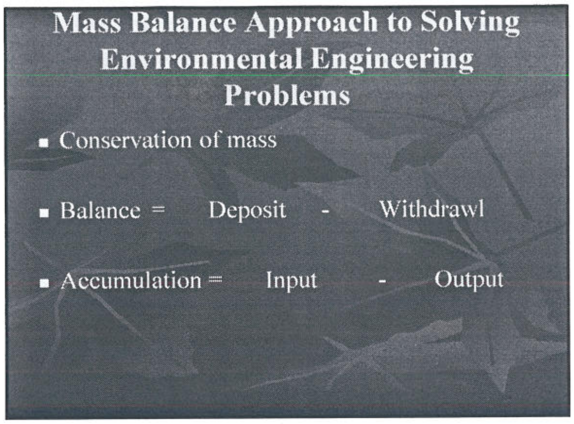
Federal approach to HW management

- Classification (Toxicity, Reactivity, Corrosivity, Flammability)
- Cradle to grave (record keeping) system
- Standards for HW TSDF owners
- Enforcement of standards through a permit program
- Authorization of state programs to operate in lieu of the federal program

Environmental Legislation and Regulation (Hazardous Wastes)

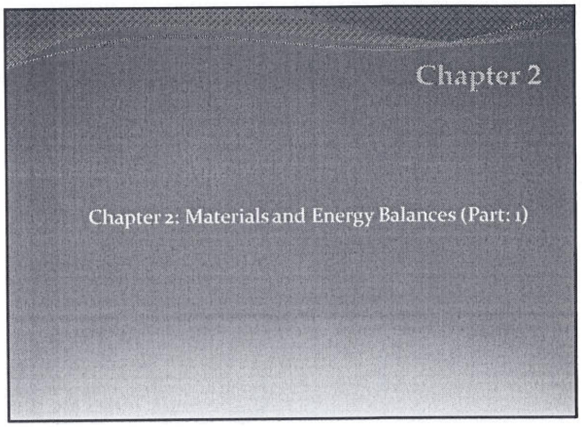
Increased scope of RCRA (1984)

- Waste minimization
- Banning of untreated waste from land disposal; establishing treatment standards
- New standards: double liners, leachate collection, ground water monitoring
- New requirements for small quantity generators
- Establishing standards for underground storage tanks (UST)
- Criteria for MSW landfills and increase monitoring requirements



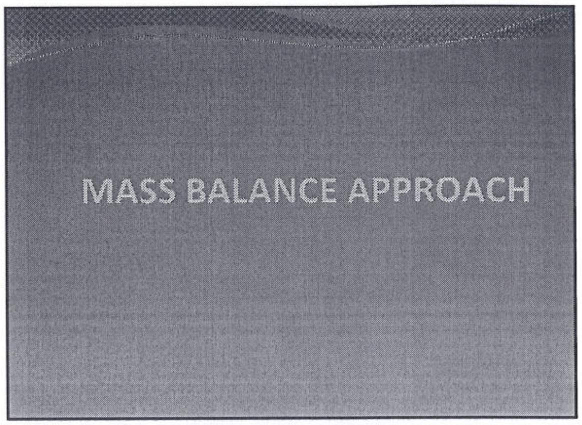
Mass Balance Approach to Solving Environmental Engineering Problems

- Conservation of mass
- Balance = Deposit - Withdrawl
- Accumulation = Input - Output

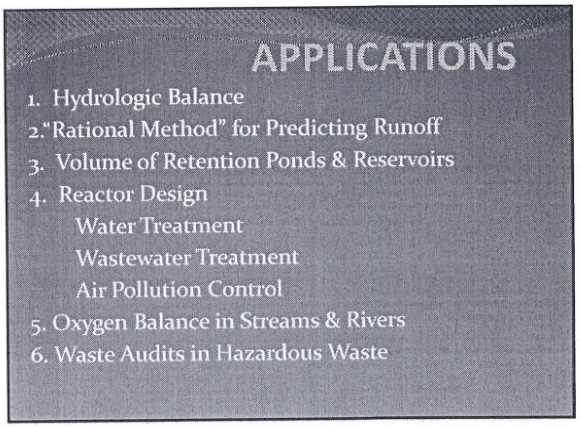


Chapter 2

Chapter 2: Materials and Energy Balances (Part: 1)

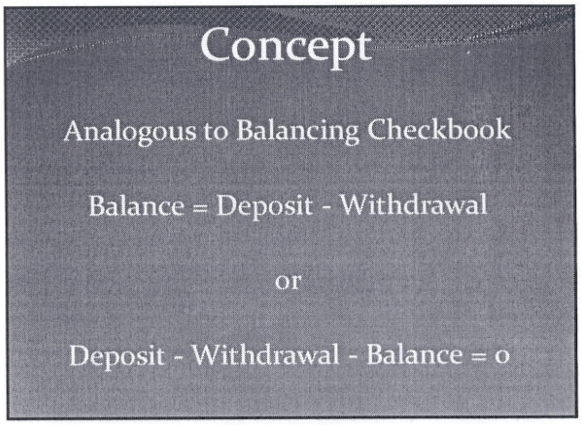


MASS BALANCE APPROACH



APPLICATIONS

1. Hydrologic Balance
2. "Rational Method" for Predicting Runoff
3. Volume of Retention Ponds & Reservoirs
4. Reactor Design
    - Water Treatment
    - Wastewater Treatment
    - Air Pollution Control
5. Oxygen Balance in Streams & Rivers
6. Waste Audits in Hazardous Waste



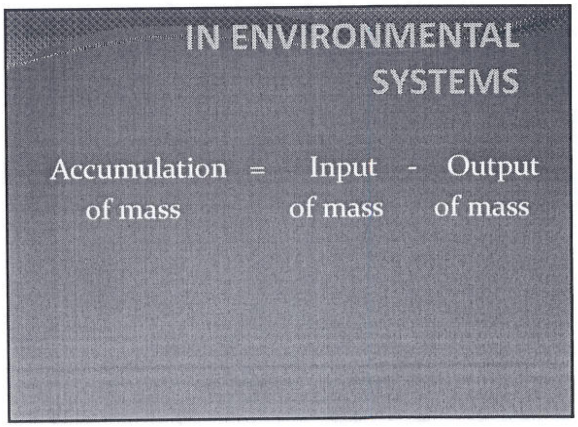
Concept

Analogous to Balancing Checkbook

Balance = Deposit - Withdrawal

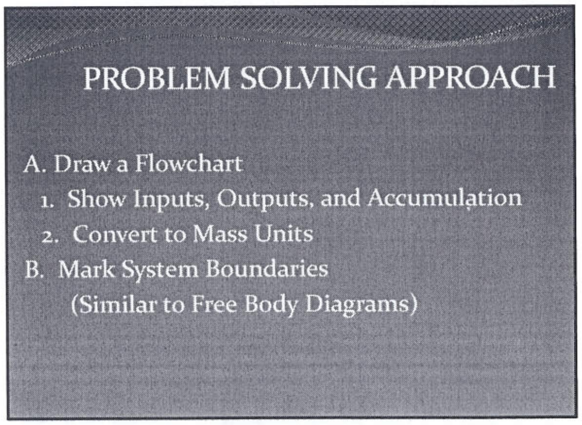
or

Deposit - Withdrawal - Balance = 0



IN ENVIRONMENTAL SYSTEMS

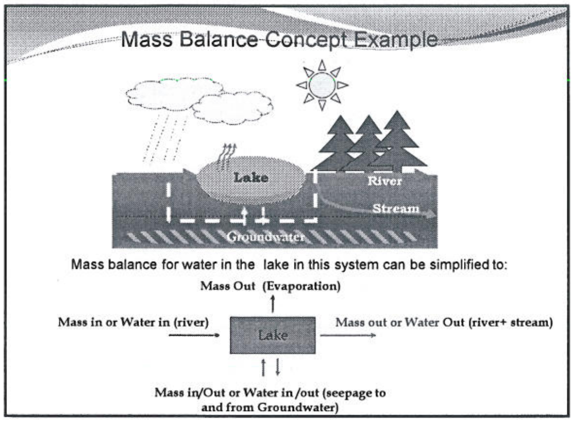
Accumulation of mass = Input of mass - Output of mass



PROBLEM SOLVING APPROACH

A. Draw a Flowchart
   1. Show Inputs, Outputs, and Accumulation
   2. Convert to Mass Units

B. Mark System Boundaries
   (Similar to Free Body Diagrams)



Mass Balance Concept Example

Mass balance for water in the lake in this system can be simplified to:

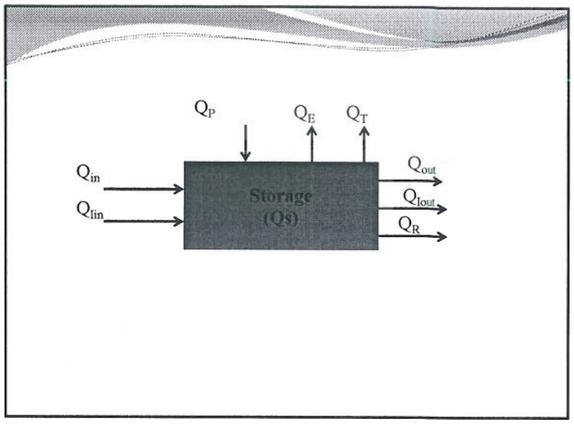
Mass Out (Evaporation)

Mass in or Water in (river)

Lake

Mass out or Water Out (river+ stream)

Mass in/Out or Water in /out (seepage to and from Groundwater)



Example Calculation of Mass

a. Flow

Mass = (Flow) (Density) (Time)

1 m³/d = ? kg

Mass = (1m³/d) (1000 kg/m³) (1d)

= 1,000kg

b. Compounds in Water

Mass = (Concentration) (Volume)

1 mg/L in 1 m³ = ? mg

Mass = (1 mg/L) (1 m³) (1,000 L/m³)

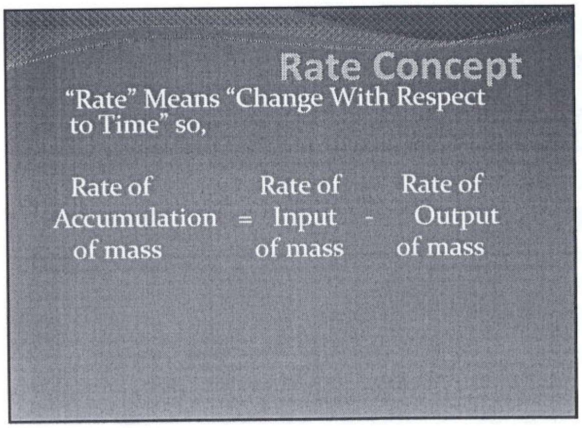
= 1,000mg

C. Write Mass Balance Equation to Account for

1. Inputs
2. Outputs
3. Accumulations

D. Verify That System "Closes" or Balances

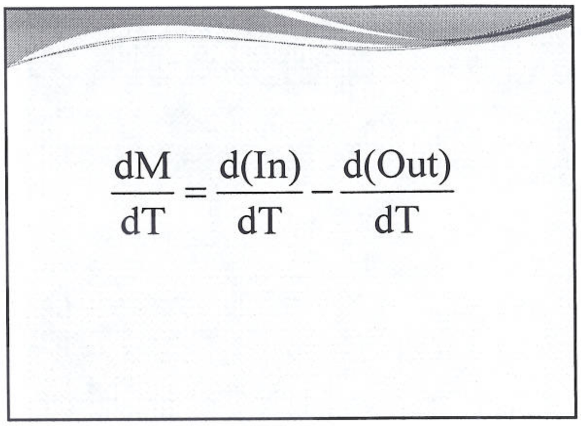
Input of mass-Accumulation of Mass – Output of Mass = 0



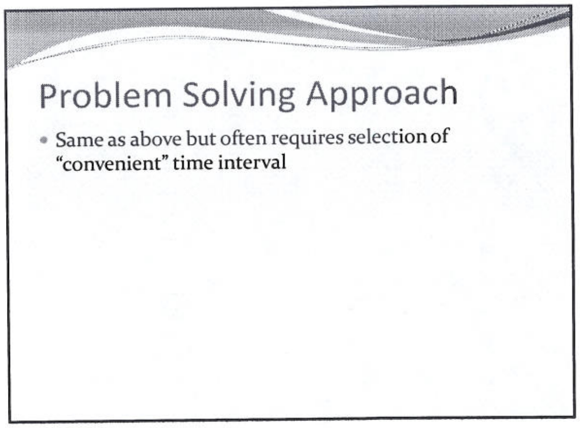
Rate Concept

"Rate" Means "Change With Respect to Time" so,

Rate of Accumulation of mass = Rate of Input of mass - Rate of Output of mass

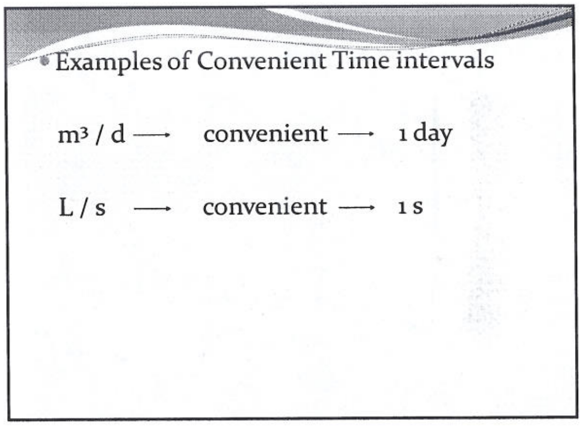


$$\frac{dM}{dT} = \frac{d(In)}{dT} - \frac{d(Out)}{dT}$$



Problem Solving Approach

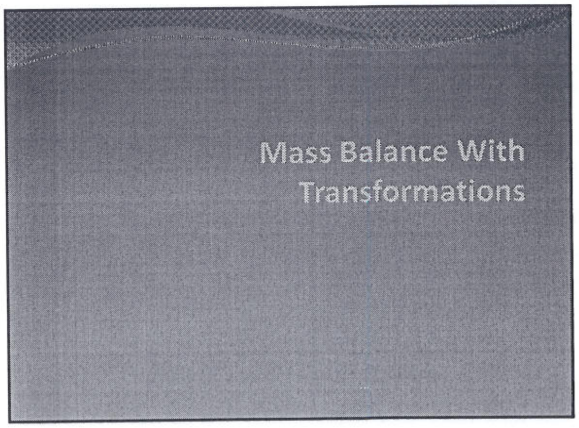
- Same as above but often requires selection of "convenient" time interval



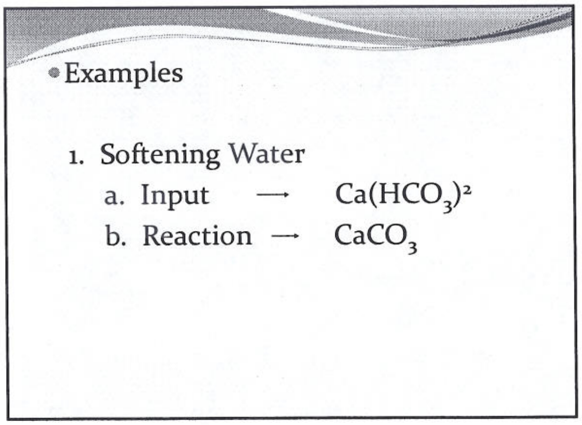
- Examples of Convenient Time intervals

m^3 / d → convenient → 1 day

L / s → convenient → 1 s



Mass Balance With Transformations



- Examples

1. Softening Water
   a. Input → $Ca(HCO_3)^2$
   b. Reaction → $CaCO_3$

2. Change of O_2 in Stream

a. Input → O_2
b. Microorganisms Use $O_2 \longrightarrow CO_2$

IN THESE INSTANCES, THE PREVIOUS EXPRESSION SHOWS ONLY THAT $Ca(HCO_3)_2$ OR O_2 "DISAPPEARED"!

MASS BALANCE WITH TRANSFORMATION

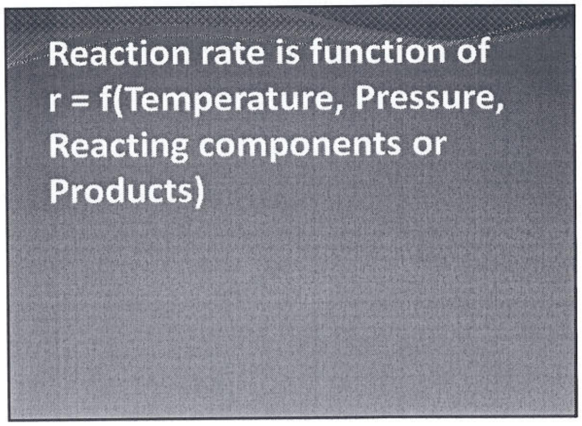
Rate of Accumulation of Mass = Rate of Input of Mass - Rate of Output of Mass ± Rate of Transformation

---

- Time Dependent Reactions are called "Kinetic Reactions"
- "Stoichiometric Reactions" are those that have achieved equilibrium.

Transformation rate is described by the "Reaction Rate" → r

$$\frac{dM}{dt} = \frac{d(In)}{dt} - \frac{d(Out)}{dt} \pm r$$



Reaction rate is function of
r = f(Temperature, Pressure, Reacting components or Products)

ENCE 3323: Introduction to Environmental Engineering

Chapter 2: Materials and Energy Balances (Part: 2)

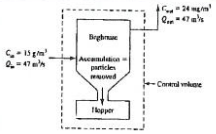
Efficiency

- Often removal of contaminants/pollutants is measured in terms of mass removal efficiency
  - η (Eta)= [(mass in – mass out)/(mass in)] * 100
  - = [(Cin *Qin – Cout* Qout)/ (Cin * Qin)* 100

Example 2-4. The air pollution control equipment on a municipal waste incinerator includes a fabric filter particle collector (known as a baghouse). The baghouse contains 424 cloth bags arranged in parallel, that is 1/424 of the flow goes through each bag. The gas flow rate into and out of the baghouse is 47 m^3/s, and the concentration of particles entering the baghouse is 15 g/m^3. In normal operation the baghouse particulate discharge meets the regulatory limit of 24 mg/m^3. During preventive maintenance replacement of the bags, one bag is inadvertently not replaced, so only 423 bags are in place.

Calculate the fraction of particulate matter removed and the efficiency of particulate removal when all 424 bags are in place and the emissions comply with the regulatory requirements. Estimate the mass emission rate when one of the bags is missing and recalculate the efficiency of the baghouse. Assume the efficiency for each individual bag is the same as the overall efficiency for the baghouse.

Solution. The mass balance diagram for the baghouse in normal operation is shown here.



In concentration and flow rate terms, the mass balance equation is

$$\frac{dM}{dt} = C_{in}Q_{in} - C_{out}Q_{out}$$

The mass rate of accumulation in the baghouse is

$$\frac{dM}{dt} = (15{,}000\ mg/m^3)(47\ m^3/s) - (24\ mg/m^3)(47\ m^3/s) = 703{,}872\ mg/s$$

The fraction of particulates removed is

$$\frac{703{,}872\ mg/s}{(15{,}000\ mg/m^3)(47\ mg/s)} = \frac{703{,}872\ mg/s}{705{,}000\ mg/s} = 0.9984$$

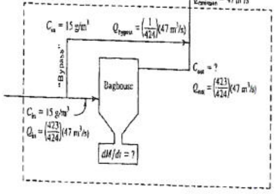
The efficiency of the baghouse is

$$\eta = \frac{15{,}000\ mg/m^3 - 24\ mg/m^3}{15{,}000\ mg/m^3}(100\%)$$
$$= 99.84\%$$

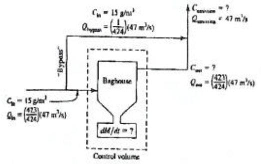
Note that the fraction of particulate matter removed is the decimal equivalent of the efficiency.

Note that the fraction of particulate matter removed is the decimal equivalent of the efficiency.

To determine the mass emission rate with one bag missing, we begin by drawing a mass balance diagram. Because one bag is missing, a portion of the flow (1/424 of Q_{out}) effectively bypasses the baghouse. The "Bypass" line around the baghouse is drawn to show this.



A judicious selection of the control volume aids in the solution of this problem. As shown in the diagram, a control volume around the overall baghouse and bypass flow yields three unknowns: the mass flow rate out of the baghouse, the rate of mass accumulation in the baghouse hopper, and the mass flow rate of the mixture. A control volume around the baghouse alone reduces the number of unknowns to two:

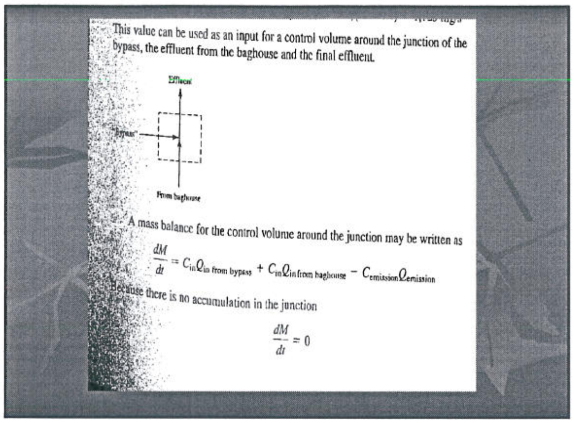


Because we know the efficiency and the influent mass flow rate, we can solve the mass balance equation for the mass flow rate out of the filter.

$$\eta = \frac{C_{in}Q_{in} - C_{out}Q_{out}}{C_{in}Q_{in}}$$

Solving for $C_{out}Q_{out}$

$$C_{out}Q_{out} = (1 - \eta)C_{in}Q_{in}$$
$$= (1 - 0.9984)(15{,}000\ mg/m^3)(47\ m^3/s)(423/424) = 1{,}125\ mg/s$$



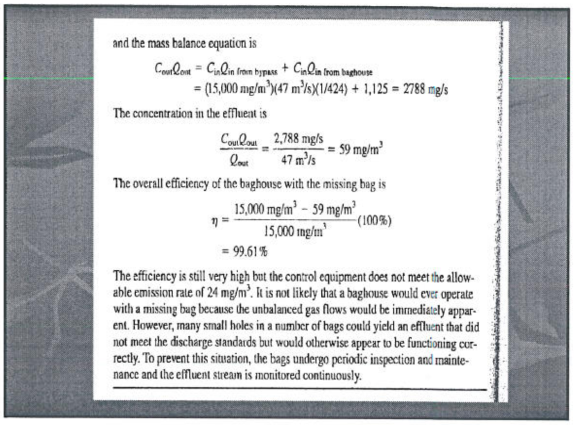
This value can be used as an input for a control volume around the junction of the bypass, the effluent from the baghouse and the final effluent.

A mass balance for the control volume around the junction may be written as

$$\frac{dM}{dt} = C_{in}Q_{in\ \text{from bypass}} + C_{in}Q_{in\ \text{from baghouse}} - C_{\text{emission}}Q_{\text{emission}}$$

Because there is no accumulation in the junction

$$\frac{dM}{dt} = 0$$



and the mass balance equation is

$$C_{out}Q_{out} = C_{in}Q_{in\ \text{from bypass}} + C_{in}Q_{in\ \text{from baghouse}}$$
$$= (15{,}000\ \text{mg/m}^3)(47\ \text{m}^3/\text{s})(1/424) + 1{,}125 = 2788\ \text{mg/s}$$

The concentration in the effluent is

$$\frac{C_{out}Q_{out}}{Q_{out}} = \frac{2{,}788\ \text{mg/s}}{47\ \text{m}^3/\text{s}} = 59\ \text{mg/m}^3$$

The overall efficiency of the baghouse with the missing bag is

$$\eta = \frac{15{,}000\ \text{mg/m}^3 - 59\ \text{mg/m}^3}{15{,}000\ \text{mg/m}^3}(100\%)$$
$$= 99.61\%$$

The efficiency is still very high but the control equipment does not meet the allowable emission rate of 24 mg/m^3. It is not likely that a baghouse would ever operate with a missing bag because the unbalanced gas flows would be immediately apparent. However, many small holes in a number of bags could yield an effluent that did not meet the discharge standards but would otherwise appear to be functioning correctly. To prevent this situation, the bags undergo periodic inspection and maintenance and the effluent stream is monitored continuously.

State of Mixing

- Plug flow systems
  - No mixing of constituents (pollutants / elements) within the system / boundary
  - Concentration is variable within the system
- Completely mixed systems
  - Constituents are well mixed
  - Concentration of constituents (pollutants / elements) within the system are identical

Plug flow system & Pulse change

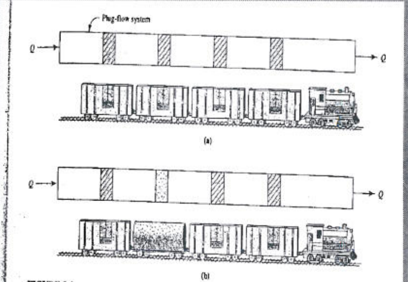
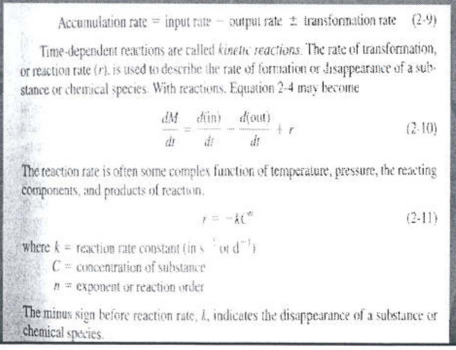


FIGURE 2-1
(*a*) Analogy of a plug-flow system and a train. (*b*) Analogy when a pulse change in influent concentration occurs.

State of Mixing (Contd..)

- Also related terms are :
- Stead State: dM/dt = 0
- Unsteady State: dM/dt ≠ 0

Reactions



Accumulation rate = input rate − output rate ± transformation rate (2-9)

Time-dependent reactions are called *kinetic reactions*. The rate of transformation, or reaction rate (r), is used to describe the rate of formation or disappearance of a substance or chemical species. With reactions, Equation 2-4 may become

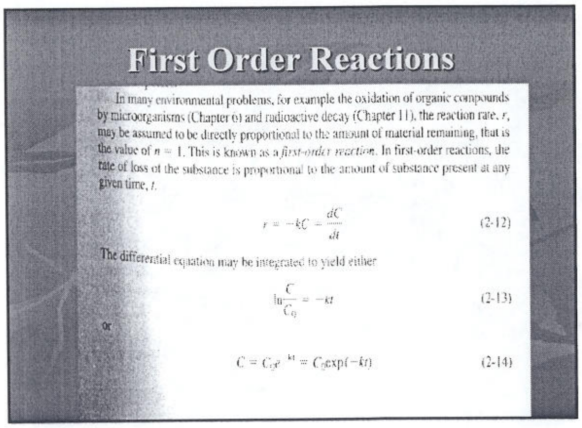
$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} + r \qquad (2\text{-}10)$$

The reaction rate is often some complex function of temperature, pressure, the reacting components, and products of reaction.

$$r = -kC^n \qquad (2\text{-}11)$$

where k = reaction rate constant (in s^{-1} or d^{-1})
C = concentration of substance
n = exponent or reaction order

The minus sign before reaction rate, k, indicates the disappearance of a substance or chemical species.



First Order Reactions

In many environmental problems, for example the oxidation of organic compounds by microorganisms (Chapter 6) and radioactive decay (Chapter 11), the reaction rate, r, may be assumed to be directly proportional to the amount of material remaining, that is the value of $n = 1$. This is known as a *first-order reaction*. In first-order reactions, the rate of loss of the substance is proportional to the amount of substance present at any given time, t.

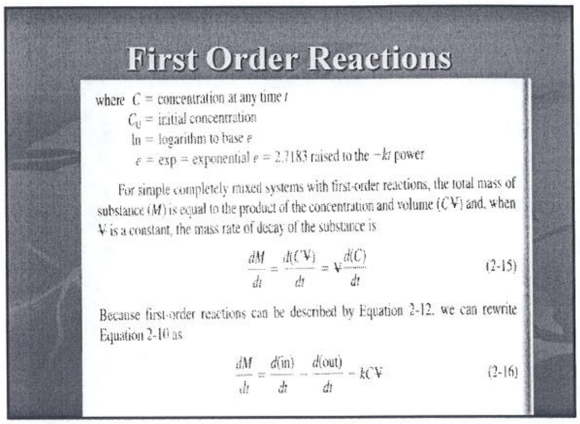
$$r = -kC = \frac{dC}{dt} \tag{2-12}$$

The differential equation may be integrated to yield either

$$\ln\frac{C}{C_0} = -kt \tag{2-13}$$

or

$$C = C_0e^{-kt} = C_0\exp(-kt) \tag{2-14}$$



First Order Reactions

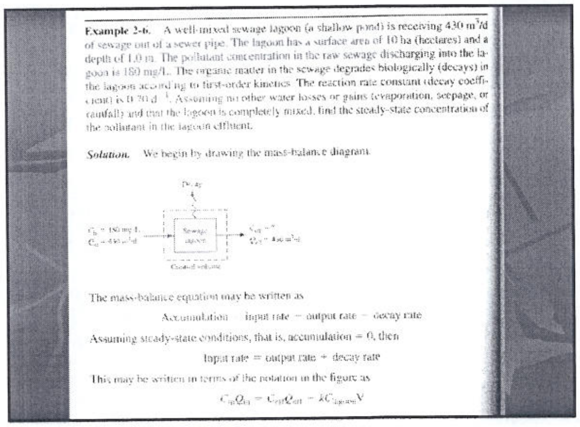
where C = concentration at any time t
C_0 = initial concentration
$\ln$ = logarithm to base e
e = exp = exponential e = 2.7183 raised to the $-kt$ power

For simple completely mixed systems with first-order reactions, the total mass of substance (M) is equal to the product of the concentration and volume (CV) and, when V is a constant, the mass rate of decay of the substance is

$$\frac{dM}{dt} = \frac{d(CV)}{dt} = V\frac{d(C)}{dt} \tag{2-15}$$

Because first-order reactions can be described by Equation 2-12, we can rewrite Equation 2-10 as

$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} - kCV \tag{2-16}$$



Example 2-6. A well-mixed sewage lagoon (a shallow pond) is receiving 430 m³/d of sewage out of a sewer pipe. The lagoon has a surface area of 10 ha (hectares) and a depth of 1.0 m. The pollutant concentration in the raw sewage discharging into the lagoon is 180 mg/L. The organic matter in the sewage degrades biologically (decays) in the lagoon according to first-order kinetics. The reaction rate constant (decay coefficient) is 0.70 d⁻¹. Assuming no other water losses or gains (evaporation, seepage, or rainfall) and that the lagoon is completely mixed, find the steady-state concentration of the pollutant in the lagoon effluent.

Solution. We begin by drawing the mass-balance diagram.

The mass-balance equation may be written as

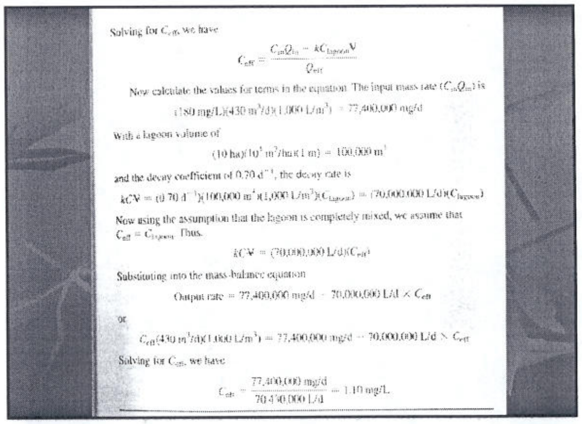
Accumulation = input rate − output rate − decay rate

Assuming steady-state conditions, that is, accumulation = 0, then

Input rate = output rate + decay rate

This may be written in terms of the notation in the figure as

$$C_{in}Q_{in} = C_{eff}Q_{eff} + kC_{lagoon}V$$



Solving for C_{eff}, we have

$$C_{eff} = \frac{C_{in}Q_{in} - kC_{lagoon}V}{Q_{eff}}$$

Now calculate the values for terms in the equation. The input mass rate ($C_{in}Q_{in}$) is

$$(180 \text{ mg/L})(430 \text{ m}^3/\text{d})(1{,}000 \text{ L/m}^3) = 77{,}400{,}000 \text{ mg/d}$$

With a lagoon volume of

$$(10 \text{ ha})(10^4 \text{ m}^2/\text{ha})(1 \text{ m}) = 100{,}000 \text{ m}^3$$

and the decay coefficient of 0.70 d⁻¹, the decay rate is

$$kCV = (0.70 \text{ d}^{-1})(100{,}000 \text{ m}^3)(1{,}000 \text{ L/m}^3)(C_{lagoon}) = (70{,}000{,}000 \text{ L/d})(C_{lagoon})$$

Now using the assumption that the lagoon is completely mixed, we assume that $C_{eff} = C_{lagoon}$. Thus,

$$kCV = (70{,}000{,}000 \text{ L/d})(C_{eff})$$

Substituting into the mass-balance equation

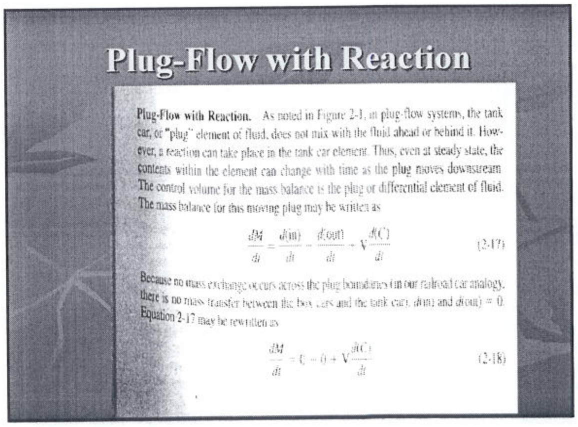
$$\text{Output rate} = 77{,}400{,}000 \text{ mg/d} - 70{,}000{,}000 \text{ L/d} \times C_{eff}$$

or

$$C_{eff}(430 \text{ m}^3/\text{d})(1{,}000 \text{ L/m}^3) = 77{,}400{,}000 \text{ mg/d} - 70{,}000{,}000 \text{ L/d} \times C_{eff}$$

Solving for C_{eff}, we have

$$C_{eff} = \frac{77{,}400{,}000 \text{ mg/d}}{70{,}430{,}000 \text{ L/d}} = 1.10 \text{ mg/L}$$



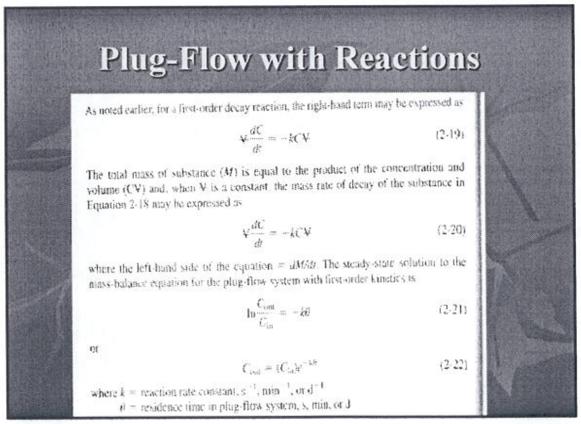
Plug-Flow with Reaction

Plug-Flow with Reaction. As noted in Figure 2-1, in plug-flow systems, the tank car, or "plug" element of fluid, does not mix with the fluid ahead or behind it. However, a reaction can take place in the tank car element. Thus, even at steady state, the contents within the element can change with time as the plug moves downstream. The control volume for the mass balance is the plug or differential element of fluid. The mass balance for this moving plug may be written as

$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} + V\frac{d(C)}{dt} \tag{2-17}$$

Because no mass exchange occurs across the plug boundaries (in our railroad car analogy, there is no mass transfer between the box cars and the tank car), d(in) and d(out) = 0. Equation 2-17 may be rewritten as

$$\frac{dM}{dt} = 0 - 0 + V\frac{d(C)}{dt} \tag{2-18}$$



Plug-Flow with Reactions

As noted earlier, for a first-order decay reaction, the right-hand term may be expressed as

$$V\frac{dC}{dt} = -kCV \tag{2-19}$$

The total mass of substance (M) is equal to the product of the concentration and volume (CV) and, when V is a constant, the mass rate of decay of the substance in Equation 2-18 may be expressed as

$$V\frac{dC}{dt} = -kCV \tag{2-20}$$

where the left-hand side of the equation = dM/dt. The steady-state solution to the mass-balance equation for the plug-flow system with first-order kinetics is

$$\ln\frac{C_{out}}{C_{in}} = -k\theta \tag{2-21}$$

or

$$C_{out} = (C_{in})e^{-k\theta} \tag{2-22}$$

where k = reaction rate constant, s⁻¹, min⁻¹, or d⁻¹
θ = residence time in plug-flow system, s, min, or d

Plug-Flow with Reactions

In a plug-flow system of length L, each plug travels for a period $= L/u$, where u = the speed of flow. Alternatively, for a cross-sectional area A, the residence time is

$$\theta = \frac{(L)(A)}{(u)(A)} = \frac{\mathcal{V}}{Q} \qquad (2\text{-}23)$$

where $\mathcal{V}$ = volume of the plug-flow system, m^3
Q = flow rate (in m^3/s)

Thus, for example, Equation 2-21, may be rewritten as

$$\ln \frac{C_{out}}{C_{in}} = -k\frac{L}{u} = -k\frac{\mathcal{V}}{Q} \qquad (2\text{-}24)$$

where L = length of the plug-flow segment, m
u = linear velocity, m/s

Although the concentration within a given plug changes over time as the plug moves downstream, the concentration at a fixed point in the plug-flow system remains constant with respect to time. Thus, Equation 2-24 has no time dependence.

Example 2-7 illustrates an application of plug-flow with reaction.

Reactors

- Reactors: Tanks in which physical, chemical, and biochemical reactions occur
- Types: Two, Batch and Continuous
- Batch Reactors:
  - Fill-and-draw type
  - Materials added, mixed, allowed to stay in for the reaction to occur, and then drained

Reactors

- Completely Mixed Flow Reactor (CMFR) or Continuous-flow Stirred Tank Reactor (CSTR)
  - Material flows in and out of the tank on a continuous, uninterrupted, basis

Plug Flow Reactors

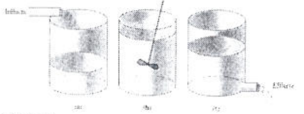


FIGURE 2-2
Batch reactor operation: (a) Materials added to the reactor. (b) Mixing and reaction. (c) Reactor is drained. Note: There is no influent or effluent during the reaction.

For a batch reactor Equation 2-16 reduces to

$$\frac{dM}{dt} = -kC\mathcal{V} \qquad (2\text{-}25)$$

As we noted in Equation 2-15

$$\frac{dM}{dt} = \mathcal{V}\frac{dC}{dt}$$

So that for a first-order reaction in a batch reactor, Equation 2-25 may be simplified to

$$\frac{dC}{dt} = -kC \qquad (2\text{-}26)$$

CMFR / CSTR

Flow reactors have a continuous type of operation: material flows into, through, and out of the reactor at all times. Flow reactors may be further classified by mixing conditions. The contents of a *completely mixed flow reactor* (CMFR), also called a continuous-flow stirred tank reactor (CSTR), ideally are uniform throughout the tank. A schematic diagram of a CMFR and the common flow diagram notation are shown in Figure 2-3. The composition of the effluent is the same as the composition in the tank.

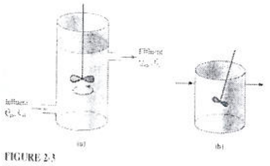


FIGURE 2-3
Schematic diagram of (a) completely mixed flow reactor (CMFR) and (b) the common diagram. The propeller indicates that the reactor is completely mixed.

Reactor Analysis

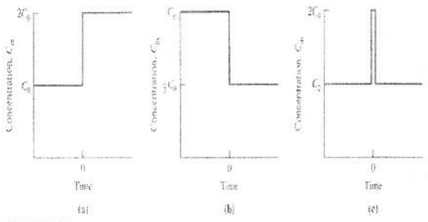
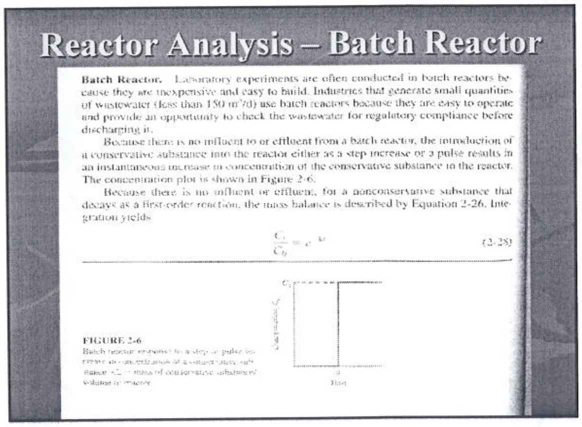


FIGURE 2-5
Example influent graphs of (a) step increase in influent concentration, (b) step decrease in influent concentration, and (c) a pulse or spike increase in influent concentration. Note: The size of the change is for illustration purposes only.



Reactor Analysis – Batch Reactor

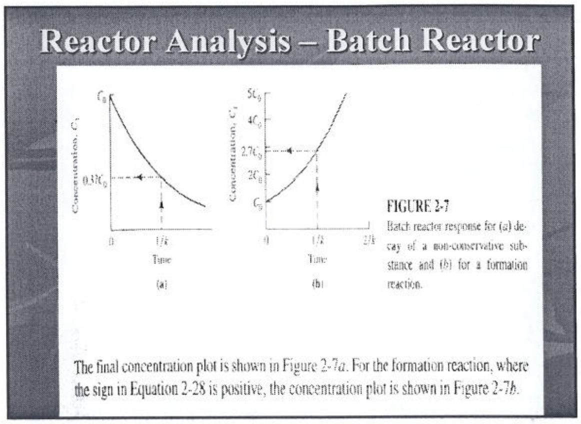
Batch Reactor. Laboratory experiments are often conducted in batch reactors because they are inexpensive and easy to build. Industries that generate small quantities of wastewater (less than 150 m^3/d) use batch reactors because they are easy to operate and provide an opportunity to check the wastewater for regulatory compliance before discharging it.

Because there is no influent to or effluent from a batch reactor, the introduction of a conservative substance into the reactor either as a step increase or a pulse results in an instantaneous increase in concentration of the conservative substance in the reactor. The concentration plot is shown in Figure 2-6.

Because there is no influent or effluent, for a nonconservative substance that decays as a first-order reaction, the mass balance is described by Equation 2-26. Integration yields

$$\frac{C_t}{C_0} = e^{-kt} \qquad (2\text{-}28)$$

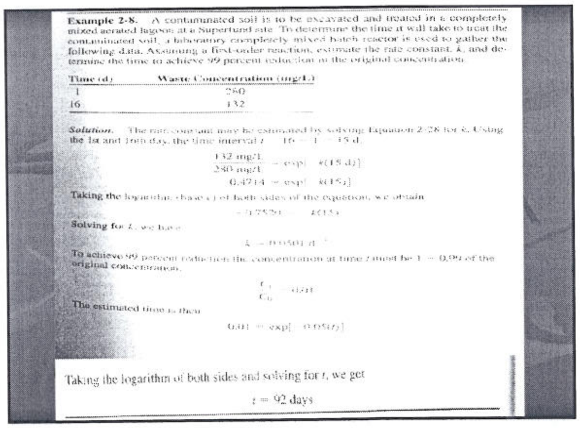
FIGURE 2-6
Batch reactor response to a step or pulse increase in concentration of a conservative substance. C_0 = mass of conservative substance/volume of reactor.



Reactor Analysis – Batch Reactor

FIGURE 2-7
Batch reactor response for (a) decay of a non-conservative substance and (b) for a formation reaction.

The final concentration plot is shown in Figure 2-7*a*. For the formation reaction, where the sign in Equation 2-28 is positive, the concentration plot is shown in Figure 2-7*b*.



Example 2-8. A contaminated soil is to be excavated and treated in a completely mixed aerated lagoon at a Superfund site. To determine the time it will take to treat the contaminated soil, a laboratory completely mixed batch reactor is used to gather the following data. Assuming a first-order reaction, estimate the rate constant, *k*, and determine the time to achieve 99 percent reduction in the original concentration.

Time (d)	Waste Concentration (mg/L)
1	280
16	132

Solution. The rate constant may be estimated by solving Equation 2-28 for *k*. Using the 1st and 16th day, the time interval $t = 16 - 1 = 15$ d.

$$\frac{132 \text{ mg/L}}{280 \text{ mg/L}} = \exp[-k(15 \text{ d})]$$

$$0.4714 = \exp[-k(15 \text{ d})]$$

Taking the logarithm (base e) of both sides of the equation, we obtain

$$-0.7520 = -k(15)$$

Solving for *k*, we have

$$k = 0.0501 \text{ d}^{-1}$$

To achieve 99 percent reduction the concentration at time *t* must be $1 - 0.99$ of the **original concentration.**

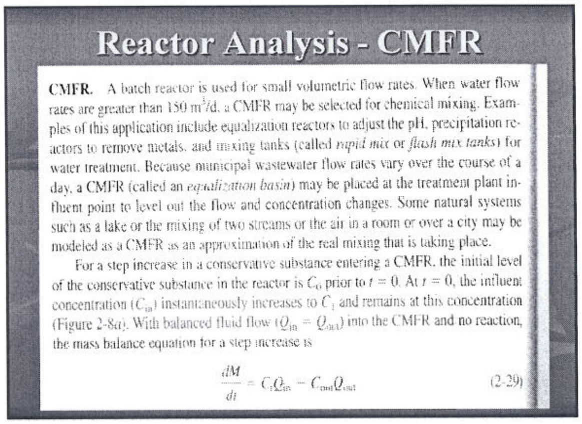
$$\frac{C_t}{C_0} = 0.01$$

The estimated time is then

$$0.01 = \exp[-0.05(t)]$$

Taking the logarithm of both sides and solving for *t*, we get

$$t = 92 \text{ days}$$

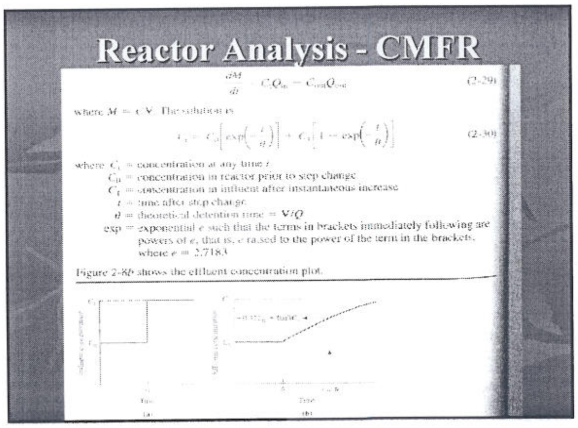


Reactor Analysis - CMFR

CMFR. A batch reactor is used for small volumetric flow rates. When water flow rates are greater than 150 m^3/d, a CMFR may be selected for chemical mixing. Examples of this application include equalization reactors to adjust the pH, precipitation reactors to remove metals, and mixing tanks (called *rapid mix* or *flash mix tanks*) for water treatment. Because municipal wastewater flow rates vary over the course of a day, a CMFR (called an *equalization basin*) may be placed at the treatment plant influent point to level out the flow and concentration changes. Some natural systems such as a lake or the mixing of two streams or the air in a room or over a city may be modeled as a CMFR as an approximation of the real mixing that is taking place.

For a step increase in a conservative substance entering a CMFR, the initial level of the conservative substance in the reactor is C_0 prior to $t = 0$. At $t = 0$, the influent concentration (C_{in}) instantaneously increases to C_1 and remains at this concentration (Figure 2-8*a*). With balanced fluid flow ($Q_{in} = Q_{out}$) into the CMFR and no reaction, the mass balance equation for a step increase is

$$\frac{dM}{dt} = C_1Q_{in} - C_{out}Q_{out} \qquad (2\text{-}29)$$



Reactor Analysis - CMFR

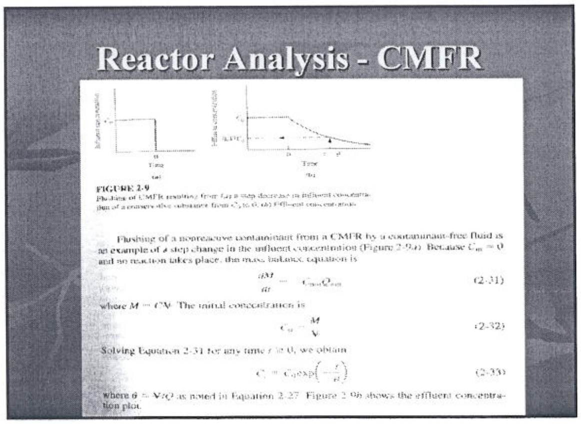
$$\frac{dM}{dt} = C_1Q_{in} - C_{out}Q_{out} \qquad (2\text{-}29)$$

where $M = CV$. The solution is

$$C_t = C_0\left[\exp\left(-\frac{t}{\theta}\right)\right] + C_1\left[1 - \exp\left(-\frac{t}{\theta}\right)\right] \qquad (2\text{-}30)$$

where C_t = concentration at any time *t*
C_0 = concentration in reactor prior to step change
C_1 = concentration in influent after instantaneous increase
t = time after step change
θ = theoretical detention time = **V**/*Q*
exp = exponential *e* such that the terms in brackets immediately following are powers of *e*, that is, *e* raised to the power of the term in the brackets, where e = 2.7183

Figure 2-8*b* shows the effluent concentration plot.



Reactor Analysis - CMFR

FIGURE 2-9
Flushing of CMFR resulting from (a) a step decrease in influent concentration of a conservative substance from C_0 to 0. (b) Effluent concentration.

Flushing of a nonreactive contaminant from a CMFR by a contaminant-free fluid is an example of a step change in the influent concentration (Figure 2-9*a*). Because $C_{in} = 0$ and no reaction takes place, the mass balance equation is

$$\frac{dM}{dt} = -C_{out}Q_{out} \qquad (2\text{-}31)$$

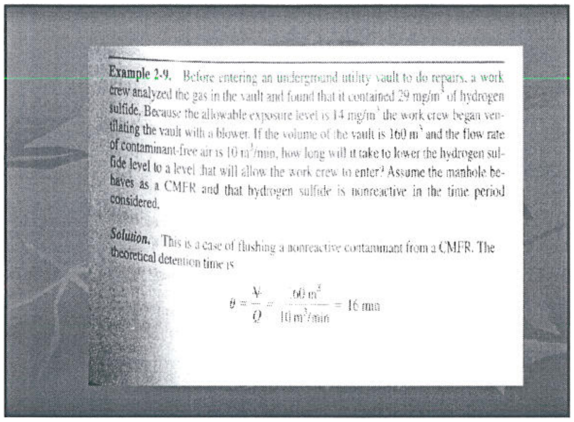
where $M = CV$. The initial concentration is

$$C_0 = \frac{M}{V} \qquad (2\text{-}32)$$

Solving Equation 2-31 for any time $t \geq 0$, we obtain

$$C_t = C_0\exp\left(-\frac{t}{\theta}\right) \qquad (2\text{-}33)$$

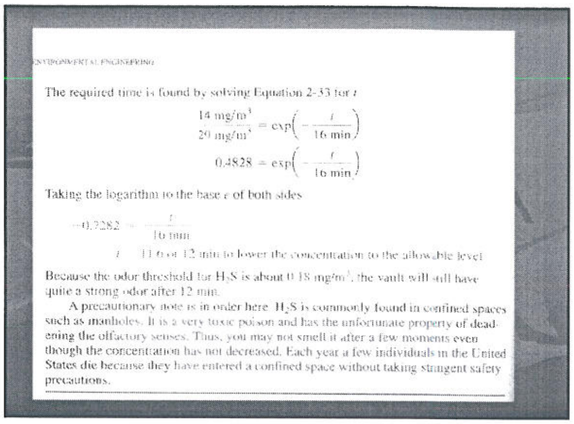
where θ = **V**/*Q* as noted in Equation 2-27. Figure 2-9*b* shows the effluent concentration plot.



Example 2-9. Before entering an underground utility vault to do repairs, a work crew analyzed the gas in the vault and found that it contained 29 mg/m^3 of hydrogen sulfide. Because the allowable exposure level is 14 mg/m^3 the work crew began ventilating the vault with a blower. If the volume of the vault is 160 m^3 and the flow rate of contaminant-free air is 10 m^3/min, how long will it take to lower the hydrogen sulfide level to a level that will allow the work crew to enter? Assume the manhole behaves as a CMFR and that hydrogen sulfide is nonreactive in the time period considered.

Solution. This is a case of flushing a nonreactive contaminant from a CMFR. The theoretical detention time is

$$\theta = \frac{V}{Q} = \frac{160 \text{ m}^3}{10 \text{ m}^3/\text{min}} = 16 \text{ min}$$



The required time is found by solving Equation 2-33 for t

$$\frac{14 \text{ mg/m}^3}{29 \text{ mg/m}^3} = \exp\left(-\frac{t}{16 \text{ min}}\right)$$

$$0.4828 = \exp\left(-\frac{t}{16 \text{ min}}\right)$$

Taking the logarithm to the base e of both sides

$$-0.7282 = -\frac{t}{16 \text{ min}}$$

$$t = 11.6 \text{ or } 12 \text{ min to lower the concentration to the allowable level}$$

Because the odor threshold for H_2S is about 0.18 mg/m^3, the vault will still have quite a strong odor after 12 min.

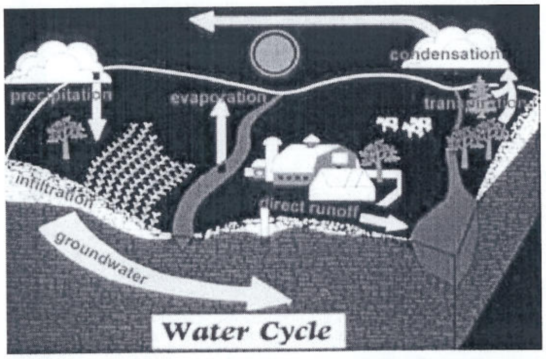
A precautionary note is in order here. H_2S is commonly found in confined spaces such as manholes. It is a very toxic poison and has the unfortunate property of deadening the olfactory senses. Thus, you may not smell it after a few moments even though the concentration has not decreased. Each year a few individuals in the United States die because they have entered a confined space without taking stringent safety precautions.

ENCE 3323: Introduction to Environmental Engineering

Chapter 3: Hydrology (Part:1)

Hydrologic Cycle

- The global system that supplies and removes water from the earth's surface
- Three things to know:
  - Evaporation (-)
  - Transpiration (-)
  - Precipitation (+)



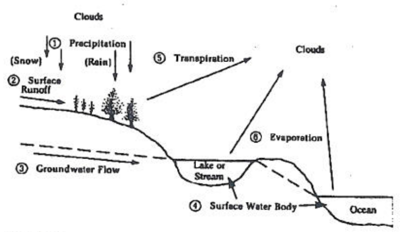


FIGURE 2-1
The hydrologic cycle.

Surface Water Hydrology

- Precipitation
  - Precipitation forms (rain, sleet, hail, or snow)
  - Precipitation factors (extent/area covered, duration, and intensity)
- Things that happen after precipitation:
  - Evaporation
  - Infiltration (in to the ground)
  - Interception (by leaves, grass, and other objects)
  - Trapping
- Abstractions (Evaporation, infiltration, interception, and trapping) – four factors that reduce direct runoff

Surface Water Hydrology
Streamflow

- Stream receives water from two main sources
  - Direct runoff from precipitation
  - Groundwater exfiltration (reverse of infiltration)
    - This is also known as base flow / dry weather flow
    - Occurs as a result of seepage of groundwater out of stream banks
- Amount of water in a stream depends on:
  - Watershed feeding the stream (+)
  - Abstractions (-)

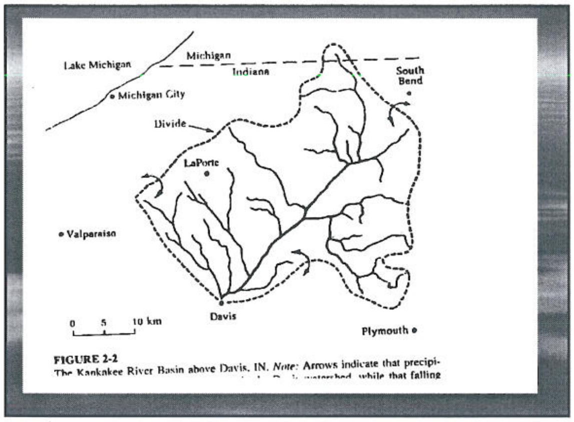
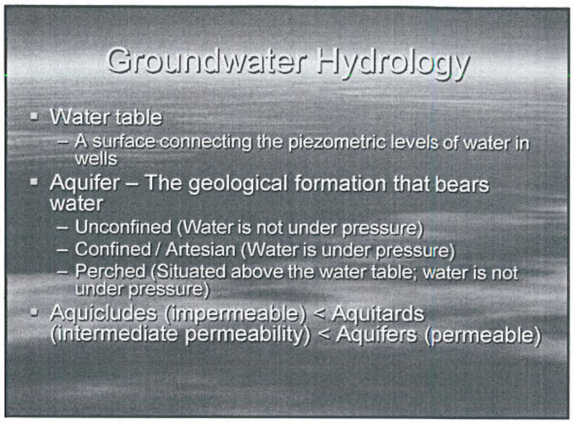


FIGURE 2-2
The Kankakee River Basin above Davis, IN. *Note:* Arrows indicate that precipi-



Groundwater Hydrology

- Water table
  - A surface connecting the piezometric levels of water in wells
- Aquifer – The geological formation that bears water
  - Unconfined (Water is not under pressure)
  - Confined / Artesian (Water is under pressure)
  - Perched (Situated above the water table; water is not under pressure)
- Aquicludes (impermeable) < Aquitards (intermediate permeability) < Aquifers (permeable)

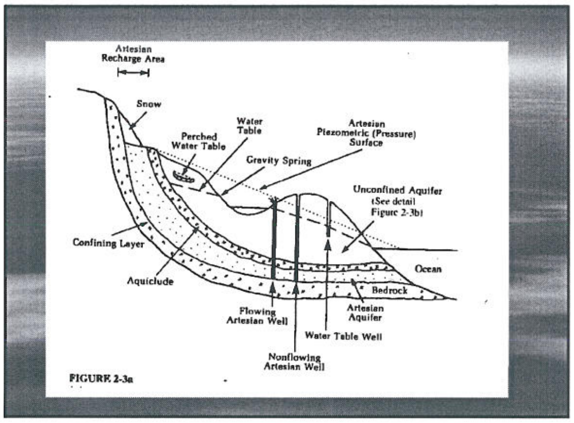


FIGURE 2-3a

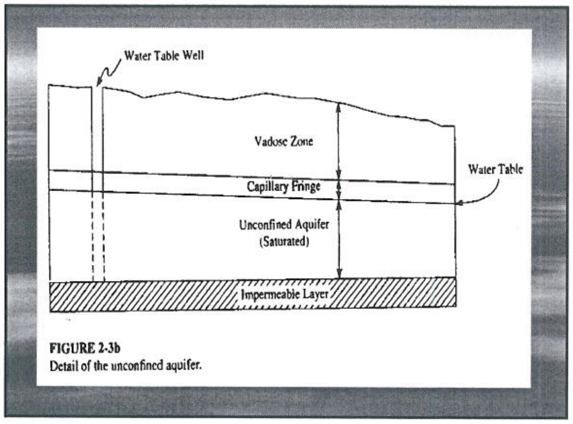


FIGURE 2-3b
Detail of the unconfined aquifer.

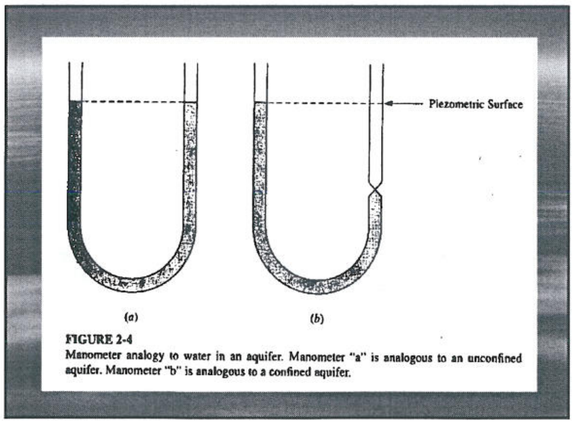
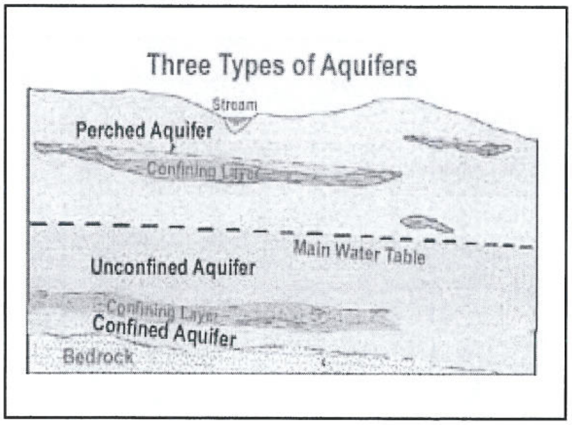
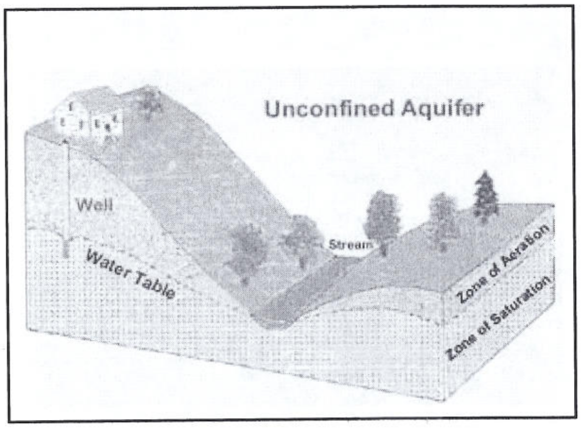
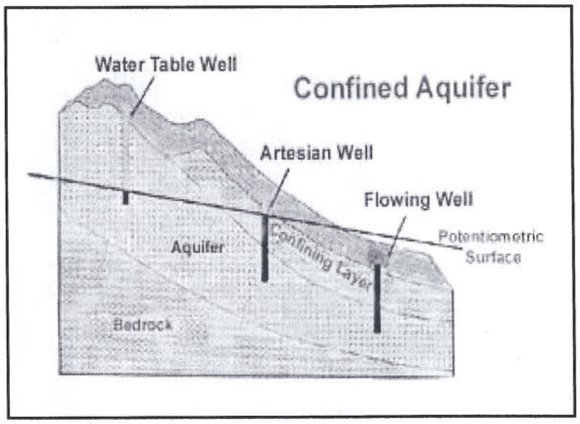


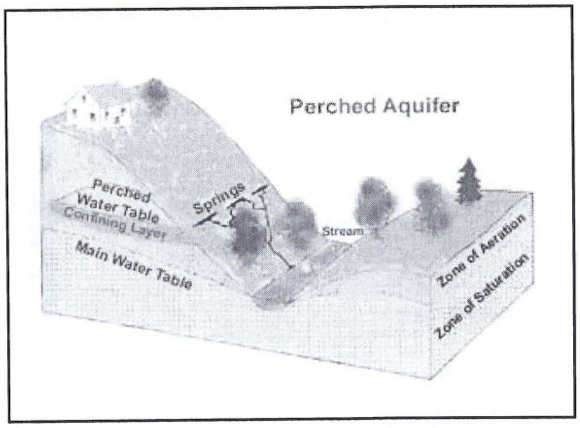
FIGURE 2-4
Manometer analogy to water in an aquifer. Manometer "a" is analogous to an unconfined aquifer. Manometer "b" is analogous to a confined aquifer.

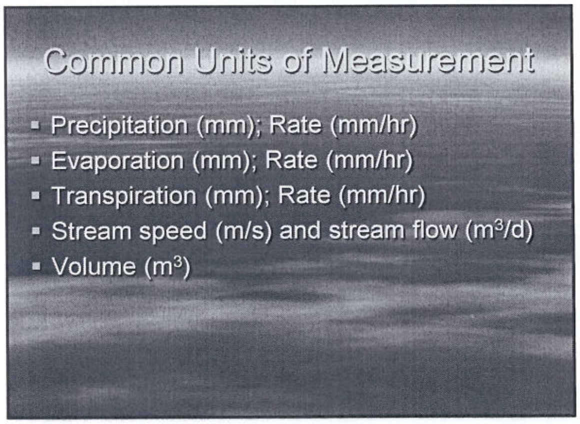


Three Types of Aquifers



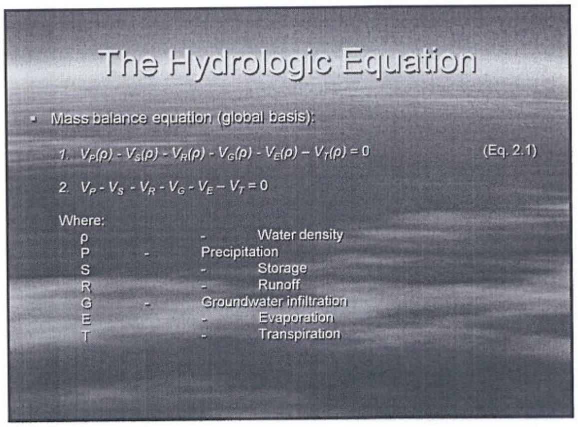






Common Units of Measurement

- Precipitation (mm); Rate (mm/hr)
- Evaporation (mm); Rate (mm/hr)
- Transpiration (mm); Rate (mm/hr)
- Stream speed (m/s) and stream flow (m^3/d)
- Volume (m^3)



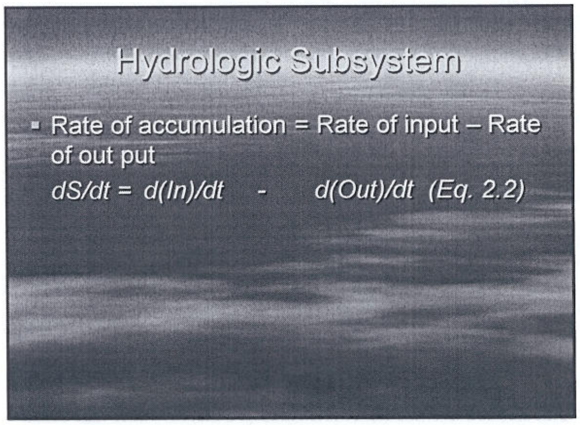
The Hydrologic Equation

- Mass balance equation (global basis):

1. $V_P(\rho) - V_S(\rho) - V_R(\rho) - V_G(\rho) - V_E(\rho) - V_T(\rho) = 0$ (Eq. 2.1)
2. $V_P - V_S - V_R - V_G - V_E - V_T = 0$

Where:

ρ - Water density
P - Precipitation
S - Storage
R - Runoff
G - Groundwater infiltration
E - Evaporation
T - Transpiration



Hydrologic Subsystem

- Rate of accumulation = Rate of input – Rate of out put

  dS/dt = d(In)/dt - d(Out)/dt (Eq. 2.2)

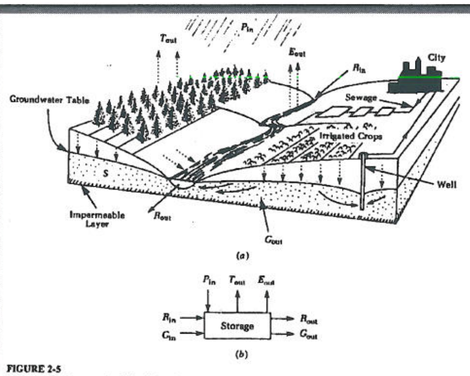


FIGURE 2-5
(*a*) Schematic diagram of a hydrologic subsystem: (*b*) mass balance diagram of hydrologic subsystem.

Infiltration

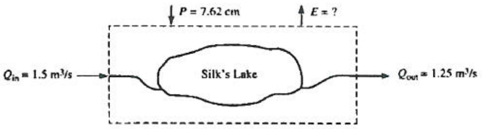
- Horton's Equation
  $f = f_c + (f_o - f_c) \;.\; e^{-kt}$ (Eq. 2.3)
  Where:
  f - infiltration rate, mm/h
  f_o - equilibrium or final infiltration rate, mm/h
  f_c - initial infiltration rate, mm/h
  k - empirical constant, 1/h
  t - time, h
- Infiltration rates and 'k' are function of soil type
- Integration of Eq. 2.3 yields Volume
  $V = f_c \,.\, t + (f_o - f_c) \,.\, (1 - e^{-kt}) / k$ (Eq. 2.4)

Evaporation

- Evaporation,
  $E = (e_s - e_a).(a + b.u)$ (Eq. 2.5)
  Where:
  E - *evaporation rate, mm/d*
  e_s - *saturation vapor pressure, kPa*
  e_a - *vapor pressures in overlaying air, kPa*
  a,b - *empirical constants*
  u - *wind speed, m/s*

Example 2-1. Silk's Lake has a surface area of 70.8 ha. For the month of April the inflow was 1.5 m³/s. The dam regulated the outflow (discharge) from Silk's Lake to be 1.25 m³/s. If the precipitation recorded for the month was 7.62 cm and the storage volume increased by an estimated 650,000 m³, what is the estimated evaporation in m³ and cm? Assume that no water infiltrates out of the bottom of Silk's Lake.

Solution. Begin by drawing the mass-balance diagram:



The mass-balance equation is:

Accumulation = Input − Output

The accumulation is given as 650,000 m³. The input consists of the inflow and the precipitation. The product of the precipitation depth and the area on which it fell (70.8 ha) will yield a volume. The output consists of outflow plus evaporation.

Noting that April has 30 days and making the appropriate units conversions:

$$\begin{aligned} 650{,}000 \text{ m}^3 = {} & (1.5 \text{ m}^3/\text{s})(30 \text{ d})(86{,}400 \text{ s/d}) \\ & + (7.62 \text{ cm})(70.8 \text{ ha})(10^4 \text{ m}^2/\text{ha})(1 \text{ m}/100 \text{ cm}) \\ & - (1.25 \text{ m}^3/\text{s})(30 \text{ d})(86{,}400 \text{ s/d}) - E \end{aligned}$$

Solving for E:

$$E = 3.89 \times 10^6 \text{ m}^3 + 5.39 \times 10^4 \text{ m}^3 - 3.24 \times 10^6 \text{ m}^3 - 6.50 \times 10^5 \text{ m}^3$$

$$E = 5.39 \times 10^4 \text{ m}^3$$

For an area of 70.8 ha, the evaporation depth is:

$$E = \frac{5.39 \times 10^4 \text{ m}^3}{(70.8 \text{ ha})(10^4 \text{ m}^2/\text{ha})} = 0.076 \text{ m or } 7.6 \text{ cm}$$

Example 2-2. During April, the wind speed over Silk's Lake was estimated to be 4.0 m/s. The air temperature averaged 20 °C and the relative humidity was 30%. The water temperature averaged 10 °C. Estimate the evaporation rate using the empirical relationship in Equation 2-6.

Solution. From the water temperature and Table 2-1, the saturation vapor pressure is estimated as e_s = 1.227 kPa. The vapor pressure in the air may be estimated as the product of the relative humidity and the saturation vapor pressure at the air temperature:

$$e_a = (2.337 \text{ kPa})(0.30) = 0.70 \text{ kPa}$$

The daily evaporation rate is then estimated to be:

$$E = 1.22(1.227 - 0.70)(4.0 \text{ m/s}) = 2.57 \text{ mm/d}$$

The monthly evaporation would then be estimated to be:

$$E = (2.56 \text{ mm/d})(30 \text{ d}) = 76.8 \text{ mm or } 7.7 \text{ cm}$$

TABLE 2-1
Water vapor pressures at various temperatures

Temperature, °C	Vapor pressure, kPa
0	0.611
5	0.872
10	1.227
15	1.704
20	2.337
25	3.167
30	4.243
35	5.624
40	7.378

Evapotranspiration

- Evaportranspiration =
  - Water loss from plants (tanspiration) + loss from the soil surface or root zone
- Factors that have influence:
  - Soil moisture
  - Soil type
  - Plant type (Oak – 160 l/d; Corn – 1.9 l/d)
  - Wind speed, and
  - Temperature

RAINFALL ANALYSIS

- Three important factors:
  - Space (aerial extent)
  - Intensity
  - Duration
  - Frequency
- Point precipitation analysis – refers to single rain gage supplying data
- Spatial analysis – multiple rain gages supply data; involves more complex methods of analysis

RAINFALL ANALYSIS
Types of Rain Gages

- Standard (manual recording over 24-hr period)
- Weighing Bucket (Continuous strip chart records the rainfall)
- Tipping Bucket (cup tips for every 0.25 mm precipitation)

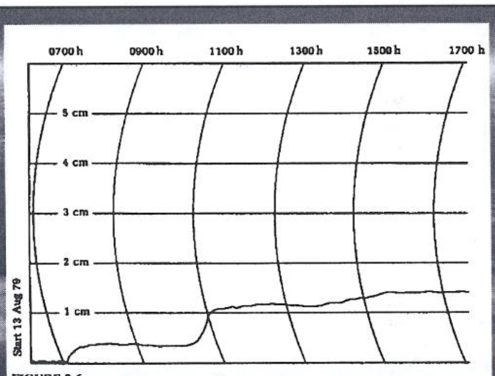


FIGURE 2-6

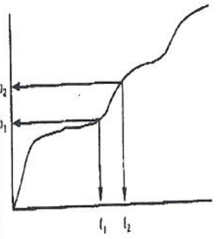


FIGURE 2-7
Computation of rainfall intensity from weighing-bucket strip chart record.

RAINFALL ANALYSIS
Intensity-duration-frequency (IDF) Curves

- IDF curves are essential for rational designing of storm drainage system.
- Avg. return period of a storm or avg. recurrence interval in yrs (T) = 1/Annual Avg. Probability
- Weibull's formula for Storm Return Period (T) = (n + 1)/m

Where, T – average return period in years
n – number of years on record
m – rank of storm, with most intense storm given a rank of 1

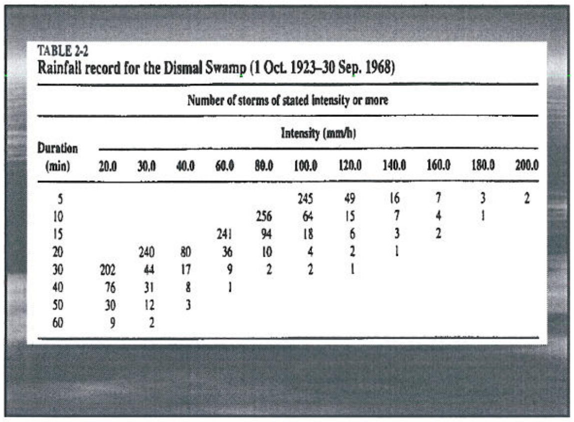
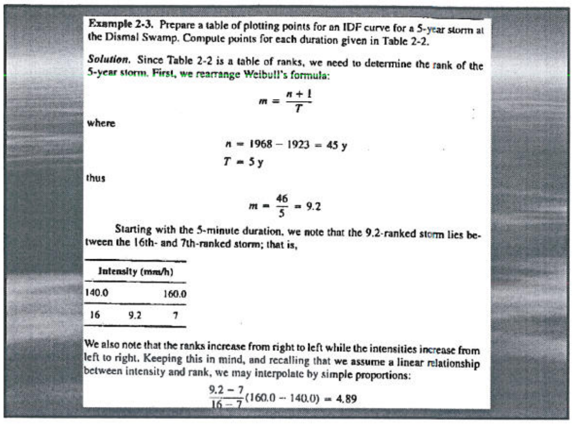


TABLE 2-2

Rainfall record for the Dismal Swamp (1 Oct. 1923–30 Sep. 1968)

Duration (min)	Number of storms of stated intensity or more										
	Intensity (mm/h)										
	20.0	30.0	40.0	60.0	80.0	100.0	120.0	140.0	160.0	180.0	200.0
5						245	49	16	7	3	2
10					256	64	15	7	4	1	
15				241	94	18	6	3	2		
20		240	80	36	10	4	2	1			
30	202	44	17	9	2	2	1				
40	76	31	8	1							
50	30	12	3								
60	9	2									



Example 2-3. Prepare a table of plotting points for an IDF curve for a 5-year storm at the Dismal Swamp. Compute points for each duration given in Table 2-2.

Solution. Since Table 2-2 is a table of ranks, we need to determine the rank of the 5-year storm. First, we rearrange Weibull's formula:

$$m = \frac{n+1}{T}$$

where

$$n = 1968 - 1923 = 45 \text{ y}$$
$$T = 5 \text{ y}$$

thus

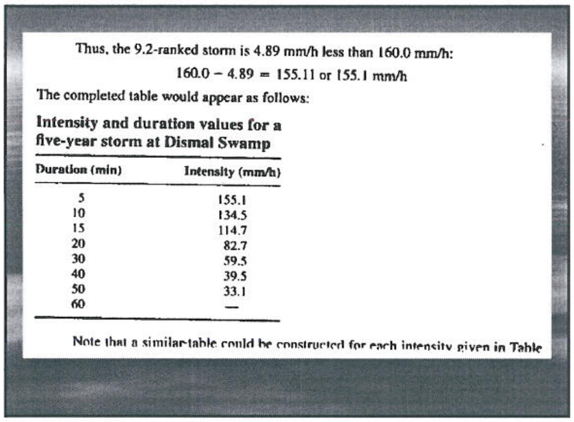
$$m = \frac{46}{5} = 9.2$$

Starting with the 5-minute duration, we note that the 9.2-ranked storm lies between the 16th- and 7th-ranked storm; that is,

Intensity (mm/h)		
140.0		160.0
16	9.2	7

We also note that the ranks increase from right to left while the intensities increase from left to right. Keeping this in mind, and recalling that we assume a linear relationship between intensity and rank, we may interpolate by simple proportions:

$$\frac{9.2-7}{16-7}(160.0 - 140.0) = 4.89$$



Thus, the 9.2-ranked storm is 4.89 mm/h less than 160.0 mm/h:

$$160.0 - 4.89 = 155.11 \text{ or } 155.1 \text{ mm/h}$$

The completed table would appear as follows:

Intensity and duration values for a five-year storm at Dismal Swamp

Duration (min)	Intensity (mm/h)
5	155.1
10	134.5
15	114.7
20	82.7
30	59.5
40	39.5
50	33.1
60	—

Note that a similar table could be constructed for each intensity given in Table

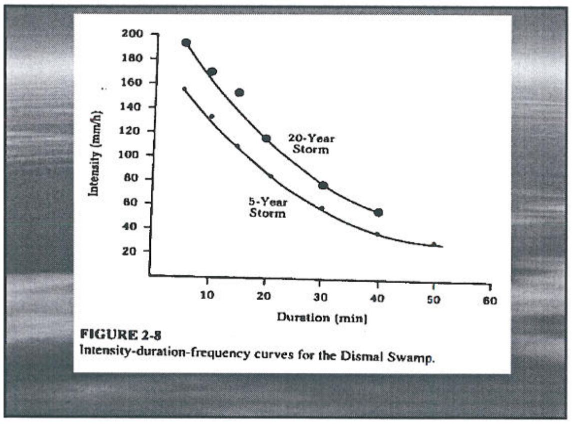
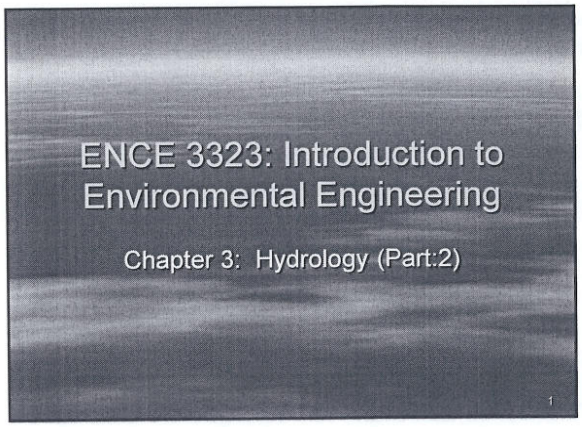
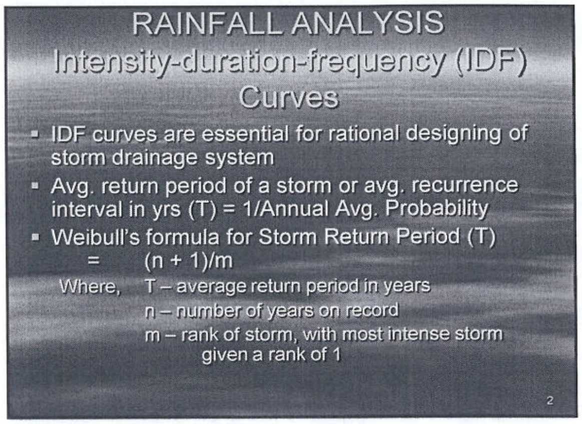


FIGURE 2-8
Intensity-duration-frequency curves for the Dismal Swamp.



ENCE 3323: Introduction to Environmental Engineering

Chapter 3: Hydrology (Part:2)



RAINFALL ANALYSIS Intensity-duration-frequency (IDF) Curves

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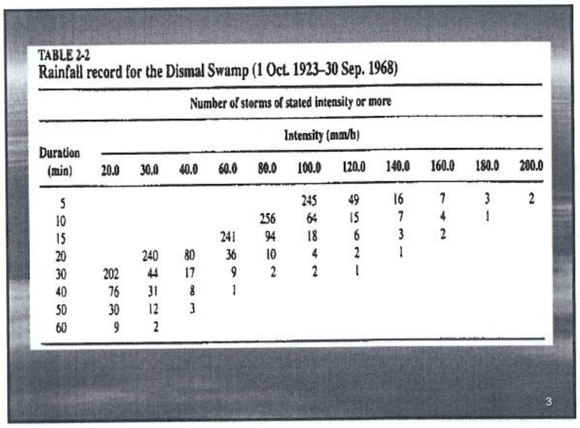

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	Intensity (mm/h)										
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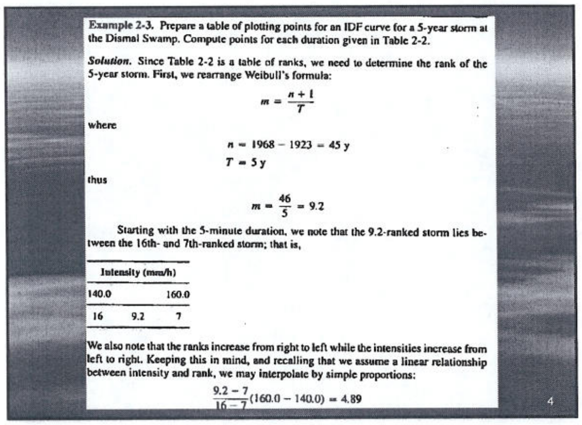
10					256	64	15	7	4	1	
15				241	94	18	6	3	2		
20		240	80	36	10	4	2	1			
30	202	44	17	9	2	2	1				
40	76	31	8	1							
50	30	12	3								
60	9	2									



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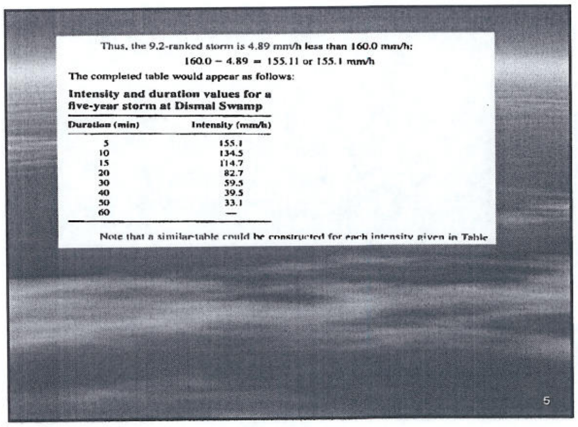
We also note that the ranks increase from right to left while the intensities increase from left to right. Keeping this in mind, and recalling that we assume a linear relationship between intensity and rank, we may interpolate by simple proportions:

$$\frac{9.2-7}{16-7}(160.0 - 140.0) = 4.89$$



Thus, the 9.2-ranked storm is 4.89 mm/h less than 160.0 mm/h:

$$160.0 - 4.89 = 155.11 \text{ or } 155.1 \text{ mm/h}$$

The completed table would appear as follows:

Intensity and duration values for a five-year storm at Dismal Swamp

Duration (min)	Intensity (mm/h)
5	155.1
10	134.5
15	114.7
20	82.7
30	59.5
40	39.5
50	33.1
60	—

Note that a similar table could be constructed for each intensity given in Table

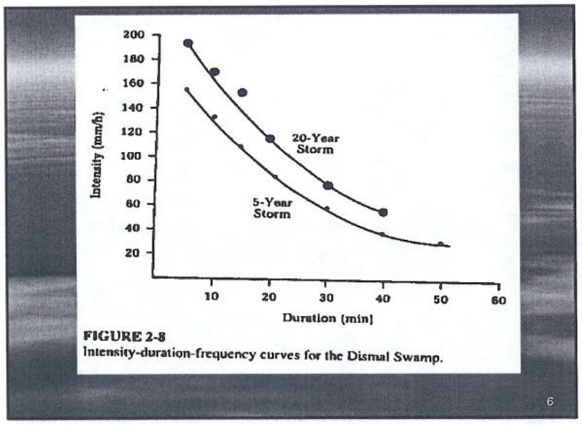
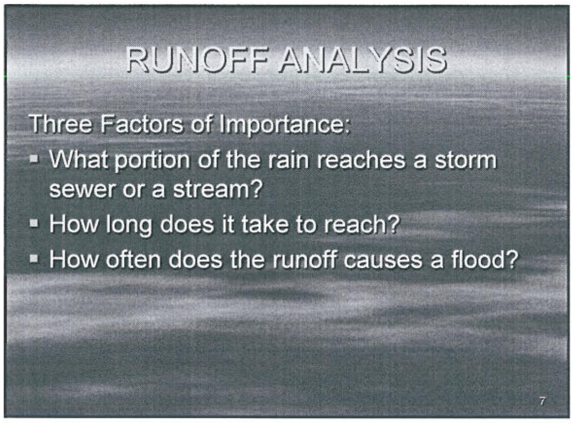


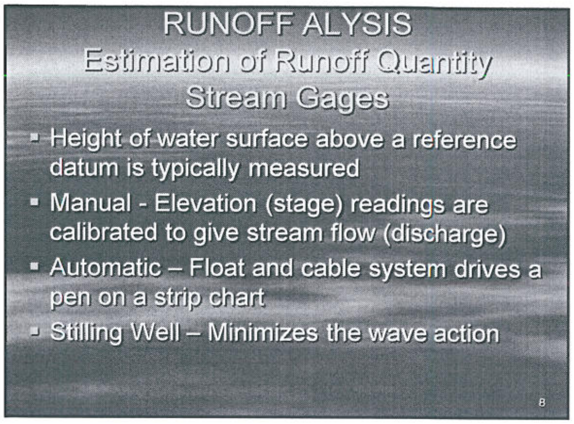
FIGURE 2-8
Intensity-duration-frequency curves for the Dismal Swamp.



RUNOFF ANALYSIS

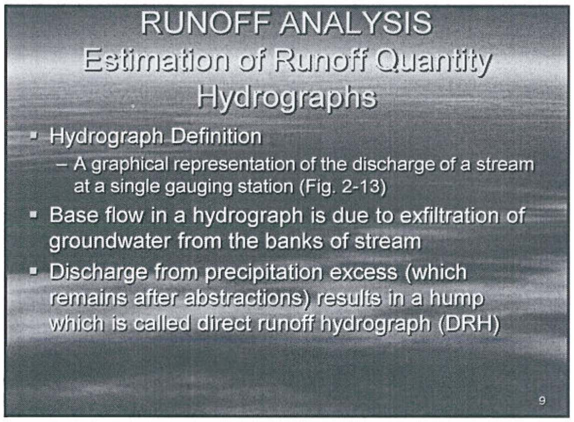
Three Factors of Importance:

- What portion of the rain reaches a storm sewer or a stream?
- How long does it take to reach?
- How often does the runoff causes a flood?



RUNOFF ALYSIS
Estimation of Runoff Quantity
Stream Gages

- Height of water surface above a reference datum is typically measured
- Manual - Elevation (stage) readings are calibrated to give stream flow (discharge)
- Automatic – Float and cable system drives a pen on a strip chart
- Stilling Well – Minimizes the wave action



RUNOFF ANALYSIS
Estimation of Runoff Quantity
Hydrographs

- Hydrograph Definition
  - A graphical representation of the discharge of a stream at a single gauging station (Fig. 2-13)
- Base flow in a hydrograph is due to exfiltration of groundwater from the banks of stream
- Discharge from precipitation excess (which remains after abstractions) results in a hump which is called direct runoff hydrograph (DRH)

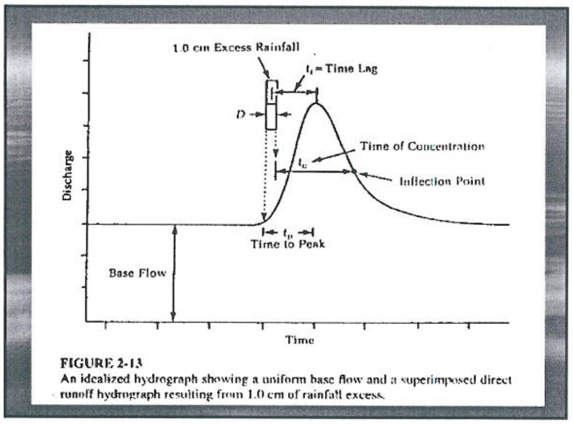
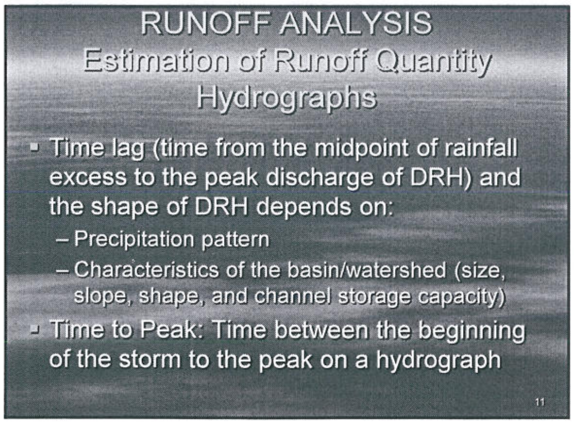
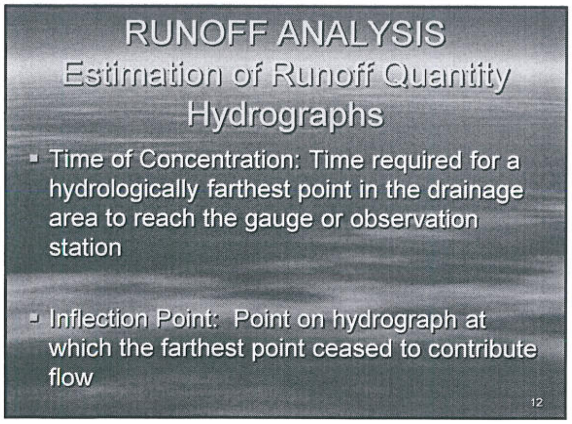


FIGURE 2-13
An idealized hydrograph showing a uniform base flow and a superimposed direct runoff hydrograph resulting from 1.0 cm of rainfall excess.



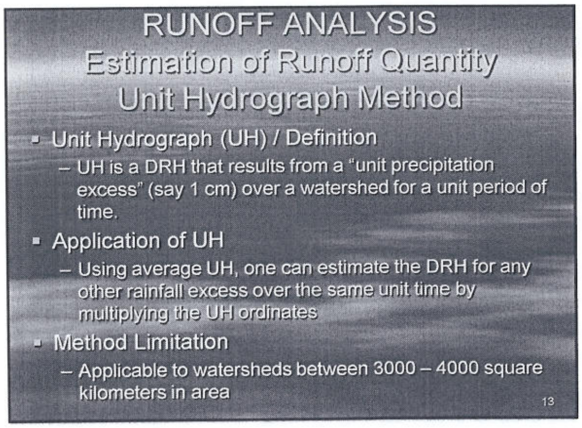
RUNOFF ANALYSIS
Estimation of Runoff Quantity
Hydrographs

- Time lag (time from the midpoint of rainfall excess to the peak discharge of DRH) and the shape of DRH depends on:
  - Precipitation pattern
  - Characteristics of the basin/watershed (size, slope, shape, and channel storage capacity)
- Time to Peak: Time between the beginning of the storm to the peak on a hydrograph



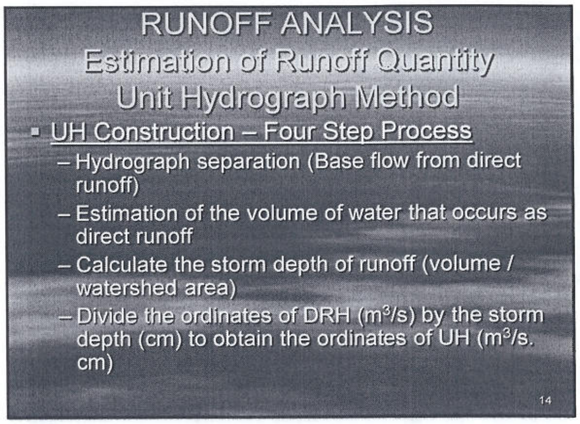
RUNOFF ANALYSIS
Estimation of Runoff Quantity
Hydrographs

- Time of Concentration: Time required for a hydrologically farthest point in the drainage area to reach the gauge or observation station
- Inflection Point: Point on hydrograph at which the farthest point ceased to contribute flow



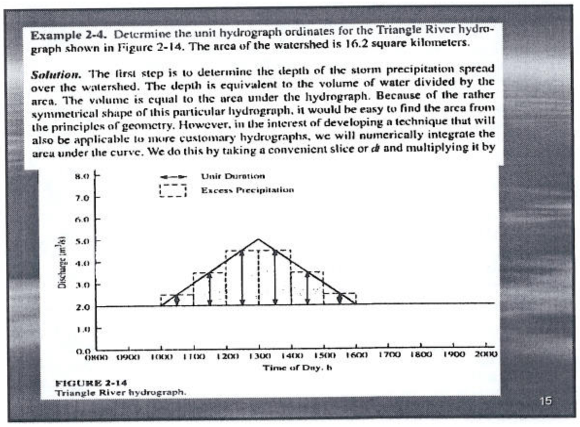
RUNOFF ANALYSIS
Estimation of Runoff Quantity
Unit Hydrograph Method

- Unit Hydrograph (UH) / Definition
  - UH is a DRH that results from a "unit precipitation excess" (say 1 cm) over a watershed for a unit period of time.
- Application of UH
  - Using average UH, one can estimate the DRH for any other rainfall excess over the same unit time by multiplying the UH ordinates
- Method Limitation
  - Applicable to watersheds between 3000 – 4000 square kilometers in area



RUNOFF ANALYSIS
Estimation of Runoff Quantity
Unit Hydrograph Method

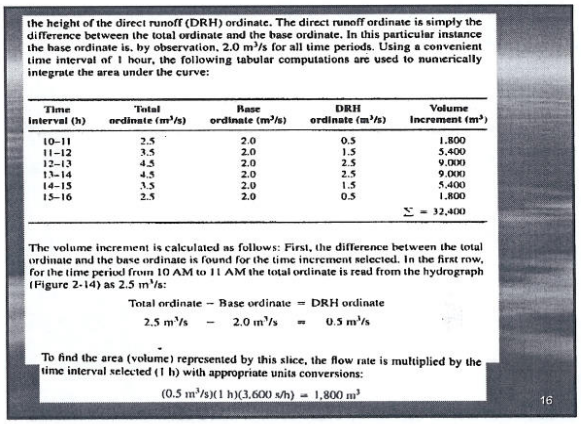
- UH Construction – Four Step Process
  - Hydrograph separation (Base flow from direct runoff)
  - Estimation of the volume of water that occurs as direct runoff
  - Calculate the storm depth of runoff (volume / watershed area)
  - Divide the ordinates of DRH (m^3/s) by the storm depth (cm) to obtain the ordinates of UH ($m^3/s.$ cm)



Example 2-4. Determine the unit hydrograph ordinates for the Triangle River hydrograph shown in Figure 2-14. The area of the watershed is 16.2 square kilometers.

Solution. The first step is to determine the depth of the storm precipitation spread over the watershed. The depth is equivalent to the volume of water divided by the area. The volume is equal to the area under the hydrograph. Because of the rather symmetrical shape of this particular hydrograph, it would be easy to find the area from the principles of geometry. However, in the interest of developing a technique that will also be applicable to more customary hydrographs, we will numerically integrate the area under the curve. We do this by taking a convenient slice or *dt* and multiplying it by

FIGURE 2-14
Triangle River hydrograph.



the height of the direct runoff (DRH) ordinate. The direct runoff ordinate is simply the difference between the total ordinate and the base ordinate. In this particular instance the base ordinate is, by observation, 2.0 m^3/s for all time periods. Using a convenient time interval of 1 hour, the following tabular computations are used to numerically integrate the area under the curve:

Time interval (h)	Total ordinate (m^3/s)	Base ordinate (m^3/s)	DRH ordinate (m^3/s)	Volume Increment (m^3)
10–11	2.5	2.0	0.5	1,800
11–12	3.5	2.0	1.5	5,400
12–13	4.5	2.0	2.5	9,000
13–14	4.5	2.0	2.5	9,000
14–15	3.5	2.0	1.5	5,400
15–16	2.5	2.0	0.5	1,800
				Σ = 32,400

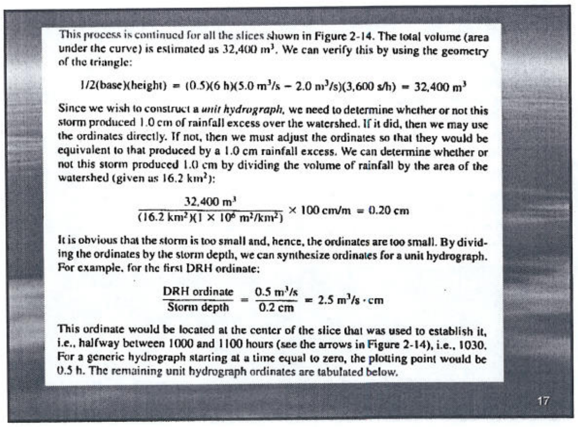
The volume increment is calculated as follows: First, the difference between the total ordinate and the base ordinate is found for the time increment selected. In the first row, for the time period from 10 AM to 11 AM the total ordinate is read from the hydrograph (Figure 2-14) as 2.5 m^3/s:

$$\text{Total ordinate} - \text{Base ordinate} = \text{DRH ordinate}$$

$$2.5\ m^3/s \quad - \quad 2.0\ m^3/s \quad = \quad 0.5\ m^3/s$$

To find the area (volume) represented by this slice, the flow rate is multiplied by the time interval selected (1 h) with appropriate units conversions:

$$(0.5\ m^3/s)(1\ h)(3,600\ s/h) = 1,800\ m^3$$



This process is continued for all the slices shown in Figure 2-14. The total volume (area under the curve) is estimated as 32,400 m^3. We can verify this by using the geometry of the triangle:

$$1/2(\text{base})(\text{height}) = (0.5)(6\ h)(5.0\ m^3/s - 2.0\ m^3/s)(3,600\ s/h) = 32,400\ m^3$$

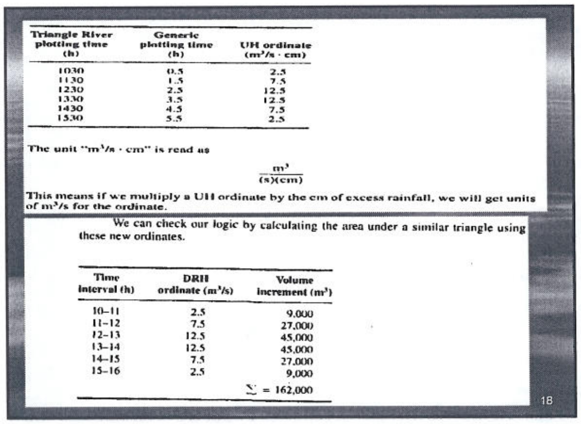
Since we wish to construct a *unit hydrograph*, we need to determine whether or not this storm produced 1.0 cm of rainfall excess over the watershed. If it did, then we may use the ordinates directly. If not, then we must adjust the ordinates so that they would be equivalent to that produced by a 1.0 cm rainfall excess. We can determine whether or not this storm produced 1.0 cm by dividing the volume of rainfall by the area of the watershed (given as 16.2 km^2):

$$\frac{32,400\ m^3}{(16.2\ km^2)(1 \times 10^6\ m^2/km^2)} \times 100\ cm/m = 0.20\ cm$$

It is obvious that the storm is too small and, hence, the ordinates are too small. By dividing the ordinates by the storm depth, we can synthesize ordinates for a unit hydrograph. For example, for the first DRH ordinate:

$$\frac{\text{DRH ordinate}}{\text{Storm depth}} = \frac{0.5\ m^3/s}{0.2\ cm} = 2.5\ m^3/s \cdot cm$$

This ordinate would be located at the center of the slice that was used to establish it, i.e., halfway between 1000 and 1100 hours (see the arrows in Figure 2-14), i.e., 1030. For a generic hydrograph starting at a time equal to zero, the plotting point would be 0.5 h. The remaining unit hydrograph ordinates are tabulated below.



Triangle River plotting time (h)	Generic plotting time (h)	UH ordinate ($m^3/s \cdot cm$)
1030	0.5	2.5
1130	1.5	7.5
1230	2.5	12.5
1330	3.5	12.5
1430	4.5	7.5
1530	5.5	2.5

The unit "$m^3/s \cdot cm$" is read as

$$\frac{m^3}{(s)(cm)}$$

This means if we multiply a UH ordinate by the cm of excess rainfall, we will get units of m^3/s for the ordinate.

We can check our logic by calculating the area under a similar triangle using these new ordinates.

Time interval (h)	DRH ordinate (m^3/s)	Volume increment (m^3)
10–11	2.5	9,000
11–12	7.5	27,000
12–13	12.5	45,000
13–14	12.5	45,000
14–15	7.5	27,000
15–16	2.5	9,000
		Σ = 162,000

Recalculating our storm depth:

$$\frac{162{,}000\ \text{m}^3}{(16.2\ \text{km}^2)(1 \times 10^6\ \text{m}^2/\text{km}^2)} \times 100\ \text{cm/m} = 1.00\ \text{cm}$$

The unit hydrograph may be applied to a sequence of storms that have the same unit duration. There are two fundamental assumptions in the technique. The first is that storms of the same unit duration have ordinates that are in proportion to the unit hydrograph ordinates. Thus, simple ratios can account for differences in runoff excess. The second assumption is that a sequence of storms may be approximated by superimposing one hydrograph over another (with appropriate time lag) and adding the ordinates together. This is illustrated in the next example.

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Unit Hydrograph Method

- Hyetograph / Definition
  - A plot between rainfall excess (cm) vs. time (h)
- Figure 2.15 shows three sequential storms that have the same durations of 1 hour

Example 2-5. Using the hyetograph in Figure 2-15, and the unit hydrograph ordinates from Example 2-4, determine the DRH ordinates and compound runoff.

Solution. The tabular computations are shown below. The explanation follows the table.

Time interval	Time (h)	Rainfall excess (cm)	DRH ordinates			Compound runoff (m^3/s)
			1	2	3	
1	0–1	0.5	1.25	N/A	N/A	1.25
2	1–2	2.0	3.75	5.0	N/A	8.75
3	2–3	1.0	6.25	15.0	2.5	23.75
4	3–4	0.0	6.25	25.0	7.5	38.75
5	4–5	0.0	3.75	25.0	12.5	41.25
6	5–6	0.0	1.25	15.0	12.5	28.75
7	6–7	0.0	0.0	5.0	7.5	12.5
8	7–8	0.0	0.0	0.0	2.5	2.5

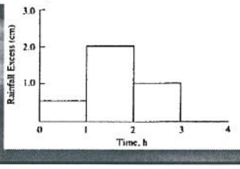


FIGURE 2-15
Hyetograph for Triangle River basin.

The time interval is simply an enumeration of the segments. For the first hour, from the hyetograph in Figure 2-15, the rainfall excess is 0.5 cm. For the second and third hours, the rainfall excesses are 2.0 and 1.0 cm, respectively. No rain falls after the end of the third hour. The column labeled DRH 1 refers to the ordinates that are generated from the rainfall excess (0.5 cm) occurring in the first hour. Likewise, the DRH 2 refers to the ordinates resulting from the 2.0-cm rainfall excess in the second hour.

The first set of ordinates is obtained by multiplying the rainfall excess by each of the UH ordinates, that is:

(Rainfall excess)(UH Ordinate) = DRH ordinate

Using the UH ordinates from Example 2-4:

$$(0.5\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 1.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 3.75\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 6.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 6.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 3.75\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 1.25\ \text{m}^3/\text{s}$$

The values for the second DRH start an hour later. Thus, under the column DRH 2, the first row is not applicable (N/A) since the rain that falls in the second hour (time interval 2) cannot reach the stream in the first hour. Likewise, under the column DRH 3, the first and second rows are N/A because rain that falls in the third hour cannot reach the stream in the first or second hour.

The DRH ordinates for the second hour of rainfall excess are obtained in the same fashion as those for the first, that is by multiplying the rainfall excess by each of the UH ordinates:

$$(2.0\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 5.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 15.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 25.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 25.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 15.0\ \text{m}^3/\text{s}$$

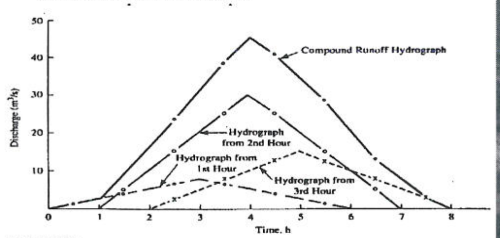


FIGURE 2-16
Compound runoff hydrograph for Triangle River. *Note:* Base flow is not shown.

You should note that the table is carried beyond the last rainfall period in the hyetograph until all of the ordinates are used since it takes some finite length of time for the last drop of rainfall excess to reach the stream.

The compound runoff is the sum of the DRH ordinates for each of the time intervals. For example:

1.25 + N/A + N/A = 1.25
3.75 + 5.0 + N/A = 8.75
6.25 + 15.0 + 2.5 = 23.75

To plot the compound runoff hydrograph, the compound runoff ordinates are plotted at 1.0-h intervals, starting 0.5 h from time zero in accordance with the plotting position of the UH ordinates specified earlier. A plot of the individual hydrographs for each of the storms, their superposition, and the resulting compound hydrograph are shown in Figure 2-16.

ENCE 3323: Introduction to Environmental Engineering

Chapter 3: Hydrology (Part: 3)

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

$$\frac{Storage}{UnitofTime} = \frac{Volumeof\Pr ecipitation}{UnitofTime} - \frac{VolumeofRunoff}{UnitofTime}$$

$$\frac{dS}{dt} = \frac{\forall_P}{dt} - \frac{\forall_R}{dt} \qquad (2\text{-}9)$$

$$\frac{\forall_P}{dt} = \frac{\forall_R}{dt} \qquad (2\text{-}10)$$

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

$$\frac{\forall_P}{dt} = iA \qquad (2\text{-}11)$$

$$Q = 0.0028 \quad CiA \qquad (2\text{-}12)$$

Q = peak runoff rate, m^3/s
C = runoff coefficient
i = average rainfall intensity, mm/h
A = area of watershed, ha
0.0028 = conversion factor, $m^3.h/mm.ha.s$

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

- Why is it called Rational Method?
- In "English Units" system, the relationship does not require any conversion factor

$$Q = CiA$$

Q = peak runoff rate, ft^3/s
C = runoff coefficient
i = average rainfall intensity, in/h
A = area of watershed, acres

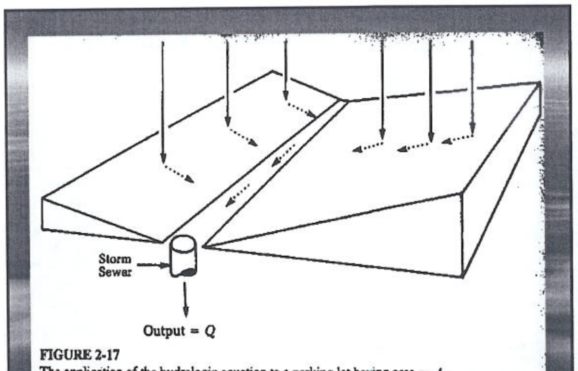
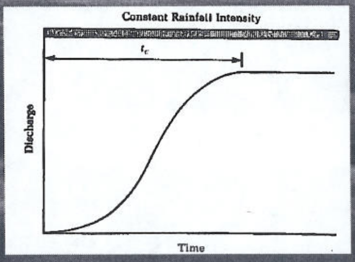
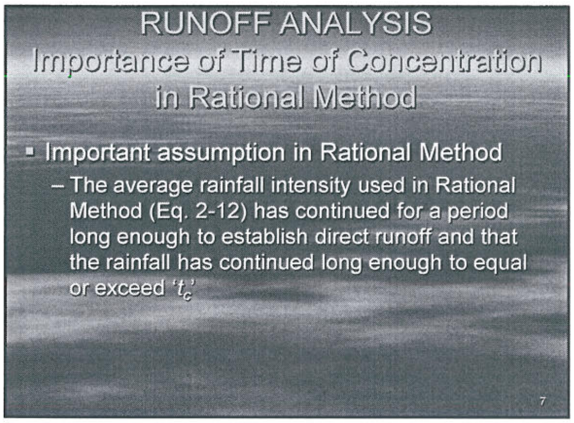


FIGURE 2-17
The application of the hydrologic equation to a parking lot having area = A.

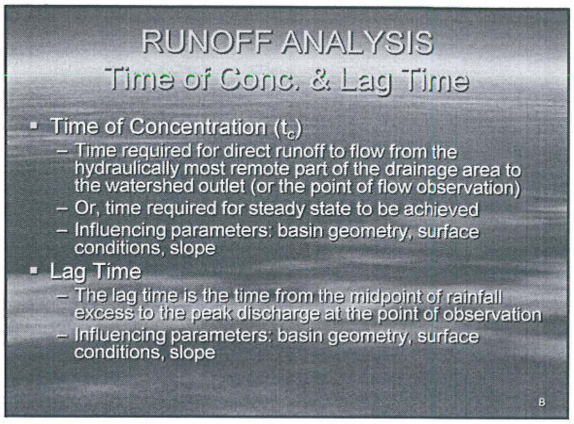
Figure 2-18 Hyetograph and hydrograph for a parking lot





RUNOFF ANALYSIS
Importance of Time of Concentration in Rational Method

- Important assumption in Rational Method
  - The average rainfall intensity used in Rational Method (Eq. 2-12) has continued for a period long enough to establish direct runoff and that the rainfall has continued long enough to equal or exceed 't_c'



RUNOFF ANALYSIS
Time of Conc. & Lag Time

- Time of Concentration (t_c)
  - Time required for direct runoff to flow from the hydraulically most remote part of the drainage area to the watershed outlet (or the point of flow observation)
  - Or, time required for steady state to be achieved
  - Influencing parameters: basin geometry, surface conditions, slope
- Lag Time
  - The lag time is the time from the midpoint of rainfall excess to the peak discharge at the point of observation
  - Influencing parameters: basin geometry, surface conditions, slope

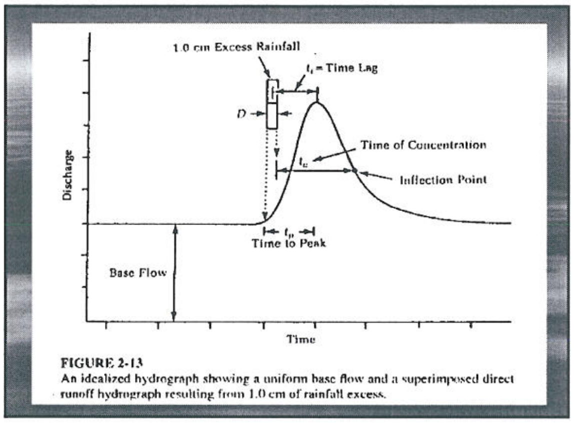
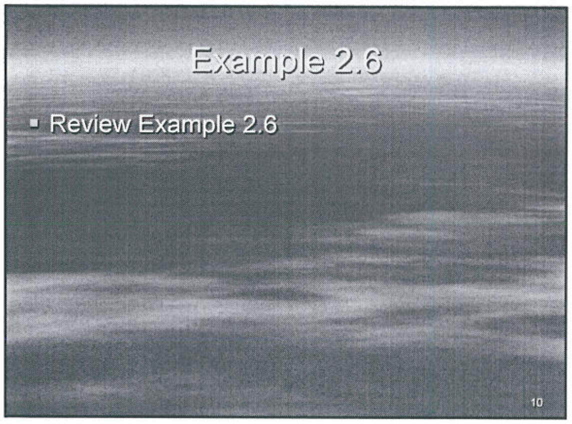
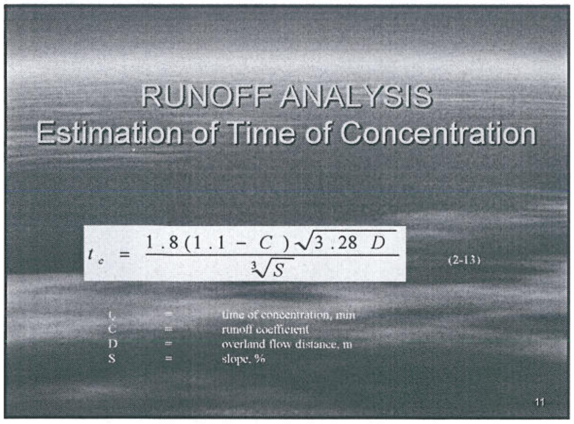


FIGURE 2-13
An idealized hydrograph showing a uniform base flow and a superimposed direct runoff hydrograph resulting from 1.0 cm of rainfall excess.



Example 2.6

- Review Example 2.6



RUNOFF ANALYSIS
Estimation of Time of Concentration

$$t_c = \frac{1.8(1.1 - C)\sqrt{3.28\,D}}{\sqrt[3]{S}} \qquad (2\text{-}13)$$

t_c = time of concentration, min
C = runoff coefficient
D = overland flow distance, m
S = slope, %

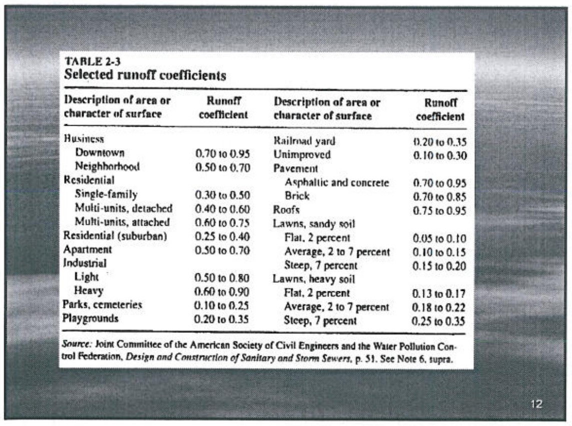
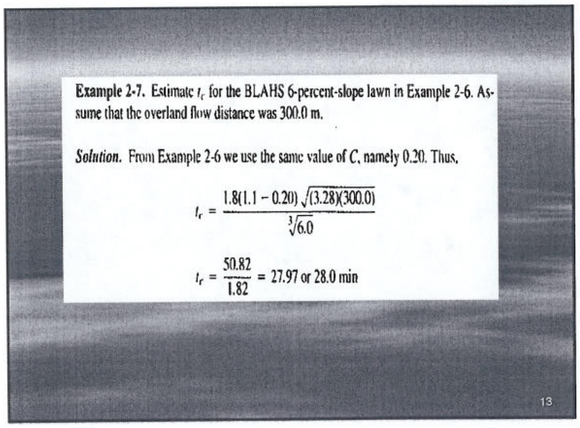


TABLE 2-3
Selected runoff coefficients

Description of area or character of surface	Runoff coefficient	Description of area or character of surface	Runoff coefficient
Business		Railroad yard	0.20 to 0.35
Downtown	0.70 to 0.95	Unimproved	0.10 to 0.30
Neighborhood	0.50 to 0.70	Pavement	
Residential		Asphaltic and concrete	0.70 to 0.95
Single-family	0.30 to 0.50	Brick	0.70 to 0.85
Multi-units, detached	0.40 to 0.60	Roofs	0.75 to 0.95
Multi-units, attached	0.60 to 0.75	Lawns, sandy soil	
Residential (suburban)	0.25 to 0.40	Flat, 2 percent	0.05 to 0.10
Apartment	0.50 to 0.70	Average, 2 to 7 percent	0.10 to 0.15
Industrial		Steep, 7 percent	0.15 to 0.20
Light	0.50 to 0.80	Lawns, heavy soil	
Heavy	0.60 to 0.90	Flat, 2 percent	0.13 to 0.17
Parks, cemeteries	0.10 to 0.25	Average, 2 to 7 percent	0.18 to 0.22
Playgrounds	0.20 to 0.35	Steep, 7 percent	0.25 to 0.35

Source: Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation, *Design and Construction of Sanitary and Storm Sewers*, p. 51. See Note 6, supra.

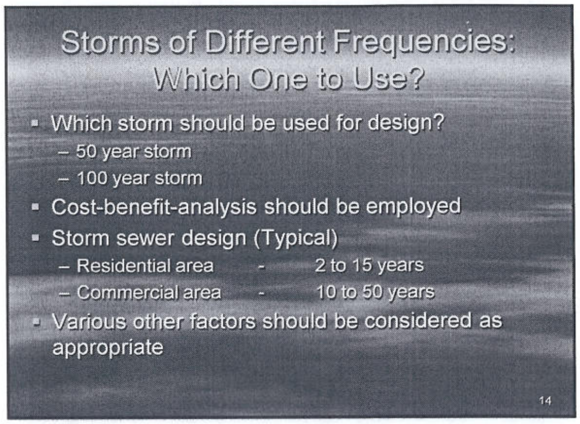


Example 2-7. Estimate t_c for the BLAHS 6-percent-slope lawn in Example 2-6. Assume that the overland flow distance was 300.0 m.

Solution. From Example 2-6 we use the same value of C, namely 0.20. Thus,

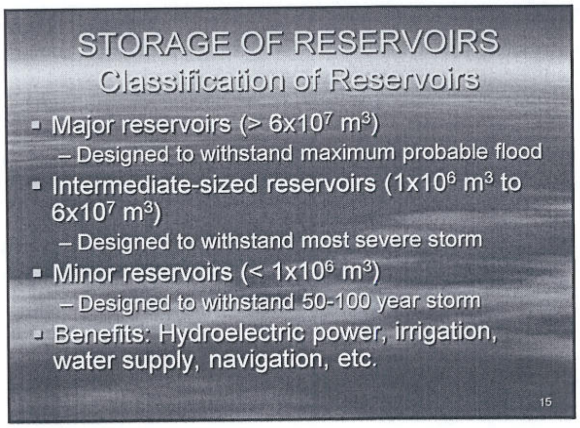
$$t_c = \frac{1.8(1.1 - 0.20)\sqrt{(3.28)(300.0)}}{\sqrt[3]{6.0}}$$

$$t_c = \frac{50.82}{1.82} = 27.97 \text{ or } 28.0 \text{ min}$$



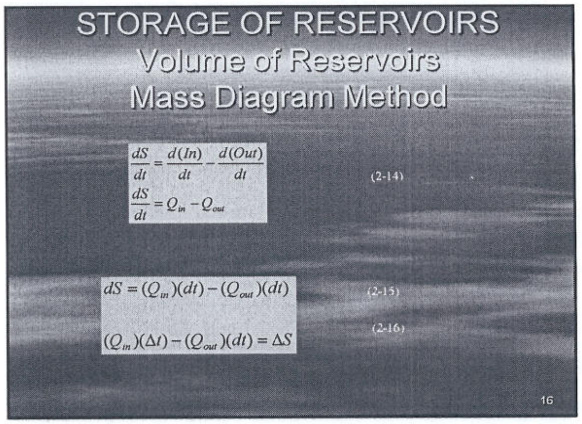
Storms of Different Frequencies: Which One to Use?

- Which storm should be used for design?
  - 50 year storm
  - 100 year storm
- Cost-benefit-analysis should be employed
- Storm sewer design (Typical)
  - Residential area - 2 to 15 years
  - Commercial area - 10 to 50 years
- Various other factors should be considered as appropriate



STORAGE OF RESERVOIRS
Classification of Reservoirs

- Major reservoirs (> $6x10^7$ m^3)
  - Designed to withstand maximum probable flood
- Intermediate-sized reservoirs ($1x10^6$ m^3 to $6x10^7$ m^3)
  - Designed to withstand most severe storm
- Minor reservoirs (< $1x10^6$ m^3)
  - Designed to withstand 50-100 year storm
- Benefits: Hydroelectric power, irrigation, water supply, navigation, etc.



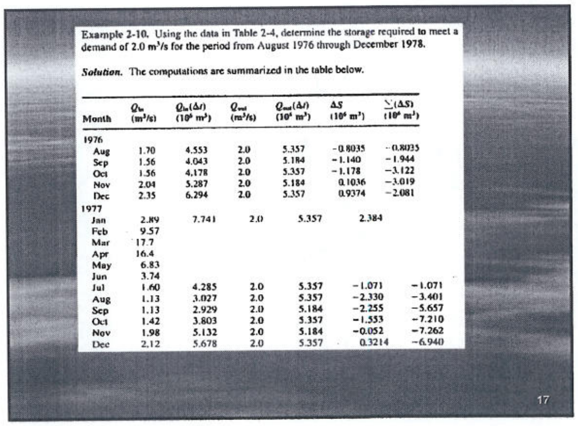
STORAGE OF RESERVOIRS
Volume of Reservoirs
Mass Diagram Method

$$\frac{dS}{dt} = \frac{d(In)}{dt} - \frac{d(Out)}{dt} \qquad (2\text{-}14)$$

$$\frac{dS}{dt} = Q_{in} - Q_{out}$$

$$dS = (Q_{in})(dt) - (Q_{out})(dt) \qquad (2\text{-}15)$$

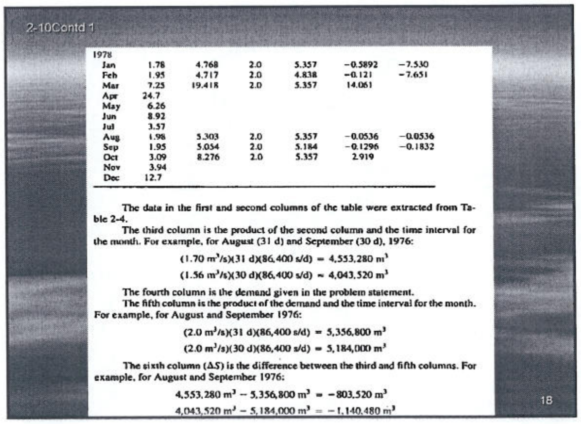
$$(Q_{in})(\Delta t) - (Q_{out})(dt) = \Delta S \qquad (2\text{-}16)$$



Example 2-10. Using the data in Table 2-4, determine the storage required to meet a demand of 2.0 m³/s for the period from August 1976 through December 1978.

Solution. The computations are summarized in the table below.

Month	Q_{in} (m^3/s)	$Q_{in}(\Delta t)$ (10^6 m^3)	Q_{out} (m^3/s)	$Q_{out}(\Delta t)$ (10^6 m^3)	ΔS (10^6 m^3)	$\sum(\Delta S)$ (10^6 m^3)
1976						
Aug	1.70	4.553	2.0	5.357	−0.8035	−0.8035
Sep	1.56	4.043	2.0	5.184	−1.140	−1.944
Oct	1.56	4.178	2.0	5.357	−1.178	−3.122
Nov	2.04	5.287	2.0	5.184	0.1036	−3.019
Dec	2.35	6.294	2.0	5.357	0.9374	−2.081
1977						
Jan	2.89	7.741	2.0	5.357	2.384	
Feb	9.57					
Mar	17.7					
Apr	16.4					
May	6.83					
Jun	3.74					
Jul	1.60	4.285	2.0	5.357	−1.071	−1.071
Aug	1.13	3.027	2.0	5.357	−2.330	−3.401
Sep	1.13	2.929	2.0	5.184	−2.255	−5.657
Oct	1.42	3.803	2.0	5.357	−1.553	−7.210
Nov	1.98	5.132	2.0	5.184	−0.052	−7.262
Dec	2.12	5.678	2.0	5.357	0.3214	−6.940



2-10Contd 1

1978						
Jan	1.78	4.768	2.0	5.357	−0.5892	−7.530
Feb	1.95	4.717	2.0	4.838	−0.121	−7.651
Mar	7.25	19.418	2.0	5.357	14.061	
Apr	24.7					
May	6.26					
Jun	8.92					
Jul	3.57					
Aug	1.98	5.303	2.0	5.357	−0.0536	−0.0536
Sep	1.95	5.054	2.0	5.184	−0.1296	−0.1832
Oct	3.09	8.276	2.0	5.357	2.919	
Nov	3.94					
Dec	12.7					

The data in the first and second columns of the table were extracted from Table 2-4.

The third column is the product of the second column and the time interval for the month. For example, for August (31 d) and September (30 d), 1976:

$$(1.70 \text{ m}^3/\text{s})(31 \text{ d})(86{,}400 \text{ s/d}) = 4{,}553{,}280 \text{ m}^3$$

$$(1.56 \text{ m}^3/\text{s})(30 \text{ d})(86{,}400 \text{ s/d}) \approx 4{,}043{,}520 \text{ m}^3$$

The fourth column is the demand given in the problem statement.

The fifth column is the product of the demand and the time interval for the month. For example, for August and September 1976:

$$(2.0 \text{ m}^3/\text{s})(31 \text{ d})(86{,}400 \text{ s/d}) = 5{,}356{,}800 \text{ m}^3$$

$$(2.0 \text{ m}^3/\text{s})(30 \text{ d})(86{,}400 \text{ s/d}) = 5{,}184{,}000 \text{ m}^3$$

The sixth column (ΔS) is the difference between the third and fifth columns. For example, for August and September 1976:

$$4{,}553{,}280 \text{ m}^3 - 5{,}356{,}800 \text{ m}^3 = -803{,}520 \text{ m}^3$$

$$4{,}043{,}520 \text{ m}^3 - 5{,}184{,}000 \text{ m}^3 = -1{,}140{,}480 \text{ m}^3$$

2-10Contd 2

The last column ($\sum(\Delta S)$) is the sum of the last value in that column and the value in the sixth column. For August 1976, it is $-803{,}520\ \mathrm{m}^3$ since this is the first value.

For September 1976, it is

$$(-803{,}520\ \mathrm{m}^3) + (-1{,}140{,}480\ \mathrm{m}^3) = -1{,}944{,}000\ \mathrm{m}^3$$

The following logic is used in interpreting the table. From August through December 1976, the demand exceeds the flow, and storage must be provided. The maximum storage required for this interval is $3.122 \times 10^6\ \mathrm{m}^3$. In January 1977, the storage (ΔS) exceeds the deficit ($\sum(\Delta S)$) from December 1976. If we view the deficit as the volume of water in a virtual reservoir with a total capacity of $3.122 \times 10^6\ \mathrm{m}^3$, then in December 1976, the volume of water in the reservoir is $1.041 \times 10^6\ \mathrm{m}^3$ ($3.122 \times 10^6 - 2.081 \times 10^6$). The January 1977 inflow exceeds the demand and fills the reservoir deficit of $2.081 \times 10^6\ \mathrm{m}^3$.

Since the inflow (Q_{in}) exceeds the demand ($2.0\ \mathrm{m}^3/\mathrm{s}$) for the months of February through June 1977, no storage is required during this period. Hence, no computations were performed.

From July 1977 through February 1978, the demand exceeds the inflow, and storage is required. The maximum storage required is $7.651 \times 10^6\ \mathrm{m}^3$. Note that the computations for storage did not stop in December 1977, even though the inflow exceeded the demand. This is because the storage was not sufficient to fill the reservoir deficit. The storage was sufficient to fill the reservoir deficit in March 1978.

You should note that these tabulations are particularly well suited to spreadsheet-type programs.

GROUNDEWATER AND WELLS

- # people served by surface water = 2 x # people served by groundwater
- # communities served by groundwater = 12 x # communities served by surface water

TABLE 2-8
People served by groundwater and surface-water systems

Size (number of people served)	Groundwater systems		Surface-water systems	
	Number of systems	Number of people	Number of systems	Number of people
25–100	16,140	934,000	1,160	69,000
101–500	15,950	3,906,000	2,261	657,000
501–1,000	4,980	3,651,000	1,227	925,000
1,001–3,300	5,814	10,774,000	2,504	4,924,000
3,301–10,000	2,374	13,769,000	1,711	10,262,000
10,001–25,000	914	14,482,000	939	15,117,000
25,001–50,000	361	12,882,000	446	15,945,000
50,001–75,000	99	5,954,000	161	9,900,000
75,001–100,000	45	3,871,000	76	6,552,000
100,001–500,000	81	15,382,000	186	38,437,000
500,001–1,000,000	7	5,079,000	27	18,395,000
More than 1,000,000	1	1,705,000	13	27,344,000

Active community water systems as of August 31 1993 (*Source:* Federal Data Reporting System)

Construction of Wells

- Sanitary Considerations
- Well Covers and Seals
- Disinfection of Wells
- Pump Housing

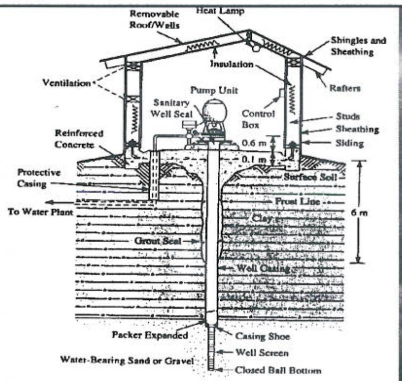


FIGURE 2-22
Pumphouse. [*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems*, (Publication No. EPA-430-9-73-003), Washington, DC: U.S.

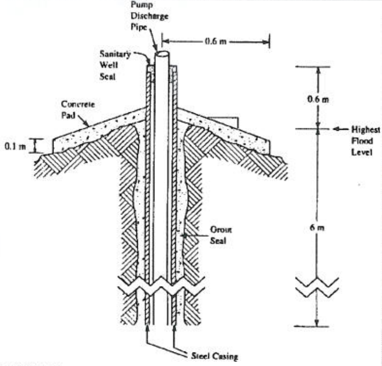


FIGURE 2-23
Sanitary considerations in well construction.

Cone of Depression

- Drawdown
- Radius of influence
- Pumping costs
  - Aquifer composition (clay, coarse sand, gravel)
  - Water table (deep and shallow)
  - Spacing of wells (closer and farther)

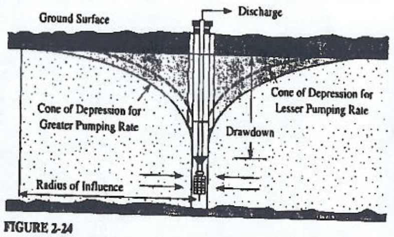


FIGURE 2-24
Effect of pumping rate on cone of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

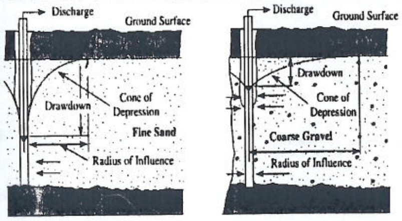


FIGURE 2-25
Effect of aquifer material on cone of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

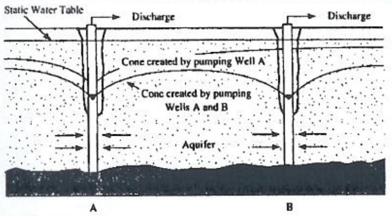
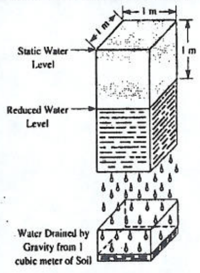


FIGURE 2-26
Effect of overlapping cones of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

Groundwater and Wells
Definition of Terms

- Porosity: Volume of voids to total volume. Units – No units
- Specific Yield: % water that is free to drain under the influence of gravity. Units – No units
  - What holds water inside aquifer? (surface tension, molecular attraction)
- Storage Coefficient: Volume of available water resulting from a unit decline in the piezometric surface over a unit horizontal cross-sectional area. Units – No units; m^3 of water / m^3 of aquifer



$$\text{Specific Yield} = \frac{\text{Volume Water}}{\text{Volume Soil}}\ (100\%)$$

FIGURE 2-27
Specific yield. (*Source:* Johnson Division, UOP, *Ground Water and Wells,* St. Paul, MN: Johnson Division, UOP, 1975. Reprinted by permission.)

Groundwater and Wells
Definition of Terms

- Hydraulic Gradient: The slope of the piezometric surface
- Change in head / horizontal distance
- dh/dr

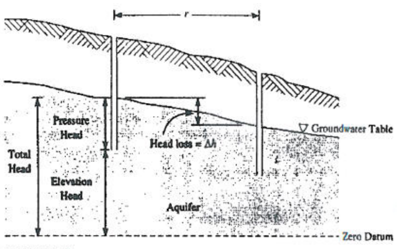
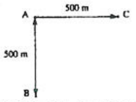


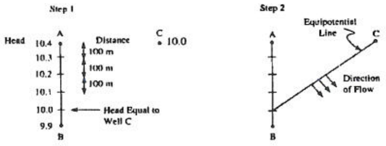
FIGURE 2-28
Geometry for definition of head and hydraulic gradient.

Example 2-11. For the wells shown in plan view below, determine the direction of flow and the hydraulic gradient. The total head is given for each well as follows:

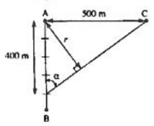
Well A = 10.4 m
Well B = 10.0 m
Well C = 9.9 m



Solution. The stepwise graphical solution procedure is shown below.



2-11Contd
1



The distance r must be determined in order to calculate the hydraulic gradient. From the plan view, we may note that the wells form a right triangle with legs of 400 m and 500 m. The angle α may be computed as:

$$\tan^{-1}(\alpha) = \frac{500}{400}$$

and $\alpha = 51.34°$
The distance r is

$$r = (400)\sin\alpha = 400\sin 51.34 = 312.35\text{ m}$$

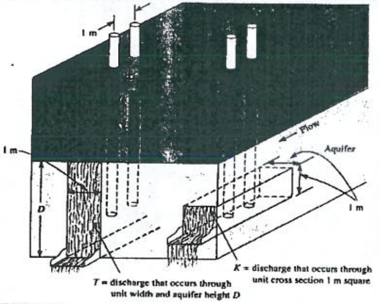
The hydraulic gradient is then:

$$\text{Hydraulic gradient} = \frac{10.4\text{ m} - 10.0\text{ m}}{312.35\text{ m}} = 0.00128$$

Note that the hydraulic gradient has no units.

Groundwater and Wells
Definition of Terms

- Hydraulic Conductivity: Property of an aquifer that is a measure of its ability to transmit water under a sloping piezometric surface
- Also, the discharge that occurs through a unit cross section of aquifer under a hydraulic gradient of '1'
- Units – m/sec



K = discharge that occurs through unit cross section 1 m square

T = discharge that occurs through unit width and aquifer height D

FIGURE 2-29
Illustration of definition of hydraulic conductivity (K) and transmissibility (T). (*Source:* Johnson Division, UOP, *Ground Water and Wells.* Reprinted by permission. See source note for Figure 2-26, supra.)

Groundwater and Wells
Definition of Terms

- Transmissibility (T): A measure of the rate at which water will flow through a unit width of aquifer extending through its full saturated thickness under a unit hydraulic gradient
- Units – m²/s

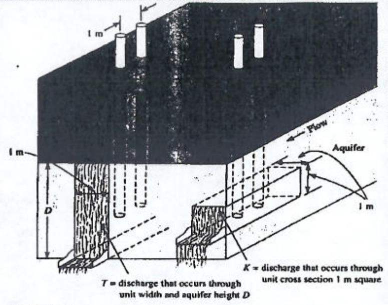


FIGURE 2-29
Illustration of definition of hydraulic conductivity (*K*) and transmissibility (*T*). (*Source:* Johnson Division, UOP, *Ground Water and Wells.* Reprinted by permission. See source note for Figure 2-26, supra.)

Well Hydraulics

- Darcy's Equation

$$v = K\frac{dh}{dr} \tag{2-19}$$

$$A'v' = Av = Q \tag{2-20}$$

$$v' = \frac{Av}{A'} \tag{2-21}$$

- Darcy's Equation

$$v' = \frac{ALv}{A'L} \tag{2-23}$$

$$v' = \frac{DarcyVelocity}{Porosity} = \frac{v}{\eta} \tag{2-24}$$

$$Q = vA = KA\frac{dh}{dr} \tag{2-25}$$

Well Hydraulics

- Darcy's Equation (2-25) has been solved for steady and non-steady (transient) flows.
- Assumptions:
  - Pumping at constant rate
  - Flow towards the well is radial and uniform
  - Initially piezometric surface is horizontal
  - Well penetrates the entire depth of aquifer
  - Aquifer is homogeneous and is of infinite length
  - Water is released from aquifer in immediate response to a drop in the piezometric surface

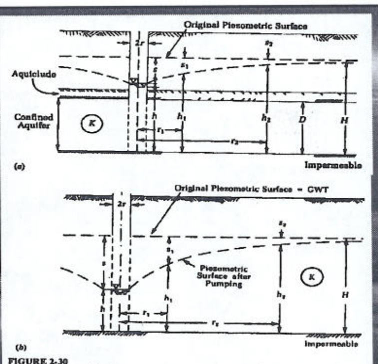
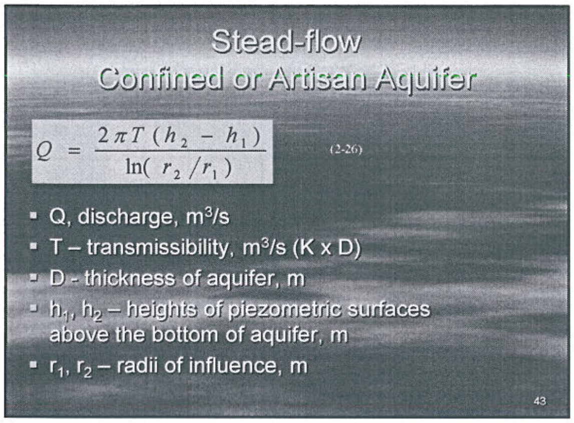


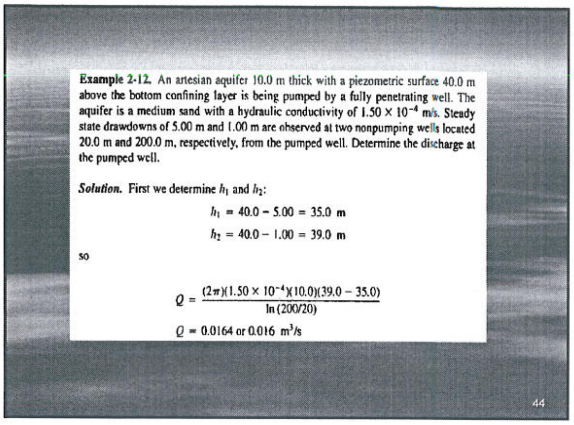
FIGURE 2-30
Geometry and symbols for a pumped well in (*a*) confined aquifer and (*b*) unconfined aquifer. (*Source:* H. Bouwer, *Groundwater Hydrology.* New York: McGraw-Hill, 1978. Reprinted by permission.)



Stead-flow
Confined or Artisan Aquifer

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2/r_1)} \quad (2\text{-}26)$$

- Q, discharge, m^3/s
- T – transmissibility, m^3/s (K x D)
- D - thickness of aquifer, m
- h_1, h_2 – heights of piezometric surfaces above the bottom of aquifer, m
- r_1, r_2 – radii of influence, m



Example 2-12. An artesian aquifer 10.0 m thick with a piezometric surface 40.0 m above the bottom confining layer is being pumped by a fully penetrating well. The aquifer is a medium sand with a hydraulic conductivity of 1.50×10^{-4} m/s. Steady state drawdowns of 5.00 m and 1.00 m are observed at two nonpumping wells located 20.0 m and 200.0 m, respectively, from the pumped well. Determine the discharge at the pumped well.

Solution. First we determine h_1 and h_2:

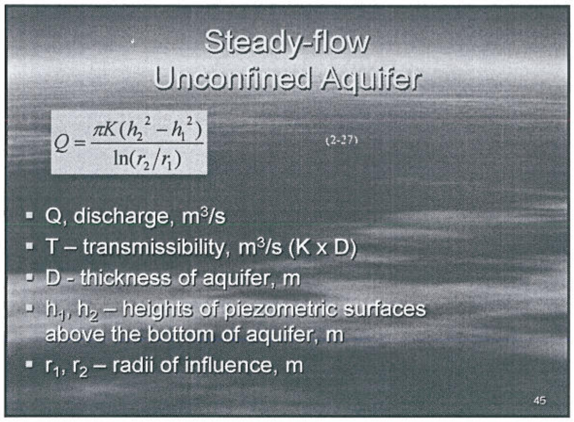
$$h_1 = 40.0 - 5.00 = 35.0 \text{ m}$$

$$h_2 = 40.0 - 1.00 = 39.0 \text{ m}$$

so

$$Q = \frac{(2\pi)(1.50 \times 10^{-4})(10.0)(39.0 - 35.0)}{\ln(200/20)}$$

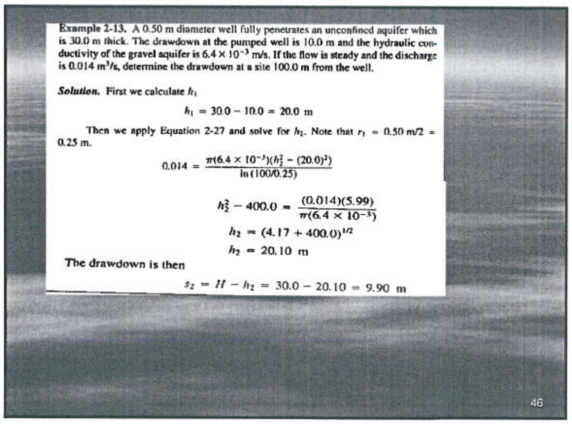
$$Q = 0.0164 \text{ or } 0.016 \text{ m}^3/\text{s}$$



Steady-flow
Unconfined Aquifer

$$Q = \frac{\pi K(h_2^2 - h_1^2)}{\ln(r_2/r_1)} \quad (2\text{-}27)$$

- Q, discharge, m^3/s
- T – transmissibility, m^3/s (K x D)
- D - thickness of aquifer, m
- h_1, h_2 – heights of piezometric surfaces above the bottom of aquifer, m
- r_1, r_2 – radii of influence, m



Example 2-13. A 0.50 m diameter well fully penetrates an unconfined aquifer which is 30.0 m thick. The drawdown at the pumped well is 10.0 m and the hydraulic conductivity of the gravel aquifer is 6.4×10^{-3} m/s. If the flow is steady and the discharge is 0.014 m^3/s, determine the drawdown at a site 100.0 m from the well.

Solution. First we calculate h_1

$$h_1 = 30.0 - 10.0 = 20.0 \text{ m}$$

Then we apply Equation 2-27 and solve for h_2. Note that $r_1 = 0.50 \text{ m}/2 = 0.25$ m.

$$0.014 = \frac{\pi(6.4 \times 10^{-3})(h_2^2 - (20.0)^2)}{\ln(100/0.25)}$$

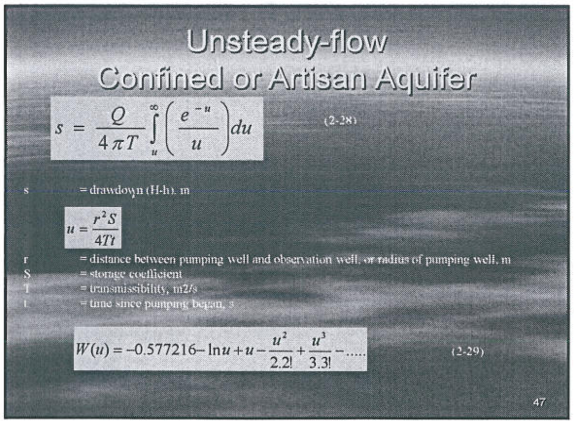
$$h_2^2 - 400.0 = \frac{(0.014)(5.99)}{\pi(6.4 \times 10^{-3})}$$

$$h_2 = (4.17 + 400.0)^{1/2}$$

$$h_2 = 20.10 \text{ m}$$

The drawdown is then

$$s_2 = H - h_2 = 30.0 - 20.10 = 9.90 \text{ m}$$



Unsteady-flow
Confined or Artisan Aquifer

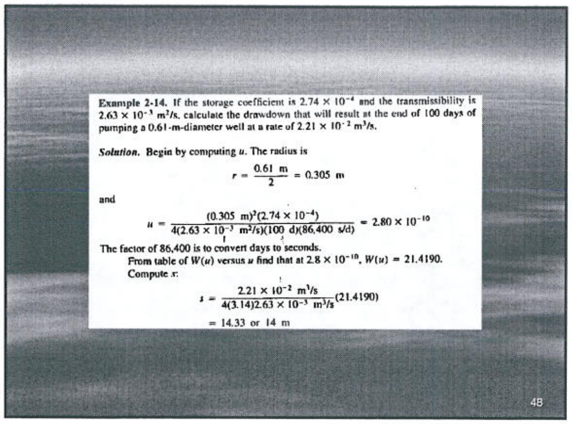
$$s = \frac{Q}{4\pi T}\int_u^\infty \left(\frac{e^{-u}}{u}\right)du \quad (2\text{-}28)$$

s = drawdown (H-h), m

$$u = \frac{r^2 S}{4Tt}$$

r = distance between pumping well and observation well, or radius of pumping well, m
S = storage coefficient
T = transmissibility, m2/s
t = time since pumping began, s

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \ldots.. \quad (2\text{-}29)$$



Example 2-14. If the storage coefficient is 2.74×10^{-4} and the transmissibility is 2.63×10^{-3} m^2/s, calculate the drawdown that will result at the end of 100 days of pumping a 0.61-m-diameter well at a rate of 2.21×10^{-2} m^3/s.

Solution. Begin by computing u. The radius is

$$r = \frac{0.61 \text{ m}}{2} = 0.305 \text{ m}$$

and

$$u = \frac{(0.305 \text{ m})^2(2.74 \times 10^{-4})}{4(2.63 \times 10^{-3} \text{ m}^2/\text{s})(100 \text{ d})(86{,}400 \text{ s/d})} = 2.80 \times 10^{-10}$$

The factor of 86,400 is to convert days to seconds.

From table of $W(u)$ versus u find that at 2.8×10^{-10}, $W(u) = 21.4190$.

Compute s:

$$s = \frac{2.21 \times 10^{-2} \text{ m}^3/\text{s}}{4(3.14)2.63 \times 10^{-3} \text{ m}^3/\text{s}}(21.4190)$$

$$= 14.33 \text{ or } 14 \text{ m}$$

Unsteady flow in Unconfined Aquifer

- No reliable solution has been developed so far

Hydraulic Properties of a Confined Aquifer – Steady State

$$T = \frac{Q \ln(r_2/r_1)}{2\pi(s_1 - s_2)} \qquad (2\text{-}30)$$

where s1=drawdown at radius r1
s2=drawdown at radius r2

Hydraulic Properties of a Confined Aquifer – Transient/Unsteady

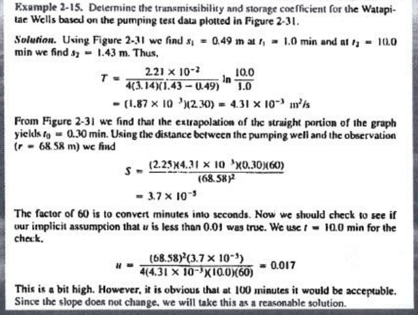
$$s = \frac{Q}{4\pi T}\ln\frac{2.25Tt}{r^2 S} \qquad (2\text{-}31)$$

Solving for T, we find

$$s_2 - s_1 = \frac{Q}{4\pi T}\ln\frac{t_2}{t_1} \qquad (2\text{-}32)$$

$$T = \frac{Q}{4\pi(s_2 - s_1)}\ln\frac{t_2}{t_1} \qquad (2\text{-}33)$$

$$S = \frac{2.25\,Tt_0}{r^2} \qquad (2\text{-}34)$$



Example 2-15. Determine the transmissibility and storage coefficient for the Watapitae Wells based on the pumping test data plotted in Figure 2-31.

Solution. Using Figure 2-31 we find $s_1 = 0.49$ m at $t_1 = 1.0$ min and at $t_2 = 10.0$ min we find $s_2 = 1.43$ m. Thus,

$$T = \frac{2.21 \times 10^{-2}}{4(3.14)(1.43 - 0.49)}\ln\frac{10.0}{1.0}$$
$$= (1.87 \times 10^{-3})(2.30) = 4.31 \times 10^{-3}\ \text{m}^2/\text{s}$$

From Figure 2-31 we find that the extrapolation of the straight portion of the graph yields $t_0 = 0.30$ min. Using the distance between the pumping well and the observation ($r = 68.58$ m) we find

$$S = \frac{(2.25)(4.31 \times 10^{-3})(0.30)(60)}{(68.58)^2}$$
$$= 3.7 \times 10^{-5}$$

The factor of 60 is to convert minutes into seconds. Now we should check to see if our implicit assumption that u is less than 0.01 was true. We use $t = 10.0$ min for the check.

$$u = \frac{(68.58)^2(3.7 \times 10^{-5})}{4(4.31 \times 10^{-3})(10.0)(60)} = 0.017$$

This is a bit high. However, it is obvious that at 100 minutes it would be acceptable. Since the slope does not change, we will take this as a reasonable solution.

10 pollutants → C_1, C_2, C_3... (organic, inorganic, microbiotical, heavy metal, ...)
$Q \times C_1 \rightarrow M_1$ (mass emission rate of that pollutant) (kg/d)

ENCE 3323: Introduction to Environmental Engineering

Class 5: Water Treatment (1/3)

NPDES permit

- type of industry, production process, raw materials, products produced, how water will be handled & quantity, quantity of ww expected (Q), list of pollutents, concentration of pollutents in ww (C)

Water treatment

- October 2002-2003 is the year of clean water
- The Clean Water Act (CWA) is the cornerstone of surface water quality protection in the United States. (The Act does not deal directly with ground water nor with water quantity issues.) The statute employs a variety of regulatory and non-regulatory tools to sharply reduce direct pollutant discharges into waterways, finance municipal wastewater treatment facilities, and manage polluted runoff.
- Water is one of the most important resources we have.
- Millions of liters of water are needed every day worldwide for washing, irrigating crops, and cooling industrial processes, not to mention leisure industries such as swimming pools and water sports centers. Despite our dependence on water, we use it as a dumping ground for all sorts of waste, and do very little to protect the water supplies we have.
- The water which is polluted needs treatment

Potable water : Water that can be consumed in any desired amount without concern for adverse effects is termed as "Potable water". Potable water does not taste good but is safe to drink

Palatable water : Water that is pleasing to drink but not necessarily safe

Water treatment should be done to provide water which is both palatable as well as potable.

Potable Water Treatment

- SDWA (1974) – federal mandate to protect public health
- ~ 40% of the world's population does not have adequate access to safe water

Physical properties of water:

Mass density : Mass density is mass per unit volume and is measured in units of kg/m^3

Specific weight : Specific weight is weight(force) per unit volume, measured in units of KN/m^3

$$\gamma = \rho g \qquad g = 9.81\ m/s^2$$

Specific gravity : Specific gravity is given by $S = \rho/\rho_0$ or γ/γ_0 where the subscript zero represents the density of water at 3.98^0 C, 1000 kg/m^3 and specific weight of water, 9.81 KN/m^3

Viscosity: A measure of friction is called viscosity. It is of two types
Dynamic viscosity or absolute viscosity, μ is mass per unit time
Kinematic viscosity, $\nu = \mu/\rho$

Impurities in water

Impurities can exist in water in one of the three classifications- suspended , colloidal, or dissolved.

Dissolved substances : Substance is homogeneously dispersed in the liquid. They are removed by distillation, adsorption, or extraction.

Suspended solids: Physical methods such as filtration, sedimentation, and centrifugation remove suspended solids.

Colloidal particles : They are in size range between dissolved substances and suspended particles. Very high-force centrifugation or filtration are used to remove colloidal particles.

The degree to which a colloidal suspension reflects light at a 90^0 angle to the entrance beam is measured by turbidity.

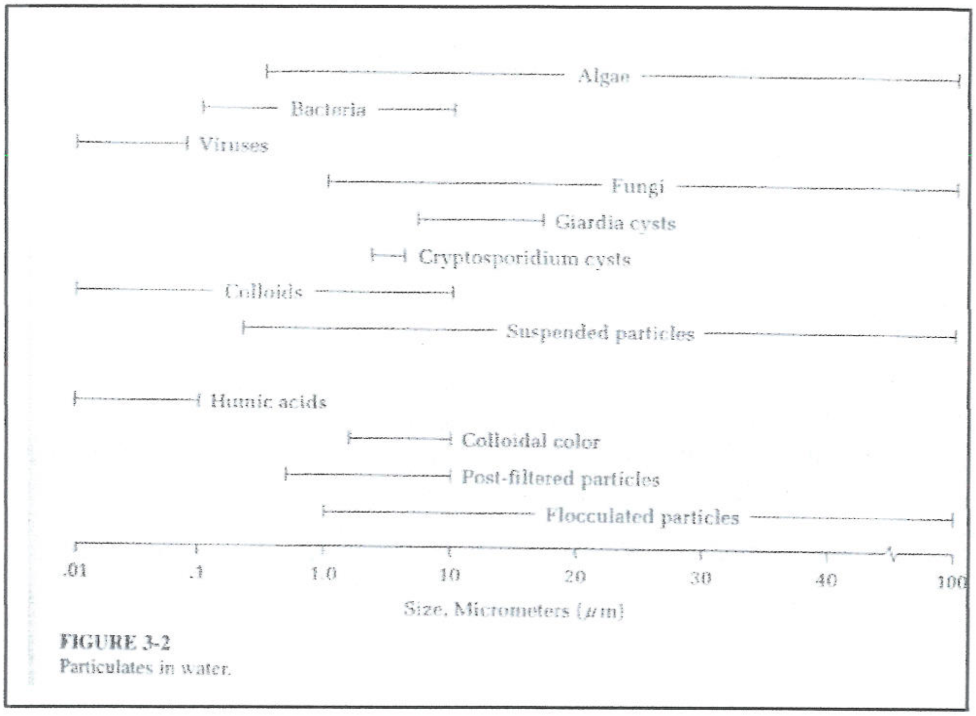
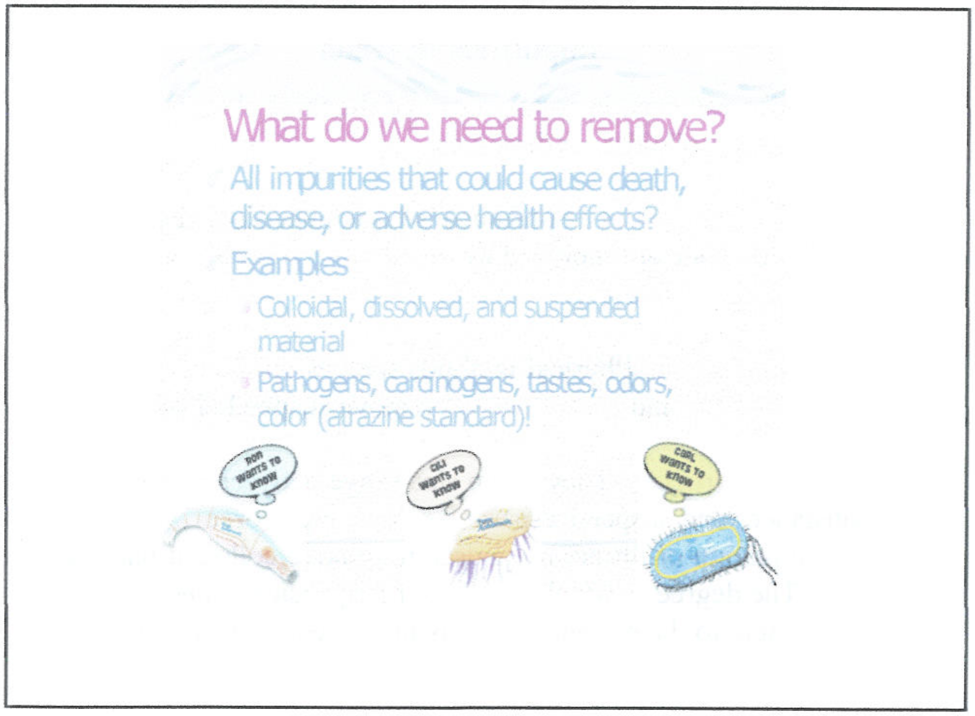


FIGURE 3-2
Particulates in water.



What do we need to remove?

All impurities that could cause death, disease, or adverse health effects?

Examples

- Colloidal, dissolved, and suspended material
- Pathogens, carcinogens, tastes, odors, color (atrazine standard)!

In order to work with chemical reactions it is necessary to convert weight concentrations to molarity or normality. A *mole* is 6.02×10^{23} molecules of a substance. Chemical reactions are expressed in integral numbers of moles. A mole of a substance has a relative weight called its *molecular weight* (MW). Molecular weight is the sum of the atomic weights. A table of atomic weights is given inside the front cover of this book. *Molarity* is the number of moles in a liter of solution. A 1-molar (1 *M*) solution has 1 mole of substance per liter of solution. Molarity is related to mg/L by

$$\begin{aligned}\text{mg/L} &= \text{molarity} \times \text{molecular weight} \times 10^3 \qquad (3\text{-}7)\\ &= (\text{moles/L})\,(\text{g/mole})\,(10^3\ \text{mg/g})\end{aligned}$$

A second unit, *equivalent weight* (EW), is frequently used in softening and redox reactions. The equivalent weight is the molecular weight divided by the number (n) of electrons transferred in redox reactions or the number of protons transferred in acid/base reactions.

The value of n depends on how the molecule reacts. In this text we are concerned with molecules that react in acid/base reactions or precipitation reactions. **In an acid/base reaction, n is the number of hydrogen ions that the molecule transfers. That is, an acid gives up an EW of hydrogen ions, and a base accepts an EW of hydrogen ions. In a precipitation reaction, n is the valence of the element in question. For compounds, n is equal to the number of hydrogen ions that would be required to replace the cation; that is, for $CaCO_3$ it would take two hydrogen ions to replace the calcium, therefore, $n = 2$. In oxidation/reduction reactions, n is equal to the change in oxidation number that the compound undergoes in the reaction.** Obviously, it is difficult to recognize reaction capacity without the context of the reaction. Common valence states of elements found in water are listed in Appendix A.

Normality (N) is the number of equivalent weights per liter of solution and is related to molarity (M) by

$$N = Mn \qquad (3\text{-}8)$$

Example 3-1. Commercial sulfuric acid, H_2SO_4, is often purchased as a 93 weight percent solution. Find the mg/L of H_2SO_4 and the molarity and normality of the solution. Sulfuric acid has a specific gravity of 1.839.

Solution. Since 1 L of water weighs 1,000 g, 1 L of 100% H_2SO_4 weighs

$$1{,}000(1.839) = 1{,}839 \text{ g}$$

93% (1,839) g = 1,710 g of H_2SO_4, or 1.7×10^6 mg/L of H_2SO_4 in a 93% solution. The molecular weight of H_2SO_4 is found by looking up the atomic weights on the inside cover of this book:

$$\begin{aligned} 2\text{H} &= 2(1) &&= 2 \\ \text{S} &= &&\ 32 \\ 4\text{O} &= 4(16) &&= \underline{64} \\ & && \ 98 \text{ g/mole} \end{aligned}$$

The molarity is found by using Equation 3-7:

$$\frac{1{,}710 \text{ g/L}}{98 \text{ g/mole}} = 17.45 \text{ mole/L or } 17.45\ M$$

The normality is found from Equation 3-8, realizing that H_2SO_4 can give up two hydrogen ions and therefore $n = 2$ equivalents/mole:

$$N = 17.45 \text{ mole/L } (2 \text{ equiv/mole}) = 34.9 \text{ equiv/L}$$

Example 3-2. Find the weight of sodium bicarbonate, $NaHCO_3$, necessary to make a 1 *M* solution. Find the normality of the solution.

Solution. The molecular weight of $NaHCO_3$ is 84; therefore by using Equation 3-7:

$$\text{mg/L} = (1 \text{ mole/L})(84 \text{ g/mole})(10^3 \text{ mg/g}) = 84{,}000$$

HCO_3^- is able to give or accept only one proton; therefore $n = 1$, and the normality is the same as the molarity.

Example 3-3. Find the equivalent weight of each of the following: Ca^{2+}, CO_3^{2-}, $CaCO_3$.

Solution. **Equivalent weight was defined as**

$$EW = \frac{\text{Atomic or molecular weight}}{n}$$

The units of EW are grams/equivalent (g/eq) or milligrams/milliequivalent (mg/meq).

For calcium, n is equal to the valence or oxidation state in water, so $n = 2$. From the table on the inside cover of the book, the atomic weight of Ca^{2+} is 40.08. The equivalent weight is then

$$EW = \frac{40.08}{2} = 20.04 \text{ g/eq or } 20.04 \text{ mg/meq}$$

For the carbonate ion (CO_3^{2-}) the oxidation state of 2^- is used for n since the base CO_3^{2-} can potentially accept 2 hydrogen ions (H^+). The molecular weight is

$$\begin{aligned} C &= & 12.01 \\ 3O &= 3(15.9994) = & 48.00 \\ & & 60.01 \end{aligned}$$

and the equivalent weight is

$$EW = \frac{60.01}{2} = 30.00 \text{ g/eq or } 30.00 \text{ mg/meq}$$

In $CaCO_3$, $n = 2$ since it would take two hydrogen ions to replace the cation (Ca^{2+}) to form carbonic acid, H_2CO_3. Its molecular weight is the sum of the atomic weights of Ca^{2+} and CO_3^{2-} and is, therefore, equal to $40.08 + 60.01 = 100.09$. Its equivalent weight is

$$EW = \frac{100.09}{2} = 50.04 \text{ g/eq or mg/meq}$$

Precipitation reactions. All complexes are soluble in water to a certain extent. Likewise, all complexes are limited by how much can be dissolved in water. Some compounds, such as NaCl, are very soluble; other compounds, such as AgCl, are very insoluble—only a small amount will go into solution. Visualize a solid compound being placed in distilled water. Some of the compound will go into solution. At some time no more of the compound will dissolve, and equilibrium will be reached. The time to reach equilibrium may be seconds or centuries. The solubility reaction is written as follows:

$$A_aB_b(s) \rightleftharpoons aA^{b+} + bB^{a-} \tag{3-19}$$

For example,

$$Ca_3(PO_4)_2(s) \rightleftharpoons 3Ca^{2+} + 2PO_4^{3-} \tag{3-20}$$

Interestingly, the product of the activity of the ions (approximated by the molar concentration) is always a constant for a given compound at a given temperature. This constant is called the solubility constant, K_s. In the general form it is written as

$$K_s = [A]^a[B]^b \tag{3-21}$$

square bracket means molar concentration
not mass concentra

where, in this text, [ ] denotes *molar* concentrations. **Do not use mg/L!** A table of constants is shown in Table 3-1 and in Appendix A. K_s values are often reported as pK_s, where

$$pK_s = -\log K_s \tag{3-22}$$

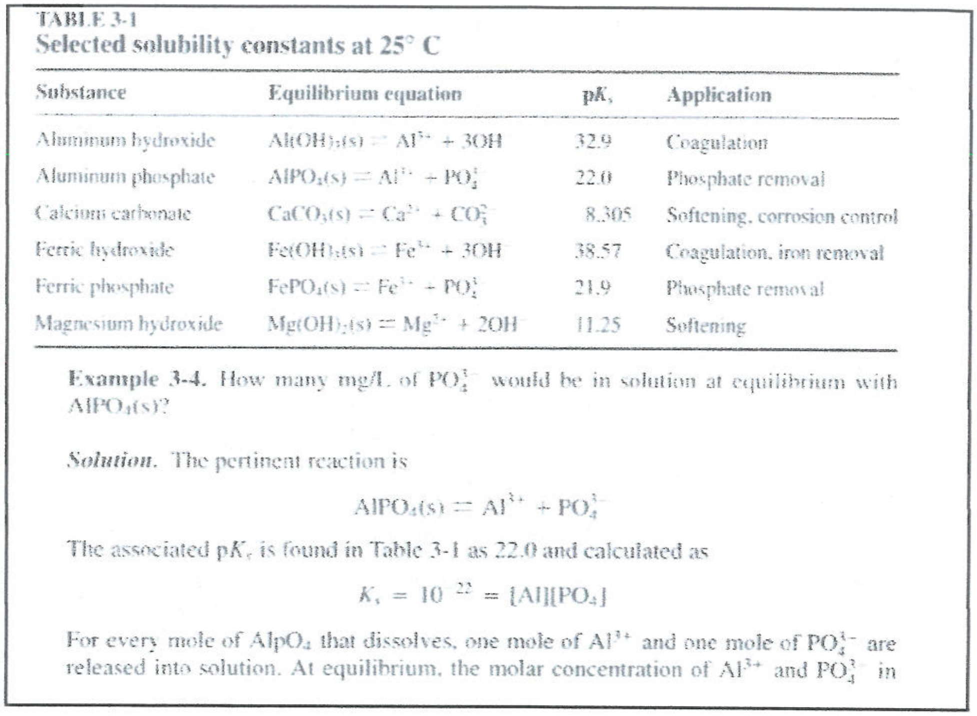


TABLE 3-1

Selected solubility constants at 25° C

Substance	Equilibrium equation	pK_s	Application
Aluminum hydroxide	$Al(OH)_3(s) \rightleftharpoons Al^{3+} + 3OH^-$	32.9	Coagulation
Aluminum phosphate	$AlPO_4(s) \rightleftharpoons Al^{3+} + PO_4^{3-}$	22.0	Phosphate removal
Calcium carbonate	$CaCO_3(s) \rightleftharpoons Ca^{2+} + CO_3^{2-}$	8.305	Softening, corrosion control
Ferric hydroxide	$Fe(OH)_3(s) \rightleftharpoons Fe^{3+} + 3OH^-$	38.57	Coagulation, iron removal
Ferric phosphate	$FePO_4(s) \rightleftharpoons Fe^{3+} + PO_4^{3-}$	21.9	Phosphate removal
Magnesium hydroxide	$Mg(OH)_2(s) \rightleftharpoons Mg^{2+} + 2OH^-$	11.25	Softening

Example 3-4. How many mg/L of PO_4^{3-} would be in solution at equilibrium with $AlPO_4(s)$?

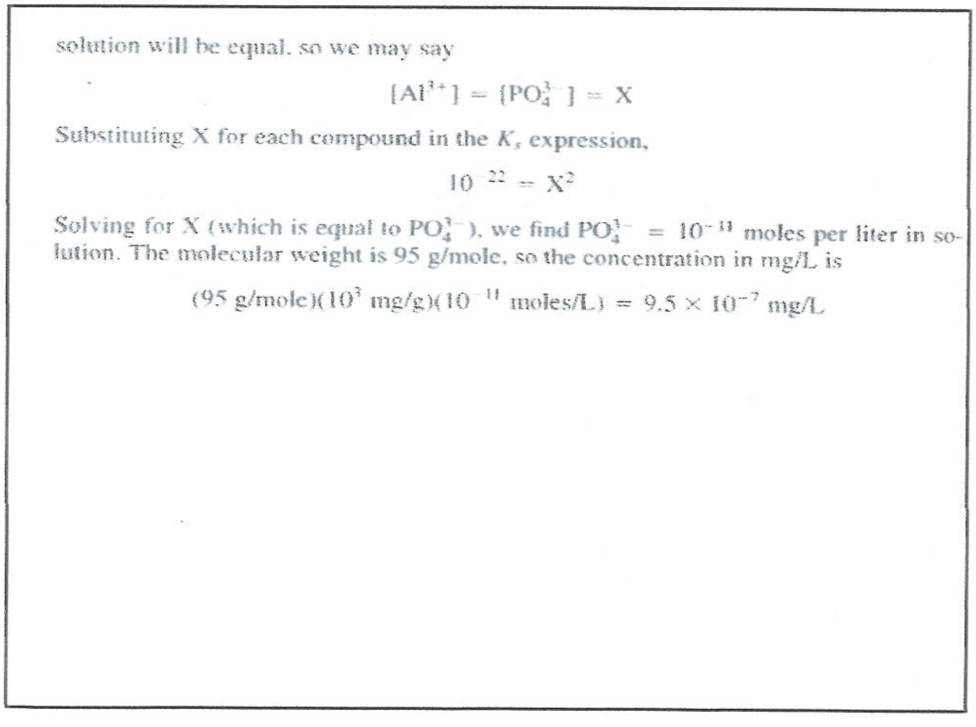
Solution. The pertinent reaction is

$$AlPO_4(s) \rightleftharpoons Al^{3+} + PO_4^{3-}$$

The associated pK_s is found in Table 3-1 as 22.0 and calculated as

$$K_s = 10^{-22} = [Al][PO_4]$$

For every mole of $AlpO_4$ that dissolves, one mole of Al^{3+} and one mole of PO_4^{3-} are released into solution. At equilibrium, the molar concentration of Al^{3+} and PO_4^{3-} in



solution will be equal, so we may say

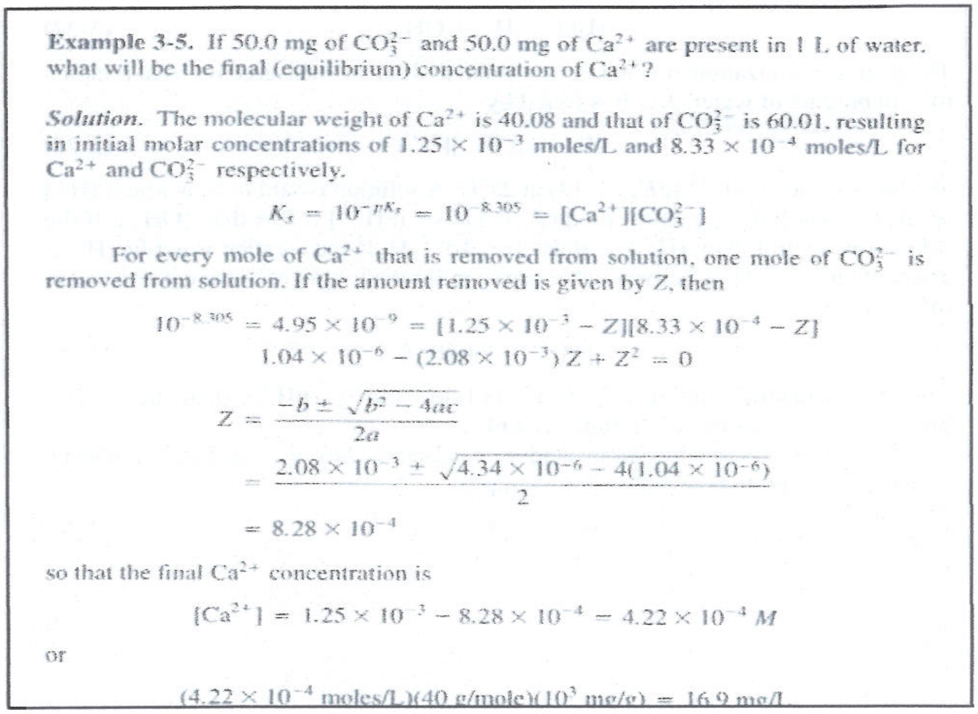
$$[Al^{3+}] = [PO_4^{3-}] = X$$

Substituting X for each compound in the K_s expression,

$$10^{-22} = X^2$$

Solving for X (which is equal to PO_4^{3-}), we find $PO_4^{3-} = 10^{-11}$ moles per liter in solution. The molecular weight is 95 g/mole, so the concentration in mg/L is

$$(95 \text{ g/mole})(10^3 \text{ mg/g})(10^{-11} \text{ moles/L}) = 9.5 \times 10^{-7} \text{ mg/L}$$



Example 3-5. If 50.0 mg of CO_3^{2-} and 50.0 mg of Ca^{2+} are present in 1 L of water, what will be the final (equilibrium) concentration of Ca^{2+}?

Solution. The molecular weight of Ca^{2+} is 40.08 and that of CO_3^{2-} is 60.01, resulting in initial molar concentrations of 1.25×10^{-3} moles/L and 8.33×10^{-4} moles/L for Ca^{2+} and CO_3^{2-} respectively.

$$K_s = 10^{-pK_s} = 10^{-8.305} = [Ca^{2+}][CO_3^{2-}]$$

For every mole of Ca^{2+} that is removed from solution, one mole of CO_3^{2-} is removed from solution. If the amount removed is given by Z, then

$$10^{-8.305} = 4.95 \times 10^{-9} = [1.25 \times 10^{-3} - Z][8.33 \times 10^{-4} - Z]$$

$$1.04 \times 10^{-6} - (2.08 \times 10^{-3})Z + Z^2 = 0$$

$$Z = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$= \frac{2.08 \times 10^{-3} \pm \sqrt{4.34 \times 10^{-6} - 4(1.04 \times 10^{-6})}}{2}$$

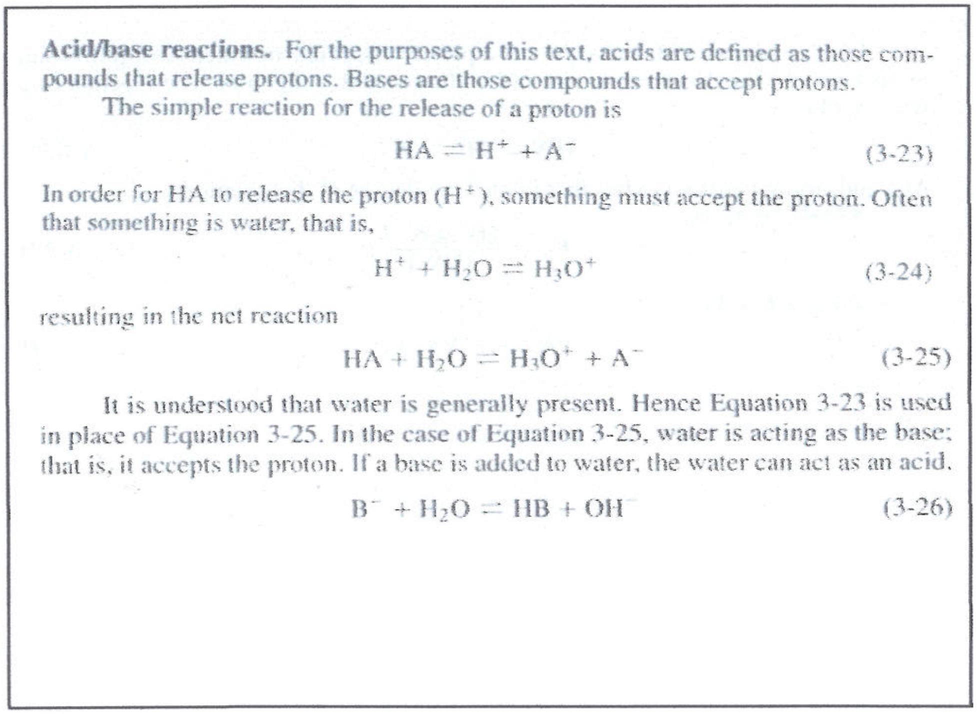
$$= 8.28 \times 10^{-4}$$

so that the final Ca^{2+} concentration is

$$[Ca^{2+}] = 1.25 \times 10^{-3} - 8.28 \times 10^{-4} = 4.22 \times 10^{-4}\ M$$

or

$$(4.22 \times 10^{-4}\ \text{moles/L})(40\ \text{g/mole})(10^3\ \text{mg/g}) = 16.9\ \text{mg/L}$$



Acid/base reactions. For the purposes of this text, acids are defined as those compounds that release protons. Bases are those compounds that accept protons.

The simple reaction for the release of a proton is

$$HA \rightleftharpoons H^+ + A^- \qquad (3\text{-}23)$$

In order for HA to release the proton (H^+), something must accept the proton. Often that something is water, that is,

$$H^+ + H_2O \rightleftharpoons H_3O^+ \qquad (3\text{-}24)$$

resulting in the net reaction

$$HA + H_2O \rightleftharpoons H_3O^+ + A^- \qquad (3\text{-}25)$$

It is understood that water is generally present. Hence Equation 3-23 is used in place of Equation 3-25. In the case of Equation 3-25, water is acting as the base; that is, it accepts the proton. If a base is added to water, the water can act as an acid.

$$B^- + H_2O \rightleftharpoons HB + OH^- \qquad (3\text{-}26)$$

$$H_2O \rightleftharpoons H^+ + OH^- \qquad (3\text{-}27)$$

The degree of ionization of water is very small and can be measured by what is called the ion product of water, K_w. It is found by

$$K_w = [OH^-][H^+] \qquad (3\text{-}28)$$

and has a value of 10^{-14} ($pK_w = 14$) at 25°C. A solution is said to be acidic if $[H^+]$ is greater than $[OH^-]$, neutral if equal, and basic if $[H^+]$ is less than $[OH^-]$. If the solution is neutral, then $[H^+] = [OH^-] = 10^{-7}$ *M*. If the solution is acidic, H^+ is greater than 10^{-7} *M*. A convenient expression for the hydrogen ion concentration is pH, given by

$$\text{pH} = -\log [H^+] \qquad (3\text{-}29)$$

Therefore, a neutral solution at 25°C has a pH of 7 (written pH 7), an acidic solution has a $\text{pH} < 7$, and a basic solution has a $\text{pH} > 7$.

Acids are classified as strong acids or weak acids. *Strong acids* have a tendency to donate their protons to water. For example,

$$HCl \rightarrow H^+ + Cl^- \qquad (3\text{-}30)$$

Weak acids are acids that do not completely dissociate in water. An equilibrium exists between the dissociated ions and undissociated compound. The reaction of a weak acid is

$$HW \rightleftharpoons H^+ + W^- \qquad (3\text{-}32)$$

An equilibrium constant exists that relates the degree of dissociation:

$$K_a = \frac{[H^+][W^-]}{[HW]} \qquad (3\text{-}33)$$

As with other *K* values,

$$pK_a = -\log K_a \qquad (3\text{-}34)$$

Example 3-6. If 100 mg of H_2SO_4 (MW = 98) is added to 1 L of water, what is the final pH?

Solution. Using the molecular weight of sulfuric acid we find

$$\left(\frac{100\text{ mg}}{1\text{ L }H_2O}\right)\left(\frac{1}{98\text{ g/mole}}\right)\left(\frac{1}{10^3\text{ mg/g}}\right) = 1.02 \times 10^{-3}\text{ mole/L}$$

The reaction is

$$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$$

and therefore $2(1.02 \times 10^{-3})M$ H^+ is produced. The pH is

$$pH = -\log(2.04 \times 10^{-3}) = 2.69$$

TABLE 3-2

Strong acids

Substance	Equilibrium equation	Significance
Hydrochloric acid	$HCl \rightarrow H^+ + Cl^-$	pH adjustment
Nitric acid	$HNO_3 \rightarrow H^+ + NO_3^-$	Analytical techniques
Sulfuric acid[a]	$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$	pH adjustment, coagulation

[a] Dissociation of the second proton, $HSO_4^- \rightleftharpoons H^+ + SO_4^{2-}$, is actually a weak acid reaction with a pK_a of 1.92. As long as the pH of the solution is above 2.5, the release of both protons may be considered complete.

TABLE 3-3

Selected weak acid dissociation constants at 25°C

Substance	Equilibrium equation	pK_a	Significance
Acetic acid	$CH_3COOH \rightleftharpoons H^+ + CH_3COO^-$	4.75	Anaerobic digestion
Carbonic acid	$H_2CO_3\ (CO_2 + H_2O) \rightleftharpoons H^+ + HCO_3^-$ $HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$	6.35 10.33	Corrosion, coagulati softening, pH control
Hydrogen sulfide	$H_2S \rightleftharpoons H^+ + HS^-$ $HS^- \rightleftharpoons H^+ + S^{2-}$	7.2 11.89	Aeration, odor contr corrosion
Hypochlorous acid	$HOCl \rightleftharpoons H^+ + OCl^-$	7.54	Disinfection
Phosphoric acid	$H_3PO_4 \rightleftharpoons H^+ + H_2PO_4^-$ $H_2PO_4^- \rightleftharpoons H^+ + HPO_4^{2-}$ $HPO_4^{2-} \rightleftharpoons H^+ + PO_4^{3-}$	2.12 7.20 12.32	Phosphate removal plant nutrient, analytical

Example 3-7. If 15 mg/L of HOCl is added to a potable water for disinfection and the final measured pH is 7.0, what percent of the HOCl is not dissociated? Assume the temperature is 25°C.

Solution. The reaction is

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

From Table 3-3, we find the pK_a is 7.54 and

$$K_a = 10^{-7.54} = 2.88 \times 10^{-8}$$

Writing the equilibrium constant expression in the form of Equation 3-33

$$K_a = \frac{[H^+][OCl^-]}{[HOCl]}$$

and substituting the values for K_a and $[H^+]$

$$2.88 \times 10^{-8} = \frac{[10^{-7}][OCl^-]}{[HOCl]}$$

Solving for the HOCl concentration

Solving for the HOCl concentration

$$[HOCl] = 3.47[OCl^-]$$

Since the fraction of HOCl that has not dissociated plus the OCl^- that was formed by the dissociation must, by the law of conservation of mass, equal 100% of the original HOCl added:

$$[HOCl] + [OCl^-] = 100\% \text{ (of the total HOCl added to the solution)}$$

then

$$3.47[OCl^-] + [OCl^-] = 100\%$$

$$4.47[OCl^-] = 100\%$$

$$[OCl^-] = \frac{100\%}{4.47} = 22.37\%$$

and

$$[HOCl] = 3.47(22.37\%) = 77.6\%$$

Buffer solutions. A solution that resists large changes in pH when an acid or base is added or when the solution is diluted is called a *buffer* solution. A solution containing a weak acid and its salt is an example of a buffer. Atmospheric carbon dioxide (CO_2) produces a natural buffer through the following reactions:

$$CO_2(g) \rightleftharpoons CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-} \quad (3\text{-}35)$$

where H_2CO_3 = carbonic acid
HCO_3^- = bicarbonate ion
CO_3^{2-} = carbonate ion

When CO_2 is bubbled into the system or is removed by passing an inert gas such as nitrogen through the liquid (a process called *stripping*), the pH will change more dramatically because the atmosphere is no longer available as a source or sink for CO_2. Figure 3-4 summarizes the four general responses of the carbonate buffer system. The first two cases are common in natural settings when the reactions proceed over a relatively long period of time. In a water treatment plant, we can alter he reactions more quickly than the CO_2 can be replenished from the atmosphere. The second two cases are not common in natural settings. They are used in water reatment plants to adjust the pH.

;URE 3-4

Behavior of the carbonate buffer system with the addition of acids and bases or the addition and removal O_2. CO_2

Case I
Acid is added to carbonate buffer system[a]

- Reaction shifts to the left as $H_2CO_3^*$ is formed when H^+ and HCO_3^- combine[b]
- CO_2 is released to the atmosphere
- pH is lowered slightly because the availability of free H^+ (amount depends on buffering capacity)

Case II
Base is added to carbonate buffer system

- Reaction shifts to the right
- CO_2 from the atmosphere dissolves into solution
- pH is raised slightly because H^+ combines with OH^- (amount depends on buffering capacity)

Case III

CO_2 is bubbled into carbonate buffer system

Reaction shifts to the right because $H_2CO_3^*$ is formed when CO_2 and H_2O combine

CO_2 dissolves into solution

pH is lowered

Case IV

Carbonate buffer system is stripped of CO_2

Reaction shifts to the left to form more $H_2CO_3^*$ to replace that removed by stripping

CO_2 is removed from solution

pH is raised

Refer to Equation 3-35

The asterisk * in the H_2CO_3 is used to signify the sum of CO_2 and H_2CO_3 in solution.

Alkalinity. Alkalinity is defined as the sum of all titratable bases down to about pH 4.5. It is found by experimentally determining how much acid it takes to lower the pH of water to 4.5. In most waters the only significant contributions to alkalinity are

he carbonate species and any free H^+ or OH^-. The total H^+ that can be taken up y a water containing primarily carbonate species is

$$\text{Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \qquad (3\text{-}36)$$

vhere [ ] refers to concentrations in moles/L. In most natural water situations (pH 6 o 8), the OH^- and H^+ are negligible, such that

$$\text{Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] \qquad (3\text{-}37)$$

Note that $[CO_3^{2-}]$ is multiplied by two because it can accept two protons. The pertinent acid/base reactions are

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \qquad pK_{a1} = 6.35 \text{ at } 25°C \qquad (3\text{-}38)$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \qquad pK_{a2} = 10.33 \text{ at } 25°C \qquad (3\text{-}39)$$

The alkalinity is then found by adding all the carbonate species and the hydroxide, and then subtracting the hydrogen ions. When using the units "mg/L as $CaCO_3$," the terms are added directly. The multiple of two for CO_3^{2-} has already been accounted for in the conversion.

From the p*K* values, some useful relationships can be found. The more importan ones are as follows:

1. Below pH of 4.5, essentially all of the carbonate species are present as H_2CO_3, and the alkalinity is negative (due to the H^+).
2. At a pH of 8.3 most of the carbonate species are present as HCO_3^-, and the alkalinity equals HCO_3^-.
3. Above a pH of 12.3, essentially all of the carbonate species are present as $CO_3^=$, and the alkalinity equals $2[CO_3^=] + [OH^-]$. The $[OH^-]$ may not be insignificant at this pH.

From Equation 3-37 and our discussion of buffer solutions, it can be seen that alkalinity serves as a measure of buffering capacity. The greater the alkalinity, the greater the buffering capacity. In environmental engineering, then, we differentiate between alkaline water and water having high alkalinity. Alkaline water has a pH greater than 7, while a water with high alkalinity has a high buffering capacity. An

By convention, alkalinity is not expressed in molarity units as shown in the above equations, but rather in mg/L as $CaCO_3$. In order to convert species to mg/L as $CaCO_3$, multiply mg/L as the species by the ratio of the equivalent weight of $CaCO_3$ to the species equivalent weight:

$$\text{mg/L as CaCO}_3 = (\text{mg/L as species})\left(\frac{EW_{CaCO_3}}{EW_{species}}\right) \qquad (3\text{-}40)$$

Example 3-8. A water contains 100.0 mg/L CO_3^{2-} and 75.0 mg/L HCO_3^- at a pH of 10. Calculate the alkalinity exactly at 25°C. Approximate the alkalinity by ignoring $[OH^-]$ and $[H^+]$.

Solution. First, convert CO_3^{2-}, HCO_3^-, OH^-, and H^+ to mg/L as $CaCO_3$.
The equivalent weights are

$$CO_3^{2-}:\ MW = 60, n = 2, EW = 30$$
$$HCO_3^-:\ MW = 61, n = 1, EW = 61$$
$$H^+:\ MW = 1, n = 1, EW = 1$$
$$OH^-:\ MW = 17, n = 1, EW = 17$$

and the concentration of H^+ and OH^- is calculated as follows: pH = 10; therefore $[H^+] = 10^{-10}$ *M*. Using Equation 3-7,

$$\text{mg/L} = (10^{-10}\ \text{moles/L})(1\ \text{g/mole})(10^3\ \text{mg/g}) = 10^{-7}$$

Using Equation 3-28,

$$[OH^-] = \frac{K_w}{[H^+]} = \frac{10^{-14}}{10^{-10}} = 10^{-4}\ \text{moles/L}$$

and

$$\text{mg/L} = (10^{-4}\ \text{moles/L})(17\ \text{g/mole})(10^3\ \text{mg/g}) = 1.7$$

Now, the mg/L as $CaCO_3$ is found by using Equation 3-40 and taking the equivalent weight of $CaCO_3$ to be 50:

$$CO_3^{2-} = 100.0\left(\frac{50}{30}\right) = 167$$

$$HCO_3^- = 75.0\left(\frac{50}{61}\right) = 61$$

$$H^+ = 10^{-7}\left(\frac{50}{1}\right) = 5 \times 10^{-6}$$

$$OH^- = 1.7\left(\frac{50}{17}\right) = 5.0$$

The exact alkalinity (in mg/L) is found by

$$\begin{aligned}\text{Alkalinity} &= 61 + 167 + 5.0 - (5 \times 10^{-6})\\ &= 233 \text{ mg/L as } CaCO_3\end{aligned}$$

It is approximated by $61 + 167 = 228$ mg/L as $CaCO_3$. This is a 2.2 percent error.

Activity Coefficients. To this point our discussions have assumed that the solutions being analyzed were dilute. That is, the total ion concentrations were low (generally less than 10^{-2} *M*). For dilute solutions, the ions in solution can be considered to act independently from one another. As the concentration of ions in solution increases, the interaction of their electric charges affects their equilibrium relationships. This interaction is measured in terms of *ionic strength*. To account for high ionic strength, the equilibrium relationships are modified by incorporating *activity coefficients*. These are symbolized by γ(ion). Activity is then the product of the molar concentration of the species and its activity coefficient. For example, the solubility product of $CaCO_3$ would be

$$K_s = \{\gamma(Ca^{2+}) \times [Ca^{2+}]\}\{\gamma(CO_3) \times [CO_3]\} \qquad (3\text{-}41)$$

ENCE 3323: Introduction to Environmental Engineering

Class 6: Water Treatment (2/3)

Review of the Last Class

- Why treat water?
  - To supply potable and palatable water
- Why do you need knowledge of water chemistry?
  - To understand the water quality
  - To optimize water treatment reactions
  - To calculate quantity of chemicals needed
  - To calculate reaction times, reactor/tank sizes

Review of the Last Class

- Physical properties of water
  - – Mass density (ρ)
  - – Specific weight ($\gamma = \rho g$)
  - – Specific gravity
  - – Dynamic viscosity (μ)
  - – Kinematic viscosity ($\nu = \mu/\rho$)

Review of the Last Class

- Impurities in water could be in one or more of the following forms
  - – Suspended form (0.2 to 100 μm)
  - – Colloidal (0.01 – 10 μm); Turbidity
  - – Dissolved

Review of the Last Class

- Concentration of pollutants in water
  - Concentration in mg/l
  - Molarity (M) [1 mole substance in one liter]
  - Normality (N) [1 equivalent weight (EW) substance dissolved in one liter]
  - N = M n

Review of the Last Class

- Most common chemical reactions in water
  - Precipitation (phase change; precipitation of salts)
  - Acid/base (hydrogen ion added or removed)
  - Ion-association ($AlOH^{2+}$)
  - Oxidation/reduction (electron exchange; corrosion of pipes and release of hydrogen gas) [Oxidation – loss of electron(s); Reduction - gain of electron(s)]

Review of the Last Class

- Various constants to remember
  - – Solubility constant, $K_s = [A]^a . [B]^b$
  - – Ion product of water, $K_w = [OH^-] . [H^+]$
  - – Equilibrium constant, $K_a = [H^+] . [W^-] / [HW]$

Review of the Last Class

- Acids: Those release protons
- Strong acids: Those completely disassociate (Hydrochloric acid)
  - – e.g.. $HCl \rightarrow H^+ + Cl^-$
- Weak acids: Those do not completely disassociate (Acetic acid)
  - – e.g.. $CH_3COOH \leftrightarrow H^+ + CH_3COO^-$

Review of the Last Class

- Degree of acid disassociation can be estimated knowing pH and pKa (equilibrium constant)
  - If pH << pKa → none of the acid is disassociated
  - If pH = pKa → acid is 50% disassociated
  - If pH >> pKa → most acid is disassociated
  - Review Example 3.7 (Page 146)

Review of the Last Class

- Buffer Solution: Resists large changes in pH when an acid or base is added
- Atmospheric CO_2 produces natural buffer in water bodies through the following reaction:
- $CO_2\,(g) \leftrightarrow CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO3^{2-}$ (3-35)
  - H_2CO_3 - Carbonic acid
  - HCO_3^- - Bicarbonate ion
  - $CO3^{2-}$ - Carbonate ion
- Why the above phenomenon important in water treatment?

Review of the Last Class

- Alkalinity: Defined as the sum of all titratable bases down to about pH of 4.5
- Determined based on how much acid it takes to lower the pH of water to 4.5
- Alkalinity =

  $[HCO_3^-] + 2[CO3^{2-}] + [OH^-] - [H^+]$
- Alkalinity most often expressed as equivalent of "mg/L of $CaCO_3$"

Review of the Last Class

- Alkalinity & Alkaline - Note the differences:
  - Alkaline water has a pH > 7
  - Water with high alkalinity has a high buffering capacity
  - An alkaline water may or may not have the buffering capacity
  - Likewise, a water with a high alkalinity may or may not have a high pH.

Today's Class – Objectives

- Reaction Kinetics
- Gas Transfer / Henry's Law
- Water Quality Parameters
- Water Quality Standards
- Coagulation (If time permits)
- Softening (If time permits)
- Reactors (If time permits)

Reaction Kinetics

- The study of how the reactions proceed is called reaction kinetics
- Homogenous reactions – Within a single phase (air, liquid, solid)
- Heterogeneous reactions – Reactions that occur at surfaces between phases

Rate of Reaction

- For homogeneous reactions:

$$r = \frac{(Moles\_or\_Milligrams)}{(UnitVolume)(UnitTime)}$$

- For heterogeneous reactions:

$$r = \frac{(Moles\_or\_Milligrams)}{(UnitSurface)(UnitTime)}$$

Reaction Rate Constant

- Consider the following reaction:

aA + bB → cC

$$\frac{d[A]}{dt} = rA = -k[A]^{\alpha}[B]^{\beta} = k[C]^{\gamma}$$

Where,

k - reaction rate constant

α, β, γ - empirically determined exponents

Order of Reaction

- Order of reaction is defined as the sum of the exponents in the reaction rate equation

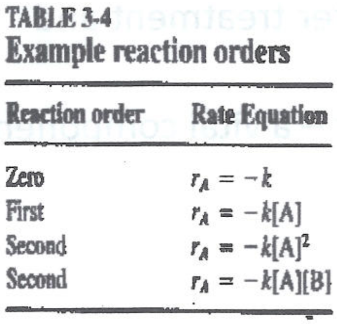


TABLE 3-4
Example reaction orders

Reaction order	Rate Equation
Zero	$r_A = -k$
First	$r_A = -k[A]$
Second	$r_A = -k[A]^2$
Second	$r_A = -k[A][B]$

More on Order of Reaction

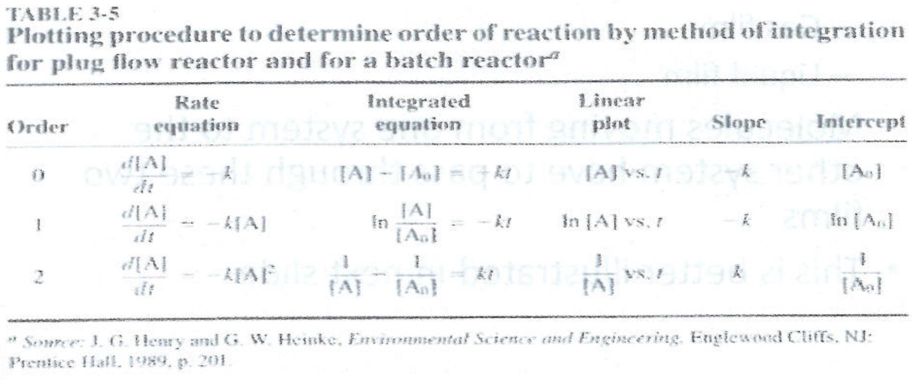


TABLE 3-5
Plotting procedure to determine order of reaction by method of integration for plug flow reactor and for a batch reactor[a]

Order	Rate equation	Integrated equation	Linear plot	Slope	Intercept
0	$\frac{d[A]}{dt} = -k$	$[A] - [A_0] = -kt$	[A] vs. t	$-k$	$[A_0]$
1	$\frac{d[A]}{dt} = -k[A]$	$\ln \frac{[A]}{[A_0]} = -kt$	ln [A] vs. t	$-k$	$\ln [A_0]$
2	$\frac{d[A]}{dt} = -k[A]^2$	$\frac{1}{[A]} - \frac{1}{[A_0]} = kt$	$\frac{1}{[A]}$ vs. t	k	$\frac{1}{[A_0]}$

[a] *Source:* J. G. Henry and G. W. Heinke, *Environmental Science and Engineering*. Englewood Cliffs, NJ: Prentice Hall, 1989, p. 201.

Gas Transfer

- Gas transfer (dissolution or volatilization) is explained by two-film theory [Lewis and Whitman, 1924]
- Why is it important in water treatment and natural water systems?
- Dissolved oxygen in water – a vital component of life support systems

Gas Transfer – Two Film Theory

- Between the bulk of gas and the bulk of liquid, there exist two layers:
  - Gas film
  - Liquid film
- Molecules moving from one system to the other system have to pass through these two films
- This is better illustrated in next slide

Gas Transfer – Two Film Theory

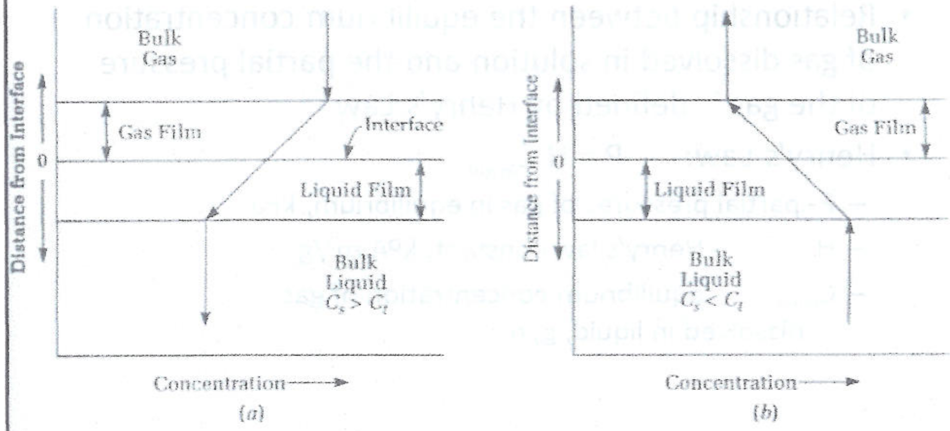


FIGURE 3-5
Two-film model of the interface between gas and liquid: (*a*) absorption mode and (*b*) desorption mode.

Gas Transfer– Two Film Theory

- For molecules to go from the bulk of gas to the bulk of liquid (dissolution), there should be a driving force, (C_s – C)
  - C_s - Saturation concentration
  - C - Actual concentration
- If C_s > C, gas dissolves into the liquid
- If C > C_s, gas leaves the liquid phase, volatilization

Gas Transfer – Henry's Law

- Relationship between the equilibrium concentration of gas dissolved in solution and the partial pressure of the gas is defined by Henry's Law
- Henry's Law: $P = H\ C_{equil}$
  - P- partial pressures of gas in equilibrium, kPa
  - H - Henry's law constant, kPA.m^3/g
  - C_{equil} - equilibrium concentration of gas dissolved in liquid, g/m^3

Gas Transfer – Henry's Law

- Henry's law (another form)
- $X = K_H.P_g$
  - X- mole fraction of the gas dissolved in the liquid at equilibrium
  - K_H - Henry's law constant, atm^{-1}
  - P_g - partial pressure of gas in equilibrium with liquid, atm
- What is partial pressure? If oxygen is 21% by volume in the atmosphere, what is the partial pressure of oxygen?

Oxygen Dissolution in Water

- Mass transfer of oxygen in water is explained by the first order reaction

$$\frac{dC}{dt} = k_a (C_s - C)$$

Where,

k_a - rate constant or mass transfer coeff., s-1 C_s
- saturation concentration of oxygen in water

C - actual concentration of oxygen in water

Example 3-9. A falling raindrop initially has no dissolved oxygen. The saturation concentration for the drop is 9.20 mg/L. If, after falling for two seconds, the droplet has an oxygen concentration of 3.20 mg/L, how long must the droplet fall (from the start of the fall) to achieve a concentration of 8.20 mg/L?

Solution. We begin by calculating the deficit after two seconds, and that at a concentration of 8.20 mg/L:

$$\text{Deficit at 2 sec} = 9.20 - 3.20 = 6.00 \text{ mg/L}$$

$$\text{Deficit at } t \text{ sec} = 9.20 - 8.20 = 1.00 \text{ mg/L}$$

Now using the integrated form of the first-order rate equation from Table 3-5, noting that the rate of change is proportional to deficit and, hence, $[A] = (C_s - C)$ and that $[A_0] = (9.20 - 0.00)$,

$$\ln \frac{6.00}{9.20} = -k\,(2.00 \text{ s})$$

$$k = 0.2137 \text{ s}^{-1}$$

With this value of k, we can calculate a value for t:

$$\ln \frac{(9.20 - 8.20)}{9.20} = -(0.2137)\,(t)$$

$$t = 10.4 \text{ s}$$

Water Quality Parameters

- How do you define if the quality of water is good or bad?
- You need to identify the important parameters
- Classification of Water Quality Parameters
  - Physical
  - Chemical
  - Biological
  - Radiological (minimum in this course)

Physical Characteristics

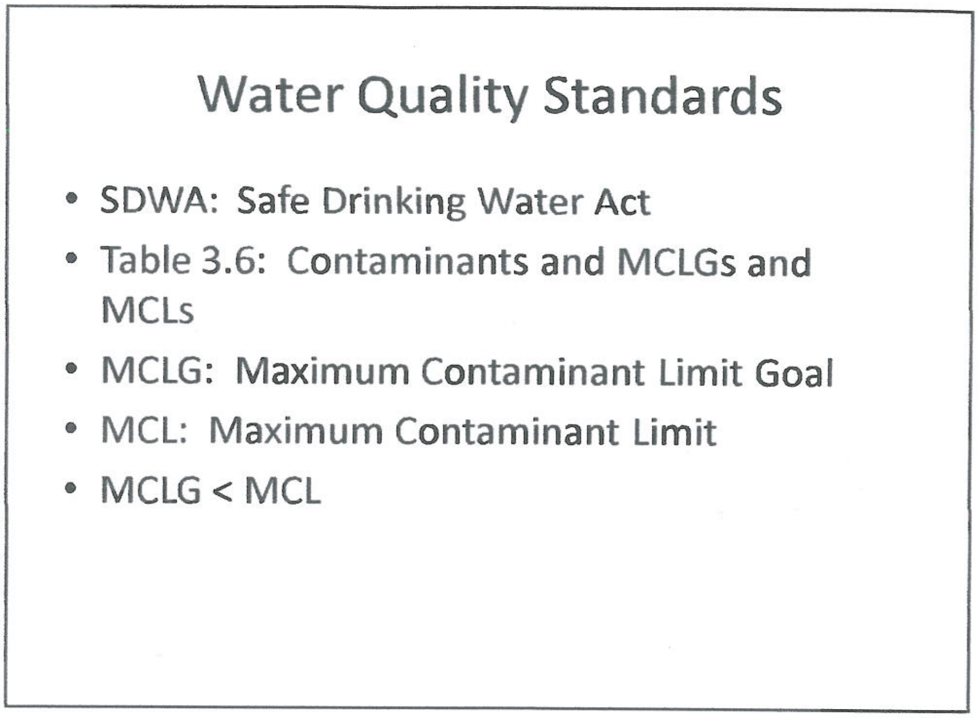
- Turbidity: The presence of suspended material such as silt, clay, finely divided organic material, plankton, and other particulate material in water is known as turbidity. Unit of turbidity is a Turbidity Unit (TU) or Nephlometric Turbidity Unit(NTU)
- Color: Dissolved organic material from decaying vegetation and certain inorganic matter cause color in water. Occasionally, excessive blooms of algae or the growth of microorganisms may also impart color.
- Taste and Odor: They are caused by foreign matter such as organic compounds, inorganic salts, or dissolved gases.
- Temperature: The most desirable drinking waters are consistently cool and do not have temperature fluctuations of more than a few degrees. Most individuals find that water having a temperature between 10-15 Deg. C is most palatable.

Chemical Characteristics

- Chloride – produces taste
  Safe range –(100 mg/l to 250 mg/l)
- Fluorides- optimum range prevents decay of teeth and excess amounts
  cause flourosis
- Iron – imparts color
- Lead – exposure to even small quantities of lead result in severe illness or death
- Manganese – imparts a brownish color to water
- Sodium – affects persons suffering from heart ,kidney or circulatory ailments
- Sulfate – waters contain sodium because of leaching of natural deposits of magnesium sulfate or sodium sulfate
- Toxic inorganic (Metals etc.)
- Toxic organic (Table 1-3)

Microbiological Characteristics

- Pathogens (disease producing)
- Viruses
- Bacteria
- Protozoa
- Helminths
- Others



Water Quality Standards

- SDWA: Safe Drinking Water Act
- Table 3.6: Contaminants and MCLGs and MCLs
- MCLG: Maximum Contaminant Limit Goal
- MCL: Maximum Contaminant Limit
- MCLG < MCL

ENCE 3323: Introduction to Environmental Engineering

Chapter 4: Water Treatment – Part 3

Today's Objectives

- Water Quality Parameters
- Water Quality Standards
- Coagulation
- Softening
- Discussion on the Midterm Test Format / Date

Water Quality Parameters

- How do you define if the quality of water is good or bad?
- You need to identify the important parameters
- Classification of Water Quality Parameters
  - Physical
  - Chemical
  - Biological
  - Radiological

Physical Characteristics

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Chemical Characteristics

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- Fluorides- optimum range prevents decay of teeth and excess amounts cause floursis
- Iron – imparts color
- Lead – exposure to even small quantities of lead result in severe illness or death
- Manganese – imparts a brownish color to water

Chemical Characteristics

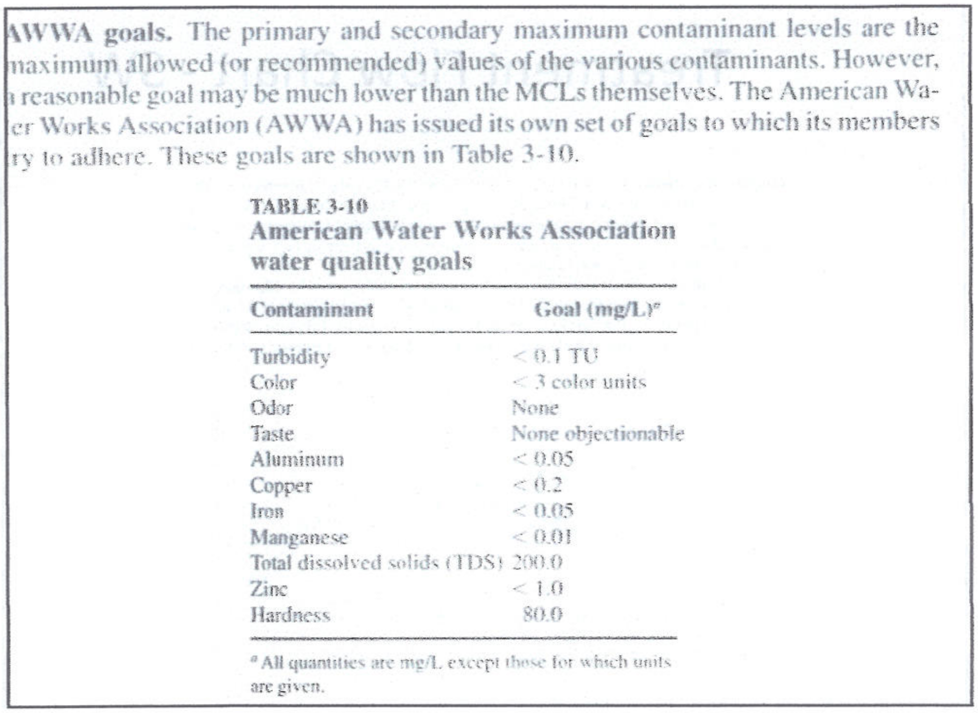
- Sodium – affects persons suffering from heart, kidney or circulatory ailments
- Sulfate – waters contain sodium because of leaching of natural deposits of magnesium sulfate or sodium sulfate
- Toxic inorganic substances: Nitrates (NO_3), cyanides (CN), and heavy metals (Table 1-6)
- Toxic organic substances: Pesticides, insecticides, solvents, and others (Table 1-6)

Microbiological Characteristics

- Pathogens (disease producing)
- Viruses
- Bacteria
- Protozoa
- Helminths
- Others

Water Quality Standards

- SDWA: Safe Drinking Water Act
- Table 4.7: Contaminants and MCLGs and MCLs
- MCLG: Maximum Contaminant Level Goal
- MCL: Maximum Contaminant Level
- MCLG < MCL

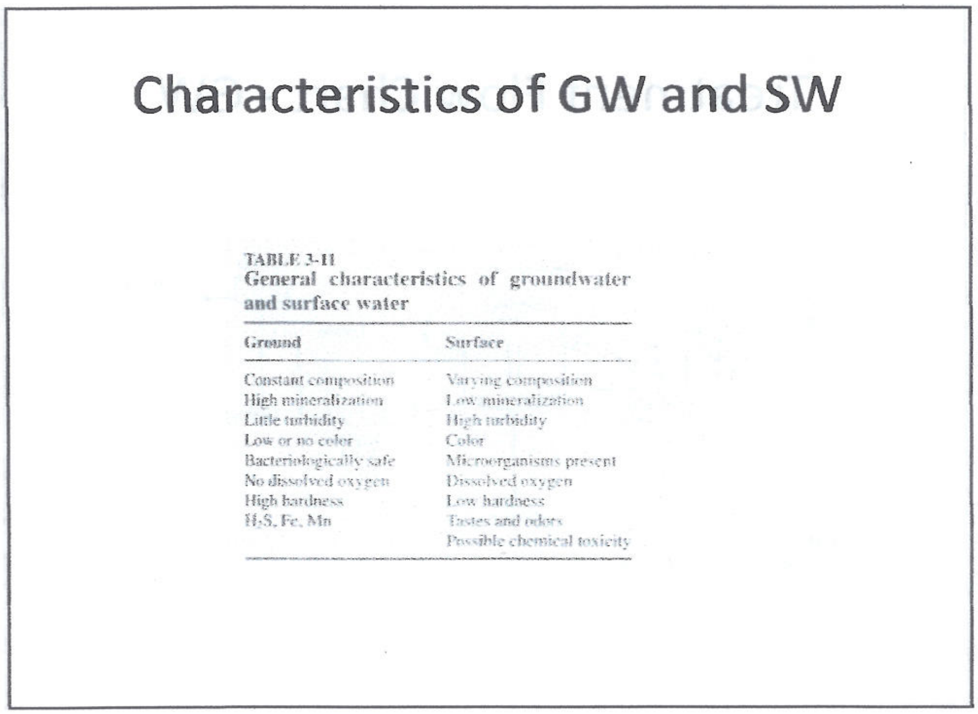


WWA goals. The primary and secondary maximum contaminant levels are the
naximum allowed (or recommended) values of the various contaminants. However,
reasonable goal may be much lower than the MCLs themselves. The American Wa-
er Works Association (AWWA) has issued its own set of goals to which its members
ry to adhere. These goals are shown in Table 3-10.

TABLE 3-10
American Water Works Association water quality goals

Contaminant	Goal (mg/L)[a]
Turbidity	< 0.1 TU
Color	< 3 color units
Odor	None
Taste	None objectionable
Aluminum	< 0.05
Copper	< 0.2
Iron	< 0.05
Manganese	< 0.01
Total dissolved solids (TDS)	200.0
Zinc	< 1.0
Hardness	80.0

[a] All quantities are mg/L except those for which units are given.



Characteristics of GW and SW

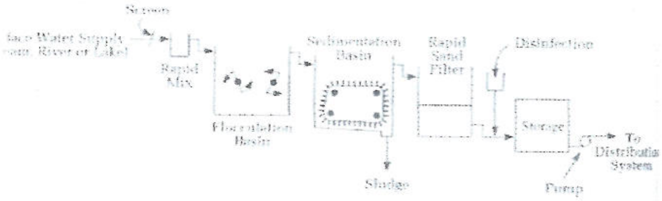
TABLE 3-11
General characteristics of groundwater and surface water

Ground	Surface
Constant composition	Varying composition
High mineralization	Low mineralization
Little turbidity	High turbidity
Low or no color	Color
Bacteriologically safe	Microorganisms present
No dissolved oxygen	Dissolved oxygen
High hardness	Low hardness
H_2S, Fe, Mn	Tastes and odors
	Possible chemical toxicity

Treatment Flow Chart - SW

Treatment systems. Treatment plants can be classified as simple disinfection, filter plants, or softening plants. Plants employing simple chlorination have a high water quality source and chlorinate to ensure that the water reaching customers contains safe bacteria levels. Generally, a filtration plant is used to treat surface water and a softening plant to treat groundwater.

In a **filtration plant**, rapid mixing, flocculation, sedimentation, filtration, and disinfection are employed to remove color, turbidity, taste and odors, and bacteria. Additional operations may include bar racks or coarse screens if floating debris and fish are a problem. Figure 3-6 shows a typical flow diagram of a filtration plant. The



URE 3-6
diagram of a conventional surface water treatment plant ("filtration plant").

Treatment Flow Chart - GW

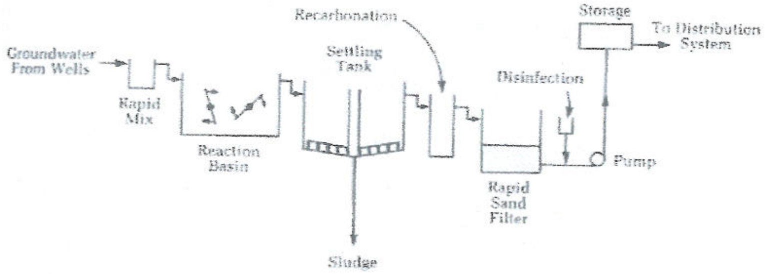


FIGURE 3-7
Flow diagram of water softening plant.

Coagulation

- Objective: Remove turbidity, color and bacteria
- Truly speaking, coagulation is removal of colloidal particles (often used in removal of dissolved ions – precipitation)
- As colloidal particles are stable due to surface charge (-), sodium ions, Na(+), are added to neutralize to make them unstable

Coagulation

- Schulze-Hardy Rule
  - Trivalent ion is 30 to 50 times more efficient than divalent and 1500 to 2000 times more efficient than monovalent ion
- So, trivalent cations, aluminum (Al3+) and ferric ion (Fe3+) are commonly used

Coagulation - Al

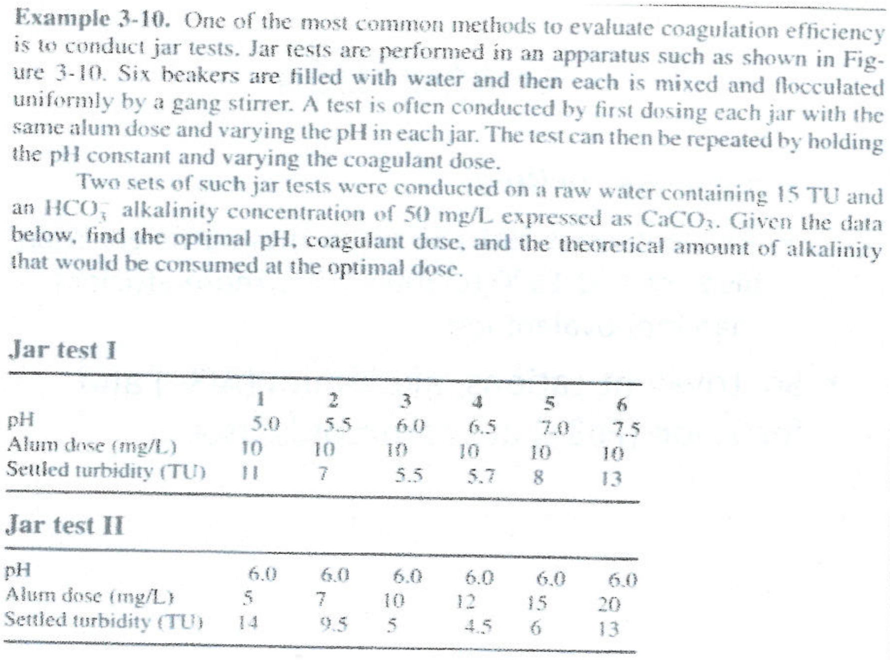
- <u>Water with Alkalinity</u>

  $Al_2(SO_4)_3.14H_2O + 6HCO_3^- \leftrightarrow$
  $2Al(OH_3)(s) + 6CO_2 + 14H_2O + 3SO_4^{2-}$

  pH is slightly reduced due to presence of Alkalinity
- <u>Water without Alkalinity</u>

  $Al_2(SO_4)_3.14H_2O \leftrightarrow$
  $2Al(OH_3)(s) + 3H_2SO_4 + 8H_2O$

  pH is drastically reduced due to non- availability of alkalinity



Example 3-10. One of the most common methods to evaluate coagulation efficiency is to conduct jar tests. Jar tests are performed in an apparatus such as shown in Figure 3-10. Six beakers are filled with water and then each is mixed and flocculated uniformly by a gang stirrer. A test is often conducted by first dosing each jar with the same alum dose and varying the pH in each jar. The test can then be repeated by holding the pH constant and varying the coagulant dose.

Two sets of such jar tests were conducted on a raw water containing 15 TU and an HCO_3^- alkalinity concentration of 50 mg/L expressed as $CaCO_3$. Given the data below, find the optimal pH, coagulant dose, and the theoretical amount of alkalinity that would be consumed at the optimal dose.

Jar test I

	1	2	3	4	5	6
pH	5.0	5.5	6.0	6.5	7.0	7.5
Alum dose (mg/L)	10	10	10	10	10	10
Settled turbidity (TU)	11	7	5.5	5.7	8	13

Jar test II

pH	6.0	6.0	6.0	6.0	6.0	6.0
Alum dose (mg/L)	5	7	10	12	15	20
Settled turbidity (TU)	14	9.5	5	4.5	6	13

Solution. The results of the two jar tests are plotted in Figure 3-11. The optimal pH was chosen as 6.25 and the optimal alum dose was about 12.5 mg/L. The experimenter would probably try to repeat the test using a pH of 6.25 and varying the alum dose between 10 and 15 to pinpoint the optimal conditions.

The amount of alkalinity that will be consumed is found by using Equation 3-51, which shows us that one mole of alum consumes six moles of HCO_3^-. With the molecular weight of alum equal to 594, the moles of alum added per liter is found by using Equation 3-7:

$$12.5 \times 10^{-3}\ \text{g/L} \quad = 2.1 \times 10^{-5}\ \text{moles/L}$$

which will consume

$$6(2.1 \times 10^{-5}) = 1.26 \times 10^{-4}\ M\ HCO_3^-$$

The molecular weight of HCO_3^- is 61, so

$$(1.26 \times 10^{-4}\ \text{moles/L})(61\ \text{g/mole})(10^3\ \text{mg/g}) = 7.7\ \text{mg/L}\ HCO_3^-$$

are consumed, which can be expressed as $CaCO_3$ by using Equation 3-40:

$$7.7\,\frac{50}{61} = 6.31\ \text{mg/L}\ HCO_3^-\ \text{as}\ CaCO_3$$

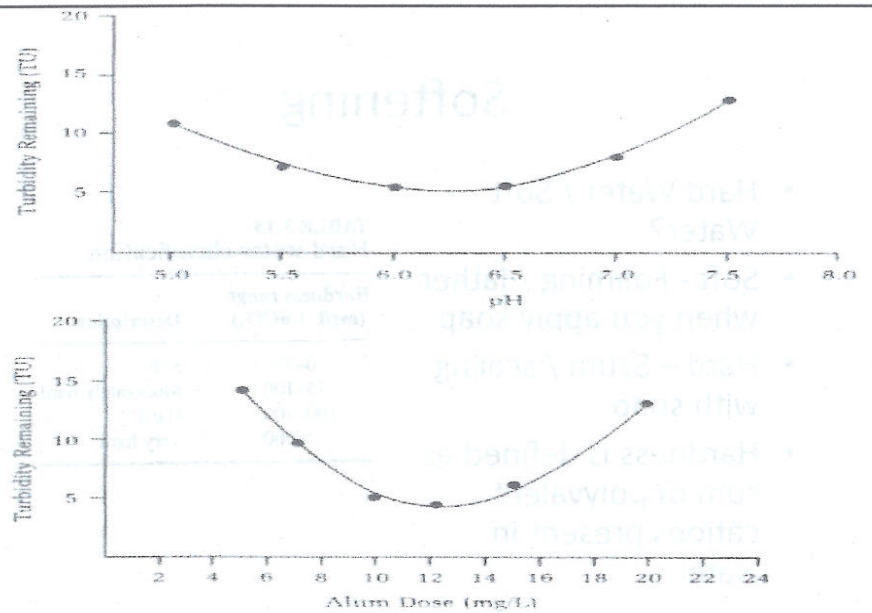


FIGURE 3-11
Results of jar test.

Figure related to example 3:10

Coagulation – Ferric Iron Ion

- Water with Alkalinity

  $FeCl_3 + 3HCO_3^- \leftarrow\rightarrow Fe(OH)_3(s) + 3CO_2 + 3Cl^-$

  pH is slightly reduced
- Water without Alkalinity

  $FeCl_3 + 3H_2O \leftarrow\rightarrow Fe(OH)_3(s) + 3HCl$

  pH is greatly reduced

Softening

- Hard Water / Soft Water?
- Soft - Foaming / lather when you apply soap
- Hard – Scum / scaling with soap
- Hardness is defined as sum of polyvalent cations present in water

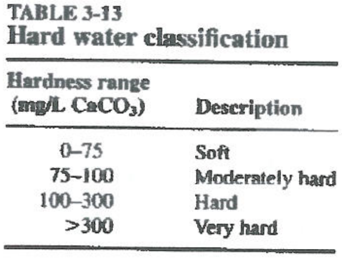
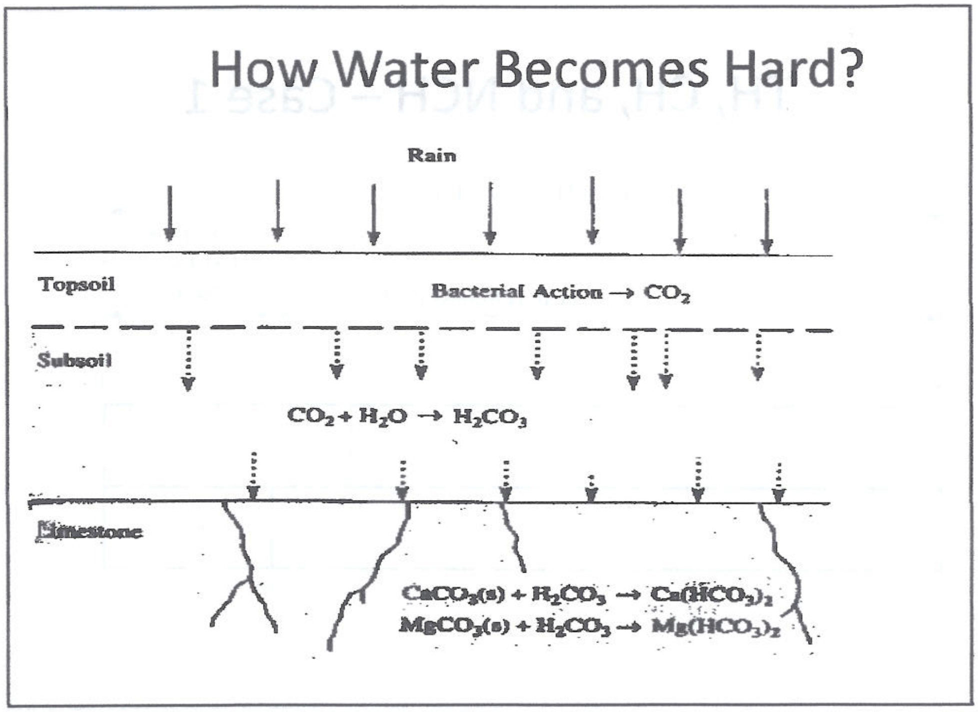


TABLE 3-13
Hard water classification

Hardness range (mg/L $CaCO_3$)	Description
0–75	Soft
75–100	Moderately hard
100–300	Hard
>300	Very hard



How Water Becomes Hard?

Total Hardness (TH)

- TH = Ca^{+2} + Mg^{+2}
- TH = CH + NCH

where,

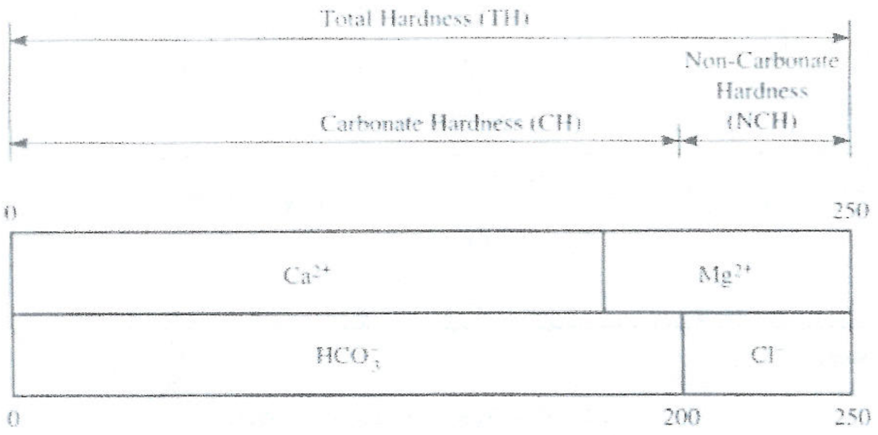
CH = Carbonate hardness

  - Hardness due to HCO_3^- anion
  - CH is equal to TH or alkalinity whichever is less
  - Also known as temporary hardness (can be removed by heating)

NCH = Non-carbonate hardness

  - Hardness due to other than HCO_3^- anion
  - NCH is the hardness in excess of alkalinity
  - Also known as permanent hardness

TH, CH, and NCH – Case 1



TH, CH, and NCH – Case 2

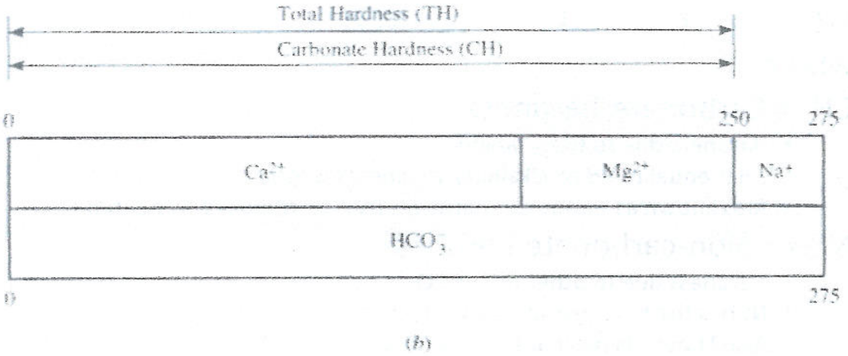
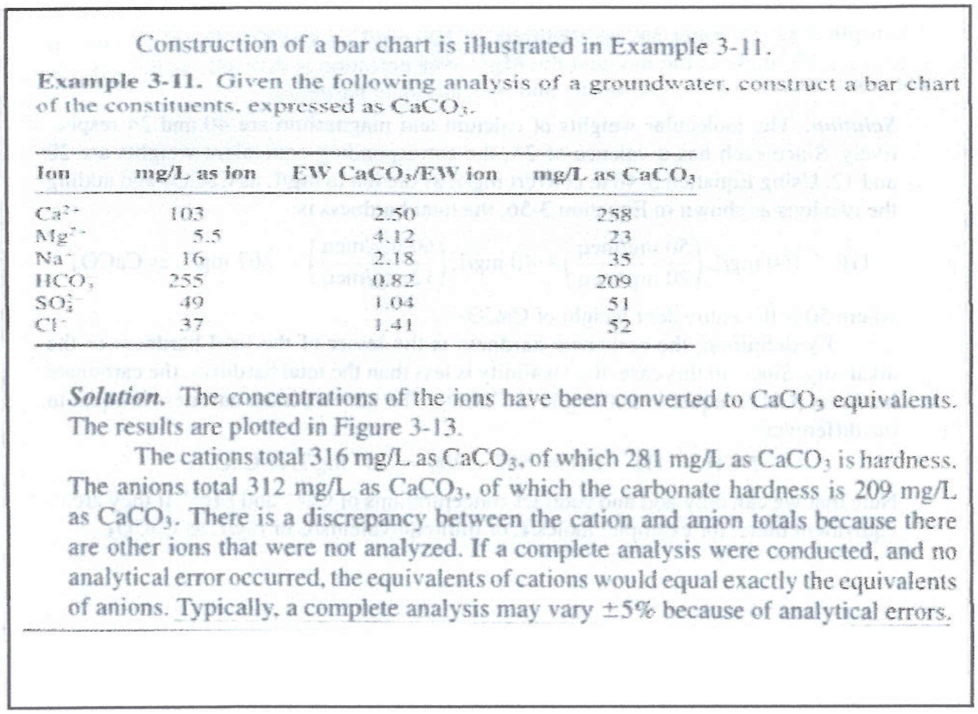


FIGURE 3-14
Relationships between total hardness, carbonate hardness, and noncarbonate hardness.



Construction of a bar chart is illustrated in Example 3-11.

Example 3-11. Given the following analysis of a groundwater, construct a bar chart of the constituents, expressed as $CaCO_3$.

Ion	mg/L as ion	EW $CaCO_3$/EW ion	mg/L as $CaCO_3$
Ca^{2+}	103	2.50	258
Mg^{2+}	5.5	4.12	23
Na^+	16	2.18	35
HCO_3^-	255	0.82	209
SO_4^{2-}	49	1.04	51
Cl^-	37	1.41	52

Solution. The concentrations of the ions have been converted to $CaCO_3$ equivalents. The results are plotted in Figure 3-13.

The cations total 316 mg/L as $CaCO_3$, of which 281 mg/L as $CaCO_3$ is hardness. The anions total 312 mg/L as $CaCO_3$, of which the carbonate hardness is 209 mg/L as $CaCO_3$. There is a discrepancy between the cation and anion totals because there are other ions that were not analyzed. If a complete analysis were conducted, and no analytical error occurred, the equivalents of cations would equal exactly the equivalents of anions. Typically, a complete analysis may vary ±5% because of analytical errors.

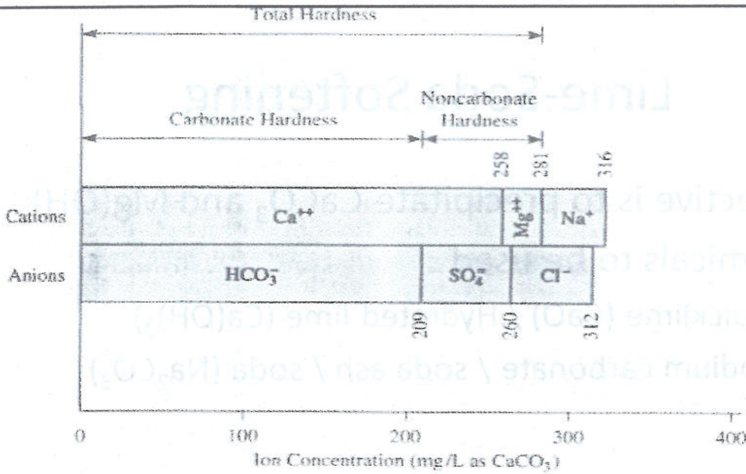
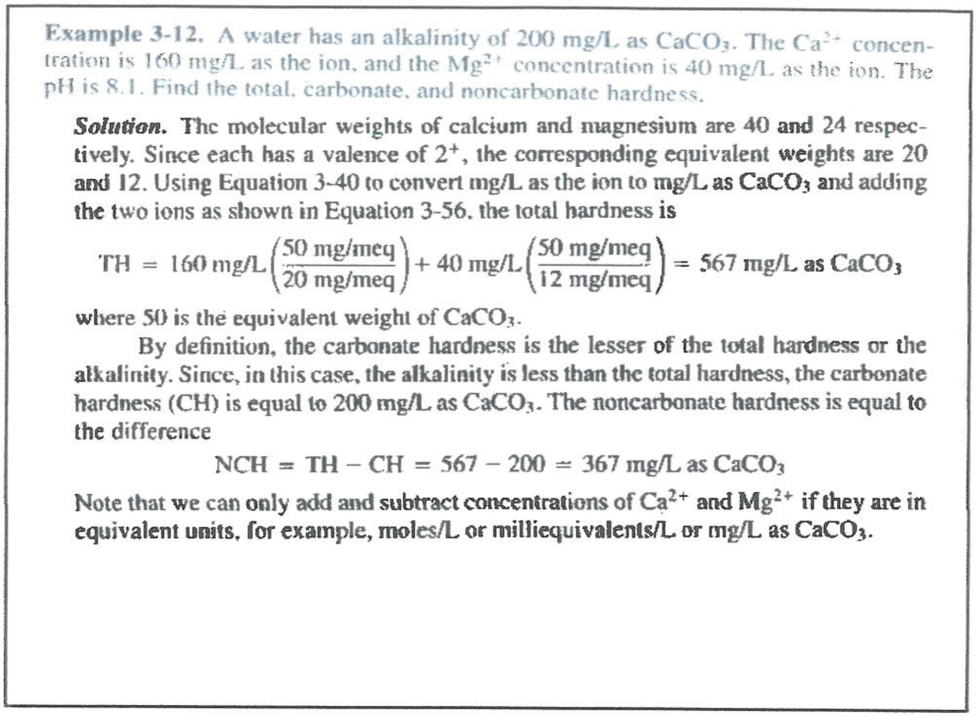


FIGURE 3-13
Bar graph of groundwater constituents.

Figure related to example 3:11



Example 3-12. A water has an alkalinity of 200 mg/L as $CaCO_3$. The Ca^{2+} concentration is 160 mg/L as the ion, and the Mg^{2+} concentration is 40 mg/L as the ion. The pH is 8.1. Find the total, carbonate, and noncarbonate hardness.

Solution. The molecular weights of calcium and magnesium are 40 and 24 respectively. Since each has a valence of 2^+, the corresponding equivalent weights are 20 and 12. Using Equation 3-40 to convert mg/L as the ion to mg/L as $CaCO_3$ and adding the two ions as shown in Equation 3-56, the total hardness is

$$\text{TH} = 160\ \text{mg/L}\left(\frac{50\ \text{mg/meq}}{20\ \text{mg/meq}}\right) + 40\ \text{mg/L}\left(\frac{50\ \text{mg/meq}}{12\ \text{mg/meq}}\right) = 567\ \text{mg/L as } CaCO_3$$

where 50 is the equivalent weight of $CaCO_3$.

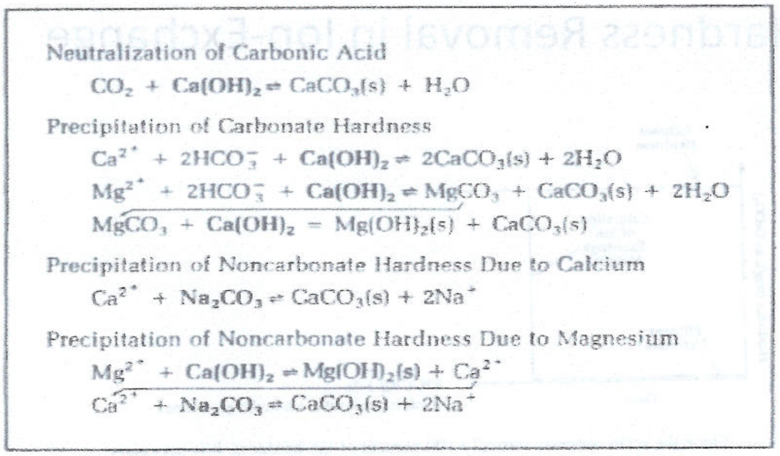
By definition, the carbonate hardness is the lesser of the total hardness or the alkalinity. Since, in this case, the alkalinity is less than the total hardness, the carbonate hardness (CH) is equal to 200 mg/L as $CaCO_3$. The noncarbonate hardness is equal to the difference

$$\text{NCH} = \text{TH} - \text{CH} = 567 - 200 = 367\ \text{mg/L as } CaCO_3$$

Note that we can only add and subtract concentrations of Ca^{2+} and Mg^{2+} if they are in equivalent units, for example, moles/L or milliequivalents/L or mg/L as $CaCO_3$.

Lime-Soda Softening

- Objective is to precipitate $CaCO_3$ and $Mg(OH)_2$
- Chemicals to be used
  - Quicklime (CaO) / Hydrated lime ($Ca(OH)_2$)
  - Sodium carbonate / soda ash / soda (Na_2CO_3)



Neutralization of Carbonic Acid

$$CO_2 + \mathbf{Ca(OH)_2} \rightleftharpoons CaCO_3(s) + H_2O$$

Precipitation of Carbonate Hardness

$$Ca^{2+} + 2HCO_3^- + \mathbf{Ca(OH)_2} \rightleftharpoons 2CaCO_3(s) + 2H_2O$$

$$Mg^{2+} + 2HCO_3^- + \mathbf{Ca(OH)_2} \rightleftharpoons MgCO_3 + CaCO_3(s) + 2H_2O$$

$$MgCO_3 + \mathbf{Ca(OH)_2} \rightleftharpoons Mg(OH)_2(s) + CaCO_3(s)$$

Precipitation of Noncarbonate Hardness Due to Calcium

$$Ca^{2+} + \mathbf{Na_2CO_3} \rightleftharpoons CaCO_3(s) + 2Na^+$$

Precipitation of Noncarbonate Hardness Due to Magnesium

$$Mg^{2+} + \mathbf{Ca(OH)_2} \rightleftharpoons Mg(OH)_2(s) + Ca^{2+}$$

$$Ca^{2+} + \mathbf{Na_2CO_3} \rightleftharpoons CaCO_3(s) + 2Na^+$$

FIGURE 3-15
Summary of softening reactions. (*Note:* The chemical added is printed in bold type. The precipitate is designated by (s). The arrow indicates where a compound formed in one reaction is used in another reaction.)

Ion-Exchange Softening

- Exchange of ions (polyvalent ions in water to Na in solid) is achieved by passing water through a column of ion-exchange material
- $Ca(HCO_3)_2$ + 2 NaR
- Ca is replaced by Na
- Alkalinity does not change

Hardness Removal in Ion-Exchange

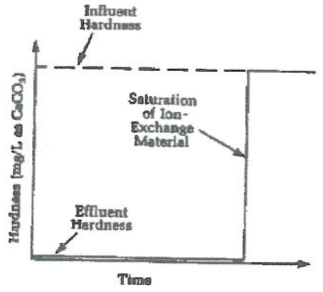


FIGURE 3-21
Hardness removal in ion-exchange column.

Since the resin removes virtually 100 percent of the hardness, it is necessary to bypass a portion of the water and then blend in order to obtain the desired final hardness.

$$\%\text{Bypass} = (100)\,\frac{\text{Hardness}_{\text{desired}}}{\text{Hardness}_{\text{initial}}} \qquad (3\text{-}71)$$

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Class 8: Water Treatment (4/4)

REACTORS

- Tanks in which physical, chemical, and biological reactions take place
- Types of reactors:
  - Batch Reactors (fill-and-draw)
  - Flow Reactors (Continuous operation)
    - Completely Stirred Tank Reactors (CSTR) / Completely Mixed-flow Reactors (CMF)
    - Plug Flow Reactors (PFR)

CSTR / CMF

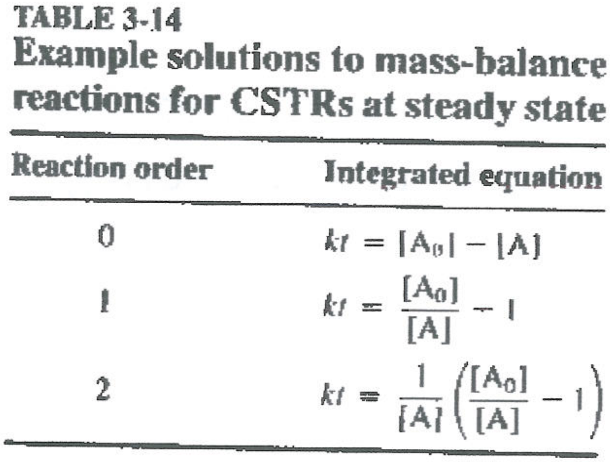


TABLE 3-14
Example solutions to mass-balance reactions for CSTRs at steady state

Reaction order	Integrated equation
0	$kt = [A_0] - [A]$
1	$kt = \frac{[A_0]}{[A]} - 1$
2	$kt = \frac{1}{[A]}\left(\frac{[A_0]}{[A]} - 1\right)$

Plug Flow Reactors

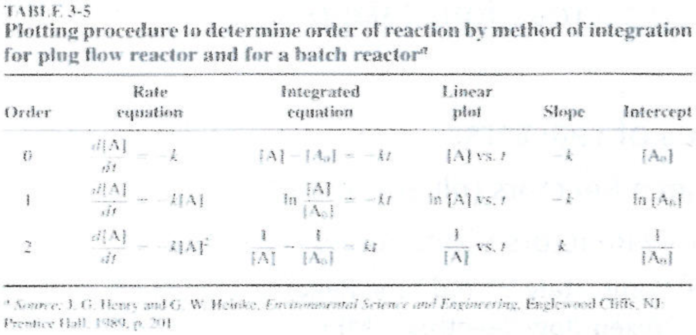


TABLE 3-5
Plotting procedure to determine order of reaction by method of integration for plug flow reactor and for a batch reactor[a]

Order	Rate equation	Integrated equation	Linear plot	Slope	Intercept
0	$\frac{d[A]}{dt} = -k$	$[A] - [A_0] = -kt$	$[A]$ vs. t	$-k$	$[A_0]$
1	$\frac{d[A]}{dt} = -k[A]$	$\ln\frac{[A]}{[A_0]} = -kt$	$\ln[A]$ vs. t	$-k$	$\ln[A_0]$
2	$\frac{d[A]}{dt} = -k[A]^2$	$\frac{1}{[A]} - \frac{1}{[A_0]} = kt$	$\frac{1}{[A]}$ vs. t	k	$\frac{1}{[A_0]}$

[a] *Source:* J. G. Henry and G. W. Heinke, *Environmental Science and Engineering*, Englewood Cliffs, NJ: Prentice Hall, 1989, p. 201.

Detention Time / Retention Time

- The time that a fluid particle remains in the reactor, from its entry to exit
- DT / RT = t_0 = V/Q
- Real tanks behave in between CSTR and Plug Flow Reactors
- Real tanks have less detention time than the theoretical detention time given by the above equation

MIXING AND FLOCCULATION

- Mixing or rapid mixing is the process in which chemicals are quickly dispersed
- Flocculation is a gentle mixing process in which particles / precipitates / flocs are brought together to allow formation of bigger flocs

Degree of Mixing, G

- Velocity gradient, G, denotes degree of mixing

$$G = \sqrt{\frac{P}{\mu V}} \text{.........}(Eq3.75)$$

Where, G = Velocity gradient, s^{-1}
P = Power input, W
V = Volume of water in tank, m3
u = Dynamic viscosity, Pa.s

Power Requirements

- Powered by Impeller in a Baffled Tank:

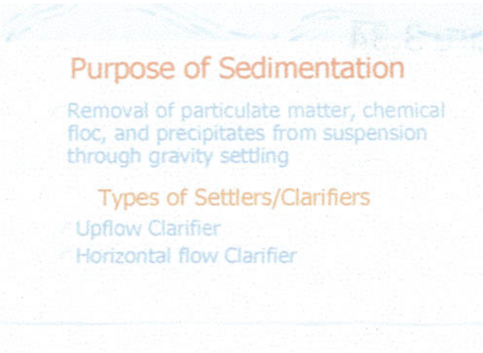
$P = K_T(n)^3(D_i)^5 \rho$ Eq. 3.76

P - Power, W
K_T - Impeller constant
n - Rotational speed
D_i - Impeller diameter, m
ρ - Density of water, kg/m^3

Power Requirements

- Review equation 3.77
- Review equation 3.78

SEDIMENTATION



Purpose of Sedimentation

Removal of particulate matter, chemical floc, and precipitates from suspension through gravity settling

Types of Settlers/Clarifiers

- Upflow Clarifier
- Horizontal flow Clarifier

SEDIMENTATION

There are two important terms to understand in sedimentation zone design. The first is the particle (floc) *settling velocity*, v_s. The second is the velocity at which the tank is designed to operate, called the *overflow rate*,

$$v_o = \frac{\text{Volume/Time}}{\text{Surface Area}} = \frac{\text{(Depth)(Surface area)}}{\text{(Time)(Surface area)}} = \frac{\text{Depth}}{\text{Time}} = \text{Liquid velocity} \qquad (3\text{-}81)$$

$$v_o = \frac{\forall/t_o}{A_s} = \frac{(h)(A_s)}{(t_o)(A_s)} = \frac{h}{t_o}$$

SEDIMENTATION

Discuss Figure 3.33

Discuss Figure 3.34

Newton's Settling Velocity

$$v_s = \left[\frac{4g(\rho_s - \rho)d}{3C_D\rho}\right]^{1/2}$$

FILTRATION

Loading Rate = $v_a = Q/A_s$

Head Loss in Filters,

Discuss equation, 3.105, Page 235

DISINFECTION

Chlorination is a popular method in municipal water treatment plants

Ozone is also used sometimes

Breakpoint Chlorination

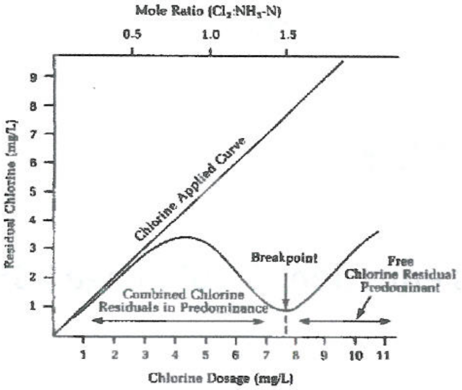


FIGURE 3-44
Breakpoint chlorination. (*Source:* American Water Works Association, *Water Treatment Plant Design*, 1969.)

Disinfection – CT Rule

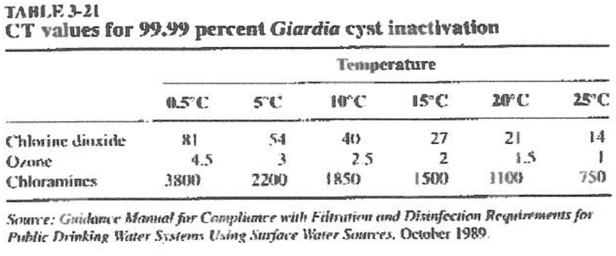


TABLE 3-21
CT values for 99.99 percent *Giardia* cyst inactivation

	Temperature					
	0.5°C	5°C	10°C	15°C	20°C	25°C
Chlorine dioxide	81	54	40	27	21	14
Ozone	4.5	3	2.5	2	1.5	1
Chloramines	3800	2200	1850	1500	1100	750

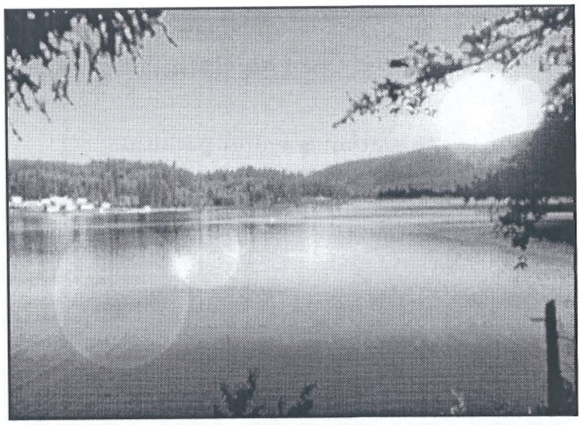
Source: Guidance Manual for Compliance with Filtration and Disinfection Requirements for Public Drinking Water Systems Using Surface Water Sources, October 1989.

ENCE 3323: Introduction to Environmental Engineering

Water Quality Management 1
Chapter 5: Part 1

What is Water Quality Mgmt?

- Control of pollution from human activity so that the water quality is not degraded
- Understanding "assimilative capacity" of a water body
- Need to know "how much is too much"



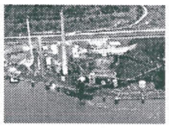
Types of Sources - Water Pollution

- Point sources (relatively easy to manage)
  - Municipal discharges (with or w/o treatment)
  - Industrial discharges (with or w/o treatment)
- Non-point sources (difficult to manage)
  - Urban runoff (combined sewer overflows)
  - Agricultural runoffs

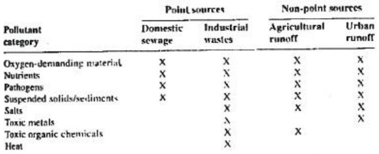
What do you see? What water quality parameter will be affected?

How do they affect water quality?

How does this industry affect the water quality?

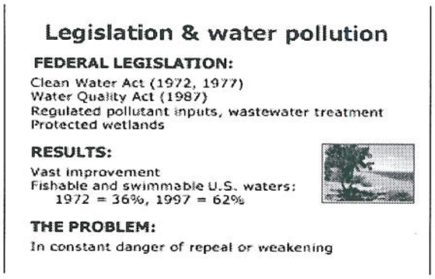


Sources and Water Pollutants



Pollutant category	Point sources Domestic sewage	 Industrial wastes	Non-point sources Agricultural runoff	 Urban runoff
Oxygen-demanding material	X	X	X	X
Nutrients	X	X	X	X
Pathogens	X	X	X	X
Suspended solids/sediments	X	X	X	X
Salts		X	X	X
Toxic metals		X		X
Toxic organic chemicals		X	X	
Heat		X		

Effects of Legislation



Legislation & water pollution

FEDERAL LEGISLATION:

Clean Water Act (1972, 1977)
Water Quality Act (1987)
Regulated pollutant inputs, wastewater treatment
Protected wetlands

RESULTS:

Vast improvement
Fishable and swimmable U.S. waters:
1972 = 36%, 1997 = 62%

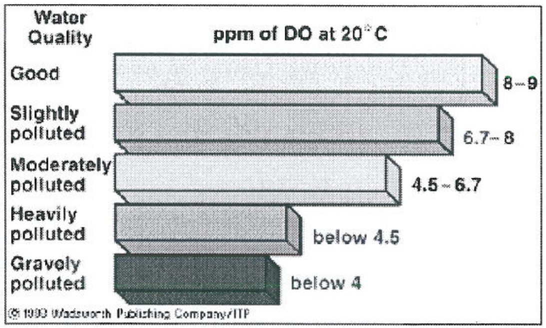
THE PROBLEM:

In constant danger of repeal or weakening

Oxygen Demanding Material

- Dissolved oxygen (DO) is important to support aquatic life
- Brook trout requires 7.5 mg/l DO
- Some can survive at much lower DO
- <u>Pollutants that exert pressure on DO need attention</u>!

DISSOLVED OXYGEN LEVELS and POLLUTION



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Measuring Oxygen Demand

- Theoretical Oxygen Demand (ThOD)
  - Amount of oxygen required to convert a substance to CO_2 and H_2O; theoretical estimate based on stoichiometry
- Chemical Oxygen Demand (COD)
  - Oxygen demand estimated using chemical means (strong oxidizing agent such as chromic acid)
- Biochemical Oxygen Demand (BOD)
  - Oxygen required by microorganisms while consuming the organic matter is food
  - $BOD < COD \leq ThOD$

Theoretical Oxygen Demand (ThOD)

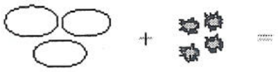
- $C6H12 + 9O2 \rightarrow 6CO2 + 6H2O$
- Theoretical OD (ThOD) would then be:
  - = 288 g (grams of oxygen used)
  - = 4 g Oxygen / g of Carbon (grams of C oxidized - 72)
  - = 3.83 Oxygen / g of C6H12 oxidized

Oxygen-demanding wastes

THE BIOLOGY:

Bacteria in water consume organic material

Use oxygen while metabolizing organics



Low dissolved oxygen

food + oxygen = carbon dioxide + energy

Use dissolved oxygen in the water

BOD and Oxygen-Equivalent Relationships

- Figure 4.1 – Page 290/291 (Eq. 4.1 through 4.4)
- Use Chalk Board
- $L_t = L_0 . e^{-kt}$
- $BOD_t = L_0 - L_t$
- $BOD_t = L_0 (1 - e^{-kt})$
- $BOD_t = L_0 (1 - 10^{-Kt})$

Effect of Temperature on BOD Rate Constant

- $k_T = k_{20} (\theta)^{T-20}$
- k_T = BOD rate constant at T, day-1
- k_{20} = BOD rate constant at 20 oC, day-1
- Θ = Constant (1.135 for T: 4-20 °C; 1.056 for T: 20-30 °C)
- T = Water temperature, °C

Lab Test for BOD

- Step 1: Dilute the sample, seed with microorganisms, add essential trace elements, fill it in 300 ml bottle, measure DO, seal for air tightness and incubate in the dark at 20 °C
- Step 2: Prepare a blank – Same as in step 1 without sample

Lab Test for BOD

- Step 3: Incubate in dark for 5 days (typical) for BOD_5
- Step 4: Measure DO in sample and blank and compute the BOD_5 of undiluted sample

More on BOD Lab Test

- Sample size (%)
  = (Vol. of sample before dilution / Vol. of sample after dilution) x 100
- Dilution fraction
  = (Vol. of sample before dilution / Vol. of sample after dilution)
- Dilution factor
  = (Vol. of sample after dilution / Vol. of sample before dilution)
  = 100 / (Sample size, %)

BOD Test - Seeding

- Seeding is often done in BOD test procedure as the sample may not contain enough microbial population
- Seeding does consume extra DO, so a blank is used to estimate this value
- Separate BOD calculations have to be used for (a) Unseeded and (b) Seeded procedures

Unseeded BOD Test Method

- BOD_5 =

  $[(DO_{s,i} – DO_{s,f})$ / (Dilution fraction)] mg/l

- $DO_{s,i}$ (mg/l) - Initial DO of sample after dilution
- $DO_{s,f}$ - Final DO of sample after incubation, 5 days (mg/l)

Seeded BOD Test Method

- BOD_5 =

  $\{[(DO_{s,i} – DO_{s,f}) – (1 – \text{Dilution fraction}).(DO_{b,I} - DO_{b,f}]\}$ / (Dilution fraction) mg/l

- $DO_{s,i}$ - Initial DO of sample after dilution (mg/l)
- $DO_{s,f}$ - Final DO of sample after incubation, 5 days (mg/l)
- $DO_{b,I}$ - Initial DO of blank (mg/l)
- $DO_{b,f}$ - Final DO of blank after incubation, 5 days (mg/l)

Example 1: Unseeded BOD Test

For a BOD test, 75 ml of a river water sample is used in the 300 ml of BOD bottles without seeding with three repetitions. The initial DO in three bottles read 8.86, 8.88, and 8.83 mg/l respectively. The DO levels after 5 days at 20 °C incubation are 5.49, 5.65 and 5.53 mg/l respectively. Find the 5-day BOD for the river water.

Example 2: Seeded BOD Test

A 10 ml sample of sewage mixed with enough water to fill a 300-ml bottle has an initial DO of 9 mg/l. After 5 days of incubation at 20 °C, the final DO was measured 2 mg/l. The DO in blank, which was 9 mg/l at the start of the test, was measure to be 8 mg/l after 5 days of incubation. Calculate the BOD5 at 20 °C.

Example 3: Unseeded BOD Test

A 10 ml sample of sewage was mixed with 290 ml dilution water and filled in a 300 ml BOD bottle. The initial DO is 5 mg/l. For an accurate test, it is desirable to have at least a 2 mg/l drop in DO during 5 day run, and the final DO should be at least 2 mg/l. For what range of BOD_5 would this dilution produce the desired results.

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Water Quality Management 2

Review of the Last Class Material

- Sources of water pollution
  - Pont & Non-point sources
- Measuring Oxygen Demand
  - ThBOD / COD / BOD
- Equations involving BOD vs. time
- BOD lab test procedure
  - Unseeded
  - Seeded

More on Water Quality Mgmt.

- Nitrogenous BOD
- DO Sag Curve
- Effects of Nutrients on Water Quality in Rivers
- Water Quality Mgmt. In Lakes
- Solve Problems
- Home Work Assignment

Carbonaceous BOD and Nitrogenous BOD

- Carbonaceous BOD refers to the oxygen demand exerted by oxidation of carbon in organic compounds
- Nitrogenous BOD refers to the oxygen demand exerted by the oxidation of ammonia to nitrate (NO_3^-)
- Oxidation of ammonia to nitrate is also known as nitrification

Nitrogenous BOD

- Nitrification is caused by nitrifying bacteria
- $NH_4^+ + 2\,O_2 \leftrightarrow NO_3^- + H_2O + 2H^+$
- NBOD = 4 x 16 / 14
  = 4.57 g of O_2 / g N

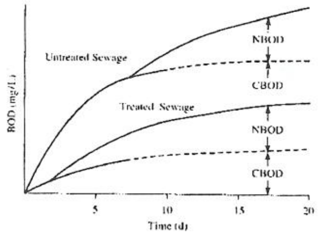


FIGURE 4-6
BOD curves showing both carbonaceous and nitrogenous BOD.

DO Sag Curve
STREETER- PHELPS MODEL

DO Sag Curve

- DO in river water indicates the health of the river
- DO levels are to be maintained above 4 – 5 mg/l to support aquatic life forms
- Oxygen demand (BOD) and the oxygen supply (re-aeration) are considered in understanding the DO sag

DO Sag Curve

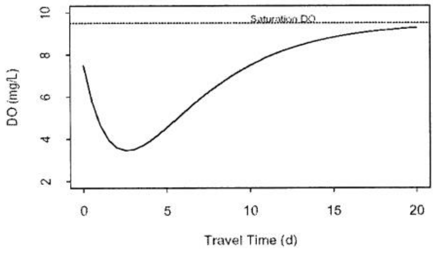


Figure 12. Typical DO sag curve

DO Sag Curve

- Be able to identify various points on the DO sag curve
- Initial deficit
- Critical point
- Critical time
- Critical deficit

Oxygen Deficit (D)

- Difference between the saturation -dissolved oxygen concentration (DO_s) to actual dissolved oxygen concentration (DO)
- $D = DO_s - DO$

Mass Balance Approach

- Mass balance approach is applied to calculate:

• DO	Equation 5.23
• BOD	Equation 5.24
• Temperature	Equation 5.30

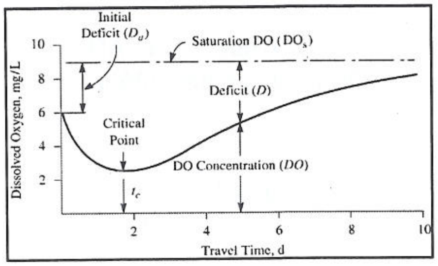


Fig 5-8: Typical DO sag curve

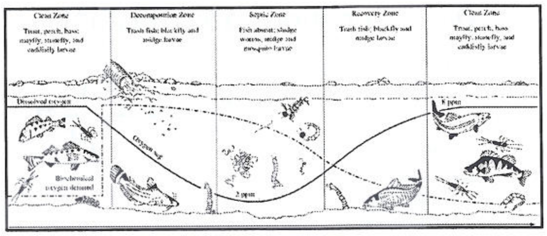


Fig 5-9:Oxygen Sag downstream of an organic source

DO Sag Curve

- Relationship is derived based on oxygen utilization and re-aeration

$$\frac{dD}{dt} = k_d L - k_r D$$

- Boundary conditions
- At t = 0, $D = D_a$; $L = L_a$
- At t = t, D = D, L = L

$$\frac{dD}{dt} = K_d L - K_r D$$

DO Sag Equation with CBOD (Streeter-Phelps Equation)

$$D = \frac{k_d L_a}{k_r - k_d}(e^{-k_d t} - e^{-k_r t}) + D_a(e^{-k_r t})$$

$$D = \frac{K_d L_a}{K_r - K_d}\left(10^{-K_d t} - 10^{-K_r t}\right) + D_a\left(10^{-K_r t}\right)$$

Deoxygenation Rate Constant

- Is different from the BOD rate constant; mostly higher
- v – stream velocity, m/s
- η (eta) – bed activity coefficient
- H – average depth of stream, m
- k – BOD rate constant at 20 Deg. C, 1/d

$$k_d = k + \frac{v}{H}\eta$$

DEOXYGENATION RATE CONSTANT at 20ºC (BASE 10)

$$K_d = K + \left[\frac{v}{2.3H}\eta\right]$$

Reaeration Rate Constant at 20ºC (BASE e)

$$k_r = \frac{3.9v^{0.5}}{H^{1.5}}$$

REAERATION RATE CONSTANT at 20ºC (BASE 10)

$$K_r = \frac{1.7v^{0.5}}{H^{1.5}}$$

CONVERTING k_r OR K_r TO STREAM TEMPERATURE

$K_t = K_{20}\,\theta^{T-20}$

$\theta = 1.024$

$$L = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r}$$

$$D_a = DO_s - \left[\frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r}\right]$$

TIME TO CRITICAL POINT

(BASE 10)

$$t = \frac{1}{K_r - K_d}\log\frac{K_r}{K_d}\left[1 - D_a\left(\frac{K_r - K_d}{K_d L_a}\right)\right]$$

Critical Time (t_c)

$$t_c = \frac{1}{k_r - k_d}\ln\frac{k_r}{k_d}[(1 - D_a\frac{k_r - k_d}{k_d L_a})]$$

DO Sag with CBOD and NBOD

$$D = \frac{k_d L_a}{k_r - k_d}(e^{-k_d t} - e^{-k_r t}) + D_a(e^{-k_r t})$$

$$+ \frac{k_n L_n}{k_r - k_n}(e^{-k_n t} - e^{-k_r t})$$

Limnology

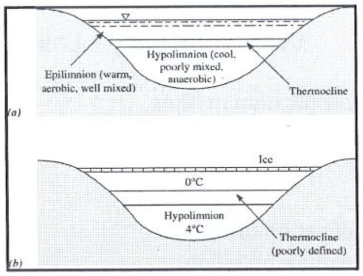


Fig 5-13: Stratification of a lake a) summer b) winter

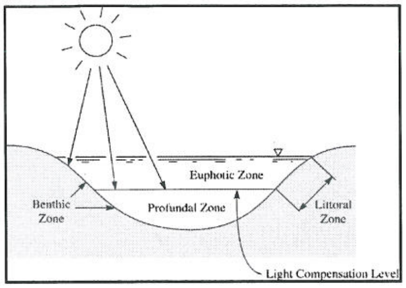


Fig 5-14: Biological zones in a lake

Types of Lakes

- Oligotrophic (Clear Water; Low Productivity)
- Eutrophic (Turbid; High Productivity)
- Mesotrophic (Intermediate productivity)
- Senescent (Shallow with rooted plants; this will eventually turn into marsh)

Effects of Nutrients in Rivers

- Nitrogen
  - NH3-N in high concentrations is toxic to fish
  - NH3 and NO3- promote algae growth
  - NH4+ to NO3- consumes high DO
- Phosphorous
  - Promotes algae growth, which in turn exerts oxygen demand
- Management Strategy: Control nutrients to limit algal blooms and eutrophication

Water Quality - Lakes

- Epilimnion (warm, aerobic, well mixed)
- Thermocline (poorly defined)
- Hypolimnion (cool, anaerobic, poorly mixed)

- Oligotrophic lakes (clear water, low productivity)
- Eutrophic lakes (turbid, high productivity)

Water Quality - Lakes

- Eutorphication in lakes
- What causes, how to control

- Acidfication of lakes
- Role of air pollution
- SO_2 and NO_x emissions from fuel combustion

Algal Growth Requirements

- Carbon
- Nitrogen
- Phosphorus
- Trace Elements

“ The” limiting Nutrient is P

H.W

Eviron Jan 19 S10 ①

2.1, 2.4, 2.5, 2.8, 2.9, 2.10, 2.11, 2.14
2.19, 2.22, 2.23, 2.26, 2.27, 2.31, 2.32,
2.36

Problem 2.1

Area = 16.2 ha   Avg. deth = 10m

msw Vol delivered = 765 m^3/day (5 days/week)
compaction → Twice the delivered density

Landfill Vol. Allowable $= 16.2\ ha \times 10{,}000\ \frac{m^2}{ha} \times 10m = \underline{\underline{16.2 \times 10^5\ m^3}}$

msw compacted Vol/week $= \frac{765 m^2}{2} = \frac{382.5}{m^3/wk}$

compacted msw in 1-yr

$= 382.5\ \frac{m^3}{wk} \times \frac{52 wk}{yr} \times 5 = 99450\ m^3/yr$

Life of Landfill in yrs $= \frac{16.2 \times 10^5\ m^3}{99450\ m^3/yr} = 16.3$ yrs.

Expl 2.4 from Slide

$M_{in} = Q_{in} \times C_{in} = 47\ \frac{m^3}{s}\left(15\ \frac{g}{m^3}\right) = 705\ g/s = 705000\ mg/s$

$M_o = 47\ m^3/s\left(24\ \frac{mg}{m^3}\right) = 1128\ \frac{mg}{s} =$

$\eta = \frac{M_{in} - M_{out}}{M_{in}} = 99.8\ \%$

1 bag not there: $15\ g/m^3\left(\frac{1}{424}\right)\left(47\ \frac{m^3}{s}\right) = 1.66\ g/s = 1660\ \frac{mg}{s}$

$\frac{423}{424}\left(47\ m^3/s\right)\left(24\ \frac{mg}{m^3}\right) = 1125.3\ mg/s$

Total mass emission rate = 2785.3 mg/s

concentration $= \frac{2785.3\ mg/s}{47\ m^3/s} =$ ____

$\eta = \cancel{\frac{15\ g/m^3 - 2.7853\ g/s}{15\ g/m^3} = 81\%}$ 99.6

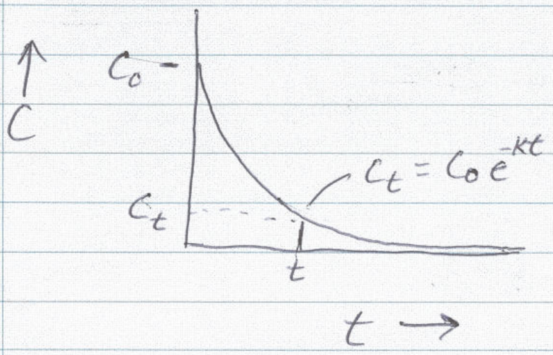
record pause stop   jump   bookmark   0% jump to position 100%   playback speed   volume can make excel into 3×5 sections?

②

$$r = -kC = \frac{dC}{dt} \rightarrow \frac{dC}{dt} = -kC$$

$$\int_{C_0}^{C} \frac{1}{C}\,dC = -k \int_0^t dt$$

$$\ln \frac{C_t}{C_0} = -kt \rightarrow \underline{\underline{C_t = C_0 e^{-kt}}}$$



Tank

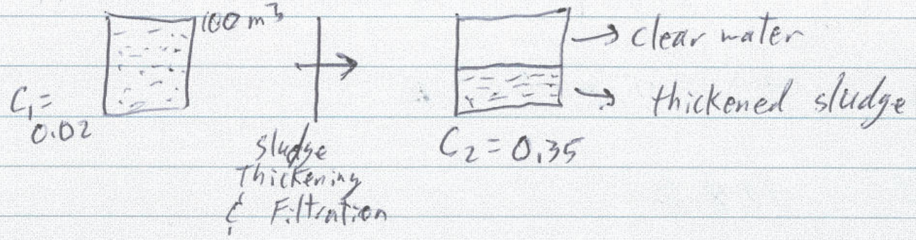
$$C_{out} = C_{in} e^{-k\theta}$$

$$\theta = \frac{V}{Q} = \frac{m^3}{m^3/hr} = hr$$

residence time
retention time

$$\frac{dM}{dt} = \frac{d(C\forall)}{dt} = \forall \frac{d(C)}{dt}$$

2-8) $V_1 = 100\,m^3$ $C_1 = 2\% = 0.02 \rightarrow C_2 = 35\% = 0.35$



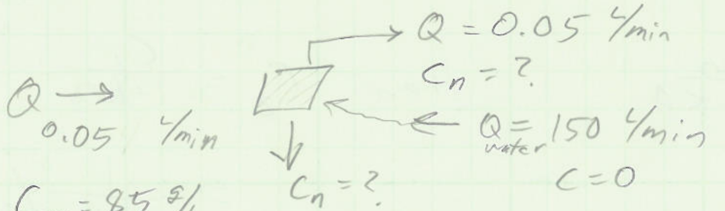
$C_1 V_1 = C_2 V_2$ $0.02(100) = 0.35\,V_2$ $V_2 = 5.7\,m^3$

Environ Jan-29 S10 ①

Duration min	Intinsity $\frac{mm}{hr}$					
	10	20	30	160	180	200
				7	3	2

highest rank storm = 1
then 2, 3 . .

2.11)



$C_m = 85\ g/L$

$Q_{I_1}C_{I_1} \qquad + \qquad - (Q_{O_1}C_{O_2} + (Q_{O_2}C_{O_2})$

$0 = 0.05\frac{L}{min}(85\ g/L) + \underbrace{Q_{I_2}C_{I_2}}_{\cancel{0}} - (0.5C_N + 150C_N)$

$C_N = 28.3\ mg/L$

2.31) $V_{ol} = 280 m^3$, $Q = 14 m^3/d$ $\quad K = 0.05 d^{-1}$

cont. mix fluid reactor

CMFR 1^{st} order $\frac{C_0}{1+K\theta}$ $\qquad \theta = \frac{V}{Q} = \frac{280}{14} = 20d$

table 2.1, 2.2

$\frac{C_1}{C_0} = \frac{1}{1+K\theta} = 0.5 \qquad \eta_{CMFR} = \frac{C_0 - C_1}{C_0} = \boxed{50\% \text{ efficient}}$

Plug flow reactor

PFR $C_t = C_0 e^{-K\theta}$

$\frac{C_t}{C_0} = e^{-K\theta} = 0.37$

$\eta = \frac{C_0 - C_t}{C_0} = 63\%$

2-26 $A = 10\ ha = 10\ ha \times 10{,}000\frac{m^2}{ha}$, depth = 1m, $Q = 8640\ m^3/d$

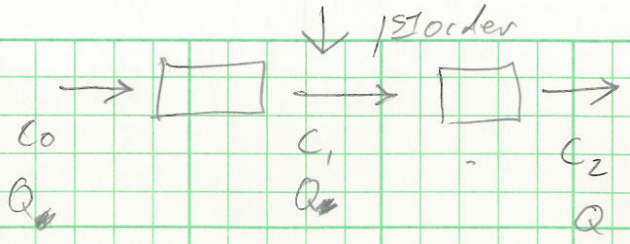
$C_0 = 100\ mg/L$, $C_1 = 20\ mg/L$

Assume CMFR from table $C_1 = \frac{C_0}{1+K\theta}$ $\qquad \theta = \frac{V}{Q} = \frac{10 \times 10000\ m^2 \times 1m}{8640\ m^3/d} = 11.574d$

$\boxed{K = 0.3456 d^{-1}}$

over

2.27)



$\forall$ for each = 5 ha 10000 $\frac{m^2}{ha}$

depth = 1m

$$Q = \frac{\forall}{Q} = \frac{5(10000\ m^2)(1m)}{8640\ m^3/d} = 5787\ \text{days}$$

1st order $C_1 = \frac{C_0}{1+k\theta}$ then $C_2 = \frac{C_1}{1+k\theta}$

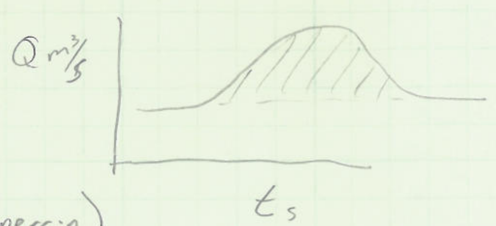
$$= \frac{1}{1+k\theta}\left(\frac{C_0}{1+k\theta}\right)$$

$$100 = \left(\frac{1}{1+k(5.787)}\right)^2 \times 20$$

$$k = 0.2136\ d^{-1}$$

Jan 2 ENVIRON 310 ①

$$V_{\text{excess water}} = Q \cdot t$$



Depth of Excess Precipitation
$$\left\{ \frac{\text{Area under curve } (\overset{\text{which is}}{\text{Vol of excess percip}})}{\text{watershed Area}} \right. = \frac{m^3}{m^2} = \underline{\underline{m}}$$

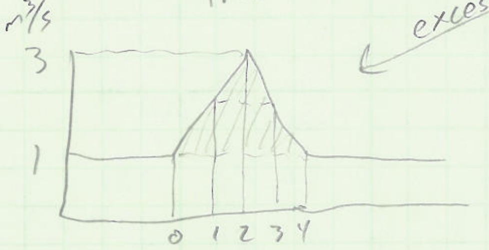
3 different storms

Time	rainfall excess (cm)		DRH ordinates 1	2	3	combined
1	0.10	(2-1)	1			1.0
2	0.20 (twice intensity)	(3-1)	2	2		4.0
3	0.05 (half intensity)	(2-1)	1	4	0.5	5.5
4	0.0		0	2	1	
5	0.0		0	0	0.5	

~~used by~~

increase in first hr. from base flow

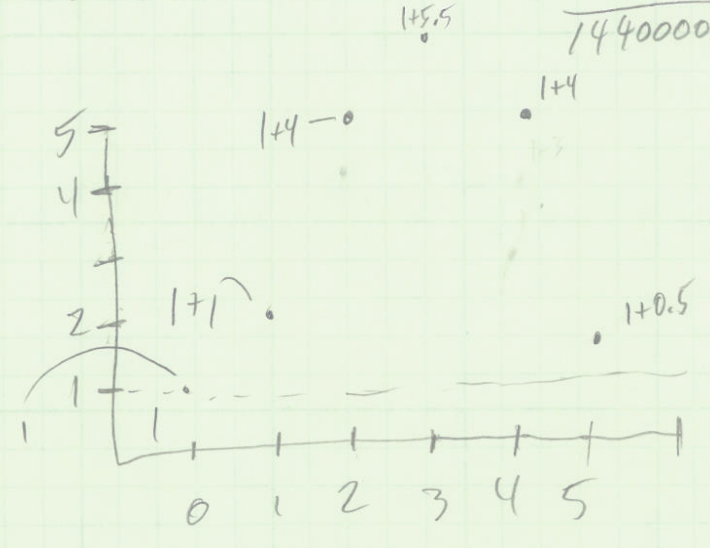
excess rainfall volume = area



$$\text{Height}_{\text{excess rainfall}} = \frac{\text{area}}{\text{watershed area}}$$

$$= \frac{14\,400\,m^3}{14\,400\,000\,m^2} = 0.001\,m = 0.1\,cm$$

∴ not unit Hydro



Darcy = superficial velocity (assumes flow through entire cross-sec area)

$Q = VA$

Pore velocity $Q = V(A \times \text{porosity})$ (actual area water flows through)

4 Part 1 40/40

4 Part 2 80/80

5th/50

GA: NAVeen Devata EN833

①

4-14) mg/L mag_{ion} = ? H_2O = 0.001000 M in hydroxyl ion @ 25°C?

p.199

$pk_s = 11.25 \qquad k_{sp} = 10^{-11.25} = 5.62 \times 10^{-12}$

$K_{sp} = Mg^{2+}[OH^-]^2$ ✓

$Mg^{2+} = \frac{5.62 \times 10^{-12}}{0.001^2} = 5.62 \times 10^{-6} \frac{mole}{L}$

10

$Mg^{2+} = (5.62 \times 10^{-6} \frac{mole}{L})(24.305 \times 10^3 \frac{mg}{mole}) = \boxed{0.1367 \frac{mg}{L}}$ ✓

4-15) 1.800 $\frac{mg}{L}$ Fe^{3+} pH = ? to precipitate all but 0.300 $\frac{mg}{L}$ @ 25°C.

p.199 $pK_s = 38.57$

$K_{sp} = 10^{-38.57} = 2.69 \times 10^{-39}$ ✓

$[Fe] = \frac{0.30 \text{ mg/L}}{55.85 \text{ g/mol} (1000 \text{ mg/g})} = 5.37 \times 10^{-6}$ mole/L

$k_{sp} = Fe[OH]^3 \qquad [OH^-] = \left(\frac{2.69 \times 10^{-39}}{5.37 \times 10^{-6}}\right)^{1/3} = (5.01 \times 10^{-33})^{1/3} = 7.94 \times 10^{-12} \frac{mol}{L}$

10

$pOH = -\log(7.94 \times 10^{-12})$

$pOH = 11.10$ & $pH = 14.00 - 11.10 = \boxed{2.90}$ ✓

4-21) pH finished H_2O = 10.74. amt ? of 0.02000 N sulfuric acid, H_2SO_4 in milliliters, req. to neutralize 1.000 L of finished water. assume buffering capacity = 0.

$pOH = 14.00 - 10.74 = 3.26$

$[OH^-] = 10^{-3.26} = 5.50 \times 10^{-4} \frac{mole}{L}$ ✓

OH^{-1} @ n = 1 normality = molarity

$N(mL) = N(mL) = 5.50(10^{-4})(1000 \text{ mL}) = (0.02000)(\text{mL acid})$

$\rightarrow$ mL acid = 27.48 mL

✓

10

H_2CO_3

4-24) pH H_2O @ 25°C = ? contains $0.6580 \frac{mg}{L}$ carbonic aid.

Assume $H^+ = HCO_3^-$ @ equilibrium neglect dissociation of H_2O

p. 202 $pK_a = 6.35$ for H_2CO_3

$$\frac{0.6580\,mg}{62.026\,\frac{g}{mole}\left(1000\,\frac{mg}{g}\right)} = 1.061 \times 10^{-5}\,\frac{mole}{L}$$

$$K_a = \frac{H^+[HCO_3^-]}{H_2CO_3} = 10^{-6.35} = 4.467 \times 10^{-7}$$ ✓

$$\frac{H^+[HCO_3^-]}{1.061 \times 10^{-5}} = 4.467 \times 10^{-7}$$ since here $H^+ = HCO_3$

✓

10

$[H^+]^2 = 4.739 \times 10^{-12}$

$H^+ = 2.177 \times 10^{-6}$

$pH = -\log(2.177 \times 10^{-6}) = 5.66$ ✓

4-26) pH_{H_2O} @ 25°C has $0.5000 \frac{mg}{L}$ of hypochlorous acid? ✓

P. 202 $pK_a = 7.54$ for HOCl

$$\frac{0.5000\,mg}{(52.45\,g/mole)(1000\,\frac{mg}{g})} = 9.53 \times 10^{-6}\,\frac{mole}{L}$$

$$K_a = \frac{H^+[OCl^-]}{HOCl} = 10^{-7.54} = 2.884 \times 10^{-8}$$ ✓

10

$H^+ = OCl^- \rightarrow [H^+]^2 = 2.748 \times 10^{-13} \rightarrow H^+ = 5.24 \times 10^{-7}$ ✓

$pH = -\log(5.24 \times 10^{-7}) = \boxed{6.28}$ ✓

4-28) Ca^{2+} (n = 2 b/c valence = 2) E.W. = $\frac{40.08}{2} = 20.04$

$\frac{mg}{L}$ as $CaCO_3 = 83.00 \frac{mg}{L}\left(\frac{50.04}{20.04}\right) = \boxed{207.3}$

✓

Mg^{2+} (n = 2 because valence = 2)

$$E.W. = \frac{24.305}{2} = 12.1525$$

$$\frac{mg}{L} \text{ as } CaCO_3 = 27.00 \frac{mg}{L}\left(\frac{50.04}{12.1525}\right) = \boxed{111.2}$$ ✓

CO_2 (n = 2 b/c H_2CO_3 has 2 H)

$$E.W. = \frac{44.01}{2} = 22.0$$

$$\frac{mg}{L} \text{ as } CaCO_3 = 48 \frac{mg}{L}\left(\frac{50.04}{22}\right) = \boxed{109.2}$$ ✓

10

HCO_3 (n = 1 b/c valence = 1)

$$E.W. = \frac{61.02}{1} = 61.02$$

$$\frac{mg}{L} \text{ as } CaCO_3 = 220 \frac{mg}{L}\left(\frac{50.04}{61.02}\right) = \boxed{180.4}$$ ✓

CO_3^{2-} (n = 2 b/c valence = 2)

$$E.W. = \frac{60.01}{2} = 30.0$$

$$\frac{mg}{L} \text{ as } CaCO_3 = 15 \frac{mg}{L}\left(\frac{50.04}{30}\right) = \boxed{25.02}$$ ✓

4-33 alkalinity_{H_2O} = ? if has 0.6580 mg/L of bicarbonate as ion @ PH = 5.66, no carbonate present.

$$0.6580 \frac{mg}{L} HCO_3^- \left(\frac{50.04}{61.016}\right) = 0.53963 \frac{mg}{L} \text{ as } CaCO_3$$

$$[H^+] = 10^{-5.66} = 2.188 \times 10^{-6} \frac{mole}{L}$$

$$\frac{mg}{L} = 2.188 \times 10^{-6} \frac{mole}{L}\left(1.0079 \times 10^3 \frac{mg}{mole}\right) = 2.205 \times 10^{-3} \frac{mg}{L}$$

$$2.205 \times 10^{-3}\left(\frac{50.04}{1.0079}\right) = 0.1098$$

$$pOH = 14 - 5.66 = 8.34$$

$$[OH] = 10^{-8.34} = 4.571 \times 10^{-7} \frac{mole}{L}\left(17.007 \times 10^3 \frac{mg}{mole}\right) = 7.774 \times 10^{-5} \frac{mg}{L}$$

$$\rightarrow \text{as } CaCO_3 \left(\frac{50.04}{17.007}\right) = 2.287 \times 10^{-4}$$

OVER

$ALK = HCO_3^- + CO_3^2 + OH^- - H^+$ ✓ 10

$= 0.53963 + 0 + 2.287\times10^{-4} - 0.10948$

$= \boxed{0.430\ \frac{mg}{L}\ \text{as } CaCO_3^-}$

4-34 $HCO_3^-\quad (120\ \frac{mg}{L})(\frac{50.04}{61.02}) = 98.41\ \frac{mg}{L}$ ✓

$CO_3^{2-}\quad (15\ \frac{mg}{L})(\frac{50.04}{30.0}) = 25.02\ \frac{mg}{L}$ ✓ 10

$ALK = 98.41 + 25.02 = \boxed{123.4\ \frac{mg}{L}\ \text{as } CaCO_3}$ ✓

4-40 $120\ CO_3^{2-}\ \frac{mg}{L}\ (\frac{50.04}{30}) = 200\ \frac{mg}{L}\ \text{as } CaCO_3 = \frac{2(4.68\times10^{-11})}{10^{-10.3}}(HCO_3^-)$ ✓

$\rightarrow HCO_3^- = \frac{200}{1.868} = 107.2\ \frac{mg}{L}\ \text{as } CaCO_3$

$HCO_3^- = 107.2(\frac{61.016}{50.04}) = \boxed{130.7\ \frac{mg}{L}}$ ✓ 10

4-41 $HCO_3^- = 120(\frac{50.04}{61.016}) = 100.053$

$CO_3^{2-} = 15(\frac{50.04}{30}) = 25.02 = \frac{2(4.68\times10^{-11})}{H^+}(100.053)$ ✓

$\rightarrow H^+ = \frac{9.365(10^{-9})}{25.02} = 3.743\times10^{-10}$ 10

$pH = -\log(3.743\times10^{-10}) = \boxed{9.43}$ ✓

4-51 assume $ALK = HCO_3^-$ $n=3$

$E.W. = \frac{162.206}{3} = 54.069$

$30(\frac{50.04}{54.069}) = 27.76\ \frac{mg}{L}\ \text{as } CaCO_3$

$HCO_3^-\ \text{remaining} = 136 - 27.8 = \boxed{108.2\ \frac{mg}{L}\ \text{as } CaCO_3}$

Not Considered

4-57 $TH = 120 + 30 = 150 \frac{mg}{L}$ as $CaCO_3$

$CH = 70 \frac{mg}{L}$ as $CaCO_3$

$NCH_i = 150 - 70 = 80 \frac{mg}{L}$ as $CaCO_3$

Lime = $CO_2 = 10$ ✓

Lime = $HCO_3 = 70$

$Mg^{2+} < 40$ add lime = 20

Total Lime = $100 \frac{mg}{L}$ as $CaCO_3$ ✓

10

$NCH_f = 80 - 40 = 40$

$NCH_R = NCH_i - NCH_f = 80 - 40 = 40$

∴ Add soda = $40 \frac{mg}{L}$ as $CaCO_3$ ✓

4-67 $TH = 200 + 100 = 300 \frac{mg}{L}$ as $CaCO_3$

$CH = 150 \frac{mg}{L}$ as $CaCO_3$

$NCH_i = 300 - 150 = 150 \frac{mg}{L}$ as $CaCO_3$

Lime = $CO_2 = 22$, Lime = $HCO_3^- = 150$, $Mg > 40$ ∴ add lime

$= 100 - 40 = 60$ ✓

$\Delta = 60 > 40$ ∴ add lime = 40

Total lime = $22 + 150 + 60 + 40 = 272 \frac{mg}{L}$ as $CaCO_3$

$NCH_f = 80 - 40 = 40$

$NCH_R = 150 - 40 = 110 \frac{mg}{L}$ as $CaCO_3$ ✓

Soda = $110 \frac{mg}{L}$ as $CaCO_3$

Lime as CaO

$$272 \left(\frac{28.04 \text{ E.W. } CaO}{50.04 \text{ E.W. } CaCO_3} \right) = 152.4 \frac{mg}{L}$$

Soda as Na_2CO_3 $\quad$ $E.W. = \frac{105.99}{2} = 53$

$$110 \left(\frac{52.99 \text{ E.W. } NaCO_3}{50.04 \text{ E.W. } CaCO_3} \right) = 116.49 \frac{mg}{L}$$

Annual Cost

$$\left(0.5 \frac{m^3}{s}\right)\left(86400 \frac{s}{d}\right)\left(365 \frac{d}{yr}\right) = 1.5768 \times 10^7 \, m^3$$

$$\left(1000 \frac{L}{m^3}\right)\left(1.58 \times 10^7 m^3\right) = 1.58 \times 10^{10} \, L$$

Over

CaO

$(152.41 \frac{mg}{L})(1.58\times10^{10} L) = 2.4\times10^{12}\ mg \xrightarrow{x} (10^{-9} \frac{Mg}{mg})(\$100\ Mg^{-1})$

$= \$240,326.45$

$NaCO_3$

$(116.49 \frac{mg}{L})(1.58\times10^{10} L)(10^{-9} \frac{Mg}{mg})(\$200\ Mg^{-1}) = \$367,376.80$

10

$\Sigma_{cost} = \text{total cost} = \boxed{\$607,703.25}$

5.16 $-K = 0.08\ d^{-1}$

$280\ BOD_5 = L(1-10^{-(0.08)(5)}) \rightarrow L = \boxed{465 \frac{mg}{L}}$

$-K = 0.120\ d^{-1}$

10

$280 = L(1-10^{-(0.12)(5)}) \rightarrow L = \boxed{374 \frac{mg}{L}}$

5.26 WW) $L_0 = \frac{590 \frac{mg}{L}}{1-e^{-(0.115)(5)}} = 1349 \frac{mg}{L} \quad \therefore L_w = 1349 \frac{mg}{L}$

Creek) $L_0 = \frac{0.6 \frac{mg}{L}}{1-e^{-(3.7)(5)}} = 0.6 \frac{mg}{L} \quad \therefore L_r = 0.6 \frac{mg}{L}$

$$L_a = \frac{0.011 m^3/s (1349 mg/L) + 1.7 m^3/s (0.6 mg/L)}{0.011 m^3/s + 1.7 m^3/s} = \boxed{9.27 \frac{mg}{L}}$$

10

$$D = \frac{0.2805(27.7)}{0.474-0.2805}\left(e^{-(0.2805)(0.462)} - e^{-(0.474)(0.462)}\right) + 2.85\,e^{-(0.474)(0.462)} = 5.3\ \frac{mg}{L}$$

✓

$$DO = 9.95 - 5.3 = 4.65\ \frac{mg}{L}$$

$$t_c = \frac{1}{0.474-0.2805}\ln\left(\frac{0.474}{0.2805}\left(1-2.85\left(\frac{0.474-0.2805}{(0.2805)(27.65)}\right)\right)\right) = 2.33d$$

$$D_c = \frac{0.2805(27.65)}{0.474-0.2805}\left(e^{-(0.2805)(2.33)} - e^{-(0.474)(2.33)}\right) + 2.85\,e^{-(0.474)(2.33)} = 8.51\ \frac{mg}{L}$$

$DO = 9.95 - 8.51 = 1.44\ \frac{mg}{L}$ @ critical pt.

distance to critical pt $= (0.39\ m/s)(86400\ s/d)(2.33d)(1\times10^{-3}\ \frac{km}{m}) = 78.5$ km

from Watapitae

<u>capacity is restricted</u> ✓

10

5-32 by inspection from given $D_a = 0$

$K_d = K_r \rightarrow t_c = \frac{1}{0.3}(1-0) = 3.33 d$

$D = [0.3(3.33)(50)+0]e^{-(0.3)(3.33)} = 18.41 \frac{mg}{L}$

$DO = 11.33 - 18.41 = -7.08 \frac{mg}{L} = 0 \frac{mg}{L}$

5-33 $k_{20} = \frac{K_{10}}{\theta^{10-20}} = \frac{0.3}{(1.135)^{-10}} = 1.064 d^{-1}$ ✓

$k_d = k_{15} = 1.0643(1.135)^{15-20} = 0.565 d^{-1}$ ✓

$k_{20} = \frac{0.3}{1.024^{-10}} = 0.380 d^{-1}$ ✓

$k_r = k_{15} = 0.380(1.024)^{15-20} = 0.338 d^{-1}$

$t_c = \frac{1}{0.338-0.565} \ln\left(\frac{0.338}{0.565}\left(1-0\left(\frac{0.338-0.565}{0.565(50)}\right)\right)\right) = 2.26$ 10

$D_c = \frac{0.565(50)}{(0.338)-0.565}\left(e^{-(0.565)(2.264)} - e^{-(0.338)(2.264)}\right)+0 = 23.3 \frac{mg}{L}$ ✓

$DO = 10.15 - 23.27 =$ neg. $= 0$

5-35 $D_c = DO_s - DO = 10.83 - 4 = 6.83 \frac{mg}{L}$ ✓

Since L_w reduces 50% c $t_c = 0$ La reduces 50%

$D_c = 0.5(6.83) = 3.415$ ∴ $DO = DO_s - D_c = 7.42 \frac{mg}{L}$ 10

5-40 $t = \frac{15.55 \text{ km}(1000 \frac{m}{km})}{(0.39 \frac{m}{s})(86400 \frac{s}{d})} = 0.462 d$ ✓

$k_d = 0.4375 + \frac{0.39}{2.8}(0.2) = 0.465$ @ 20°C ✓

$kd = 0.4654(1.135)^{16-20} = 0.2805 d^{-1}$ @ 16°C ✓

$K_r = \frac{3.9(0.39)^{0.5}}{2.8^{1.5}} = 0.5212$ @ 20°C

$Kr = 0.5212(1.024)^{16-20} = 0.474 d^{-1}$ @ 16°C ✓

$D_a = 9.95 \frac{(0.1507)(1)+(1.08)(7.95)}{0.1507+1.08} = 2.85 \frac{mg}{L}$

$L_w = \frac{128}{1-e^{-(0.4375)(5)}} = 144.2 \frac{mg}{L}$ ✓

$L_a = \frac{0.1507(144.2)+(1.08)(11.40)}{0.1507+1.08} = 27.7 \frac{mg}{L}$

over

~~40~~ ~~50~~ / 160

ENCE 3323 S10 H.W. #1 Donald Jerolleman p.1 of

2-1) Given: Avail. Landfill space: 16.2 ha, depth = 10m, 765 m^3 waste (solid) dumped 5×/week, Compacted 2× its delivery density

Req'd: Draw mass-balance dia. & est. expected life of landfill in yrs.

Sol'n:

$$\text{Avail space} = 16.2\text{ ha}\left(10000\ \frac{m^2}{ha}\right) = 162{,}000\ m^2$$

$$\text{" vol.} = 162000\ m^2 (10m) = \underline{1{,}620{,}000\ m^3}$$

$$\text{msw compacted Vol./wk} = \left(\frac{765 m^3}{2}\right)\times 5 = 1912.5\ m^3/wk$$

10

$$/yr = 1912.5\ \frac{m^3}{wk}\left(\frac{52\ wk}{yr}\right) = \underline{99450\ m^3/yr}$$

$$\text{Approx Life} = \frac{\text{Avail vol.}}{\text{Vol. Disposed / yr}} = \frac{1620000\ m^3}{99450\ m^3/yr} = \boxed{16.3\text{ yrs}}$$ ✓

$$\text{mass-balance diagram:}\quad \text{compacted mass} \longrightarrow \boxed{\text{Accumulation}} \longrightarrow \emptyset$$

2-4) Given: vapor emission (splash-fill) ≈ 2.75 $\frac{kg}{m^3}$ of gas delivered.
vapor emission (sealed-fill) ≈ 0.095 $\frac{kg}{m^3}$ " " "
Fill rate: $4\ m^3/wk \left(\frac{1000\ L}{m^3}\right) = 4000\ L/wk$

Req'd: mass-balance diagram, Value of fuel captured in sealed method

$\gamma_{vapors} = 0.800\ g/mL \left(\frac{1000 mL}{L}\right) = 800\ g/L$, $\text{Cost}_{gas} = \$1.06 / L$

Solution: Δ vapor emissions = splash − sealed = $2.75 - 0.095 = 2.655\ \frac{kg}{m^3}$

~~8~~
10

$$2.655\ \frac{kg}{m^3}\left(\frac{1000 g}{kg}\right)\left(\frac{1 m^3}{1000 L}\right) = 2.655\ g/L \text{ saved}$$ ~~✗~~ ✓

$$4000\ \frac{L}{wk}\left(2.655\ \frac{g}{L}\right)(\cancel{800})\left(\frac{1}{800}\ \frac{L}{g}\right) = 13.275\ L/wk\ (1.06\ \$/L)$$ ~~✗~~ ✓

$$\boxed{= \$14.07 / wk}$$ ~~✗~~ ✓

$$\text{Mass balance}_{splash} \xrightarrow{4\ m^3/wk} \boxed{} \xrightarrow{\text{leak}} 2.75\ kg/m^3$$

$$\text{mass balance}_{sealed} \xrightarrow{4\ m^3/wk} \boxed{} \xrightarrow{\text{leak}} 0.095\ kg/m^3$$

● record ‖ pause ■ stop | jump | ★ bookmark | 0% jump to position 100% | − + playback speed | ▲ ▼ volume

2-5) $Q_{Warrenton} = 3.00\ \frac{m^3}{s}$, $Q_{TinPot} = 0.05\ m^3/s$, Concentration min = 1.0mg/L for detection

GIVEN:

Req'd: a) Find min concentration added to Tin Pot so that 1.0mg/L of tracer can be measured. (b) what mass rate (kg/d) of tracer must be added to Tin Pot. ← (day?)

Solution: (a) $\Sigma Q_{out} = \Sigma Q_{in} = 3.00\ \frac{m^3}{s} + 0.05\ \frac{m^3}{s} = 3.05\ \frac{m^3}{s}$

Similarly: $C_{out} Q_{out} = \Sigma C_{in} Q_{in}$ (Plugging in 1.0mg/L for C_{out})

$$(1.0\ \frac{mg}{L})(3.05\ \frac{m^3}{s})(\frac{1000L}{1m^3}) = (3.00\ \frac{m^3}{s})(0\ \frac{mg}{L}) + (0.05\ \frac{m^3}{s})(\frac{1000L}{m^3})(C_{Added})$$

6 ✓

→ $\boxed{C_{added} = 61\ mg/L}$

(b) $C_{added}(Q_{TinPot}) = 61\ \frac{mg}{L}(0.05\ \frac{m^3}{s})(\frac{1000L}{m^3})(\frac{60s}{1hr})(\frac{12hr}{1day})(\frac{kg}{10^6 mg})$

$= \boxed{2.196\ kg/day}$ +

2-8) $C_{initial\ from\ reaction} = 2\%\ (20{,}000\ mg/L)$, $V_{sludge} = 100m^3 = 100\,000L$, $C_{Post\ filter} = 35\%$

Req'd: Find Vol. sludge after filtration

10

Sol'n: $\Sigma C_{in} V_{in} = \Sigma C_{out} V_{out} = (0.02)(100\,000L) = (0.35)(V_{out})$ ✓

→ $\boxed{V_{out} = 5714\ L}$

2-9) standard = 99.99% (4 nine DRE), especially toxic = 99.9999 (6 nine DRE)

See Fig P-2-9 p. 86

Req'd: Draw mass-balance dia., Find allowable amt. of C to exit stream if incinerator is burning 1.0000 g/s. If 90% efficient what scrubber efficiency is req'd.

Sol'n:

mass IN → $\boxed{\text{burner}}$ → $\boxed{\text{Scrubber}}$ → $\boxed{\text{Precipitator}}$ → $\boxed{\text{fan}}$ → $\boxed{\text{stack}}$ → mass out

$\boxed{\text{cont}}$

Donald Jerolleman ENCE 3323 S10 H.W. #I p. 3 of

2-9 con't) $\Sigma C_{in} Q_{in} = \Sigma C_{out} Q_{out}$

$$C_{out} Q_{out} = (C_{in} \; Q_{in}) - (C_{in} Q_{in} \; 0.9999)$$

$$C_{out} Q_{out} = C_{in} Q_{in} (1 - 0.9999) \quad \text{where } Q_{in} = Q_{out}$$

$$C_{out} Q_{out} = 1.0000 \, g/s (0.0001) = \boxed{0.00010 \, g/s}$$

<u>If @ 90% efficient:</u>

$$\underset{burner}{C_{out}} \; \underset{burner}{Q_{out}} = 1.0000 \, g/s (1 - 0.90) = \boxed{0.10000 \, g/s}$$

$$n = \frac{0.1000 - 0.0010}{0.1000} = 0.999 = \boxed{99.9\%}$$

Donald Jarolleman
ENCE 3323
S10
H.W. #1

Environmental Donald Jerolleman H.W #1

2-10) $Filter_1 = 1941$ $Filter_2 = 63$ $t = 10 min$

stage 1: $n = \frac{C_2}{C_1}$ stage 2: $n = \frac{C_3}{C_2}$

$C_2 = C_1 - 1941$ $C_3 = C_1 - 2004$

$\underline{C_2}$

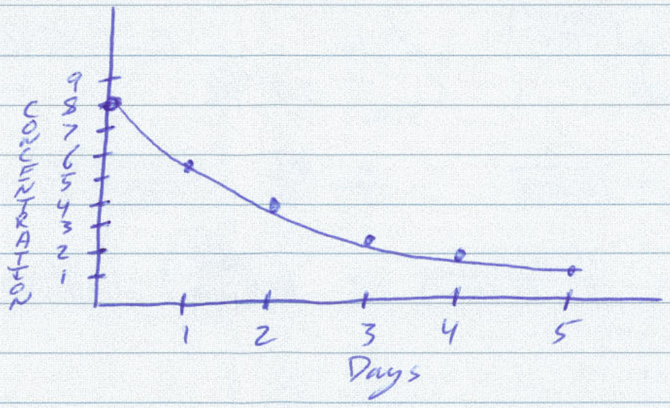
2-11) solution = 85 g/L nickel remove 0.05 L/min soution to rinse tank
Q rinse water to tank = 150 L/min

$$Q_{in} C_{in} + Q_{rinse} \overset{0}{\cancel{C_{rinse}}} - Q_{remove} C_{Nickel} - Q_{rinse} C_{nickle} = 0$$

$$C_{nickle} = \frac{Q_{in} C_{in}}{Q_{remove} + Q_{rinse}} = \frac{(0.05 \text{ L/min})(85 \text{ g/L})}{0.05 \text{ L/min} + 150 \text{ L/min}} = \boxed{0.0283 \text{ g/L}}$$

2-14) - batch reactor - 1st order reaction $t = 5d$ $C_i = 8 \text{ mg/L}$ $k = 0.35 d^{-1}$

Day	C_2 remaining
1	5.64
2	3.97
3	2.79
4	1.97
5	1.39



Environmental Donald Jerolleman H.W. #1

2-19) - CMFR 0.20 m^3 E_i 8.0 MJ/kg $E_N = 10.0$ MJ/kg $Q = 4.0$ L/s

$t = ?$ @ $E = 9$ MJ/kg

$$9\,\tfrac{MJ}{kg} = 8\,\tfrac{MJ}{kg}\, e^{-t/\theta} + 10\,\tfrac{MJ}{kg}\left(1 - e^{-t/\theta}\right), \quad \theta = \frac{0.2\,m^3}{4\,L/s\left(\frac{m^3}{1000\,L}\right)} = 50\,s$$

$$\boxed{t = 34.7\,s}$$

2-22) 20,000 m^3 brine pond w/ 25000 mg/L ~~Salt~~ ocean $C = 30{,}000$ mg/L +

$Q_{Fresh} = ?$ such that $C = 500$ mg/L in $t = 1$ yr.

$$500\,mg/L = 25000\,mg/L\; e^{-1yr/\theta} \rightarrow \theta = 0.256\,y$$

$$Q = \frac{20000\,m^3}{\theta} = 78{,}240\,m^3/y \rightarrow Q\left(\frac{y}{365\,d}\right)\left(\frac{d}{24\,hr}\right)\left(\frac{hr}{3600\,s}\right) = \boxed{0.0025\,m^3/s}$$

2-23) $V = 1900\,m^3$ $C_{Cl} = 15\,mg/m^3$ $C_{ALW} = 0.0015$ mg/L $Q_{air} = 2.35\,m^3/s$

$= 0.0015\,\frac{mg}{L}\left(\frac{1000\,L}{m^3}\right) = 1.5\,mg/m^3$

$$\theta = \frac{1900\,m^3}{2.35\,m^3/s} = 808.51\,s$$

$$\boxed{t = 1861.7\,s}$$

2-26) $A_{la} = 10\,ha\left(\frac{10000\,m^2}{ha}\right)$ $d = 1\,m$ $Q_i = 8640\,m^3/d$ $C_i = 100$ mg/L

Steady State $C_{o_{max}} = 20$ mg/L $k = ?$ 1st order reaction

Using $C_t = \dfrac{C_o}{1 + k\theta}$ $\quad \theta = \dfrac{Vol}{Q} = \dfrac{100000\,m^2(1\,m)}{8640\,m^3/d} = 11.57\,d$

$$20\,mg/L = \frac{100\,mg/L}{1 + k(11.57\,d)} \rightarrow k = \left(\left(\frac{\overset{100}{\cancel{20}}}{\underset{20}{\cancel{100}}}\right) - 1\right)\frac{1}{11.57\,d} = \boxed{0.346\,d^{-1}}$$

Donald Jerolleman H.W. #1

2-27) Same as 2-26 but $A = 5\,ha\left(\frac{10000\,m^2}{ha}\right)$ @ 2 lagoons in series

$$C_1 = \frac{C_0}{1+K\theta}, \quad C_t = \frac{C_1}{1+K\theta} = \frac{\frac{C_0}{1+K\theta}}{1+K\theta} = \frac{C_0}{(1+K\theta)^2}$$

$$\theta = \frac{50000\,m^3}{8640\,m^3/d} = 5.787\,d$$

$$20\,mg/L = \frac{100\,mg/L}{(1+K(5.787d))^2}$$

$$K = \left(\sqrt{\frac{100}{20}} - 1\right)\frac{1}{5.787\,d} = \boxed{0.214\,\bar{d}}$$

2-31) UN-steady state, 1st order, $\forall_{re} = 280\,m^3$, $Q = 14\,m^3/d$, $K = 0.05\,\bar{d}$

<u>CMFR</u>: $C_t = \frac{C_0}{1+K\theta}$, $\theta = \frac{280\,m^3}{14\,m^3/d} = 20\,d$

$$\frac{C_t}{C_0} = \frac{1}{1+0.05(20)} = 0.5 \qquad \text{taking } C_0 \text{ as unity}$$

$$\eta = \frac{C_0 - \left(\frac{C_t}{C_0}\right)C_0}{C_0} = 0.5 = \underline{\underline{50\%}}$$

<u>PFR</u>: $\frac{C_t}{C_0} = e^{-K\theta} = 0.368$ $\qquad \eta = \frac{1-0.368}{1} = 0.632 = \underline{\underline{63.2\%}}$

∴ PFR is more efficient

2-32) $\forall_{re} = ?$, $\eta = 95\%$, steady state, 1st order, $Q = 14\,m^3/d$, $K = 0.05\,d^{-1}$

working backwards taking C_0 as unity

$$0.95 = \frac{C_0 - \left(\frac{C_t}{C_0}\right)C_0}{C_0} \rightarrow 0.95 = 1 - \frac{C_t}{C_0} \rightarrow \frac{C_t}{C_0} = 0.05$$

<u>CMFR</u> $\frac{C_t}{C_0} = \frac{1}{1+K\theta} \rightarrow 0.05 = \frac{1}{1+0.05(\theta)} \rightarrow \theta = 380\,d = \frac{\forall}{Q}$

$$\rightarrow \forall = 380d(14\,m^3/d) = \boxed{5320\,m^3}$$

<u>PFR</u> $\frac{C_t}{C_0} = 0.05 = e^{-(0.05)\theta} \rightarrow \theta = \ln(0.05)\frac{1}{-0.05} = 59.9\,d = \frac{\forall}{Q}$

$$\rightarrow \forall = \boxed{839\,m^3}$$

2-36) $Q_{Low} = 40\ m^3/s$ $T_{river} = \overset{291\ K}{18^\circ C}$ $Q_{Plant} = 2\ m^3/s$ $T_{Plant} = \overset{353\ K}{80^\circ C}$

$\rho_{H_2O} = 1000\ kg/m^3$

$$Q_{low}(\rho)\overset{\text{gets hotter}}{(\Delta T)_{river}} = Q_{Plant}(\rho)\overset{\text{gets coole-}}{(\Delta T)_{plant}}$$

$40(T_f - 291) = 2(353 - T_f)$

$40T_f - 11640 = 706 - 2T_f$

$40T_f + 2T_f = 706 + 11640 = 12346$

$T_f(42) = 12346$

$T_f = 294\ K = \boxed{21^\circ C}$

Donald Jerolleman
Intro. to Environmental
510

Polychlorinated biphenyls (PCBs)

Hazard: prob. of adverse effects in a particular situation.

Risk: measure of the prob. - If measure is subjective it is called perceived risk.

Chronic Dosage: Small doses over long period of time

Acute Exposure: Large dose at one (or short period of) time

LD 50 = Lethal Dose where 50% Animals die

NOAEL = No observed Adverse effect level

Glossary of toxicological terms

ARAR: APPROPRIATE Relevent Requirements

TRIC: Toxicity, Reactivity, Ignitability, Corrosability

classify if waste is Hazardous

Technical Paper Scope, Format, and Suggested Topics
ENCE3323: Introduction to Environmental Engineering

Objective and Scope of the Technical Paper:

Objective of the technical paper to be submitted as part of ENCE 3323 course work is to demonstrate student's knowledge and understanding of (1) sustainability and (2) the contemporary topics that are highly related to sustainability. In the first part of the paper, each student is expected to define/explain what are "sustainability" and "sustainable societies" with respect to human consumption (resources, energy, food, manufactured goods, and more), multimedia waste generation, economics, and the society. Second part of the paper should discuss (1) student selected topic, (2) its relationship to sustainability, (3) student's perception of problems, (4) and possible solutions to keep the future generations sustainable.

Students are expected to do independent reading/research of the open literature and develop a good understanding on sustainability and their selected topics. Topics learnt in the classroom (water resources management, water treatment, water quality management, wastewater treatment, solid wastes, hazardous wastes, and air pollution) and the sustainability discussions held should give students a jump start on topic selection.

Format:

The technical paper to be submitted should be five pages in length (8.5" x 11"), single spaced, Times New Roman font of size 12 with 1" margin on all sides. Any literature sited should be referenced in the text and should be listed at the end of the paper. Any Websites visited should be referenced with the appropriate URLs and the dates visited. Students are cautioned about plagiarism and other academic dishonesty, and are further referred to UNO guidelines.

Technical papers will be graded as follows:

Title (should be provocative and create interest among the readers):	5 points
Student understanding/description of sustainability and sustainable society	10 points
Relevance of the selected topic to sustainability:	5 points
Main body of the topic (background, current/future problems, new trends, possible solutions as seen by others)	30 points
Summary and conclusions (does student agree/disagree with the solutions offered in the literature; what is the opinion of the student if the identified problems have to be solved? Evaluation of various solutions based on the three pillars of sustainability (a) environment, (b) economics, and (c) society	30 points
References	10 points
Overall appeal (figures, charts, creativity, articulation)	10 points
Total	**100 points**

Lab 1: PSD and Metal Analysis of Airborne Dust

ENCE 3323 Introduction to Environmental
Engineering

Introduction

- Particle size distribution (PSD) is the distribution of particles into different size ranges
- Particle size distribution (PSD) also known as grain size distribution
- To understand the physical and chemical properties of the material
- We will use Cascade Impactor to carry the PSD
- Cascade Impactor uses the principle of inertial separation to size segregate particles from a stream

Introduction

- Heavy metals include transition metals, metalloids, lanthanides and actinides
- Also called as toxic metals
- Some of these metals (Fe, Co, Cr, Cu, Ni) are necessary for humans in minute amounts but excess amounts can be damaging
- Other heavy metals like Pb, Hg, Pu etc. are toxic even if present in traces. And their accumulation in organisms may cause serious illness

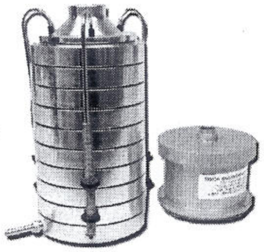
Sources of Heavy Metals

A few commonly known sources are:

- Cigarette smoking
- Medicinal compounds
- Auto exhaust
- Construction Materials ⇦
- Insulated wiring
- Pesticides, etc.

Equipment

- Ambient Cascade Impactor



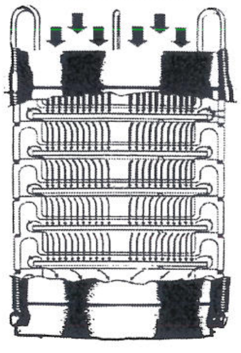
Equipment

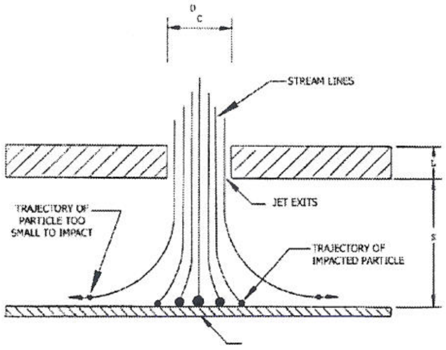
- Innovex X-Ray Fluorescence Spectrometer

Cascade Impactor

- It is an eight stage cascade impactor
- High sample rate
- Separates airborne particles into aerodynamic size classes
- Particles are sampled through a series of stacked stages containing multiple orifices with sequential smaller diameters
- Air enters the inlet and cascades through the succeeding orifice stages with successively higher orifice velocities from stage#0 to stage#7
- Successively smaller aerodynamic sized particles are inertially impacted on to the collection media. Particles passing through stage#7 are collected in the final filter (filtration stage)
- The air is drawn into the impactor using a vacuum pump controlled at constant rate (28.3 ALPM/1 ACFM)

AMBIENT AIR FLOW

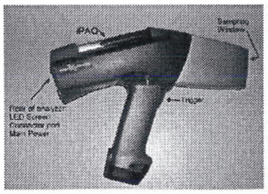


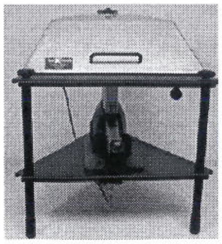


Particle Size Range

Stage	Size Range in Micrometers
Pre-separator	10.0 & Above
0	9.0- 10.0
1	5.8-9.0
2	4.7-5.8
3	3.3-4.7
4	2.1-3.3
5	1.1-2.1
6	0.7-1.1
7	0.4-0.7
Backup Filter	0.0-0.4

Innovex X-Ray Fluorescence Spectrometer



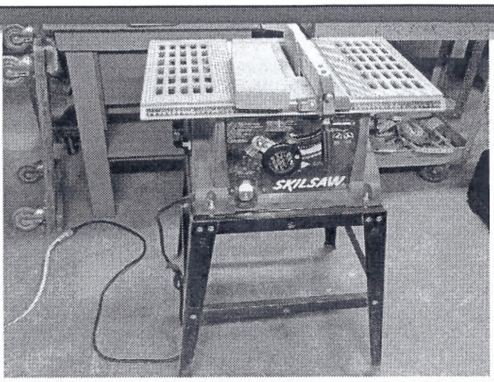


Innovex X-Ray Fluorescence Spectrometer

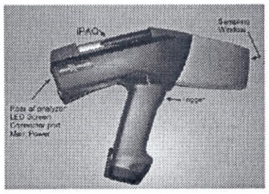
- Works on X-rays
- Emits X-rays from the lens to detect the metals
- Quickly and easily quantifies the elements over a wide dynamic concentration range
- Its is accurate and quicker than many other elemental analysis
- Can also be used as handheld device (Portable)
- Ideally suited for field analysis of alloys, lead based paints, environmental soils, filters, forensics, archaeometry etc.
- An IPAQ (handheld computer)is provided to read and store the data. Data can be transferred from the IPAQ to the computer for further analysis

Lab 1 Discussions

ENCE 3323 Introduction to
Environmental Engineering



Innovex X-Ray Fluorescence Spectrometer



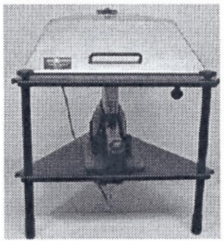


Table 1: Results from the Cascade Impactor

Stage	Size Range	Initial W (mg)eight	Final Weight (mg)	Net Weight (mg)	% in size Range	Cumulative % less than size range	ECD micrometers
Pre-separator	10.0 & Above						
0	9.0- 10.0						
1	5.8-9.0						
2	4.7-5.8						
3	3.3-4.7						
4	2.1-3.3						
5	1.1-2.1						
6	0.7-1.1						
7	0.4-0.7						
Backup Filter	0.0-0.4						

Stage	TARE (g)'	Final (g)	Net (mg)	% in size range	Cumulative % less than size range	Size range micrometers	ECD micrometers
Pre-separator	0	0.00009	0.09	0.7 }	98.7	10.0 & above	10.0
0	1.000	1.00009	0.09	0.6 }		9.0 – 10.0	9.0
1	1.000	1.00017	0.17	1.2 }	97.5	5.8 – 9.0	5.8
2	1.000	1.00082	0.82	5.7	91.8	4.7 – 5.8	4.7
3	1.000	1.00194	1.94	13.6	78.2	3.3 – 4.7	3.3
4	1.000	1.00472	4.72	33.1	45.1	2.1 – 3.3	2.1
5	1.000	1.00431	4.31	30.2	14.9	1.1 – 2.1	1.1
6	1.000	1.00100	1.00	7.0	7.9	0.7 – 1.1	0.7
7	1.000	1.00082	0.82	5.7	2.2	0.4 – 0.7	0.4
Backup Filter	1.000	1.00031	0.31	2.2	0	0 – 0.4	0
			14.27				

Table 2 (Results From XRF analyzer)

Filter No./Trial No.	As	As +/-	Fe	Fe +/-
Standardization				
1/1				
1/2				
1/3				
1/4				
1/5				
Aerage				
2/1				
2/2				
2/3				
2/4				
2/5				
Average				

Table 3: Summary Results of XRF
(Units: microgram per square centimeters)

		Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
F1	AVG	16.54	0.60	1.87	6.79	16.89	0.88	1.97	54.85	1.01	2.96
F 2	AVG	19.14	0.60	0.64	2.72	9.44	0.74	1.64	62.14	0.69	2.46
F3	AVG	18.75	0.47		1.10	6.49	0.58	1.61	61.22	0.55	2.18
F4	AVG	19.03	0.54		1.39	7.21	0.53	1.58	60.38	0.61	2.26
F5	AVG	19.60	0.52		0.86	6.04	0.53	1.55	61.63	0.54	2.09
F6	AVG	20.32	0.46		0.51	5.91	0.56	1.51	62.85	0.59	2.14
F7	AVG	20.70	0.49			4.45		1.59	62.78	0.49	2.07
F8	AVG	18.79	0.53			4.61	0.67	1.50	62.39	0.54	2.12

Table 4 : Mass of Pollutants (grams)

	Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
F1										
F2										
F3										
F4										
F5										
F6										
F7										
F8										

To be completed

- Complete the PSD table: Table 1
- Do not worry about Table 2
- Table 3 is provided
- Finish Table 4
- Compute emission rates of each pollutant

Graphs

- Plot a graph with Particle size (ECD) on x-axis and Cumulative % less than size range on Y-axis
- Also plot the above on Log normal graph
- Plot Particle size (ECD) on x-axis and Mass of Pollutant on Y axis. (Keep all the pollutants in the same graph)

Lab Reports

Need to submit a full report which includes

- Title
- Objective
- Equipment Used
- Procedure
- Results (All tables and a sample calculation)
- Graphs
- Discussions

Donald Jerolleman
Intro. to Environmental Engineering
Spring 2010
Lab 1: Air Quality - Particle Types, Concentration, and Sizes

Objective:

Our experiment will take an air sample during the process of cutting masonry block and indentify the concentrations, types, and size of some of the dust particles present. The particles tested for are heavy metals which include, transition metals, metalloids, lanthanides, and actinides (also called toxic metals). The data will then be used to create a particle size distribution (PSD) chart, mass of pollutant chart, particle size (ECD) verse cumulative percent less than size range graphs, and particle size (ECD) verse mass of pollutant graphs.

Equipment Used:

- Innovex X-Ray Fluorescence Spectrometer
- Laptop and Spectrometer Software
- Masonry Block
- Masonry Circular Saw
- Small, Unventilated room
- Ambient Cascade Impactor

Procedure:

- Set up sample, saw, and Ambient Cascade Impactor
- Observe safety precautions for personnel (eg. masks, goggles, etc.)
- Cut sample while taking air samples (10 min)
- Clean up area to prevent possible exposure to individuals who may enter area later
- Carefully remove filters and fold in half twice to crate a cone look (this prevents loss of contaminants
- Carry out X-ray analysis (5-8 times per filter)
- Log data and perform calculation

Discussion:

Based on the results, the particles are composed of very dangerous metals. The highest concentrations appear to be Zn (Zinc - by far the largest), Ba (Barium), and Fe (Iron) respectively.

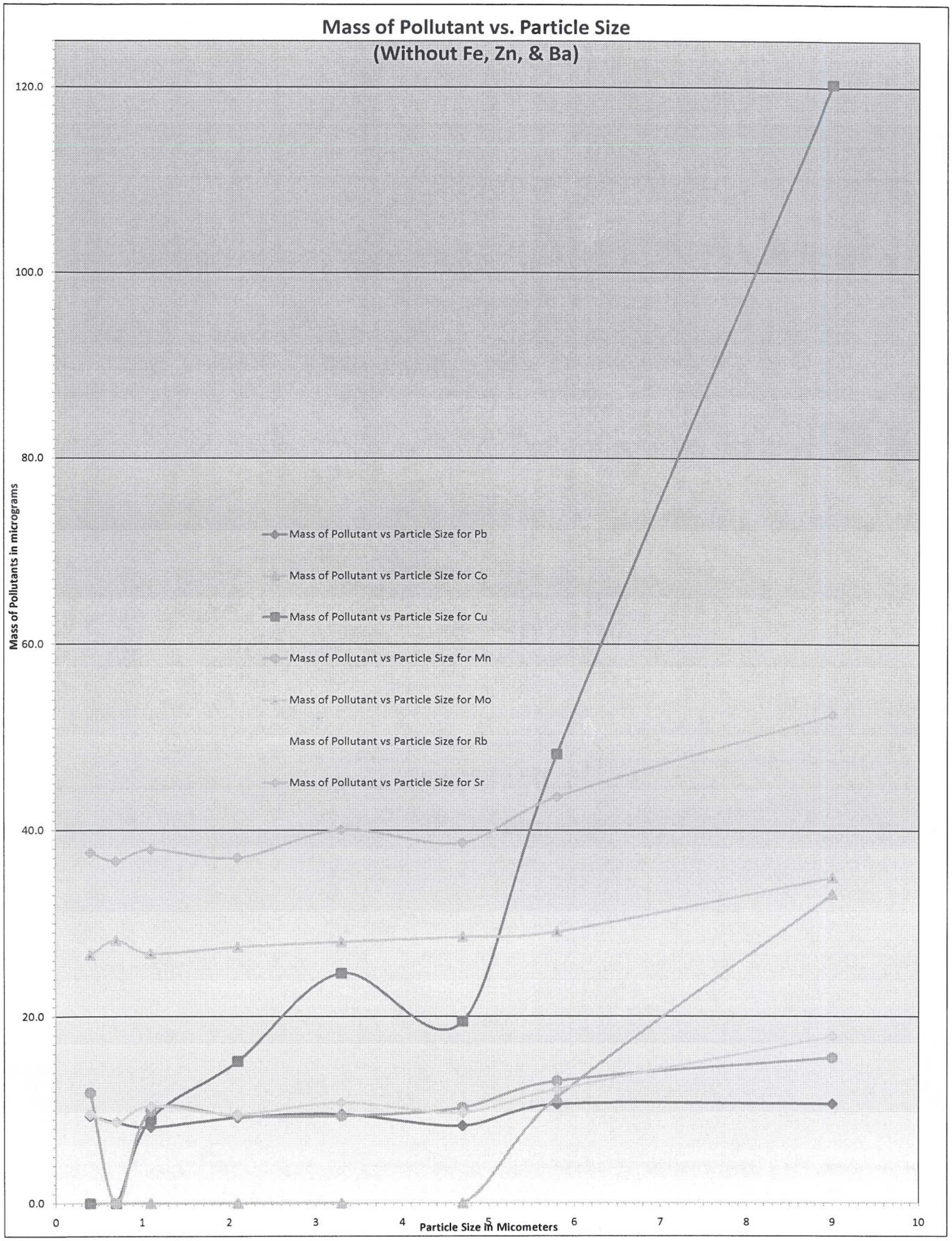
Unfortunately, I do not have the knowledge or the information to make any claims as to the risks posed by these concentrations found.

Stage	Size Range	Initial Weight (g)	Final Weight (g)	Net Weight (g)	% in size Range	Cumulative % Less than size range	ECD (µm)
Pre-Separator	10 & above					100%	10
0	9 -10	0.307	0.418	0.111	70.70%	29%	9
1	5.8 - 9	0.335	0.339	0.004	2.55%	27%	5.8
2	4.7 - 5.8	0.336	0.345	0.009	5.73%	21%	4.7
3	3.3 - 4.7	0.335	0.349	0.014	8.92%	12%	3.3
4	2.1 - 3.3	0.333	0.341	0.008	5.10%	7%	2.1
5	1.1 -2.1	0.331	0.336	0.005	3.18%	4%	1.1
6	0.7 - 1.1	0.336	0.339	0.003	1.91%	2%	0.7
7	0.4 - 0.7	0.31	0.313	0.003	1.91%	0%	0.4
			SUM:	0.157	100.00%		

Miscellaneous Notes		
Run Time	:	10 min
Dia. of filter (cm)	:	9.5
Area (sq.cm.)	:	70.88
1/4 of A (sq.cm.)	:	17.72

Microgram per sq.cm.		Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
Filter 1	avg	16.54	0.60	1.87	6.79	16.89	0.88	1.97	54.85	1.01	2.96
Filter 2	avg	19.14	0.60	0.64	2.72	9.44	0.74	1.64	62.14	0.69	2.46
Filter 3	avg	18.75	0.47	0.00	1.10	6.49	0.58	1.61	61.22	0.55	2.18
Filter 4	avg	19.03	0.54	0.00	1.39	7.21	0.53	1.58	60.38	0.61	2.26
Filter 5	avg	19.60	0.52	0.00	0.86	6.04	0.53	1.55	61.63	0.54	2.09
Filter 6	avg	20.32	0.46	0.00	0.51	5.91	0.56	1.51	62.85	0.59	2.14
Filter 7	avg	20.70	0.49	0.00	0.00	4.45	0.00	1.59	62.78	0.49	2.07
Filter 8	avg	18.79	0.53	0.00	0.00	4.61	0.67	1.50	62.39	0.54	2.12

Mass of Pollutant	in µg	Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
Filter 1	avg	293.1	10.6	33.1	120.3	299.3	15.6	34.9	972.0	17.9	52.5
Filter 2	avg	339.2	10.6	11.3	48.2	167.3	13.1	29.1	1101.2	12.2	43.6
Filter 3	avg	332.3	8.3	0.0	19.5	115.0	10.3	28.5	1084.9	9.7	38.6
Filter 4	avg	337.2	9.6	0.0	24.6	127.8	9.4	28.0	1070.0	10.8	40.0
Filter 5	avg	347.3	9.2	0.0	15.2	107.0	9.4	27.5	1092.1	9.6	37.0
Filter 6	avg	360.1	8.2	0.0	9.0	104.7	9.9	26.8	1113.7	10.5	37.9
Filter 7	avg	366.8	8.7	0.0	0.0	78.9	0.0	28.2	1112.5	8.7	36.7
Filter 8	avg	333.0	9.4	0.0	0.0	81.7	11.9	26.6	1105.6	9.6	37.6
	Sum	2708.9	74.6	44.5	236.9	1081.7	79.6	229.5	8651.9	89.0	323.9


Mass of Pollutant vs. Particle Size
(Without Fe, Zn, & Ba)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Mass of Pollutants in micrograms
Mass of Pollutant vs Particle Size for Pb
Mass of Pollutant vs Particle Size for Co
Mass of Pollutant vs Particle Size for Cu
Mass of Pollutant vs Particle Size for Mn
Mass of Pollutant vs Particle Size for Mo
Mass of Pollutant vs Particle Size for Rb
Mass of Pollutant vs Particle Size for Sr
0
1
2
3
4
5
6
7
8
9
10
Particle Size in Micometers

Chapter 7: Air Pollution HA Problems

Problems: 7.12, 7.15, 7.19, 7.21, 7.24 and Following

20.1 For an emission rate of 200 g/s, an effective stack height of 80m, Call C stability, and a wind speed at stack height of 8 m/s, calculate the ground-level concentration of a nonreactive pollutant: (a) 1000 m directly downwind; and (b) 5000 m directly downwind.

20.3 On a clear night with a surface wind speed of 2 m/s, 50 g/s of a nonreactive pollutant is released at ground level (H=0). Calculate the ground-level concentration: (a) 500 m directly down-wind and (b)1000 m directly downwind.

20.4 At noon on a summer day with a surface wind speed of 4 m/s, SO2 is released over rough terrain from a 90 m stack at a rate of 400 g/s. Assume that the plume rise is 60 m. Calculate the ground-level concentration: (a) 3000 m downwind; (b) 3000 m downwind and 100 m crosswind; and (c) 3000 m downwind and 500 m crosswind.

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$\frac{77}{80}$

7-12) molecular weight = 2H + S = 2(1.0079) + 32.06 = 34.07 g/mole ✓

$$n = \frac{250 \frac{mg}{L}}{34.07\ g/mole \left(\frac{10^3 mg}{g}\right)} = \underline{\underline{7.34 \times 10^{-3} \frac{mole}{L}}}$$ ✓

$$P_{H_2S} = 7.34 \times 10^{-3} \frac{mole}{L} \left(8{,}314 \frac{J}{K \cdot mole}\right)(273\ K)\left(\frac{1000 L}{m^3}\right) = \underline{\underline{16700 Pa}}$$

10

7-15) moles of O_2 → $$n = \frac{21.224\ kPa \left(10^3 \frac{Pa}{kPa}\right)(22.414 L)\left(\frac{m^3}{1000 L}\right)}{8.314 \frac{J}{K \cdot mole}\ (273.15 K)} = \underline{\underline{0.209\ moles}}$$ ✓

moles of N_2 → $$n = \frac{79.119(10^3)(22.414)\left(\frac{1}{1000}\right)}{8.314\ (273.15)} = \underline{\underline{0.781\ moles}}$$ ✓

moles of Ar → $$n = \frac{0.946(10^3)(22.414)\left(\frac{1}{1000}\right)}{8.314\ (273.15)} = \underline{\underline{0.00934\ moles}}$$ ✓

moles of CO_2 → $$n = \frac{0.036(10^3)(22.414)\left(\frac{1}{1000}\right)}{8.314\ (273.15)} = \underline{\underline{0.00036\ moles}}$$ ✓

mass O_2 → $M_{O_2} = (0.209)(32) = \underline{\underline{6.7}}$

mass N_2 → $M_{N_2} = (0.781)(28.2) = \underline{\underline{21.9}}$

mass Ar → $M_{Ar} = (0.00934)(39.95) = \underline{\underline{0.373}}$

mass CO_2 → $M_{CO_2} = (0.00036)(44.01) = \underline{\underline{0.0156}}$

10

Molecular weight = Σ masses = 6.7 + 21.9 + 0.373 + 0.0156 = $\underline{\underline{29\ g/mole}}$ ✓

7.19) molecular weight CO_2 = $C + O_2(2)$ = 12.01 + 16(2) = $\underline{44.01\ g/mole}$ ✓

$$M_p = \frac{370 ppm \left(\frac{1000\ \mu g}{g}\right)(44.01\ g/mole)}{(22.414)\left(\frac{20 + 273.15}{273.15}\right)\left(1\ (\text{equal pressures})\right)} = \underline{\underline{676{,}900 \frac{\mu g}{m^3}}}$$ ✓

10

7.21) A) $$\frac{0.1°C + 4.49°C}{339m - 1.5m} = -0.0136 \frac{°C}{m} \xrightarrow[Per\ 100m]{RATE} \frac{1.36°C}{100m}$$ ✓

p.583
p.584 ∴ atm = stable (most stable possible)
∴ atm = Inversion b/c temp increases w/elevation p.585

B) $$\frac{19.67°C - 28.05°C}{279m - 12m} = -0.0314 \frac{°C}{m} \xrightarrow[Per\ 100m]{RATE} \frac{-3.14°C}{100m}$$ ✓

∴ atm = UNSTABLE ✓

C) $$\frac{18.93°C - 19.55°C}{339m - 8m} = -0.00187 \frac{°C}{m} \xrightarrow[Per\ 100m]{RATE} -\frac{0.187°C}{100m}$$ ✓

10

∴ atm = STABLE ✓

Donald Jerolleman | H.W. Chap 7 (Part I) | p. 2 of 3

7.24) A) stability = A ✓

p. 594 table 7-8

B) " = D ✓

C) " = D ✓

D) " = E ✓

10

20.1) E = 200g/s, h + ΔH = H = 80m, stability → C
Wind @ h = 8m/s

$X(1000_m, 0, 0, 80_m) = \frac{200\ g/s}{\pi(104m)(60m)(8\ m/s)} e^{-\frac{1}{2}\left(\frac{0}{104}\right)^2} e^{-\frac{1}{2}\left(\frac{80m}{60m}\right)^2}$ ✓

$= 0.0012753\ g/m^3 (1)(0.41111) = 0.0005243\ \frac{g}{m^3} = \underline{\underline{524.3\ \mu g/m^3}}$ ✓ 10

$X(5000, 0, 0, 80) = \frac{200\ g/s}{\pi(438)(264)(8)} e^{-\frac{1}{2}\left(\frac{0}{438}\right)^2} e^{-\frac{1}{2}\left(\frac{80}{264}\right)^2}$

$= 0.00006882(1)(0.955124) = \underline{\underline{65.7\ \mu g/m^3}}$ ✓

20.3) Clear, night, u_{OL} = 2m/s, 50g/s (NON-Reac), H = 0

→ K_{py} = F

x = 500 → $S_y = 34(0.5km)^{0.894} = 18.3m$ ✓

$S_z = 14.35(0.5)^{0.74} + (-0.35) = 8.24m$ ✓

$X(500, 0, 0, 0) = \frac{50\ g/s}{\pi(18.3)(8.24)(2\ m/s)} (1)(1) = \underline{\underline{0.0528\ g/m^3}}$ ✓ 10

$x(1000, 0, 0, 0) = \frac{50}{\pi(34)(14.35 + (-0.35))(2)} = \underline{\underline{0.01672\ g/m^3}}$ ✓

20.4) NOON, summer, DAY, U_{OL} = 4 m/s, SO_2 = 400g/s, rough terrain,
h = 90m, ΔH = 60 → H = 150m = E, stability = B

$U_z = 4\ m/s\left(\frac{90m}{10m}\right)^{0.07} = 4.67\ m/s$ $X(3000, 0, 0, 150) = \frac{400\ g/s}{\pi(156(3^{0.894}))\underbrace{(108.2(3^{1.098}) + 2)}_{363}(4.67)}$

$e^{-0.5\left(\frac{150}{363}\right)^2} = 0.0001803(0.91866) = \underline{\underline{0.1656\ \frac{mg}{m^3}}}$

7

$$X(3000, 100, 0, 150) = \frac{400}{\pi(4.67)(156)(3)^{0.894}[108.2(3^{1.098})+2]} e^{-0.5\left(\frac{100}{416.6}\right)^2} e^{-0.5\left(\frac{150}{363}\right)^2} = 0.0001803(0.9716)(0.91866) = \underline{\underline{0.1609 \frac{mg}{m3}}}$$

$$X(3000, 500, 0, 150) = 0.0001803\Big(\underbrace{e^{-0.5\left(\frac{500}{4166}\right)^2}}_{0.48664}\Big)(0.91866)$$

$$= 80.6 \frac{ug}{m^3}$$

Donald Jerolleman
Chap 7
Part I

Air Pollution Control
Basic Terminology

1. Normal air Composition

Gas	Concentration (PPM)
Nitrogen	780,900
Oxygen	209,400
Argon	9,300
Carbon dioxide	315
Neon	18
Helium	5.2
Methane	1.0 - 1.2

Other trace gases include:

Krypton
Nitrous oxide
Hydrogen
Xenon
Nitrogen dioxide
Ozone

2. Ambient Air

Out side air (not enclosed)

3. Global Warming

- CO_2, methane, nitrous oxide, CFCs
- Heat retention capacity of the atmosphere
- Short wave radiation and long wave radiation
- Transparent to incoming radiation and opaque to out going radiation

Effects

Flooding, Loss of Wetlands, Disappearance of low-lying countries like Bangladesh, Egypt, and Netherlands, Changes in Crop Pattern, Sea Level Rise.

4. Green House Effect

- CO_2 and water vapor
- Heat retention capacity of the atmosphere

5. Ozone Hole

CFCs, inert in lower atmosphere and breakdown in the stratosphere releasing Cl_2 atoms. Cl_2 and other radicals remove stratospheric ozone.

Effects:

Skin cancer, reduced crop yield due to incoming UV radiation from Sun.

6. Emission Factor

Pollutants expressed as mass/mass of product or mass/mass of raw materials used in the process.

7. Emission Rate

Mass rate of pollutants per unit time.

8. Emission Standard

A limit on how much pollutant a facility can emit into the atmosphere.

9. Stack

A physical structure (long pipe) through which industrial flue gases are discharged.

10. Stack Emissions

Emissions through Stack.

11. Fugitive Emissions

Equipment leaks, leaks from valves, fittings, emissions escaping through process buildings etc.

12. Ambient Air Quality Standards

A limit on ambient air quality decided based on the health risk criteria.

13. CAA

Clean Air Act. CAAA - Clean Air Act Amendments of 1990.
Administered by EPA with the help of state pollution control boards.

Title I	Provisions for Attainment and Maintenance of National Ambient Air Quality Standards
Title II	Provisions Relating to Mobile Sources
Title III	Hazardous Air Pollutants
Title IV	Acid Deposition Control
Title V	Permits
Title VI	Stratospheric Ozone Protection
Title VII	Provisions Relating to Enforcement
Title VIII	Miscellaneous Provisions
Title IX	Clean Air Research
Title X	Disadvantaged Business Concerns
Title XI	Clean Air Employment Transaction Assistance

14. Acid Rain

Mainly caused due to increased SO_2 and NO_x in ambient air.

<u>Effects:</u>

Decreased crop yield, fish kill, hazard to human health/safety, damage to property (e.g. corrosion of buildings, bridges),

15. Criteria Pollutants

A pollutant for which a National Ambient Air Quality Standard (NAAQS) has been established.

Primary Criteria Pollutants

Particulates (PM10)
Sulphur dioxide
Nitorgen dioxide
Carbon monoxide
Particulate lead

Secondary Criteria Pollutants

Ozone

16. NAAQS

National Ambient Air Quality Standards

17. NSPS

New Source Performance Standards
Emission standards for specific new and modified sources based on best available control technology (BACT).

18. SIP

State Implementation Plan. Document prepared by states and submitted to EPA for approval. The document identifies state's prgorams and to implement its responsibilities under CAA.

19. PM10

Particulate matter less than 10 micron size.

20. EPA

The United States Environmental Protection Agency.

CHAPTER 10
SOLUTIONS

10-1 Lifetime CDI for occupational exposure to Cr(VI)

Given: Concentration = 0.05 mg/m^3, exposure = 8 h/d for age 18 to 65, 5 d/wk, 50 wk/y

Solution:

a. Exposure = (65-18) = 47 years

b. Inhalation rate = $\frac{20\text{m}^3}{24\text{h}}$ = 0.833 m^3/h

c. Using the inhalation form of the equation in Table 10-8

$$\text{CDI} = \frac{(0.05\,\text{mg/m}^3)(0.833\,\text{m}^3/\text{h})(8\,\text{h/d})(5\,\text{d/wk})(50\,\text{wk/y})(47\,\text{y})}{(70\text{kg})(70\text{y})(365\text{d})}$$

$$\text{CDI} = 2.2 \times 10^{-3}\ \text{mg/kg} \bullet \text{d}$$

10-2 CDI for sulfur dioxide

Given: NAAQS = 80 μg/m^3, lifetime (24 h/d, 365 d/y), average adult.

Solution:

a. Using the assumptions in Table 10-8

$$\text{CDI} = \frac{(80\,\mu\text{g/m}^3)(20\,\text{m}^3/\text{d})(365\,\text{d/y})(70\text{y})}{(78\text{kg})(70\text{y})(365\text{d})}$$

$$\text{CDI} = 20.51\ \mu\text{g/kg} \bullet \text{d} \ \text{ or } \ 2.05 \times 10^{-2}\ \text{mg/kg} \bullet \text{d}$$

10-3 Comparison of adult and child CDI for nitrate

Given: Drinking water at 10 mg/L, one year averaging time, 1 year old child.

Solution:

a. Using Table 10-9 values for 1 year old child

$$CDI = \frac{(10\,mg/L)(1\,L/d)(365\,d/y)(1y)}{(16kg)(1y)(365\,d/y)}$$

CDI = 0.625 mg/kg • d

b. Using Table 10-9 for an adult

$$CDI = \frac{(10\,mg/L)(2\,L/d)(365\,d/y)(1y)}{(65.4kg)(1y)(365\,d/y)}$$

CDI = 0.31 mg/kg • d

10-4 Ingestion of soil with 2, 4-D

Given: Soil concentration of 2, 4-D = 10 mg/kg, child = 3 years old, adult, 1 year averaging time, 1 d/week, 20 weeks/y, FI = 0.10

Solution:

a. Using Table 10-9 values for 3 year old child

$$CDI = \frac{(10\,mg/kg)(200\,mg/d)(10^{-6}\,kg/mg)(0.10)(1\,d/wk)(20\,wk/y)(1y)}{(16kg)(1\,d/wk)(20\,wk/y)(1y)}$$

CDI = 1.25 x 10^{-5} mg/kg • d

b. For adult

$$CDI = \frac{(10\,mg/kg)(100\,mg/d)(10^{-6}\,kg/mg)(0.10)(1\,d/wk)(20\,wk/y)(1y)}{(70kg)(1\,d/wk)(20\,wk/y)(1y)}$$

CDI = 1.43 x 10^{-6} mg/kg • d

10-5 Estimating chronic daily intake

Given: Adult female consumes water, bathes 20 min/d and does not swim is exposed to toluene at drinking water limit.

Solution:

a. Routes of exposure are:

1. Ingestion of drinking water

2. Dermal contact with water during bath

3. Inhalation during bath

b. Drinking water standard is 1.0 mg/L

c. Ingestion (Eqn 10-10)

$$CDI = \frac{(1.0\,mg/L)(2.3\,L/d)(365\,d/y)(70y)}{(65.4kg)(70y)(365\,d/y)}$$

$CDI = 3.52 \times 10^{-2}$ mg/kg • d

d. Dermal contact (Eqn 10-12). NOTE: 80% submergence, $PC = 9.0 \times 10^{-6}$ m/h, and

$$ET = \frac{20\,min/d}{60\,min/h} = 0.3333\,h/d$$

$$AD = \frac{(1.0\,mg/L)(1.69m^2)(9.0\times10^{-6}\,m/h)(0.3333\,h/d)(365\,d/y)(70y)(10^3\,L/m^3)}{(65.4kg)(70y)(365\,d/y)}(0.80)$$

$AD = (7.75 \times 10^{-5})(0.80) = 6.20 \times 10^{-5}$ mg/kg • d

e. Inhalation during bath (Eqn 10-15). NOTE: $IR = 20\ m^3/d = 0.8333\ m^3/h$

$$CDI = \frac{(1.0\,\mu g/m^3)(10^{-3}\,mg/\mu g)(0.8333\,m^3/h)(0.3333\,h/d)(365\,d/y)(70y)}{(65.4kg)(70y)(365\,d/y)}$$

$CDI = 4.25 \times 10^{-6}$ mg/kg • d

f. Total CDI

$CDI = 3.52 \times 10^{-2} + 6.20 \times 10^{-5} + 4.25 \times 10^{-6} = 3.53 \times 10^{-2}$

or 3.5×10^{-2} mg/kg • d

10-6 Estimating chronic daily intake

Given: Child exposed for 5 years to 1,1,1-trichloroethane at drinking water limit. She swims, bathes. Average age is 8 years over exposure period.

Solution:

a. Routes of exposure are:

1. Ingestion of drinking water
2. Ingestion while swimming
3. Dermal contact while swimming
4. Dermal contact with water during bath
5. Inhalation during bath

b. Drinking water standard is 0.2 mg/L.

c. Ingestion of drinking water (Eqn 10-10)

$$\mathrm{CDI} = \frac{(0.2\,\mathrm{mg/L})(1.0\,\mathrm{L/d})(365\,\mathrm{d/y})(5\mathrm{y})}{(26\mathrm{kg})(5\mathrm{y})(365\,\mathrm{d/y})}$$

$\mathrm{CDI} = 7.69 \times 10^{-3}\ \mathrm{mg/kg \bullet d}$

d. Ingestion while swimming (Eqn 10-11)

$$\mathrm{ET} = \frac{30\,\mathrm{min/wk}}{60\,\mathrm{min/h}} = 0.5\,\mathrm{h/wk}$$

$$\mathrm{CDI} = \frac{(0.2\,\mathrm{mg/L})(50\,\mathrm{mL/h})(10^{-3}\,\mathrm{L/mL})(0.5\,\mathrm{h/wk})(52\,\mathrm{wk/y})(5\mathrm{y})}{(26\mathrm{kg})(5\mathrm{y})(365\,\mathrm{d/y})}$$

$\mathrm{CDI} = 2.74 \times 10^{-5}\ \mathrm{mg/kg \bullet d}$

e. Dermal contact while swimming (Eqn 10-12). NOTE: Assume 100% of body is exposed during swimming (a bit high but no other data given) $\mathrm{PC} = 6.0 \times 10^{-3}$ m/h, and

$$\mathrm{ET} = \frac{30\,\mathrm{min/wk}}{60\,\mathrm{min/h}} = 0.5\,\mathrm{h/wk}$$

$$\mathrm{AD} = \frac{(0.2\,\mathrm{mg/L})(0.925\mathrm{m}^2)(6.0\times10^{-3}\,\mathrm{m/h})(0.5\,\mathrm{h/wk})(52\,\mathrm{wk/y})(5\mathrm{y})(10^3\,\mathrm{L/m}^3)}{(26\mathrm{kg})(5\mathrm{y})(365\,\mathrm{d/y})}$$

$$AD = 3.04 \times 10^{-3}\ \text{mg/kg} \bullet \text{d}$$

f. Dermal contact while bathing (Eqn 10-12). NOTE: 50% submergence, PC = 6.0×10^{-3} m/h, and

$$ET = \frac{10\,\text{min/d}}{60\,\text{min/h}} = 0.1667\,\text{h/d}$$

$$AD = \frac{(0.2\,\text{mg/L})(0.925\text{m}^2)(6.0\times10^{-3}\ \text{m/h})(0.1667\,\text{h/d})(365\,\text{d/y})(5\text{y})(10^3\ \text{L/m}^3)}{(26\text{kg})(5\text{y})(365\,\text{d/y})}(0.50)$$

$$AD = (7.12 \times 10^{-3})(0.50) = 3.56 \times 10^{-3}\ \text{mg/kg} \bullet \text{d}$$

g. Inhalation during bath (Eqn 10-15). NOTE: IR = 5 m^3/d = 0.2083 m^3/h

$$CDI = \frac{(1.0\,\mu\text{g/m}^3)(10^{-3}\ \text{mg}/\mu\text{g})(0.2083\,\text{m}^3/\text{h})(0.1667\,\text{h/d})(365\,\text{d/y})(5\text{y})}{(26\text{kg})(5\text{y})(365\,\text{d/y})}$$

$$CDI = 1.34 \times 10^{-6}\ \text{mg/kg} \bullet \text{d}$$

h. Total CDI

$$CDI = 7.69 \times 10^{-3} + 2.74 \times 10^{-5} + 3.04 \times 10^{-3} + 3.56 \times 10^{-3} + 1.34 \times 10^{-6}$$

$$CDI = 1.43 \times 10^{-2}\ \text{mg/kg} \bullet \text{d}$$

10-7 Hexavalent chromium risk

Given: Data in Problem 10-1

Solution:

a. The slope factor for Cr(VI) from Table 10-5 is 42 kg • d/mg. From Problem 10-1 CDI = 2.2×10^{-3} mg/ kg • d. The risk is then:

$$\text{Risk} = (2.2 \times 10^{-3}\ \text{mg/ kg} \bullet \text{d})(42\ \text{kg} \bullet \text{d/mg}) = 9.24 \times 10^{-2}$$

b. This is greater than 0.01 so the risk must be calculated with Eqn. 10-18:

$$\text{Risk} = 1 - \exp[9.24 \times 10^{-2}] = 8.83 \times 10^{-2} \text{ or } 0.09$$

10-8 Concentration of hexavalent chromium = 10^{-5} risk

Given: Standard assumptions

Solution:

a. Using the slope factor from Table 10-5, calculate the CDI

risk = (SF)(CDI)

$10^{-5} = (42\ \text{kg} \bullet \text{d/mg})(\text{CDI})$

$\text{CDI} = 2.38 \times 10^{-7}\ \text{mg/kg} \bullet \text{d}$

b. Using assumptions from Table 10-9

$$2.38\times10^{-7}\ \text{mg/kg}\cdot\text{d} = \frac{(\text{CA})(20\,\text{m}^3/\text{d})(365\,\text{d/y})(70\text{y})}{(78\text{kg})(70\text{y})(365\,\text{d/y})}$$

$\text{CA} = 9.28 \times 10^{-7}\ \text{mg/m}^3$

10-9 Characterize risk

Given: toluene, barium, and xylenes

Solution:

a. These are not carcinogens so calculate hazard index using Eqn 10-19 and 10-22 and Table 10-6

$$\text{HI} = \frac{0.03}{0.2} + \frac{0.06}{0.05} + \frac{0.3}{2.0}$$

$\text{HI} = 0.15 + 1.2 + 0.15 = 1.5$

10-10 Characterize risk

Given: tetrachloroethylene, arsenic, dichloromethane

Solution:

a. These are all carcinogens so calculate risk using Eqn 10-17 and 10-20 and slope factors from Table 10-5

Risk = $(1.34 \times 10^{-4})(0.052) + (1.43 \times 10^{-3})(1.5) + (2.34 \times 10^{-4})(0.0075)$

Risk = 2.15×10^{-3}

10-11 Identifying RCRA hazardous waste

Given: Municipal wastewater containing 2.0 mg/L of selenium

Solution:

a. Municipal wastewater containing 2.0 mg/L of selenium is

not a RCRA hazardous waste

because municipal wastewaters are excluded (Figure 10-6)

10-12 Identifying RCRA hazardous waste

Given: An empty pesticide container that a homeowner wishes to discard

Solution:

a. An empty pesticide container that a homeowner wishes to discard

is **not** a RCRA hazardous waste

because household waste is excluded (Figure 10-6)

10-13 Fluorescent light bulb storage

Given: 250 kg/mo of light bulbs

Solution:

a. From http://www.gpoaccess.gov

Click on Code of Federal Regulations

Search under "Browse and/or search the CFR"

Under Titles column select 40

Select July 1 for current year

In 2006 select the range 266-299

Then select 273 Standards for universal waste

Then select 273.15 (accumulation time limits) for answer

The answer (in 2006) is 1 year

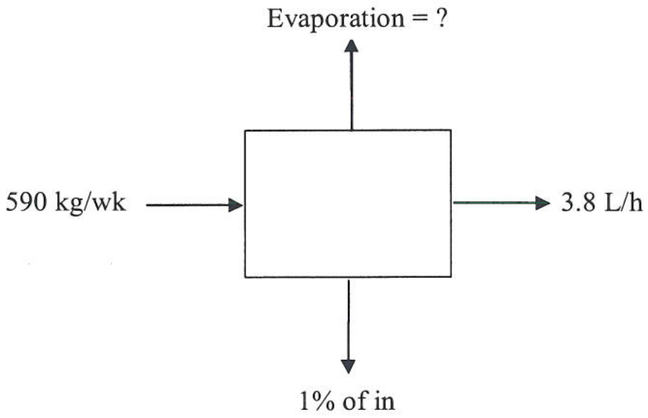
Alternatively, search by CFR code (40CFR273.15) at the browse step

10-14 TCE Evaporation Loss

Given: 590 kg/wk of TCE added, never dumped, drag out = 3.8 L/h, 8 h/d, 5 d/wk operation, sludge = 1.0% of incoming TCE, density = 1.460 kg/L

Solution:

a. Mass balance diagram



Figures S-10-14: Mass balance

b. Sludge mass

$M_{sludge} = (0.01)(590 \text{ kg/wk}) = 5.9 \text{ kg/wk}$

c. Drag out

$M_{drag\ out} = (3.8 \text{ L/h})(8 \text{ h/d})(5 \text{ d/wk})(1.460 \text{ kg/L}) = 221.92 \text{ kg/wk}$

d. Mass balance

$M_{evaporation} = 590 - 221.92 - 5.9 = 362.18$ or 360 kg/wk

10-15 Mass flow condensate tank

Given: Flows and concentrations

Solution:

a. Mass flow into stripper (Sample location #1)

$(5{,}858 \text{ mg/L})(40.5 \text{ L/min})(1{,}440 \text{ min/d})(10^{-6} \text{ kg/mg}) = 341.63 \text{ kg/d}$

b. Mass flow in wastewater (Sample location #2)

$(0.037 \text{ mg/L})(44.8 \text{ L/min})(1{,}440 \text{ min/d})(10^{-6} \text{ kg/mg}) = 0.002386 \text{ kg/d}$

c. Mass flow from vent

GMW of methylene chloride (from Appendix A, Table A-8, note that methylene chloride = dichloromethane) = 84.93 g/mole

Volumetric flow rate of gas = (57 L/min)(0.4413) = 25.154 L/min

Assuming ideal gas law applies

$$n = \frac{PV}{RT} = \frac{(101.325\text{kPa})(25.154\,\text{L/min})}{(8.3143\,\text{J/K}\cdot\text{mole})(293\text{K})} = 1.046\,\text{moles}$$

Mass flow

$(1.046 \text{ moles})(84.93 \text{ g/mole})(1{,}440 \text{ min/d})(10^{-3} \text{ kg/g}) = 128.03 \text{ kg/d}$

d. Mass balance

Mass in = Mass out WW + Mass out vent + Mass to condensate

Mass to condensate = Mass in - Mass out WW - Mass out vent

Mass to condensate = 341.63 - 0.002386 - 128.03 = 213.59 kg/d

10-16 Efficiency of vent condenser

Given: Problem 10-15

Solution:

a. Efficiency

$$\text{Efficiency} = \frac{\text{IN} - \text{OUT}}{\text{IN}} \times 100\%$$

$$\text{Efficiency} = \frac{341.63 - 0.002386 - 128.03}{341.63} \times 100\%$$

Efficiency = 62.5%   Not very efficient!

10-17 Amount of lime to neutralize HCl and TDS formed

Given: Flow of 5 L/min containing 100 mg/L of HCl

Solution:

a. Write reaction

$$2\text{HCl} + \text{Ca(OH)}_2 \rightarrow 2\text{H}_2\text{O} + \text{CaCl}_2$$

b. Gram molecular weights

GMW_{HCl} = 36.5 g/mole

$\text{GMW}_{\text{Ca(OH)2}}$ = 74 g/mole

$\text{GMW}_{\text{CaCl2}}$ = 111 g/mole

c. Molar flow of HCl

$$\frac{(100\,\text{mg/L})(5\,\text{L/min})}{(1000\,\text{mg/g})(36.5\,\text{g/mole})} = 0.0137\,\text{mole/min}$$

d. Molar flow of lime to neutralize

From the reaction in "a" one mole of lime will neutralize two moles of HCl or 1/2 mole of lime will neutralize one mole of HCl or 1/2(0.0137) = 0.006849 moles/min of lime

e. Mass flow of lime

$$\frac{(0.006849\,\text{mole/min})(74\,\text{g/mole})(1440\,\text{min/d})}{(1000\,\text{g/kg})} = 0.730\,\text{kg/d}$$

f. Total dissolved solids

TDS = moles of $CaCl_2$ formed

TDS = 1/2 moles of HCl destroyed = 0.006849 moles/min

In mg/L

$$\frac{(0.006849\,\text{moles/min})(111\,\text{g/mole})(1000\,\text{mg/g})}{(5\,\text{L/min})} = 152\,\text{mg/L}$$

10-18 Amount of sulfuric acid to neutralize NaOH and TDS formed

Given: Flow of 200 L/min containing 15 mg/L of NaOH

Solution:

a. Write reaction

$$2\text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow 2\text{H}_2\text{O} + \text{Na}_2\text{SO}_4$$

b. Gram molecular weights

GMW_{NaOH} = 40 g/mole

GMW_{H2SO4} = 98 g/mole

GMW_{Na2SO4} = 142 g/mole

c. Molar flow of NaOH

$$\frac{(15\,\text{mg/L})(200\,\text{L/min})}{(1000\,\text{mg/g})(40\,\text{g/mole})} = 0.075\,\text{mole/min}$$

d. Molar flow of sulfuric acid to neutralize

From the reaction in "a" one mole of sulfuric acid will neutralize two moles of NaOH or 1/2 mole of sulfuric acid will neutralize one mole of NaOH or 1/2(0.075) = 0.0375 moles/min of sulfuric acid

e. Mass flow of sulfuric acid

$$\frac{(0.0375\,\text{mole/min})(98\,\text{g/mole})(1440\,\text{min/d})}{(1000\,\text{g/kg})} = 5.292\,\text{kg/d}$$

f. Total dissolved solids

TDS = moles of Na_2SO_4 formed

TDS = 1/2 moles of NaOH destroyed = 0.0375 moles/min

In mg/L

$$\frac{(0.0375\,\text{mole/min})(142\,\text{g/mole})(1000\,\text{mg/g})}{(200\,\text{L/min})} = 26.625\,\text{mg/L}$$

10-19 Estimated pH of bath mixture

Given: 1500 L of 5.00% H_2SO_4 by volume, 1500 L of 5.00% NaOH by weight, Specific gravity of H_2SO_4 = 1.841, H_2SO_4 purity = 96%, NaOH purity = 100%

Solution:

a. Calculate moles of H_2SO_4

(1500 L)(0.05) = 75.0 L pure

at 96% purity

(75.0 L)(0.96) = 72.0 L

at 1.841 kg/L the mass of H_2SO_4 is

(72.0 L)(1.841 kg/L) = 132.55 kg or 132,552 g

moles of H_2SO_4

$$\frac{132{,}552\text{g}}{98\,\text{g/mole}} = 1{,}352.57\text{moles}$$

b. Calculate moles of NaOH (5.00%)

(1500 L)(0.05)(1.0 kg/L) = 75.00 kg or 75,000 g of NaOH

moles of NaOH

$$\frac{75{,}000\text{g}}{40\,\text{g/mole}} = 1{,}875\text{moles}$$

c. Strong base – Strong acid reaction

$$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + H_2O$$

So, 2705.14 moles of NaOH are required to neutralize 1352.57 moles of H_2SO_4

And 1352.57 moles of H_2SO_4 forms 1352.7 moles of Na_2SO_4

Thus there is an excess of H^+ equal to

2705.14 moles required – 1875 moles available

= 830.14 moles of H^+ in excess

d. The estimated pH is then

$$\frac{830.14\text{moles}\cdot H^+}{3000\text{L}} = 0.277\,\text{mole/L}$$

$$\text{pH} = \log\left(\frac{1}{0.277}\right) = 0.558 \text{ or } 0.56$$

e. TDS formation is result of Na_2SO_4

f. The estimated TDS

2 moles of NaOH form 1 mole of Na_2SO_4

$$\frac{1875}{2} = 937.5 \text{ moles of } Na_2SO_4 \text{ formed}$$

Excess acid of 830.14 moles H^+ forms

$$\frac{830.14}{2} = 415.07 \text{ moles } H_2SO_4$$

$$\text{TDS} = \frac{(937.5\text{moles}\cdot Na_2SO_4)(142\,\text{g/mole}) + (415.07\text{moles}\cdot H_2SO_4)(98\,\text{g/mole})}{3000\text{L}}$$

TDS = 57.93 g/L or 57,933 mg/L or 58,000 mg/L

10-20 Reaction to oxidize sodium cyanide

Given: NaCN to be oxidized with NaOCl

Solution:

a. Using two step reaction as in Eqns. 10-23 and 10-24

$$\mathrm{NaCN + NaOCl \rightarrow NaCNO + NaCl}$$

$$\mathrm{2NaCNO + 3NaOCl + H_2O \rightarrow 3NaCl + N_2 + 2HaHCO_3}$$

10-21 Reaction to oxidize cyanide with ozone

Given: Ozone to oxidize NaCN

Solution:

a. First step

$$\mathrm{NaCN + O_3 \rightarrow NaCNO + O_2}$$

b. Second step

$$\mathrm{2NaCNO + O_3 + H_2O \rightarrow 2NaHCO_3 + N_2}$$

10-22 Reaction to reduce hexavalent chromium

Given: Cr^{6+} to be reduced with $NaHSO_3$

Solution:

a. Using two step reaction and redox balance

$$\mathrm{NaHSO_3 + H_2O \rightarrow NaOH + H_2SO_3}$$

$$\mathrm{Cr_2O_7 + 3H_2SO_3 \rightarrow Cr_2(SO_4)_3 + 4H_2O}$$

10-23 Hydroxide concentration and pH to precipitate copper

Given: copper concentration to be reduced to 1.3 mg/L, $K_{sp} = 2.00 \times 10^{-19}$

Solution:

a. Reaction

$$Cu + 2OH \rightarrow Cu(OH)_2$$

b. Gram molecular weight

GMW of Cu = 63.54 g/mole

c. K_{sp} equation

$$K_{sp} = [Cu][OH]^2 = 2.00 \times 10^{-19}$$

d. Solving for [OH]

$$[OH] = \left(\frac{2 \times 10^{-19}}{(1.3\,mg/L)(10^{-3}\ g/mg)(63.54\,g/mole)} \right)^{1/2}$$

$[OH] = 1.56 \times 10^{-9}$ mole

e. Estimate of pH

pOH = -log [OH] = -log [1.56 x 10-9]

pOH = 8.81

pH = 14 - pOH = 14 – 8.81 = 5.19

10-24 pH and dose of lime to achieve standard

Given: Q = 100 L/min, 50.0 mg/L Zn in solution, standard = 2.6 mg/L

Solution:

a. Calculate final desired zinc concentration in moles/L

$$[Zn] = \frac{2.6\,mg/L}{65.4 \times 10^3\ mg/mole} = 3.98 \times 10^{-5}\ mole/L$$

b. From Table in Appendix A

K_{sp} for $Zn(OH)_2 = 7.68 \times 10^{-17}$

c. From solubility product equation

$7.68 \times 10^{-17} = [Zn][OH]^2 = (3.98 \times 10^{-5})[OH]^2$

$[OH] = (1.93 \times 10^{-12})^{1/2} = 1.39 \times 10^{-6}$ mole/L

d. Calculate pH

$pOH = -\log(1.39 \times 10^{-6}) = 5.86$

$pH = 14.00 - 5.86 = 8.14$

e. Estimate dose of hydrated lime ($Ca(OH)_2$)

$$Zn + Ca(OH)_2 \rightarrow Zn(OH)_2 + Ca$$

$GMW_{Zn} = 65.4$

$GMW_{Ca(OH)2} = 74$

Zinc to be removed

50.0 mg/L – 2.6 mg/L = 47.4 mg/L

Moles to me removed

$$\frac{47.4\,\text{mg/L}}{65.4\times10^{3}\,\text{mg/mole}} = 7.25\times10^{-4}\,\text{mole/L}$$

Dose of lime

Because 1 mole of lime reacts with 1 mole of Zn

$(7.25 \times 10^{-4}$ mole/L$)(74$ g/mole$)(100$ L/min$) = 5.36$ g/min

10-25 Volume reduction with filter press and dryer

Given: 1.0 m^3/d of metal plating sludge with solids concentration of 4%; filter press yields solids concentration of 30%; dryer yields solids concentration of 80%.

Solution:

a. Filter press volume

Using Eqn. 4-122 and solving for $\forall_2$

$$\frac{\forall_2}{1.0\,\text{m}^3/\text{d}} = \frac{0.04}{0.30}$$

$\forall_2 = 0.133\ \text{m}^3/\text{d}$

b. Dryer volume

$$\frac{\forall_2}{0.133\,\text{m}^3/\text{d}} = \frac{0.30}{0.80}$$

$\forall_2 = 0.05\ \text{m}^3/\text{d}$

10-26 Change in ferrocyanide concentration after filter press

Given: Problem 10-25, ferrocyanide concentration of 400 mg/kg at 4% solids

Solution:

a. The concentration of Fe-CN is the mass of Fe-CN divided by the mass per unit volume of solids. If the Fe-CN is part of the precipitate, then the reduction in solids volume will increase the Fe-CN concentration.

b. Set up mass balance

$(\text{Fe-CN}_{\text{in}})(Q_{\text{in}}) = (\text{Fe-CN}_{\text{out}})(Q_{\text{out}})$

c. Solve for $\text{Fe-CN}_{\text{out}}$

$$\text{Fe}-\text{CN}_{\text{out}} = \frac{(400\,\text{mg/kg})(1.0\,\text{m}^3/\text{d})}{0.133\,\text{m}^3/\text{d}} = 3000\,\text{mg/kg}$$

10-27 Design packed tower stripper for Oscoda, MI

Given: Design and operating parameters

Solution:

a. Calculate water flow (L) from gas/liquid ratio (G/L)

$$L = \frac{\text{gas}\cdot\text{flow}\cdot\text{rate}}{\frac{\text{gas}}{\text{liguid}}\,\text{ratio}} = \frac{60\,\text{m}^3/\text{min}}{18} = 3.33\,\text{m}^3/\text{min}$$

b. Find volume of tower $(Z_T)(A)$ using Eqn. 10-26

First computing the numerator

$$\ln\left[\frac{6000}{1.5} - \frac{(3.33)(8.206\times10^{-5})(298)}{(60)(6.74\times10^{-3})}\left(\frac{6000}{1.5} - 1\right)\right] = 8.069$$

Next computing the denominator

$$(0.720)\left(1 - \frac{(3.33)(8.206\times10^{-5})(298)}{(60)(6.74\times10^{-3})}\right) = 0.5749$$

$$(Z_T)(A) = 3.33\frac{8.069}{0.5749} = 46.787\text{m}^3$$

c. Assuming a maximum column height (Z_T) of 6 m

$$A = \frac{46.787\text{m}^3}{6\text{m}} = 7.798\text{m}^2$$

d. Calculating a diameter

$$d = \left(\frac{(4)(7.798)}{\pi}\right)^{1/2} = 3.15\text{m}$$

NOTE: other column height/diameter combinations are possible within the constraints that $Z_T < 6$ m and $d < 4$ m

10-28 Design packed tower stripper for Watapitae

Given: Design and operating parameters

Solution:

a. Find volume of tower (Z_T)(A) using Eqn. 10-26

First computing the numerator

$$\ln\left[\frac{440}{0.2}-\frac{(0.22)(8.206\times10^{-5})(293)}{(15)(100\times10^{-4})}\left(\frac{440}{0.2}-1\right)\right]=7.66$$

Next computing the denominator

$$(13.5\times10^{-3})\left(1-\frac{(0.22)(8.206\times10^{-5})(293)}{(15)(100\times10^{-4})}\right)=0.013024$$

$$(Z_T)(A)=0.22\frac{7.66}{0.013024}=129.4\text{m}^3$$

b. Assuming a maximum column height (Z_T) of 6 m

$$A=\frac{129.4\text{m}^3}{6\text{m}}=21.566\text{m}^2$$

c. Calculating a diameter

$$d=\left(\frac{(4)(21.566)}{\pi}\right)^{1/2}=5.24\text{m}$$

This exceeds the maximum column diameter of 4 m.

d. Assuming a maximum column diameter of 4 m

$$A=\frac{\pi(4.0)^2}{4}=12.566\text{m}^2$$

e. Recalculating column height

$$Z_T=\frac{129.4\text{m}^3}{12.566\text{m}^2}=10.29\text{m}$$

This is too tall for one column but two columns in series each with a height of 5.15 m would work. NOTE: other column height/diameter combinations are possible within the constraints that $Z_T < 6$ m and $d < 4$ m.

10-29 Packed tower stripping of ethylbenzene

Given: LaGrega form of stripping equation, $H_c = 6.44 \times 10^{-3}$ m^3-atm/mole, $T_g = 20$ °C, L = 7.13 L/s, $K_La = 1.6 \times 10^{-2}$ s^{-1}, column diameter ≤ 4.0 m, column height ≤ 6.0 m

Solution:

a. Converting liquid flow rate to mole/s

Mass rate = (1.0 kg/L)(7.13 L/s) = 7.13 kg/s

$$\text{Molar rate} = \frac{(7.13\,\text{kg/s})(10^3\,\text{g/kg})}{18\,\text{g/mole}} = 396.11\,\text{mole/s}$$

b. See following spreadsheet calculations

C_1	1000	μg/m³		
C_2	35	μg/m³		
H_c	6.44E-03	m³ - atm/mole		
T_g	20	°C =	293.15	K
R	8.21E-05	atm-m³/mole-K		
K_La	1.60E-02	s		
M_w	55600	moles/m³		
L	396.11	moles/s		

Assume values for diameter and air flow rate

Diameter	1	m
Cross sectional area	0.7853975	m²
Air flow rate	8000	moles/s

Compute H'

H' = 2.68E-01

Compute R_{sf}

R_{sf} = 5.4067792

Compute height of transfer unit

HTU = 5.67E-01

Number of transferr units	
R_{sf} /Rsf -1 =	1.2269231
C_1/C_2 =	28.571429
Rsf -1 =	4.4067792
NTU =	3.86E+00
Z =	2.19E+00 m
Plus 20% =	2.63 m

Note: numerous solutions are available depending on the choice of G and diameter. Some are shown below.

For the following diameters with air flow rate = 8000 mole/s

	Z	
0.5 m	10.5 m	Too tall for specification
2.0 m	0.66 m	Columns are normally have Z>dia. This height is not very practical
3.0 m	0.24 m	Columns are normally have Z>dia. This height is not very practical
4.0 m	0.14 m	Columns are normally have Z>dia. This height is not very practical

For the follwing air flow rates with diameter = 1.0 m

	Z
2000 moles/s	5.25 m
4000 moles/s	3.12 m
10000 moles/s	2.55 m
20000 moles/s	2.41 m

10-30 Ion exchange column for nickel

Given: laboratory scale column data and corresponding breakthrough data

Solution:

Begin by calculating the coefficients using the laboratory scale data

a. Calculate the equivalent weight of C_0

$$\text{Equivalent weight} = \frac{58.7}{2} = 29.35\,\text{mg/meq}$$

$$C_0 = \frac{55\,\text{mg/L}}{29.35\,\text{mg/meq}} = 1.87\,\text{meq/L}$$

b. Calculate the quantity (C_0/C) - 1 as shown in following table

Volume [L]	C [mg/L]	C [meq/L]	C/C_o	Co/C	(Co/C)-1
0.16	4.23	0.144123	0.076909	13.00236	
0.32	5.14	0.175128	0.093455	10.70039	9.700389
0.48	10.03	0.341738	0.182364	5.483549	4.483549
0.64	16.65	0.567291	0.302727	3.303303	2.303303
0.8	23.62	0.80477	0.429455	2.328535	1.328535
0.96	29.54	1.006474	0.537091	1.861882	0.861882
1.12	35.46	1.208177	0.644727	1.551043	0.551043
1.28	39.04	1.330153	0.709818	1.408811	0.408811
1.44	44.04	1.500511	0.800727	1.248865	0.248865
1.6	49.54	1.687905	0.900727	1.110214	
1.76	53.32	1.816695	0.969455	1.031508	0.031508
1.92	54.14	1.844634	0.984364	1.015885	0.015885
2.08	53.22	1.813288	0.967636	1.033446	0.033446

c. Plot the data on semi-log paper as shown below.

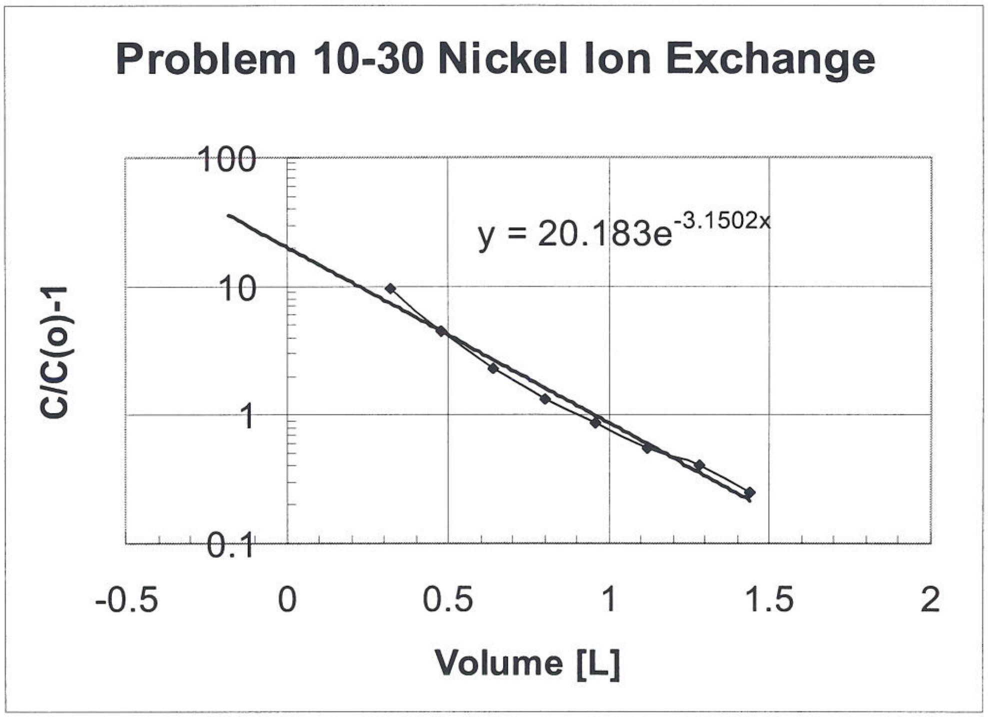


Figure S-10-30: Nickel ion exchange

d. From equation of trendline

$$b = \ln 20.18 = 3.00$$

e. From equation of trendline

slope = -3.1502 L^{-1}

f. Calculate k

$$k = (3.1502)\left(\frac{7.68\,L/d}{1.87\,meq/L}\right) = 12.94\,L/d \cdot meq$$

g. Calculate the dry weight of resin in the test column

M = (5.2 g)(1- 0.17) = 4.316 g

h. Calculate q_0

$$q_0 = \frac{(3.00)(7.68)}{(12.94)(4.316)} = 0.4125\,meq/mg$$

i. Now calculate the mass of resin for the full scale system

Using the influent and allowable effluent concentrations, calculate the left hand side of Equation 10-27

$$\ln\left(\frac{55}{2.6} - 1\right) = 3.00$$

The first term on the right hand side of Eqn 10-27 is

$$\frac{(12.94\,L/d \cdot meq)(0.4125\,meq/mg)(M)}{36{,}000} = 1.48 \times 10^{-4}(M)$$

where M is the unknown quantity of resin required

The operating cycle of 5 d and flow rate of 36,000 L/d gives

$\text{V\kern-0.5em-} = (36{,}000)(5) = 180{,}000$ L

The second term on the right hand side of Eqn 10-27 is

$$\frac{(12.94\,L/d \cdot meq)(1.87)(180{,}000)}{36{,}000} = 1.21 \times 10^{2}$$

Solving Eqn 10-27 for M

$$3.00 = 1.48 \times 10^{-4} (M) - 1.21 \times 10^{2}$$

$$M = 8.38 \times 10^{5} \text{ g or } 840 \text{ kg}$$

10-31 Ion exchange column for silver

Given: laboratory scale column data and corresponding breakthrough data

Solution:

Begin by calculating the coefficients using the laboratory scale data

a. Calculate the equivalent weight of C_0

$$\text{Equivalent weight} = \frac{108}{1} = 108\,\text{mg/meq}$$

$$C_0 = \frac{10\,\text{mg/L}}{108\,\text{mg/meq}} = 0.0926\,\text{meq/L}$$

b. Calculate the quantity $(C_0/C) - 1$ as shown in following table

Volume [L]	C [mg/L]	C [meq/L]	C/C_0	Co/C	(Co/C)-1
0.3	0.01	0.00	0.001	1000.00	999.00
0.4	0.02	0.00	0.002	500.00	499.00
0.5	0.04	0.00	0.004	250.00	249.00
0.6	0.08	0.00	0.008	125.00	124.00
0.7	0.16	0.00	0.016	62.50	61.50
0.8	0.31	0.00	0.031	32.26	31.26
0.9	0.61	0.01	0.061	16.39	15.39
1.0	1.15	0.01	0.115	8.70	7.70
1.1	2.00	0.02	0.200	5.00	4.00
1.2	3.33	0.03	0.333	3.00	2.00
1.3	5.00	0.05	0.500	2.00	1.00
1.4	6.67	0.06	0.667	1.50	0.50
1.5	8.00	0.07	0.800	1.25	0.25
1.6	8.89	0.08	0.889	1.12	0.12
1.7	9.41	0.09	0.941	1.06	0.06
1.8	9.69	0.09	0.969	1.03	0.03
1.9	9.84	0.09	0.984	1.02	0.02

c. Plot the data on semi-log paper as shown below

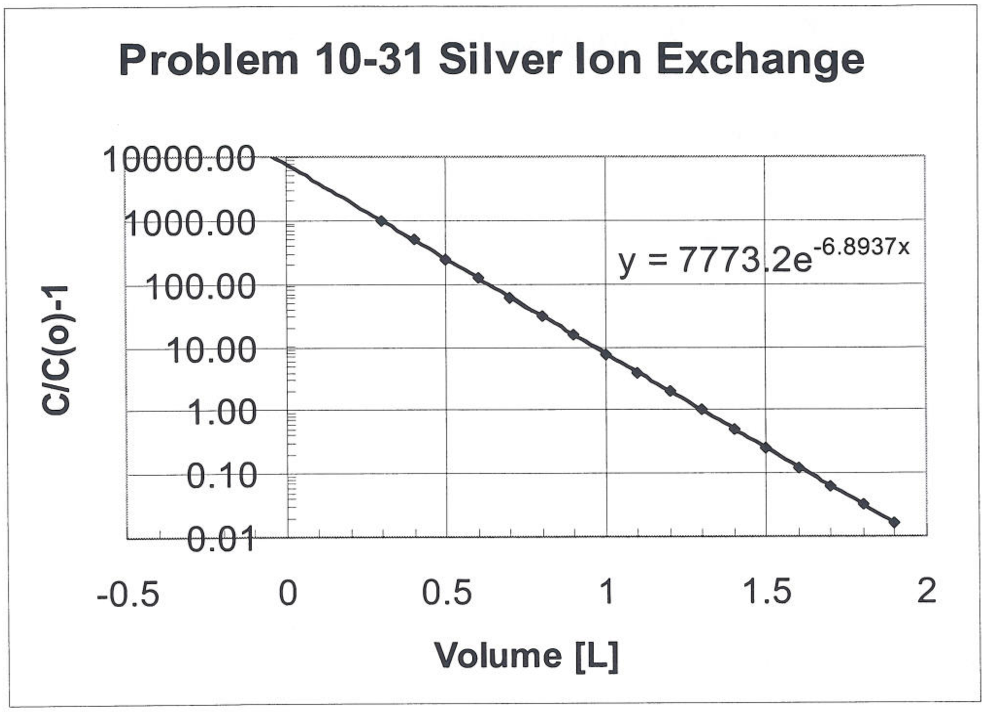


Figure S-10-31: Silver ion exchange

d. From equation of trendline

$$b = \ln 7773 = 8.96$$

e. From equation of trendline

$$\text{slope} = -6.89\ \text{L}^{-1}$$

f. Calculate k

$$k = \left(6.89\text{L}^{-1}\right)\left(\frac{4.523\,\text{L/d}}{0.0926\,\text{meq/L}}\right) = 336.54\,\text{L/d}\cdot\text{meq}$$

g. Calculate the dry weight of resin in the test column

$$M = (7.58\text{g})(1- 0.34) = 5.00\ \text{g}$$

h. Calculate q_0

$$q_0 = \frac{(8.96)(4.523)}{(336.54)(5.00)} = 0.0241\,\text{meq/mg}$$

i. Now calculate the mass of resin for the full scale system

Using the influent and allowable effluent concentrations, calculate the left hand side of Equation 10-27

$$\ln\left(\frac{10}{0.24} - 1\right) = 3.7054$$

The first term on the right hand side of Eqn 10-27 is

$$\frac{(336.54\,\text{L/d}\cdot\text{meq})(0.0241\,\text{meq/mg})(\text{M})}{3600} = 2.25\times10^{-3}(\text{M})$$

where M is the unknown quantity of resin required

The operating cycle of 5 d and flow rate of 3,600 L/d gives

V = (3,600)(5) = 18,000 L

The second term on the right hand side of Eqn 10-27 is

$$\frac{(336.54\,\text{L/d}\cdot\text{meq})(0.0926)(18{,}000)}{3600} = 1.56\times10^{2}$$

Solving Eqn 10-27 for M

$3.70 = 2.25 \times 10^{-3}$ (M) - 1.56×10^{2}

M = 7.10×10^{4} g or 71 kg

10-32 Ion exchange column for hardness

Given: Ca = 107 mg/L as ion, Mg = 18 mg/L as ion, data on size of pilot column

Solution:

Begin by calculating the coefficients using the pilot scale data

a. Calculate equivalent weight of C_0 where C_0 is the total hardness in meq/L

For Ca, the equivalent weight is 40.0/2 = 20 g/eq or 20 mg/meq

$$\frac{107\,\text{mg/L}}{20.0\,\text{mg/meq}} = 5.35\,\text{meq/L}$$

For Mg, the equivalent weight is 24.3/2 = 12.15 mg/meq

$$\frac{18\,\text{mg/L}}{12.15\,\text{mg/meq}} = 1.48\,\text{meq/L}$$

C_0 equals the total hardness

$$C_0 = 5.35 + 1.48 = 6.83\ \text{meq/L}$$

b. Use a spreadsheet to estimate slope and intercept

Volume [m^3]	C [meq/L]	C/C_o	Co/C	(Co/C)-1
2.35	0.21	0.0307	32.5309	
2.90	0.48	0.0703	14.2323	13.2323
3.10	1.10	0.1610	6.2104	5.2104
3.26	1.64	0.2401	4.1655	3.1655
3.39	2.47	0.3616	2.7658	1.7658
3.49	3.22	0.4713	2.1216	1.1216
3.56	3.56	0.5211	1.9190	0.9190
3.71	4.52	0.6616	1.5114	0.5114
3.81	5.07	0.7422	1.3474	0.3474
4.03	5.96	0.8724	1.1462	0.1462
4.62	6.78	0.9925	1.0076	

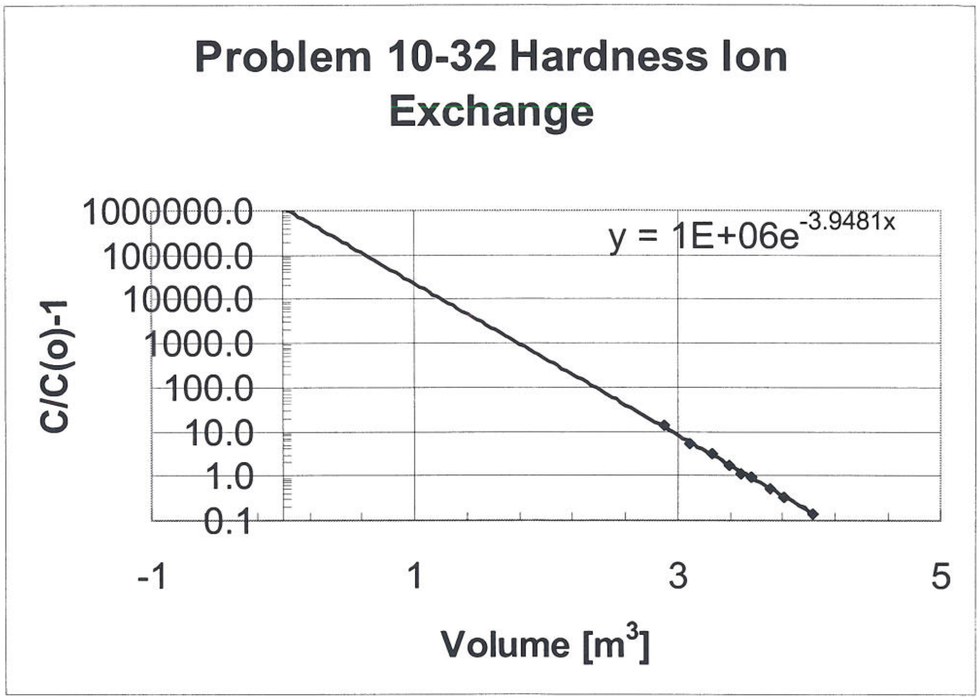


Figure S-10-32: Hardness ion exchange

c. From the equation of trendline

$$b = \ln(1 \times 10^6) = 13.82$$

d. From the equation of trendline

$$\text{slope} = -3.95\ (\text{m}^3)^{-1}$$

e. Calculate k (Note conversions to days and m^3)

$$k = \left(3.95(\text{m}^3)^{-1}\right)\left(\frac{(2.25\,\text{L/h})(24\,\text{h/d})(10^{-3}\,\text{m}^3/\text{L})}{6.83\,\text{meq/L}}\right) = 3.12\times10^{-2}\ \text{L/d}\cdot\text{meq}$$

f. Calculate the dry weight of resin in the test column

$$M = (5.0\ \text{kg})(1 - 0.34) = 3.30\ \text{kg}$$

g. Calculate q_0 (Note units in answer)

$$q_0 = \frac{(13.82)(2.25\,\text{L/h})(24\,\text{h/d})}{(3.12\times10^{-2}\,\text{L/d}\cdot\text{meq})(3.30\text{kg})} = 7.24\times10^3\ \text{meq/kg}$$

h. Now calculate mass of resin for full scale system

Using the influent and desired effluent concentrations, calculate the left hand side of equation 10-27. Begin by converting 10 mg/L as $CaCO_3$ to meq/L. The equivalent weight of $CaCO_3$ is 50 mg/meq.

$$\frac{10\,\text{mg/L as}\cdot\text{CaCO}_3}{50\,\text{mg/meq}} = 0.20\,\text{meq/L}$$

Then

$$\ln\left(\frac{6.83}{0.20} - 1\right) = 3.50$$

The first term on the right hand side of equation 10-27 is

$$\frac{(3.12\times10^{-2}\ \text{L/d}\cdot\text{meq})(7.24\times10^{3}\ \text{meq/kg})(\text{M})}{(570\,\text{m}^3/\text{d})(10^3\ \text{L/m}^3)} = 3.96\times10^{-4}\,\text{kg}^{-1}(\text{M})$$

Where M is the unknown quantity of resin. Note the units conversions.

The operating cycle is 60 days

$$\forall = (570\ \text{m}^3/\text{d})(60\ \text{d}) = 34{,}200\ \text{m}^3$$

The second term on the right hand side of equation 10-27 is

$$\frac{(3.12\times10^{-2}\ \text{L/d}\cdot\text{meq})(6.83\,\text{meq/L})(34{,}200\text{m}^3)}{570\,\text{m}^3/\text{d}} = 12.79$$

Solving Equation 10-27 for M

$$3.50 = (3.96 \times 10^{-4}\ \text{kg}^{-1})(\text{M}) - 12.79$$

$$\text{M} = 41{,}136 \text{ or } 41{,}000 \text{ kg or } 41 \text{ Mg}$$

10-33 Blending waste to achieve 30% by mass chlorine

Given: Trichloroethylene = 18.9 m^3; 1,1,1 Trichloroethane = 5.3 m^3; Toluene = 21.3 m^3, o-Xylene = 4.8 m^3

Solution:

a. Using Appendix A obtain formulas, molecular weights and densities

Trichloroethylene

formula = $ClCH{=}CCl_2$, GMW = 131.29, density = 1.476 g/mL

1,1,1 Trichloroethane

formula = CH_3CCl_3, GMW = 133.41, density = 1.3390 g/mL

Toluene

formula = $C_6H_5CH_3$, GMW = 92.14, density = 0.8669 g/mL

o-Xylene

formula = $(CH_3)_2C_6H_4$, GMW = 106.17, density = 0.8802 g/mL

b. Fraction of compound that is chlorine

Trichloroethylene

formula = $ClCH{=}CCl_2$, GMW = 131.29

3 chlorines with GMW of 35.5 = 3(35.5) = 106.5

$$\text{chlorine fraction} = \frac{106.5}{131.29} = 0.811$$

1,1,1 Trichloroethane

formula = CH_3CCl_3, GMW = 133.41

3 chlorines with GMW of 35.5 = 3(35.5) = 106.5

$$\text{chlorine fraction} = \frac{106.5}{133.41} = 0.798$$

Toluene

contains no chlorine

o-Xylene

contains no chlorine

c. Compute mass of each compound

Trichloroethylene

density = 1.476 g/mL = 1,476 kg/m^3

mass = (1,476 kg/m^3)(18.9 m^3) = 27,896.4 kg

1,1,1 Trichloroethane

density = 1.3390 g/mL = 1,3390 kg/m^3

mass = (1,339 kg/m^3)(5.3 m^3) = 7,096.7 kg

Toluene

density = 0.8669 g/mL = 866.9 kg/m^3

mass = (866.9 kg/m^3)(21.3 m^3) = 18,464.97 kg

o-Xylene

density = 0.8802 g/mL = 880.2 kg/m^3

mass = (880.2 kg/m^3)(4.8 m^3) = 4,224.96 kg

Total mass

27,896.4 + 7,096.7 + 18,464.97 + 4,224.96 = 57,683.03 kg

d. Compute % chlorine

$$\%\text{Cl} = \frac{(0.811)(27{,}896.4)+(0.798)(7{,}096.7)}{57{,}683.03}(100)$$

%Cl = 49.03 or 49%

The operator cannot achieve 30% chlorine by mixing these waste quantities.

10-34 Blending waste to achieve 30% by mass chlorine

Given: Carbon tetrachloride = 1.2 m^3, Hexachlorobenzene = 15.3 m^3, Pentachlorophenol = 25.0 m^3, Methanol as required

Solution:

a. Using Appendix A obtain formulas, molecular weights and densities

Carbon tetrachloride

formula = CCl_4, GMW = 153.82, density = 1.594 g/mL

Hexachlorobenzene

formula = C_6Cl_6, GMW = 284.79, density = 1.5691 g/mL

Pentachlorophenol

formula = Cl_5C_6OH, GMW = 266.34, density = 1.978 g/mL

Methanol (NOTE: not in Appendix A)

formula = CH_3OH, GMW = 32.04, density = 0.7913 g/mL

b. Fraction of compound that is chlorine

Carbon tetrachloride

formula = CCl_4, GMW = 153.82

4 chlorines with GMW of 35.5 = 4(35.5) = 142.0

$$\text{Chlorine fraction} = \frac{142.0}{153.82} = 0.923$$

Hexachlorobenzene

formula = C_6Cl_6, GMW = 284.79

6 chlorines with GMW of 35.5 = 6(35.5) = 213.0

$$\text{Chlorine fraction} = \frac{213.0}{284.79} = 0.748$$

Pentachlorophenol

formula = Cl_5C_6OH, GMW = 266.34

5 chlorines with GMW of 35.5 = 5(35.5) = 177.5

$$\text{Chlorine fraction} = \frac{177.5}{266.34} = 0.667$$

c. Compute mass of each compound

Carbon tetrachloride

density = 1.594 g/mL = 1,594 kg/m^3

mass = $(1{,}594\ kg/m^3)(12.2\ m^3) = 19{,}446.8$ kg

Hexachlorobenzene

density = 1.5691 g/mL = 1,569.1 kg/m^3

mass = $(1{,}569.1\ kg/m^3)(153\ m^3) = 240{,}072.3$ kg

Pentachlorophenol

density = 1.978 g/mL = 1,978 kg/m^3

mass = $(1{,}978\ kg/m^3)(2.5\ m^3) = 4{,}945.0$ kg

Total mass

19,446.8 + 240,072.3 + 4,945.0 = 264,464.1 kg

d. Compute % chlorine

$$\%Cl = \frac{(0.923)(19{,}446.8) + (0.748)(240{,}072.3) + (0.667)(4{,}945)}{264{,}464.1} = 0.759$$

%Cl = 75.9 %

e. Compute amount of methanol that must be added

The chlorine fraction of the combination must be 30%, so the weighted fraction would be

$$\text{Chlorine fraction} = \frac{(0.759)(264{,}464.1) + (0.0)(M_{CH_3OH})}{264{,}464.1 + M_{CH_3OH}} = 0.30$$

where M_{CH3OH} = Mass of methanol with a chlorine content of 0.0%

Solving for M_{CH3OH}

$(0.759)(264{,}464.1) + 0.0 = 0.3(264{,}464.1 + M_{CH3OH})$

$M_{CH3OH} = 404{,}630$ kg

Calculate volume based on density of 7,913 kg/m^3

$$\forall = \frac{404{,}630\,\text{kg}}{7{,}913\,\text{kg/m}^3} = 51.135 \text{ or } 51\ \text{m}^3$$

10-35 Mass flow of methylene chloride in aqueous feed

Given: Methylene chloride concentration = 5,858 mg/L, flow rate of aqueous stream = 40.5 L/min

Solution:

(5,858 mg/L)(40.5 L/min) = 237,249 mg/min or 237.25 g/min

10-36 Mass flow of methylene chloride in flue gas

Given: Methylene chloride concentration = 211.86 μg/L, flow rate of flue gas = 597.55 m^3/min

Solution:

(211.86 μg/L)(597.55 m^3/min) = 126,596.9 μg/m^3 or 0.1266 g/min

10-37 DRE for Problems 10-35 and 10-36

Given: Problems 10-35 and 10-36

Solution:

a. Using Eqn. 10-31

$$\text{DRE} = \frac{237.25 - 0.1266}{237.25}(100) = 99.947\%$$

10-38 DRE for xylene

Given: mass flow into incinerator = 481 kg/h, mass flow in stack = 72.2 g/h

Solution:

a. Using Eqn. 10-31

$$\text{DRE} = \frac{481 - 0.0722}{481}(100) = 99.985\%$$

Incinerator does not comply with 99.99% DRE

10-39 Incinerator compliance for dichlorobenzene

Given: Incinerator operating conditions and stack gas concentrations after APC equipment

Solution:

a. Mass flow into incinerator

1,2 Dicholorobenzene data from Appendix A

formula = Cl_2-C_6H_4, GMW = 147.01, density = 1.3048 g/mL

mass flow = (13.0 g/L)(173.0 L/min) = 2,249 g/min

$$\text{molar flow} = \frac{2249\,\text{g/min}}{147.01\,\text{g/mole}} = 15.298\,\text{mole/min}$$

Hydrogen Chloride

Moles of HCl per mole of Cl_2-C_6H_4 = 2

mass flow = 2(15.298 moles/min)(36.5 g/mole) = 1,116.75 g/min

b. Mass flows out of incinerator

1,2 Dichlorobenzene

$(338.8\ \mu g/m^3)(10^{-6}\ g/\mu g)(6.70\ m^3/s)(60\ s/min) = 0.136\ g/min$

Hydrogen Chloride

without APC

$(1{,}116.75\ g/min)(10^{-3}\ kg/g)(60\ min/h) = 67.0\ kg/h$

with APC

$(77.2\ mg/m^3)(10^{-3}\ g/mg)(6.70\ m^3/s)(60\ s/min) = 31.03\ g/min$

or $(31.03\ g/min)(10^{-3}\ kg/g)(60\ min/h) = 1.86\ kg/h$

c. Compliance computations

DRE for 1,2 Dicholorobenzene

$$\text{DRE} = \frac{2249 - 0.136}{2249}(100) = 99.994\ \text{ Passes}$$

HCl

1.86 kg/h exceeds 1.8 kg/h, therefore check 1% limit

$(0.01)(1{,}116.75\ g/min) = 11.17\ g/min$

After the APC the emission is 31.03 g/min. This exceeds the 1% limit. Therefore the incinerator fails to comply with the HCl limits.

Particulates

The limit is 180 mg/dscm, therefore the incinerator emission of 181.6 mg/dscm fails to comply with the particulate limits.

10-40 Trial burn compliance for POHCs

Given: Temperature = 1,100 °C, Q_{stack} = 5.90 dscm/s, 10% oxygen, assume chlorine = HCl, inlet and outlet emissions

Solution:

a. Calculate DRE's

Benzene

$$\text{DRE} = \frac{913.98 - 0.2436}{913.98}(100) = 99.9733\% \quad \text{Fails}$$

Chlorobenzene

$$\text{DRE} = \frac{521.63 - 0.0494}{521.63}(100) = 99.9905\% \quad \text{Passes}$$

Xylenes

$$\text{DRE} = \frac{1378.91 - 0.5670}{1378.91}(100) = 99.9589\% \quad \text{Fails}$$

b. Calculate HCl

Emission rate of 4.85 kg/h exceeds emission limit of 1.8 kg/h. Now check % removal:

Inlet HCl

GMW of chlorobenzene = 112.5 g/mole

Moles of HCL per moles of chlorobenzene (C_6H_5Cl) = 1

$$\text{Molar flow of } C_6H_5Cl = \frac{(521.63\,\text{kg/h})(10^3\ \text{g/kg})}{112.5\,\text{g/mole}} = 4636.71\,\text{mole/h}$$

Mass flow of HCl = (1)(4636.71 mole/h)(36.5 g/mole) = 169,239.95 g/h

= 169.24 kg/h

Removal efficiency

$$= \frac{169.24\,\text{kg/h} - 4.85\,\text{kg/h}}{169.24\,\text{kg/h}}(100) = 97.13\%$$

97.13% is less than 99% required.

The HCl emissions fail on both requirements.

c. Particulate emissions

Convert the emissions rate to concentration

$$\frac{(10.61\,\text{kg/h})(10^6\ \text{mg/kg})}{(5.90\,\text{m}^3/\text{s})(3600\,\text{s/h})} = 499.53\,\text{mg/m}^3$$

Corrected to 10% oxygen

$$P_c = 499.53\left(\frac{14}{21-10}\right) = 635.76\,\text{mg/m}^3$$

This exceeds the allowable particulate emission of 180 mg/m^3

10-41 Incinerator compliance for trichloroethylene, 1,1,1 trichloroethane, and toluene

Given: Incinerator operating conditions and stack gas concentrations after APC equipment

Solution:

a. Mass flow into incinerator (@ 5% of volumetric flow)

Trichloroehtylene data from Appendix A

formula = $ClCH{=}CCl_2$, GMW = 131.29, density = 1.476 g/mL

mass flow = (0.05)(40.0 L/min)(1,476 g/L) = 2,952 g/min

$$\text{molar flow} = \frac{2952\,\text{g/min}}{131.29\,\text{g/mole}} = 22.485\,\text{mole/min}$$

Hydrogen chloride

Moles of HCl per mole of $ClCH{=}CCl_2$ = 3

mass flow = 3(22.485 moles/min)(36.5 g/mole) = 2,462 g/min HCl

1,1,1 Trichloroethane data from Appendix A

formula = CH_3CCl_3, GMW = 133.41, density = 1.3390 g/mL

mass flow = (0.05)(40.0 L/min)(1,339 g/L) = 2,678 g/min

$$\text{molar flow} = \frac{2678\,\text{g/min}}{133.41\,\text{g/mole}} = 20.07\,\text{mole/min}$$

Hydrogen chloride

Moles of HCl per mole of $CH_3CCl_3 = 3$

mass flow = 3(20.07 moles/min)(36.5 g/mole) = 2,198 g/min HCl

Toluene data from Appendix A

formula = $C_6H_5CH_3$, GMW = 92.14, density = 0.8669 g/mL

mass flow = (0.05)(40.0 L/min)(866.9 g/L) = 1,733.8 g/min

Hydrogen chloride

Moles of HCl per mole of $C_6H_5CH_3 = 0.0$

b. Mass flow out of incinerator

Trichloroethylene

$(170\ \mu g/m^3)(10^{-6}\ g/\mu g)(9.0\ m^3/s)(60\ s/min) = 0.0918\ g/min$

1,1,1 Trichloroethane

$(353\ \mu g/m^3)(10^{-6}\ g/\mu g)(9.0\ m^3/s)(60\ s/min) = 0.190\ g/min$

Toluene

$(28\ \mu g/m^3)(10^{-6}\ g/\mu g)(9.0\ m^3/s)(60\ s/min) = 0.0151\ g/min$

HCl

without APC

Total mass of HCl = 2,462 + 2,198 = 4,660 g/min

$(4{,}660\ g/min)(10^{-3}\ kg/g)(60\ min/h) = 279.6\ kg/h$

with APC

$(83.2\ mg/m^3)(10^{-3}\ g/mg)(9.0\ m^3/s)(60\ s/min) = 44.928\ g/min$

or (44.928 g/min)(10^{-3} kg/g)(60 min/h) = 2.696 or 2.7 kg/h

c. Compliance computations

DRE for Trichloroethylene

$$\text{DRE} = \frac{2952 - 0.0918}{2952}(100) = 99.9968\% \quad \text{Passes}$$

DRE for 1,1,1 Trichloroethane

$$\text{DRE} = \frac{2678 - 0.190}{2678}(100) = 99.9929\% \quad \text{Passes}$$

DRE for Toluene

$$\text{DRE} = \frac{1733.8 - 0.0151}{1733.8}(100) = 99.9991\% \quad \text{Passes}$$

HCl

2.7 kg/h exceeds 1.8 kg/h, therefore check 1% limit

(0.01)(4,660 g/min) = 46.6 g/min

After the APC the emission is 44.928 g/min. This is less than the 1% limit. Therefore the incinerator complies with the HCl limits.

Particulates

The limit is 180 mg/dscm, therefore the incinerator emission of 123.4 mg/dscm complies with the particulate limits.

The incinerator complies with all emission limits.

10-42 Incinerator compliance for hexachlorobenzene, pentachlorophenol, acetone

Given: Incinerator operating conditions and stack gas concentrations after APC equipment

Solution:

a. Mass flow into incinerator (@ 9.3% of volumetric flow)

Hexachlorobenzene data from Appendix A

formula = C_6Cl_6, GMW = 284.79, density = 1.5691 g/mL

mass flow = (0.093)(140.0 L/min)(1,569.1 g/L) = 20,430 g/min

$$\text{molar flow} = \frac{20{,}430\,\text{g/min}}{284.79\,\text{g/mole}} = 71.74\,\text{mole/min}$$

Hydrogen chloride

Moles of HCl per mole of C_6Cl_6 = 6

mass flow = 6(71.74 moles/min)(36.5 g/mole) = 15,710 g/min HCl

Pentachlorophenol data from Appendix A

formula = Cl_5C_6OH, GMW = 266.34, density = 1.978 g/mL

mass flow = (0.093)(140.0 L/min)(1,978 g/L) = 25,754 g/min

$$\text{molar flow} = \frac{25{,}754\,\text{g/min}}{266.34\,\text{g/mole}} = 96.69\,\text{mole/min}$$

Hydrogen chloride

Moles of HCl per mole of Cl_5C_6OH = 5

mass flow = 5(96.69 moles/min)(36.5 g/mole) = 17,647 g/min HCl

Acetone data from Appendix A

formula = CH_3COCH_3, GMW = 58.08, density = 0.79 g/mL

mass flow = (0.093)(140.0 L/min)(790 g/L) = 10,286 g/min

Hydrogen Chloride

Moles of HCl per mole of CH_3COCH_3 = 0.0

b. Mass flow out of incinerator

Hexachlorobenzene

$(170\ \mu g/m^3)(10^{-6}\ g/\mu g)(28.32\ m^3/s)(60\ s/min) = 0.2889\ g/min$

Pentachlorophenol

$(353\ \mu g/m^3)(10^{-6}\ g/\mu g)(28.32\ m^3/s)(60\ s/min) = 0.5998\ g/min$

Acetone

$(28\ \mu g/m^3)(10^{-6}\ g/\mu g)(28.32\ m^3/s)(60\ s/min) = 0.04758\ g/min$

HCl

without APC

Total mass of HCl = 17,647 + 10,286 = 27,933 g/min

$(27{,}933\ g/min)(10^{-3}\ kg/g)(60\ min/h) = 1{,}676\ kg/h$

with APC

$(83.2\ mg/m^3)(10^{-3}\ g/mg)(28.32\ m^3/s)(60\ s/min) = 141.37\ g/min$

or $(141.37\ g/min)(10^{-3}\ kg/g)(60\ min/h) = 8.48\ kg/h$

c. Compliance computations

DRE for Hexachlorobenzene

$$\text{DRE} = \frac{20{,}430 - 0.2889}{20{,}430}(100) = 99.9986\% \ \text{ Passes}$$

DRE for Pentachlorophenol

$$\text{DRE} = \frac{25{,}754 - 0.5998}{25{,}754}(100) = 99.9977\% \ \text{ Passes}$$

DRE for Acetone

$$\text{DRE} = \frac{10{,}286 - 0.04758}{10{,}286}(100) = 99.9995\% \ \text{ Passes}$$

HCl

8.48 kg/h exceeds 1.8 kg/h, therefore check 1% limit

(0.01)(27,933 g/min) = 279.33 g/min

After the APC the emission is 141.37 g/min. This is less than the 1% limit. Therefore the incinerator complies with the HCl limits.

Particulates

Correct 14% oxygen to 7% concentration using Eqn. 10-32

$$P_c = 123.4\left(\frac{14}{21-14}\right) = 246.8$$

The limit is 180 mg/dscm, therefore the incinerator emission of 246.8 mg/dscm fails to comply with the particulate limits.

The incinerator complies with all emission limits except particulates.

10-43 Rotary kiln

Given: Retention time required = 1.0 h, diameter = 3.00 m, length = 6.00 m, slope = 2.00%, peripheral speed = 1.5 m/min

Solution:

a. Calculate revolutions per minute

$$N = \frac{\text{PeripheralSpeed}}{\text{Circumference / rev}} = \frac{1.5\,\text{m/min}}{\pi(3.00\text{m})/\text{rev}} = 0.159\,\text{rev/min}$$

b. Slope

$$S = 2.00\% = 0.02 \text{ m/m}$$

c. Time

$$t = \frac{0.19(6.00\text{m}/3.00\text{m})}{(0.02\,\text{m/m})(0.159\,\text{rev/min})} = 119.4\,\text{min}$$

This is > 1 hour so permit conditions have been met.

10-44 Time to test 10^{-7} cm/s hydraulic conductivity

Given: Standard permeameter dimensions and measurements

Solution:

a. Compute area (A) of sample

$$A = \frac{\pi(5.0\text{cm})^2}{4} = 19.64\text{cm}^2$$

b. Solve permeameter equation for t

$$t = \frac{Q \cdot L}{k \cdot h \cdot A \cdot t}$$

$$t = \frac{(100.0\text{cm}^3)(10\text{cm})}{(10^{-7}\ \text{cm/s})(100\text{cm})(19.64\text{cm}^2)(86400\,\text{s/d})} = 58.95 \text{ or } 60\text{ d}$$

10-45 Redesign of permeameter

Given: Figure P-10-44, 30 d for 100 mL minimum

Solution:

Note: there are many solutions that will work. I chose to double head to 2 m.

a. Solve equation for t

$$t = \frac{Q \cdot L}{k \cdot h \cdot A}$$

b. Area of sample

$$A = \frac{\pi(5.0\text{cm})^2}{4} = 19.64\text{cm}^2$$

c. Solve for t

$$t = \frac{(100.0\text{cm}^3)(10\text{cm})}{(10^{-7}\ \text{cm/s})(200\text{cm})(19.64\text{cm}^2)(86400\,\text{s/d})} = 29.5\text{d}$$

10-46 Soil hydraulic conductivity from falling head permeameter test

Given: Falling head permeameter dimensions and test results

Solution:

a. Calculate area of sample (A)

$$A = \frac{\pi(10.0\text{cm})^2}{4} = 78.54\text{cm}^2$$

b. Calculate area of stand pipe (a)

$$a = \frac{\pi(0.1\text{cm})^2}{4} = 0.007854\text{cm}^2$$

c. Calculate hydraulic conductivity (14 d = 1,209,600 s)

$$K = \frac{2.3(0.007854)(25)}{(78.54)(1,209,600)}\log\left(\frac{100}{25}\right) = 2.86\times10^{-9}\text{ cm/s}$$

The nominal permeability acceptable for a hazardous waste landfill is 10^{-7} cm/s. Thus, this is excellent.

10-47 Estimate of leachate volume

Given: 100 hectare landfill, permeability of 10^{-7} cm/s

Solution:

a. Convert cm/s to m/d

$$k = (10^{-7}\text{ cm/s})(10^{-2}\text{ m/cm})(86,400\text{ s/d}) = 8.64 \text{ x } 10^{-5}\text{ m/d}$$

b. Calculate flow

$$Q = (8.64 \text{ x } 10^{-5}\text{ m/d})(100\text{ hectares})(104\text{ m}^2\text{/hectare}) = 86.4\text{ m}^3\text{/d}$$

10-48 Time for leachate to migrate

Given: Three soils with differing permeability and depth

Solution:

SOIL A

a. Hydraulic gradient

$$i = \frac{H+T}{T} = \frac{0.3m + 3m}{3m} = 1.10$$

b. Darcy velocity

$$v = (1.8 \text{ x } 10^{-7} \text{ cm/s})(1.10) = 1.98 \text{ x } 10^{-7} \text{ cm/s}$$

c. Seepage velocity

$$v' = \frac{1.98 \times 10^{-7} \text{ cm/s}}{0.55} = 3.60 \times 10^{-7} \text{ cm/s}$$

d. Travel time

$$t = \frac{(3.0\text{m})(100\,\text{cm/m})}{(3.60 \times 10^{-7} \text{ cm/s})(86400\,\text{s/d})} = 9645\text{d}$$

SOIL B

a. Hydraulic gradient

$$i = \frac{H+T}{T} = \frac{0.3m + 3m + 10m}{10m} = 1.33$$

b. Darcy velocity

$$v = (2.2 \text{ x } 10^{-5} \text{ m/s})(1.33) = 2.93 \text{ x } 10^{-5} \text{ m/s}$$

c. Seepage velocity

$$v' = \frac{2.93 \times 10^{-5} \text{ m/s}}{0.25} = 1.17 \times 10^{-4} \text{ m/s}$$

d. Travel time

$$t = \frac{(10.0\text{m})}{(1.17 \times 10^{-4} \text{ m/s})(86400\,\text{s/d})} = 0.99\text{d}$$

SOIL C

a. Hydraulic gradient

$$i = \frac{H+T}{T} = \frac{0.3\text{m}+3\text{m}+10\text{m}+12\text{m}}{12\text{m}} = 2.11$$

b. Darcy velocity

$$v = (5.3 \times 10^{-5} \text{ mm/s})(2.11) = 1.12 \times 10^{-4} \text{ mm/s}$$

c. Seepage velocity

$$v' = \frac{1.12\times10^{-4}\text{ mm/s}}{0.35} = 3.19\times10^{-4}\text{ mm/s}$$

d. Travel time

$$t = \frac{(12.0\text{m})(1000\text{ mm/m})}{(3.19\times10^{-4}\text{ mm/s})(86400\text{ s/d})} = 435\text{d}$$

TOTAL TIME

$$\text{Time} = \frac{9645\text{d}+0.99\text{d}+435\text{d}}{365\text{ d/y}} = 27.6 \text{ or } 28 \text{ y}$$

10-49 Cubic meters of water contaminated at PQL

Given: PQL for trichloroethylene = 5 μg/L, 0.12 m^3 barrel leaks to ground water

Solution:

a. Calculate mass of trichloroethylene in 0.12 m^3

From Appendix A, density = 1.476 g/mL = 1,476 kg/m^3

mass = (0.12 m^3)(1,476 kg/m^3) = 177.12 kg
In μg = (177.12 kg)(10^9 μg/kg) = 1.7712 x 10^{11} μg

b. Volume of water contaminated

$$\frac{1.7712\times10^{11}\,\mu\text{g}}{(5\,\mu\text{g/L})(10^3\text{ L/m}^3)} = 35{,}424{,}000 \text{ or } 3.54 \times 10^7 \text{ m}^3$$

10-50 Travel time with retardation

Given: Hydraulic gradient = 8.6 x 10^{-4}, hydraulic conductivity = 200 m/d, porosity = 0.23, retardation factor = 2.3

Solution:

a. Find the Darcy velocity

$$v = k(i) = (200\ \text{m/d})(8.6 \text{ x } 10^{-4}) = 0.172\ \text{m/d}$$

b. Find average linear velocity

$$v' = \frac{v}{n} = \frac{0.172}{0.23} = 0.748\,\text{m/d}$$

c. Calculate the retardation factor

$$v'_R = \frac{v'}{R} = \frac{0.748\,\text{m/d}}{2.3} = 0.325\,\text{m/d}$$

d. Travel time

$$t = \frac{\text{dis tan ce}}{\text{speed}} = \frac{100\text{m}}{0.325\,\text{m/d}} = 307.55 \text{ or } 308 \text{ d}$$

10-51 Pumping rate for purge well

Given: Depth of unconfined aquifer = 60.00 m, permeability = 6.4 x 10^{-3} m/s, plume depth at 130 m from center of leak is 0.1 m and plume does not extend beyond 150 m.

Solution:

a. Using Equation 3-30

Computing h1 and h2

h1 = H - s1 = 60.00 - 0.1 = 59.90 m

h2 = H - s2 = 60.00 - 0.0 = 60.00 m

$$Q = \frac{\pi(6.4\times10^{-3}\ \text{m/s})\left[(60.00\text{m})^2 - (59.90\text{m})^2\right]}{\ln\left(\frac{150}{130}\right)} = 1.68\,\text{m}^3/\text{s}$$

10-52 Single intercept well system

Given: 0.12 m^3 of CCl_4, $K = 7 \times 10^{-4}$ cm/s, $n = 0.38$, GWT = 3.0 m, $i = 0.002$, aquifer = 28 m, $Q_w = 0.014\ m^3/s$

Solution:

a. Calculate the Darcy velocity

$$v = k(i) = (7 \times 10^{-4}\ m/s)(0.002) = 1.40 \times 10^{-6}\ m/s$$

b. Width of capture zone at the well

$$\frac{Q}{D(v)} = \frac{0.014\,m^3/s}{(28.0m)(1.40\times10^{-6}\ m/s)} = 357.14 \text{ or } 360 \text{ m}$$

10-53 Location of well

Given: Data in Problem 10-52, leading edge = 200 m width

Solution:

a. The well should be at a distance equal to x_{sp} (Eqn. 10-39)

$$x_{sp} = \frac{(0.014\,m^3/s)}{2\pi(28.0m)(1.40\times10^{-6}\ m/s)} = 56.8 \text{ or } 57 \text{ m}$$

DISCUSSION QUESTIONS

10-1 Dioxin toxicity

Given: LD50 for 2,3,7,8-TCDD

Solution:

The LD50 toxicity is based on oral intake for a particular species. This statement may be misleading if it is assumed to be the same for humans, the route of exposure is not orally, and because toxicity may manifest itself in forms other than death, i.e the slope of the dose-response curve may yield greater effects at lower doses but have a higher LD50.

10-2 Land ban

Given: Does "land ban" actually ban the disposal of hazardous waste?

Solution:

The "land ban" only prohibits land disposal of hazardous waste if there are no concentration levels or methods of treatment of waste established by EPA. A better term is "Land Disposal Restrictions (LDR).

10-3 Joint and several liability

Given: one drum identified, may be responsible for all others

Solution:

This is correct because CERCLA and courts have established strict, joint, and several liability.

10-4 Is recycling best first step?

Given: Instituting a program to minimize waste

Solution:

The best first step is to prevent the generation of pollution in the first place. Waste exchange and then recycling are logic follow-on steps.

10-5 Recycle, reuse or recover?

Given: plating sludge treated to recover nickel

Solution:

Treatment of the sludge to recover nickel is considered to be reclaiming. Since reclaiming is a form of recycling - it is also recycling.

10-6 Measuring POHCs

Given: True/false statement

Solution:

The statement is true. Only designated POHCs need to be measured.

Chapter 10: Hazardous Waste Management
Sample Problems and Solutions

10-1 Lifetime CDI for occupational exposure to Cr(VI)

Given: Concentration = 0.05 mg/m^3, exposure = 8 h/d for age 18 to 65, 5 d/wk, 50 wk/y

Solution:

a. Exposure = (65-18) = 47 years

b. Inhalation rate = $\frac{20\text{m}^3}{24\text{h}}$ = 0.833 m^3/h

c. Using the inhalation form of the equation in Table 10-8

$$\text{CDI} = \frac{(0.05\,\text{mg/m}^3)(0.833\,\text{m}^3/\text{h})(8\,\text{h/d})(5\,\text{d/wk})(50\,\text{wk/y})(47\,\text{y})}{(70\text{kg})(70\text{y})(365\text{d})}$$

$\text{CDI} = 2.2 \times 10^{-3}$ mg/kg • d

10-2 CDI for sulfur dioxide

Given: NAAQS = 80 µg/m^3, lifetime (24 h/d, 365 d/y), average adult.

Solution:

a. Using the assumptions in Table 10-8

$$\text{CDI} = \frac{(80\,\mu\text{g/m}^3)(20\,\text{m}^3/\text{d})(365\,\text{d/y})(70\text{y})}{(78\text{kg})(70\text{y})(365\text{d})}$$

CDI = 20.51 µg/kg • d or 2.05×10^{-2} mg/kg • d

10-4 Ingestion of soil with 2, 4-D

Given: Soil concentration of 2, 4-D = 10 mg/kg, child = 3 years old, adult, 1 year averaging time, 1 d/week, 20 weeks/y, FI = 0.10

Solution:

a. Using Table 10-9 values for 3 year old child

$$\mathrm{CDI} = \frac{(10\,\mathrm{mg/kg})(200\,\mathrm{mg/d})(10^{-6}\,\mathrm{kg/mg})(0.10)(1\,\mathrm{d/wk})(20\,\mathrm{wk/y})(1\mathrm{y})}{(16\mathrm{kg})(1\,\mathrm{d/wk})(20\,\mathrm{wk/y})(1\mathrm{y})}$$

$\mathrm{CDI} = 1.25 \times 10^{-5}$ mg/kg • d

b. For adult

$$\mathrm{CDI} = \frac{(10\,\mathrm{mg/kg})(100\,\mathrm{mg/d})(10^{-6}\,\mathrm{kg/mg})(0.10)(1\,\mathrm{d/wk})(20\,\mathrm{wk/y})(1\mathrm{y})}{(70\mathrm{kg})(1\,\mathrm{d/wk})(20\,\mathrm{wk/y})(1\mathrm{y})}$$

$\mathrm{CDI} = 1.43 \times 10^{-6}$ mg/kg • d

10-6 Estimating chronic daily intake

drink = 0.2 mg/L

Given: Child exposed for 5 years to 1,1,1-trichloroethane at drinking water limit. She swims, bathes. Average age is 8 years over exposure period.

1-5yr old 5yr

swim $\frac{30 min}{wk}$

bath $\frac{10 min}{d}$

$\frac{\text{Avg age}}{\text{Exp. period}} = 8$

air bath = 1 ug/m3

dermal PC = 0.006 $\frac{m}{h}$

bath = 50%

Solution:

a. Routes of exposure are:

1. Ingestion of drinking water
2. Ingestion while swimming
3. Dermal contact while swimming
4. Dermal contact with water during bath
5. Inhalation during bath

b. Drinking water standard is 0.2 mg/L.

c. Ingestion of drinking water (Eqn 10-10)

$$CDI = \frac{(0.2\,mg/L)(1.0\,L/d)(365\,d/y)(5y)}{(26kg)(5y)(365\,d/y)}$$

$CDI = 7.69 \times 10^{-3}$ mg/kg • d

d. Ingestion while swimming (Eqn 10-11)

$$ET = \frac{30\,min/wk}{60\,min/h} = 0.5\,h/wk$$

$$CDI = \frac{(0.2\,mg/L)(50\,mL/h)(10^{-3}\,L/mL)(0.5\,h/wk)(52\,wk/y)(5y)}{(26kg)(5y)(365\,d/y)}$$

✓

$CDI = 2.74 \times 10^{-5}$ mg/kg • d

e. Dermal contact while swimming (Eqn 10-12). NOTE: Assume 100% of body is exposed during swimming (a bit high but no other data given) PC = 6.0×10^{-3} m/h, and

$$ET = \frac{30\,min/wk}{60\,min/h} = 0.5\,h/wk$$

$$AD = \frac{(0.2\,mg/L)(0.925m^2)(6.0\times10^{-3}\,m/h)(0.5\,h/wk)(52\,wk/y)(5y)(10^3\,L/m^3)}{(26kg)(5y)(365\,d/y)}$$

$AD = 3.04 \times 10^{-3}$ mg/kg • d

f. Dermal contact while bathing (Eqn 10-12). NOTE: 50% submergence, $PC = 6.0 \times 10^{-3}$ m/h, and

$$ET = \frac{10\,\text{min/d}}{60\,\text{min/h}} = 0.1667\,\text{h/d}$$

$$AD = \frac{(0.2\,\text{mg/L})(0.925\text{m}^2)(6.0\times10^{-3}\,\text{m/h})(0.1667\,\text{h/d})(365\,\text{d/y})(5\text{y})(10^3\,\text{L/m}^3)}{(26\text{kg})(5\text{y})(365\,\text{d/y})}(0.50)$$

$AD = (7.12 \times 10^{-3})(0.50) = 3.56 \times 10^{-3}$ mg/kg • d

g. Inhalation during bath (Eqn 10-15). NOTE: $IR = 5\,\text{m}^3/\text{d} = 0.2083\,\text{m}^3/\text{h}$

$$CDI = \frac{(1.0\,\mu\text{g/m}^3)(10^{-3}\,\text{mg}/\mu\text{g})(0.2083\,\text{m}^3/\text{h})(0.1667\,\text{h/d})(365\,\text{d/y})(5\text{y})}{(26\text{kg})(5\text{y})(365\,\text{d/y})}$$

$CDI = 1.34 \times 10^{-6}$ mg/kg • d

h. Total CDI

$CDI = 7.69 \times 10^{-3} + 2.74 \times 10^{-5} + 3.04 \times 10^{-3} + 3.56 \times 10^{-3} + 1.34 \times 10^{-6}$

$CDI = 1.43 \times 10^{-2}$ mg/kg • d

10-8 Concentration of hexavalent chromium = 10^{-5} risk

Given: Standard assumptions

Solution:

a. Using the slope factor from Table 10-5, calculate the CDI

risk = (SF)(CDI)

10^{-5} = (42 kg • d/mg)(CDI)

$CDI = 2.38 \times 10^{-7}$ mg/kg • d

b. Using assumptions from Table 10-9

$$2.38\times10^{-7}\,\text{mg/kg}\cdot\text{d} = \frac{(CA)(20\,\text{m}^3/\text{d})(365\,\text{d/y})(70\text{y})}{(78\text{kg})(70\text{y})(365\,\text{d/y})}$$

$CA = 9.28 \times 10^{-7}\,\text{mg/m}^3$

10-9 Characterize risk

Given: toluene, barium, and xylenes

Solution:

a. These are not carcinogens so calculate hazard index using Eqn 10-19 and 10-22 and Table 10-6

$$HI = \frac{0.03}{0.2} + \frac{0.06}{0.05} + \frac{0.3}{2.0}$$

$$HI = 0.15 + 1.2 + 0.15 = 1.5$$

ENCE 3323: Introduction to Environmental Engineering

Air Pollution Control
(Chapter 7)

Ideal Gas Law

$$\rho = \frac{1}{R}\frac{PM}{T}$$

ρ = density of gas, kg/m^3
P = absolute pressure, kPa
M = molecular mass, grams/mole
T = absolute temperature, K
R = universal gas constant = 8.3143 J/K · mole

General Form

$$PV = nRT \qquad (6\text{-}2)$$

where V is the volume occupied by n moles of gas. At 273.15 K and 101.325 kPa, one mole of an ideal gas occupies 22.414 L.

- Sampling instruments are calibrated with air. So corrections are necessary
- Dalton's law of partial pressures is useful in calculating these correction factors

In mathematical terms,

$$P_t = P_1 + P_2 + P_3 + \ldots \qquad (6\text{-}3)$$

where P_t = total pressure of mixture
P_1, P_2, P_3 = pressure of each gas if it were in container alone, that is, *partial pressure*

Dalton's law also may be written in terms of the ideal gas law:

$$P_t = n_1\frac{RT}{V} + n_2\frac{RT}{V} + n_3\frac{RT}{V} + \ldots$$

$$= (n_1 + n_2 + n_3 + \ldots)\frac{RT}{V}$$

Thermodynamic Processes in Air

- Adiabatic Process: a process that takes place with ***no addition or removal of heat*** and it is sufficiently slow to assume ***equilibrium of gases*** at all times

(Heat added to gas) = (increase in thermal energy)
+ (external work done by or on the gas)

- Increase in thermal energy = work done which reflects in a change in temperature of the gas
- ***If a gas is expanded adiabatically, its temperature will decrease….!!!***

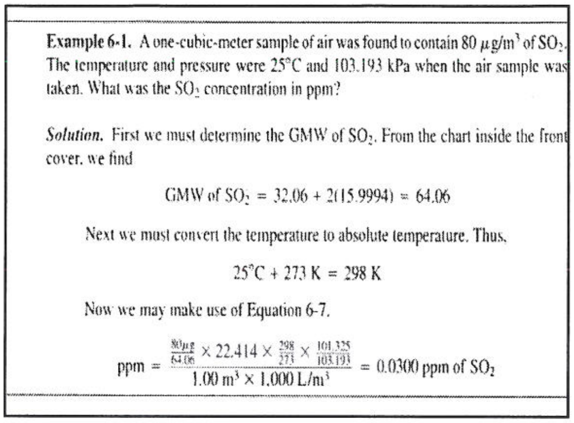
Measurement Units

- Concentration Units –
  - micrograms/m^3,
  - parts per million ***(ppm)*** - volume to volume ratio, hence temperature and pressure don't change the ratio of pollutant volume to air volume
- Particle Size Units – microns (10^{-6} meters)

Conversion from μg/m^3 to ppm

$$\text{ppm} = \frac{\frac{M_P}{\text{GMW}} \times 22.414 \times \frac{T_2}{273\text{ K}} \times \frac{101.325\text{ kPa}}{P_2}}{V_a \times 1{,}000\text{ L/m}^3} \qquad (6\text{-}7)$$

- GMW = molecular weight of pollutant (grams)
- M_P = pollutant mass (grams)
- T_2 = absolute temperature (K)
- P_2 = absolute pressure (kPa)
- V_a = volume of air (m^3) at that temperature & pressure (assume 1 m^3 if not stated)



Example 6-1. A one-cubic-meter sample of air was found to contain 80 $\mu g/m^3$ of SO_2. The temperature and pressure were 25°C and 103.193 kPa when the air sample was taken. What was the SO_2 concentration in ppm?

Solution. First we must determine the GMW of SO_2. From the chart inside the front cover, we find

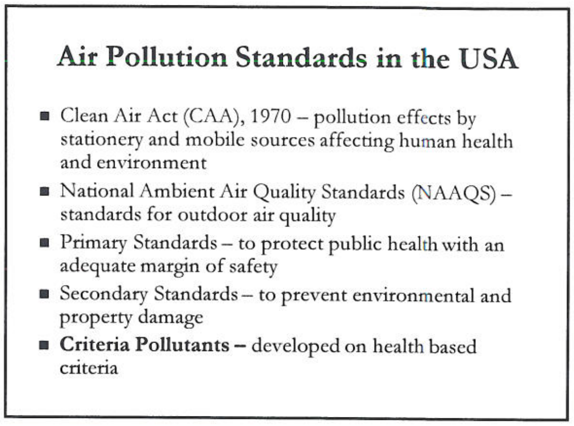
$$\text{GMW of } SO_2 = 32.06 + 2(15.9994) = 64.06$$

Next we must convert the temperature to absolute temperature. Thus,

$$25^\circ C + 273\ K = 298\ K$$

Now we may make use of Equation 6-7.

$$\text{ppm} = \frac{\frac{80\mu g}{64.06} \times 22.414 \times \frac{298}{273} \times \frac{101.325}{103.193}}{1.00\ m^3 \times 1{,}000\ L/m^3} = 0.0300 \text{ ppm of } SO_2$$

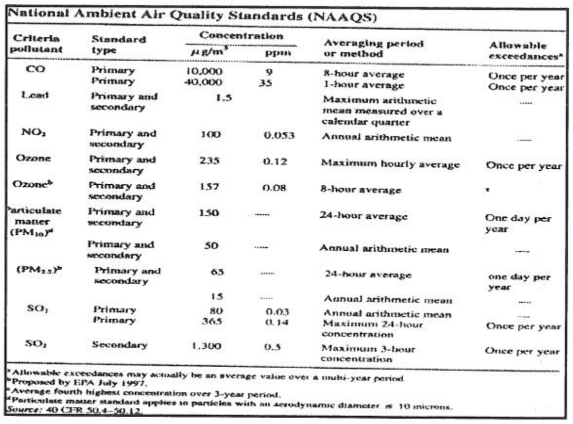


Air Pollution Standards in the USA

- Clean Air Act (CAA), 1970 – pollution effects by stationery and mobile sources affecting human health and environment
- National Ambient Air Quality Standards (NAAQS) – standards for outdoor air quality
- Primary Standards – to protect public health with an adequate margin of safety
- Secondary Standards – to prevent environmental and property damage
- **Criteria Pollutants –** developed on health based criteria

Air Pollution Standards in the USA…

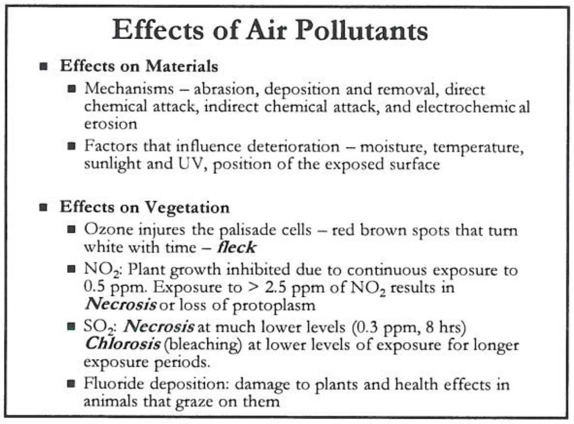
- Air Quality Control Regions (AQR's) – divisions of states
  - Attainment Area – if air quality in an AQR meets the primary standards
  - Nonattainment Area – areas those don't meet the primary standards
- National Emission Standards for Hazardous Air Pollutants (NESHAPs), 1990 – 189 HAPs
- MACT – Maximum Achieveable Control Technology – process changes, material substitutions or air pollution control equipment



National Ambient Air Quality Standards (NAAQS)

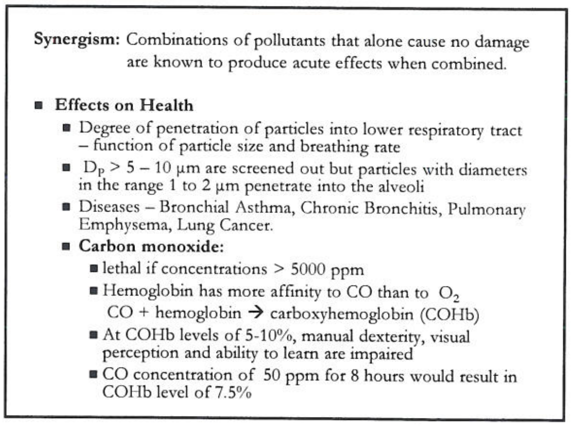
Criteria pollutant	Standard type	Concentration		Averaging period or method	Allowable exceedances[a]
		$\mu g/m^3$	ppm		
CO	Primary	10,000	9	8-hour average	Once per year
	Primary	40,000	35	1-hour average	Once per year
Lead	Primary and secondary	1.5		Maximum arithmetic mean measured over a calendar quarter	-----
NO_2	Primary and secondary	100	0.053	Annual arithmetic mean	-----
Ozone	Primary and secondary	235	0.12	Maximum hourly average	Once per year
Ozone[b]	Primary and secondary	157	0.08	8-hour average	[c]
Particulate matter (PM_{10})[d]	Primary and secondary	150	-----	24-hour average	One day per year
	Primary and secondary	50	-----	Annual arithmetic mean	-----
($PM_{2.5}$)[b]	Primary and secondary	65	-----	24-hour average	one day per year
		15	-----	Annual arithmetic mean	-----
SO_2	Primary	80	0.03	Annual arithmetic mean	-----
	Primary	365	0.14	Maximum 24-hour concentration	Once per year
SO_2	Secondary	1,300	0.5	Maximum 3-hour concentration	Once per year

[a] Allowable exceedances may actually be an average value over a multi-year period.
[b] Proposed by EPA July 1997.
[c] Average fourth highest concentration over 3-year period.
[d] Particulate matter standard applies to particles with an aerodynamic diameter ≤ 10 microns.
Source: 40 CFR 50.4–50.12.



Effects of Air Pollutants

- **Effects on Materials**
  - Mechanisms – abrasion, deposition and removal, direct chemical attack, indirect chemical attack, and electrochemical erosion
  - Factors that influence deterioration – moisture, temperature, sunlight and UV, position of the exposed surface
- **Effects on Vegetation**
  - Ozone injures the palisade cells – red brown spots that turn white with time – ***fleck***
  - NO_2: Plant growth inhibited due to continuous exposure to 0.5 ppm. Exposure to > 2.5 ppm of NO_2 results in ***Necrosis*** or loss of protoplasm
  - SO_2: ***Necrosis*** at much lower levels (0.3 ppm, 8 hrs) ***Chlorosis*** (bleaching) at lower levels of exposure for longer exposure periods.
  - Fluoride deposition: damage to plants and health effects in animals that graze on them



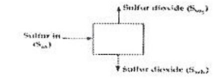
Synergism: Combinations of pollutants that alone cause no damage are known to produce acute effects when combined.

- **Effects on Health**
  - Degree of penetration of particles into lower respiratory tract – function of particle size and breathing rate
  - $D_p > 5 - 10\ \mu m$ are screened out but particles with diameters in the range 1 to 2 µm penetrate into the alveoli
  - Diseases – Bronchial Asthma, Chronic Bronchitis, Pulmonary Emphysema, Lung Cancer.
  - **Carbon monoxide:**
    - lethal if concentrations > 5000 ppm
    - Hemoglobin has more affinity to CO than to O_2
      CO + hemoglobin → carboxyhemoglobin (COHb)
    - At COHb levels of 5-10%, manual dexterity, visual perception and ability to learn are impaired
    - CO concentration of 50 ppm for 8 hours would result in COHb level of 7.5%

- **Hazardous Air Pollutants (HAPs):**
  - Can cause cancer, lung diseases, birth defects, damage to immune and nervous systems
- **Lead (Pb):**
  - Anemia, fatigue, irritability, mild head ache occurs when lead level in the blood rises to 60 – 120 μg/100 grams of whole blood
  - Chronic exposure results in brain damage, mental incompetence and highly active aggressive behavior leading to eventual paralysis
- **Nitrogen-di-oxide (NO_2):**
  - Affects the respiratory tract adversely and causes fluid accumulation in the lung due to continued exposure.

Example 6-2. An Illinois coal is burned at a rate of 1.00 kg per second. If the analysi of the coal reveals a sulfur content of 3.00 percent, what is the annual rate of emissio of SO_2?

Solution. Using the mass-balance approach, we begin by drawing a mass-balance di agram:



The mass balance equation may be written as

$$S_{in} = S_{ash} + S_{SO_2}$$

From the problem data, the mass of "sulfur in" is

$$S_{in} = 1.00\ \text{kg/s} \times 0.030 = 0.030\ \text{kg/s}$$

In one year,

$$S_{in} = 0.030\ \text{kg/s} \times 86{,}400\ \text{s/d} \times 365\ \text{d/y} = 9.46 \times 10^5\ \text{kg/y}$$

The sulfur in the ash is 5 percent of the input sulfur:

$$S_{ash} = (0.05)(9.46 \times 10^5\ \text{kg/y}) = 4.73 \times 10^4\ \text{kg/y}$$

The amount of sulfur available for conversion to SO_2:

$$S_{SO_2} = S_{in} - S_{ash} = 9.46 \times 10^5 - 4.73 \times 10^4 = 8.99 \times 10^5\ \text{kg/y}$$

The amount of sulfur formed is determined from the proportional weights of the oxidation reaction (Equation 6-14):

$$S + O_2 \rightarrow SO_2$$

$$\text{GMW} = 32 + 32 = 64$$

The amount of sulfur dioxide formed is then 64/32 of the sulfur available for conversion.

$$S_{SO_2} = \frac{64}{32}(8.99 \times 10^5\ \text{kg/y}) = 1.80 \times 10^6\ \text{kg/y}$$

Acid Rain

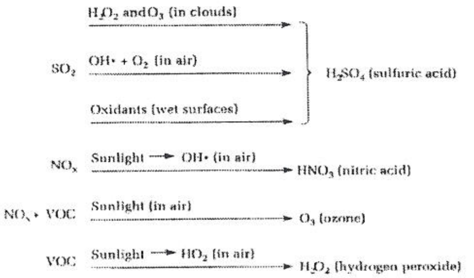


FIGURE 6-8
Acid rain precursors and products.

Ozone Depletion

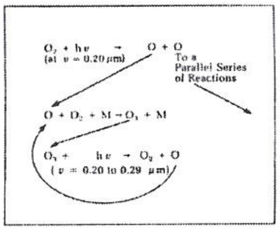


FIGURE 6-9
Photoreactions of ozone.

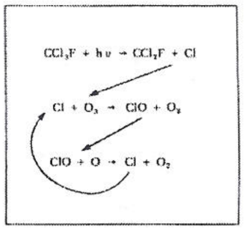
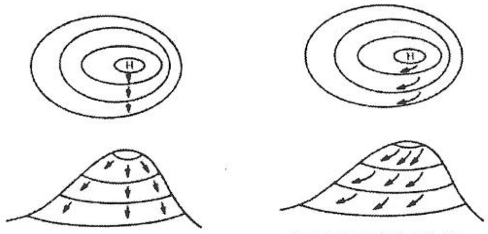


FIGURE 6-10
Ozone destruction by chlorofluoromethane.

Montreal Protocol (1990 & 1992) – ban the use of CFC's, carbon tetra chloride, and methyl chloroform as of January 1996

Air Pollution Meteorology

- Coriolis Effect: Wind flows from a high pressure to low pressure area. Since the earth rotates, an angular thrust called the *Coriolis Effect* is added to this motion. This results in:
- *Anticyclones* for highs – associated with good weather, and
- *Cyclones* for lows – associated with foul weather eg. tornadoes and hurricanes.



(a) Anticyclone without Coriolis effect

(b) Anticyclone with Coriolis effect

Wind flow due to pressure gradient.

Stability

The tendency of the atmosphere to resist or enhance vertical motion is termed *stability*. It is related to both wind speed and the change of air temperature with height (*lapse rate*). For our purpose, we may use the lapse rate alone as an indicator of the stability condition of the atmosphere.

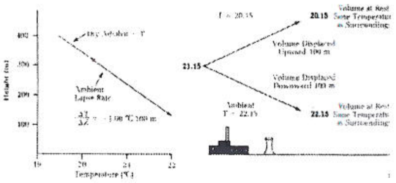
There are three stability categories. When the atmosphere is classified as *unstable*, mechanical turbulence is enhanced by the thermal structure. A *neutral* atmosphere is one in which the thermal structure neither enhances nor resists mechanical turbulence. When the thermal structure inhibits mechanical turbulence, the atmosphere is said to be *stable*. Cyclones are associated with unstable air. Anticyclones are associated with stable air.

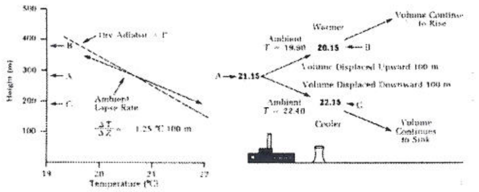
Neutral stability. The lapse rate for a neutral atmosphere is defined by the rate of temperature increase (or decrease) experienced by a parcel of air that expands (or contracts) *adiabatically* (without the addition or loss of heat) as it is raised through the atmosphere. This rate of temperature decrease (dT/dz) is called the *dry adiabatic lapse rate*. It is designated by the Greek letter gamma (Γ). It has a value of approximately −1.00°C/100 m.

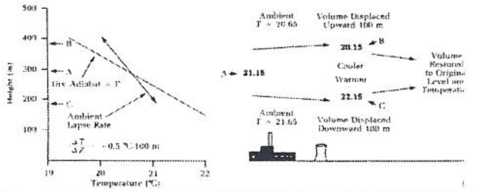
Unstable atmosphere. If the temperature of the atmosphere falls at a rate greater than Γ (for example, −1.01°C/100 m), the lapse rate is said to be *superadiabatic*, and the atmosphere is unstable.

Stable atmosphere. If the temperature of the atmosphere falls at a rate less than Γ (for example, −0.99°C/100 m), it is called *subadiabatic*, and the atmosphere is stable.

Lapse rate and displaced air volume.







Types of Subadiabatic Lapse Rate

- ***Isothermal*** – No change in temperature with elevation
- ***Inversion*** – Temperature increases with elevation
  - More severe form of a stable temperature profile
  - Associated with restricted air volumes resulting in air pollution episodes

Example 6-3. Given the following temperature and elevation data, determine the stability of the atmosphere.

Elevation (m)	Temperature (°C)
2.00	14.35
324.00	11.13

Solution. Begin by determining the existing lapse rate:

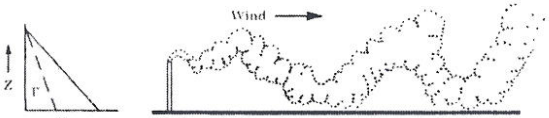
$$\frac{\Delta T}{\Delta Z} = \frac{T_2 - T_1}{Z_2 - Z_1}$$

$$= \frac{11.13 - 14.35}{324.00 - 2.00} = \frac{-3.22}{322.00}$$

$$= -0.0100°\text{C/m} = -1.00°\text{C}/100\ \text{m}$$

Now we compare this with Γ and find that they are equal. Thus, the atmospheric stability is neutral.

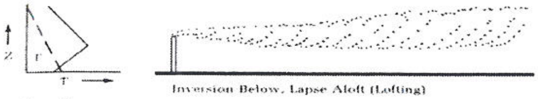
Six Types of Plume Behavior



Strong Lapse Condition (Looping)

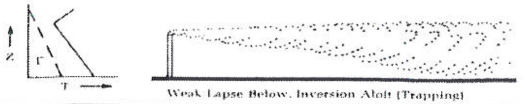
Weak Lapse Condition (Coning)

Inversion Condition (Fanning)

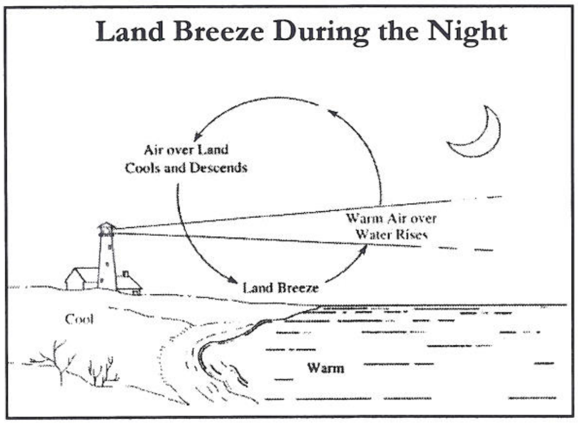


Inversion Below, Lapse Aloft (Lofting)

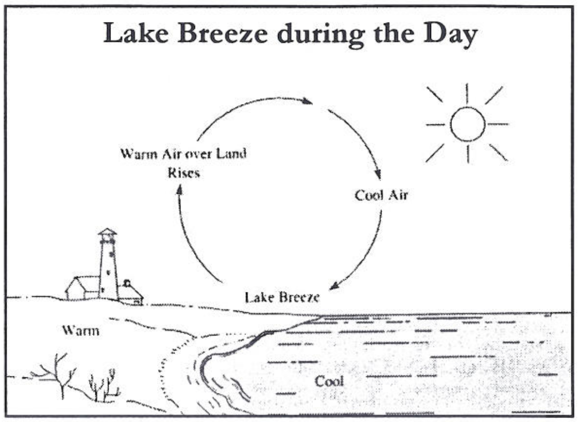
Lapse Below, Inversion Aloft (Fumigation)



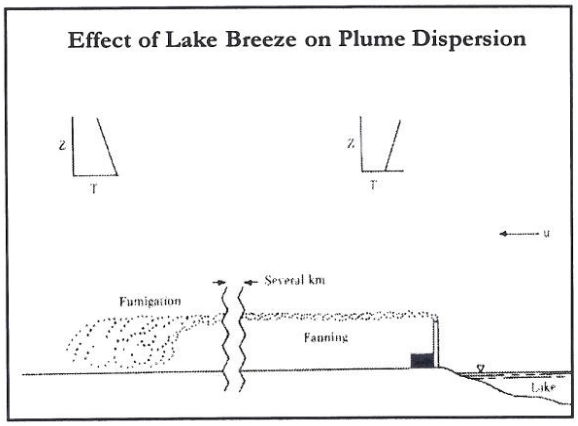
Weak Lapse Below, Inversion Aloft (Trapping)



Land Breeze During the Night



Lake Breeze during the Day



Effect of Lake Breeze on Plume Dispersion

Atmospheric Dispersion

- Factors affecting dispersion of air pollutants:
  - Source Characteristics
    - Plume rise + physical stack height = effective stack height
  - Downwind Distance
  - Wind Speed and Direction
  - Stability
- Dispersion Modeling
  - Short term models
  - Climatological models

Short Term Models

- To estimate ambient concentrations where it is impractical to sample (eg) – rivers, lakes, etc
- To estimate the required emergency source reductions associated with periods of air stagnations under air pollution episode alert conditions; and
- To estimate the most probable locations of high, short-term, ground level concentrations as part of a site selection evaluation for the location of air monitoring equipment.

Climatological Models

- To estimate mean concentrations over a long period of time
- To estimate mean concentrations that exist at particular times of the day for each season over a long period of time
- Used as aids for developing emission standards

Example 6-5. Determine the distance downwind from a stack at which we must switch to the "inversion form" of the dispersion model given the following meteorologic situation:

Effective stack height: 50 m
Inversion base: 350 m
Wind speed: 7.3 m/s
Cloud cover: none
Time: 1130 h
Season: summer

Solution. Determine the stability class using Table 6-6. At > 6 m/s with strong radiation, the stability class is C.

Calculate the value of s_z.

$$s_z = 0.47(350 \text{ m} - 50 \text{ m}) = 141 \text{ m}$$

Using Figure 6-20, find x_L. With $s_z = 141$, draw a horizontal line to stability class C. Drop a vertical line to the "distance downwind." Find $x_L = 2.5$ km.

Therefore, at any distance equal to or greater than 5 km downwind ($2x_L$), use the "inversion form" of the equation (Equation 6-25.)

For distances less than 5 km, we use Equation 6-19 with s_z determined from the distance to the point of interest and the stability. Thus, in no case do we use s_z computed from Equation 6-24 to calculate χ.

Indoor Air Quality Model

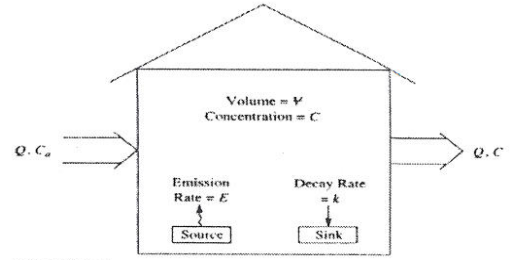


FIGURE 6-22
Mass-balance model for indoor air pollution.

$$\begin{matrix}\text{Rate of}\\\text{pollutant}\\\text{increase}\\\text{in box}\end{matrix} = \begin{matrix}\text{Rate of}\\\text{pollutant}\\\text{entering}\\\text{box from}\\\text{outdoors}\end{matrix} + \begin{matrix}\text{Rate of}\\\text{pollutant}\\\text{entering box}\\\text{from indoor}\\\text{emissions}\end{matrix} - \begin{matrix}\text{Rate of}\\\text{pollutant}\\\text{leaving box}\\\text{by leakage}\\\text{to outdoors}\end{matrix} - \begin{matrix}\text{Rate of}\\\text{pollutant}\\\text{leaving box}\\\text{by decay}\end{matrix} \qquad (6\text{-}26)$$

or

$$\forall \frac{dC}{dt} = QC_a + E - QC - kC\forall \qquad (6\text{-}27)$$

where $\forall$ = volume of box, m^3
C = concentration of pollutant, g/m^3
Q = rate of infiltration of air into and out of box, m^3/s
C_a = concentration of pollutant in outdoor air, g/m^3
E = emission rate of pollutant into box from indoor source, g/s
k = pollutant reaction rate coefficient, s^{-1}

Reaction rate coefficients for a selected list of pollutants are given in Table 6-8.

The general solution for Equation 6-27 is

$$C_t = \frac{\dfrac{E}{\forall} + C_a\dfrac{Q}{\forall}}{\dfrac{Q}{\forall} + k}\left[1 - \exp\left(-\left(\frac{Q}{\forall} + k\right)t\right)\right] + C_0\exp\left[-\left(\frac{Q}{\forall} + k\right)t\right] \qquad (6\text{-}28)$$

The steady-state solution for Equation 6-27 may be found by setting $dC/dt = 0$ and solving for C:

$$C = \frac{QC_a + E}{Q + k\forall} \qquad (6\text{-}29)$$

When the pollutant is conservative and does not decay with time or have a significant reactivity, $k = 0$. In the special case when the pollutant is conservative and the ambient concentration is negligible and the initial indoor concentration is zero, Equation 6-27 reduces to:

$$C_t = \frac{E}{Q}\left[1 - \exp\left(-\left(\frac{Q}{\forall}\right)t\right)\right] \qquad (6\text{-}30)$$

Example 6-6. An unvented kerosene heater is operated for one hour in an apartment having a volume of 200 m^3. The heater emits SO_2 at a rate of 50 μg/s. The ambient air concentration (C_a) and the initial indoor air concentration (C_0) of SO_2 are 100 μg/m^3.

If the rate of ventilation is 50 L/s, and the apartment is assumed to be well mixed, what is the indoor air concentration of SO_2 at the end of one hour?

Solution. The concentration may be determined using the general solution form of the indoor air quality model (Equation 6-28). The decay rate for SO_2 from Table 6-8 is 6.39×10^{-5} s^{-1} and 50 L/s is equivalent to 0.050 m^3/s.

$$C_t = \frac{\dfrac{50\ \mu\text{g/s}}{(200\text{ m}^3)} + 100\ \mu\text{g/m}^3\dfrac{0.050\text{ m}^3\text{/s}}{200\text{ m}^3}}{\dfrac{0.050\text{ m}^3\text{/s}}{200\text{ m}^3} + 6.39 \times 10^{-5}\text{ s}^{-1}}$$

$$\times\left[1 - \exp\left(-\left(\frac{0.050\text{ m}^3\text{/s}}{200\text{ m}^3} + 6.39 \times 10^{-5}\text{ s}^{-1}\right)(3600\text{ s})\right)\right]$$

$$+ (100\ \mu\text{g/m}^3)\exp\left[-\left(\frac{0.050\text{ m}^3\text{/s}}{200\text{ m}^3} + 6.39 \times 10^{-5}\text{ s}^{-1}\right)(3600\text{ s})\right]$$

$$= 876.08(1 - \exp(-1.13)) + 100\exp(-1.13) = 876.08(1 - 0.323) + 100(0.323)$$

$$= 593.09 + 32.3 = 625.39 \text{ or } 630\ \mu\text{g/m}^3$$

Air Pollution Control of Stationary Sources

- Gaseous Pollutants:
  - Absorption
    - Diffusion of pollutant gas to the surface of the liquid
    - Transfer across the gas/liquid interface (dissolution)
    - Diffusion of the dissolved gas away from the interface into the liquid
  - Adsorption
    - The gas ***(adsorbate)*** penetrates into the pores of the solid ***(adsorbent)*** but not into the lattice itself.
      - Physical Bonds (Vander Wall's forces) – ***Physisorption***
      - Chemical Bonds - ***Chemisorption***

- Combustion
- Flue Gas Desulfurization (FGD)
- Nonregenerative Systems – nine commercially available non-regeneration systems.

Control Technologies for NO_X

- Prevention
- Post-Combustion

Control Technologies for Particulate Pollutants

- Cyclones
- Fabric Filters
- Liquid Scrubbing
- Electrostatic Precipitation (ESP)

Cyclones

- For particle sizes > 10 μm in diameter
- This is an inertial collector with no moving parts
- Particle-laden gas is accelerated through a spiral motion, which imparts a centrifugal force to the particles
- Particles are hurled out of the spinning gas and impact on the cylinder wall of the cyclone

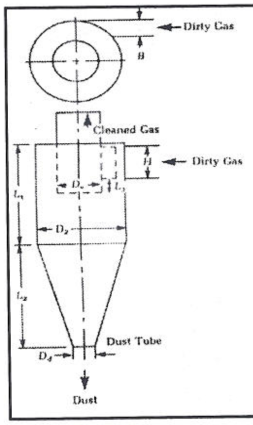


FIGURE 6-31
Standard reverse flow cyclone proportions.
Note: Standard cyclone proportions are as follows:

Length of cylinder, $L_1 = 2D_2$
Length of cone, $L_2 = 2D_2$
Diameter of exit, $D_e = 0.5D_2$
Height of entrance, $H = 0.5D_2$
Width of entrance, $B = 0.25D_2$
Diameter of dust exit, $D_d = 0.25D_2$
Length of exit duct, $L_3 = 0.125D_2$

(*Source:* M. Crawford, *Air Pollution Control Theory,* New York: McGraw-Hill, 1976. Reprinted by permission.)

$$d_{0.5} = \left[\frac{9\mu B^2}{\rho_p Q_g}\frac{H}{\theta}\right]^{1/2} \qquad (6\text{-}56)$$

$d_{0.5}$ = cut diameter, the particle size for which the collection efficiency is 50 percent
μ = dynamic viscosity of gas, Pa·s
B = width of entrance, m
H = height of entrance, m
ρ_p = particle density, kg/m³s

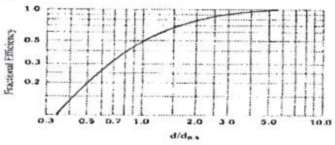


FIGURE 6-32
Empirical cyclone collection efficiency. (*Source:* C. E. Lapple, "Processes Use Many Collection Types," *Chemical Engineer,* vol. 58, p. 147, 1951.)

Q_g = gas flow rate, m³/s
θ = effective number of turns made in traversing the cyclone as defined in Equation 6-57.

The value of θ may be determined approximately by the following:

$$\theta = \frac{\pi}{H}(2L_1 + L_2) \qquad (6\text{-}57)$$

where L_1 and L_2 are the length of the cylinder and cone, respectively.

Example 6-9. Determine the efficiency of a "standard" cyclone having the following characteristics for particles 10 μm in diameter with a density of 800 kg/m^3:

Cyclone barrel diameter = 0.50 m
Gas flow rate = 4.0 m^3/s
Gas temperature = 25°C

Solution. From the standard cyclone dimensions we can calculate the following:

$$B = (0.25)(0.50 \text{ m}) = 0.13 \text{ m}$$
$$H = (0.50)(0.50 \text{ m}) = 0.25 \text{ m}$$
$$L_1 = L_2 = (2.00)(0.50 \text{ m}) = 1.0 \text{ m}$$

The number of turns i is then

$$\theta = \frac{\pi}{0.25}[2(1.0) + 1.0]$$
$$= 37.7$$

From the gas temperature and Table A-4 of Appendix A, we find the dynamic viscosity is 18.5 $\mu Pa \cdot s$. The cut diameter is then

$$d_{0.5} = \left[\frac{9(18.5 \times 10^{-6} \text{ Pa}\cdot\text{s})(0.13 \text{ m})^2(0.25 \text{ m})}{(800 \text{ kg/m}^3)(4.0 \text{ m}^3/\text{s})(37.7)}\right]^{1/2}$$
$$= 2.41 \times 10^{-6} \text{ m} = 2.41 \ \mu\text{m}$$

The ratio of particle sizes is

$$\frac{d}{d_{0.5}} = \frac{10 \ \mu\text{m}}{2.41 \ \mu\text{m}} = 4.15$$

From Figure 6-32 we find that the collection efficiency is about 95 percent.

Baghouses

- High efficiency control of particles smaller than 5 µm is desired, a filter may be selected as the control method.
- Two types:
  - The deep bed filter – furnace filter, and
  - The bag house.

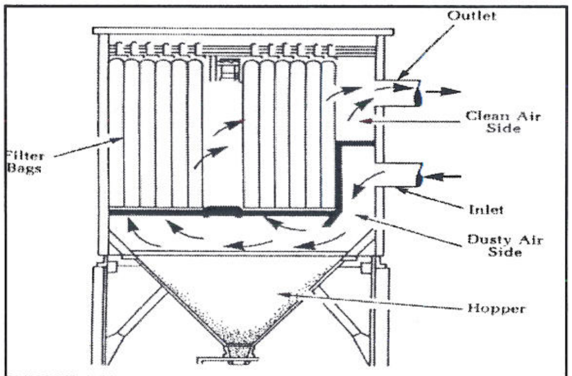
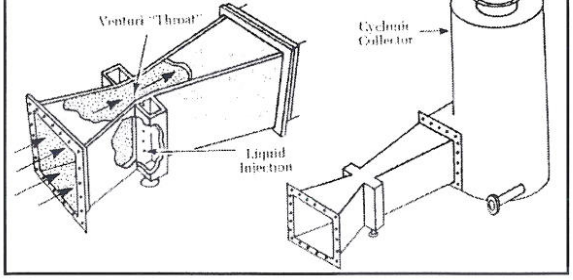


FIGURE 6-33
Baghouse.

Liquid Scrubbing

Venturi Scrubber



$$\eta = 1 - \exp(-\kappa R \sqrt{\psi}) \qquad (6\text{-}58)$$

η = efficiency
exp = exponential to base e
κ = correlation coefficient, m^3 of gas/m^3 of liquid
R = liquid flow rate, m^3/m^3 of gas
ψ = inertial impaction parameter defined by Equation 6-59

Inertial Impact Parameter

$$\psi = \frac{C \rho_p v_g (d_p)^2}{18 d_d \mu} \qquad (6\text{-}59)$$

C = Cunningham correction factor defined by Equation 6-60, unitless
ρ_p = particle density, kg/m^3
v_g = speed of gas at throat, m/s

d_p = diameter of particle, m
d_d = diameter of droplet, m
μ = dynamic viscosity of gas, Pa · s

The Cunningham factor may be approximated with the following equation:[65]

$$C = 1 + \frac{6.21 \times 10^{-4}(T)}{d_p} \qquad (6\text{-}60)$$

where T = absolute temperature, K
d_p = diameter of particle, μm

Example 6-10. Given the scrubber described below, write an expression for collection efficiency that is a function of particle size. Assume the particles are fly ash with a density of 700 kg/m³ and a minimum size of 10 μm diameter.

Venturi characteristics:
Throat area = 1.00 m²
Gas flow rate = 94.40 m³/s
Gas temperature = 150°C
Liquid flow rate = 0.13 m³/s
Coefficient κ = 200
Droplet diameter = 100 μm

Solution. We begin by determining the value of the Cunningham correction factor for the smallest particle to see if the d_p term in the denominator must be retained.

$$C = 1 + \frac{6.21 \times 10^{-4}(423\text{ K})}{10\ \mu\text{m}}$$
$$= 1 + 0.0263$$

For this we can see that the term containing d_p will be small for all particles greater than 10 μm and we can use the approximation:

$$C = 1$$

Before we can proceed to calculate a value for ψ, we must determine the gas velocity at the throat:

$$v_g = \frac{Q_g}{A_t}$$

where A_t = cross-sectional area of throat

$$v_g = \frac{94.40\text{ m}^3/\text{s}}{1.00\text{ m}^2} = 94.40\text{ m/s}$$

The dynamic viscosity of the gas is determined from Table A-4 of Appendix A and from the temperature of the gas (150°C). It is 25.2 μPa · s.

Now we can calculate in terms of d_p in μm. Note that $C = 1$ and that 18 is a constant.

$$\psi = \frac{(1)(700\text{ kg/m}^3)(94.40\text{ m}^3/\text{s})(1 \times 10^{-12}\ \mu\text{m}^2/\text{m}^2)(d_p)^2}{(18)(100 \times 10^{-6}\text{ m})(25.2 \times 10^{-6}\text{ Pa}\cdot\text{s})}$$
$$= (1.46)(d_p)^2$$

Taking the square root of ψ and computing R as 0.13/94.40, the expression for efficiency as a function of diameter is then

$$\eta = 1 - \exp[-(200)(1.38 \times 10^{-3})(1.21)d_p]$$
$$= 1 - \exp[-0.33(d_p)]$$

Electrostatic Precipitators (ESP's)

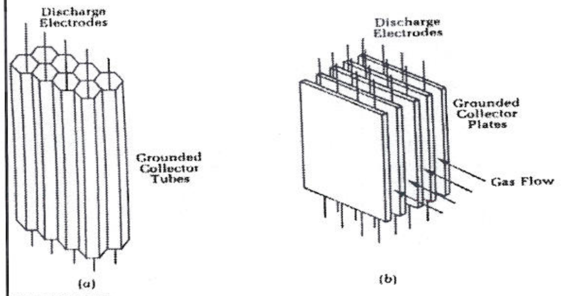


FIGURE 6-35
Electrostatic precipitator with (*a*) wire in tube, (*b*) wire and plate. (*Source:* EPA Training Manual.)

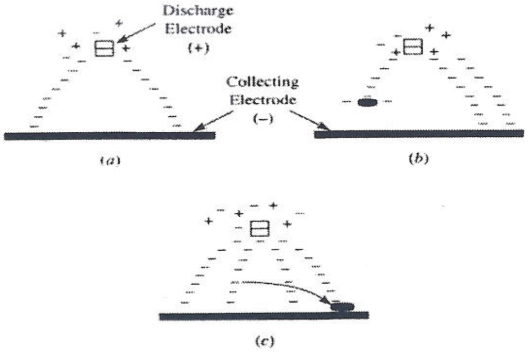


FIGURE 6-36
Particle charging and collection in ESP. (*Source:* EPA Training Manual.)

The classic ESP efficiency equation is the one proposed by Deutsch.[66]

$$\eta = 1 - \exp\left(-\frac{Aw}{Q_g}\right) \qquad (6\text{-}61)$$

where A = collection area of plates, m²
w = migration velocity of particles, m/s
Q_g = gas flow rate, m³/s

The migration velocity of the particles is a function of the electrostatic force. The migration velocity is described by the following equation:

$$w = \frac{qE_pC}{6\pi r\mu} \qquad (6\text{-}62)$$

where q = charge, coulombs (C)
E_p = collection field intensity, volts/m
r = particle radius, m
μ = dynamic viscosity of gas, Pa · s
C = Cunningham correction factor

Example 6-11. Determine the collection efficiency of the electrostatic precipitator described below for a particle 154 μm in diameter having a drift velocity of 0.184 m/s. What is the effect of reducing the plate spacing to one-half of its current value and doubling the number of plates?

ESP specifications:

Height = 7.32 m
Length = 6.10 m
Number of passages = 5
Plate spacing = 0.28 m
Gas flow rate = 19.73 m^3/s

Solution. First we calculate the area of the plates. For a single plate.

$$A = 7.32 \times 6.10 = 44.65 \text{ m}^2$$

Since there are eight collecting surfaces (two for each plate, 4 plates form 5 passages):

$$A = 44.65 \text{ m}^2 \times 8 = 357.2 \text{ m}^2$$

The efficiency is then calculated in a straightforward manner using Equation 6-61.

$$\eta = 1 - \exp\left[-\frac{(357.2)(0.184)}{19.73}\right]$$
$$= 0.964$$

Therefore the efficiency is 96.4 percent. Now what is the effect of reducing the plate spacing? The spacing enters into the efficiency equation through the calculation of the collection field intensity (E_p). Treating everything else in Equation 6-62 as a constant, we can write the following equation:

$$w = KE_p$$

where E_p is measured in volts per meter. If the distance between the plates is reduced, the collection field intensity is proportionately increased:

$$w = KE_p\frac{0.28}{0.14} = 2KE_p$$

Thus, w increases by a factor of two. In order to maintain the same gas velocity, the number of plates and, hence, the surface area (A) must double. The new efficiency would then be:

$$\eta = 1 - \exp\left[-\frac{(714.4)(0.368)}{19.73}\right]$$
$$= 1 - 0.0000016$$
$$= 0.999998 \text{ or } 1.00$$

Thus, the efficiency would be increased to 100 percent. This plate spacing may not be feasible because of sparkover problems.

Air Pollution from Mobile Sources

- **Sources:**
  - Gasoline engine
  - Diesel engine
  - Jet engine
- **Effect of Design and Operating Variables on Emissions:**
  - Air-to-fuel Ratio
  - Load or Power Level
  - Speed
  - Spark Timing
  - Exhaust Back Pressure
  - Valve Overlap
  - Intake Manifold Pressure

- Effect of Design and Operating Variables on Emissions.........
  - Combustion Chamber Deposit Buildup
  - Surface Temperature
  - Surface-to-Volume Ratio
  - Combustion Chamber Design
  - Stroke-to-bore Ratio
  - Displacement per Cylinder
  - Compression Ratio

Control of Automobile Emissions

- Blowby
- Fuel Tank Evaporation Losses
- Carburetor Evaporation Losses
- Engine Exhaust
- Inspection/maintenance (I/M) Programs

CHAPTER 7
SOLUTIONS

7-1 Density of oxygen

Given: Temperature = 273.0 K, pressure = 98.0 kPa

Solution:

a. Assume 1 gram mole of oxygen

From inside front cover of book GMW of O = 16.00

For $O_2 = 2(16.00) = 32.00$ g/mole

b. Calculate density (Equation 7-1)

$$\rho = \left(\frac{1}{8.3143\,\text{J/K}\cdot\text{mole}}\right)\left(\frac{(98.0\text{kPa})(1\text{mole})(32.00\,\text{g/mole})}{273\text{K}}\right)\left(\frac{1000\text{Pa}}{\text{kPa}}\right)\left(\frac{10^{-3}\,\text{kg}}{\text{g}}\right)$$

$\rho = 1.382$ kg/m^3

7-2 Density of Carbon monoxide (CO)

Given: Temperature = 298.0 K, pressure = 102.0 kPa

Solution:

a. Assume 1 gram mole of CO

From inside front cover of book find GMW of C = 12.01 and O = 16.00
CO = 28.01 g/mole

b. Calculate density (Equation 7-1)

$$\rho = \left(\frac{1}{8.3143\,\text{J/K}\cdot\text{mole}}\right)\left(\frac{(102.0\text{kPa})(1\text{mole})(28.01\,\text{g/mole})}{298.0\text{K}}\right)\left(\frac{1000\text{Pa}}{\text{kPa}}\right)\left(\frac{10^{-3}\,\text{kg}}{\text{g}}\right)$$

$\rho = 1.153$ kg/m^3

7-3 Density of methane (CH_4)

Given: Temperature = 273.0 K, pressure = 101.325 kPa

Solution:

a. Assume 1 gram mole of CH_4

From inside front cover of book find GMW of C = 12.01 and H = 1.008

CH_4 = 16.042 g/mole

b. Calculate density (Equation 7-1)

$$\rho = \left(\frac{1}{8.3143\,\text{J/K}\cdot\text{mole}}\right)\left(\frac{(101.325\text{kPa})(1\text{mole})(16.042\,\text{g/mole})}{273\text{K}}\right)\left(\frac{1000\text{Pa}}{\text{kPa}}\right)\left(\frac{10^{-3}\text{kg}}{\text{g}}\right)$$

$\rho = 5.954\ \text{kg/m}^3$

7-4 Show one mole = 22.414 L at STP

Given: STP = 273.16 K, 101.325 kPa

Solution:

a. Solve Eqn. 7-2 for V. Note that J = (N)(m) and that Pa = N/m^2 so that units are

$$V = \frac{(\text{mole})\left(\frac{\text{N}\cdot\text{m}}{\text{K}\cdot\text{mole}}\right)(\text{K})}{\frac{\text{N}}{\text{m}^2}} = \text{m}^3$$

b. Using Equation 7-2 with n = 1

$$V = \frac{(1\text{mole})(8.3143\,\text{J/K}\cdot\text{mole})(273.16\text{K})}{(101.325\text{kPa})(1000\,\text{Pa/kPa})}\left(1000\,\text{L/m}^3\right)$$

V = 22.414 L

7-5 Volume occupied by 1 mole

Given: T = 25.0 °C, 101.325 kPa

Solution:

a. Solve Eqn. 7-2 for V. Note that J = (N)(m) and that Pa = N/m^2 so that units are

$$V = \frac{(\text{mole})\left(\frac{\text{N}\cdot\text{m}}{\text{K}\cdot\text{mole}}\right)(\text{K})}{\frac{\text{N}}{\text{m}^2}} = \text{m}^3$$

b. Using Eqn. 7-2 with n = 1

$$V = \frac{(1\text{mole})(8.3143\,\text{J/K}\cdot\text{mole})(298.0\text{K})}{(101.325\text{kPa})(1000\,\text{Pa/kPa})}\left(1000\,\text{L/m}^3\right)$$

$$V = 24.453\ \text{L}$$

7-6 Partial pressures of oxygen and nitrogen

Given: STP, oxygen = 8.583 moles/m^3, nitrogen = 15.93 moles/m^3, 1.0 m^3 of air

Solution:

a. Solve Eqn. 7-2 for P. Note that J = (N)(m) and that Pa = N/m^2 so that units are

$$P = \frac{(\text{mole})\left(\frac{\text{N}\cdot\text{m}}{\text{K}\cdot\text{mole}}\right)(\text{K})}{\text{m}^3} = \frac{\text{N}}{\text{m}^2} = \text{Pa}$$

b. Partial pressure of oxygen (Equation 7-2)

$$P_{O_2} = \frac{\left(8.563\,\text{mole/m}^3\right)(8.3143\,\text{J/K}\cdot\text{mole})(273.16\text{K})}{1.0\text{m}^3}\left(10^{-3}\,\text{kPa/Pa}\right)$$

$$P_{O_2} = 19.45\ \text{kPa}$$

b. Partial pressure of nitrogen (Equation 7-3)

$$P_{N_2} = \frac{\left(15.93\,\text{mole/m}^3\right)(8.3143\,\text{J/K}\cdot\text{mole})(273.16\text{K})}{1.0\text{m}^3}\left(10^{-3}\,\text{kPa/Pa}\right)$$

$$P_{N_2} = 36.18\ \text{kPa}$$

7-7 Partial pressures of oxygen, nitrogen, carbon dioxide

Given: T = 25.0 °C, oxygen = 8.32 moles, nitrogen = 16.40 moles, carbon dioxide = 16.15 moles, 1.0 m^3 tank

Solution:

a. Solve Eqn. 7-2 for P. Note that J = (N)(m) and that Pa = N/m^2 so that units are

$$P = \frac{(\text{mole})\left(\frac{N \cdot m}{K \cdot \text{mole}}\right)(K)}{m^3} = \frac{N}{m^2} = Pa$$

b. Convert temperature to K

$$T = 25.0 + 273 = 298\ K$$

c. Partial pressure of oxygen (Eqn. 7-2)

$$P_{O_2} = \frac{(8.32\text{mole})(8.3143\,J/K \cdot \text{mole})(298K)}{1.0m^3}\left(10^{-3}\ kPa/Pa\right)$$

$$P_{O_2} = 20.61kPa$$

d. Partial pressure of nitrogen (Eqn. 7-2)

$$P_{N_2} = \frac{(16.40\text{mole})(8.3143\,J/K \cdot \text{mole})(298K)}{1.0m^3}\left(10^{-3}\ kPa/Pa\right)$$

$$P_{N_2} = 40.63kPa$$

e. Partial pressure of carbon dioxide (Eqn. 7-2)

$$P_{CO_2} = \frac{(16.15\text{mole})(8.3143\,J/K \cdot \text{mole})(298K)}{1.0m^3}\left(10^{-3}\ kPa/Pa\right)$$

$$P_{CO_2} = 40.01kPa$$

7-8 Moles of O_2, N_2, and CO_2

Given: P_{O2} = 45.39 kPa, P_{N2} = 40.63 kPa, P_{CO2} = 15.24 kPa, V = 1.000 m^3, T = 25.0 °C

Solution:

a. Solve Equation 7-2 for moles/m^3 for O_2

Note: J/K-mole = Pa-m^3/K-mole

$$n = \frac{(45.39\text{kPa})(1.0\text{m}^3)}{(8.314\,\text{J/K}\cdot\text{mole})(298\text{K})}(10^3\ \text{Pa/kPa})$$

n = 18.32 moles

b. For N_2

$$n = \frac{(40.63\text{kPa})(1.0\text{m}^3)}{(8.314\,\text{J/K}\cdot\text{mole})(298\text{K})}(10^3\ \text{Pa/kPa})$$

n = 16.40 moles

c. For CO_2

$$n = \frac{(15.24\text{kPa})(1.0\text{m}^3)}{(8.314\,\text{J/K}\cdot\text{mole})(298\text{K})}(10^3\ \text{Pa/kPa})$$

n = 6.15 moles

7-9 Volume of carbon dioxide

Given: carbon dioxide = 5.2 kg, P = 152.0 kPa, T = 315.0 K

Solution:

a. Compute number of moles

GMW = 12.011 + 2(16.00) = 44.0098

$$n = \frac{5200\text{g}}{44.0\,\text{g/mole}} = 118.18\text{moles}$$

b. Compute volume as in Problem 7-5

$$V = \frac{(118.18\text{mole})(8.3143\,\text{J/K}\cdot\text{mole})(315.0\text{K})}{(152.0\text{kPa})(1000\,\text{Pa/kPa})}(1000\,\text{L/m}^3)$$

V = 2,036 L

7-10 Mass of oxygen

Given: volume = 5.0 m^3, pressure = 568.0 Pa, temp. = 263.0 K

Solution:

a. Solve Eqn. 7-2 for n

$$n = \frac{PV}{RT} = \frac{(568.0\text{Pa})(5.0\text{m}^3)}{(8.314\,\text{J/K}\cdot\text{mole})(263.0\text{K})}$$

n = 1.2988 moles

b. Compute mass

M_{O2} = (1.2988 moles)(31.9988 g/mole) = 41.562 g

7-11 Volume of 235 µg of O_3

Given: 1.00 m3 of air; STP: 273.15 K, 101.325 kPa

Solution:

a. Calculate number of moles of O_3

GMW of O = 16.00 from inside cover of book

GMW of O_3 = (3)(16.00) = 48.00 g/mole

$$n = \frac{(235\mu g)(10^{-6}\,g/\mu g)}{48.00} = 4.896\times10^{-6}\,\text{moles}$$

b. From ideal gas law with T = 273.15 K

$$V = \frac{(4.896\times10^{-6})(8.314)(273.15)}{101.325} = 1.097\times10^{-4}\,\text{L}$$

c. Volumetric ratio

$$\frac{V_P}{V_{air}} = \frac{(1.097\times10^{-4}\,\text{L})(10^{-3}\,\text{m}^3/\text{L})}{1.0\text{m}^3} = 1.097\times10^{-7}\,\text{V/V}$$

7-12 Partial pressure of H2S

Given: 250 mg/L of H_2S, Temperature = 0 °C, pressure = 108.26 kPa

Solution:

a. Compute number of moles

GMW = 2(1.0079) + 32.06 = 34.07 g/mole

$$n = \frac{250\,\text{mg/L}}{34.07\,\text{g/mole}\left(10^3\,\text{mg/g}\right)} = 0.0073366\,\text{mole/L}$$

b. Solve Eqn. 7-2 for P (see Problem 7-7)

$$P_{H_2S} = \frac{(0.0073366\text{moles})(8.314\,\text{J/K}\cdot\text{mole})(273.0\text{K})}{1.0\text{L}}\left(\frac{1000\text{L}}{\text{m}^3}\right)\left(\frac{\text{kPa}}{1000\text{Pa}}\right)$$

$$P_{H_2S} = 16.7\text{kPa}$$

7-13 Partial pressures of CH_4, N_2, and CO_2

Given: 28 L volume, Temperature = 300 K, 11 g methane, 1.5 g nitrogen, 16 g carbon dioxide

Solution:

a. Compute moles of each gas

GMW_{CH4} = 12.011 + 4(1.0079) = 16.04 g/mole

$$n = \frac{11\text{g}}{16.04\,\text{g/mole}} = 0.6856\text{moles}$$

GMW_{N2} = 2(14.0067) = 28.013 g/mole

$$n = \frac{1.5\text{g}}{28.013\,\text{g/mole}} = 0.05355\text{moles}$$

GMW_{CO2} = 12.011 + 2(15.9994) = 44.01

$$n = \frac{16\text{g}}{44.01\,\text{g/mole}} = 0.6856\text{moles}$$

b. Compute partial pressures (Eqn. 7-2)

$$P_{CH_4} = \frac{(0.6857\text{moles})(8.314\,\text{J/K}\cdot\text{mole})(300.0\text{K})}{28.0\text{L}}\left(\frac{1000\text{L}}{\text{m}^3}\right)\left(\frac{\text{kPa}}{1000\text{Pa}}\right)$$

$$P_{CH_4} = 61.08 \text{ or } 61 \text{ kPa}$$

$$P_{N_2} = \frac{(0.05355\text{moles})(8.314\,\text{J/K}\cdot\text{mole})(300.0\text{K})}{28.0\text{L}}\left(\frac{1000\text{L}}{\text{m}^3}\right)\left(\frac{\text{kPa}}{1000\text{Pa}}\right)$$

$$P_{N_2} = 4.77 \text{ or } 4.8 \text{ kPa}$$

$$P_{CO_2} = \frac{(0.3633\text{moles})(8.314\,\text{J/K}\cdot\text{mole})(300.0\text{K})}{28.0\text{L}}\left(\frac{1000\text{L}}{\text{m}^3}\right)\left(\frac{\text{kPa}}{1000\text{Pa}}\right)$$

$$P_{CO_2} = 32.36 \text{ or } 32 \text{ kPa}$$

7-14 Moles of gas present in Problem 7-13

Given: See Problem 7-13

Solution:

a. Compute moles of each gas

(Note: this is essentially a repetition of part of Problem 7-12 computed here with significant figures equal to that given)

$GMW_{CH4} = 12.011 + 4(1.0079) = 16.04$ g/mole

$$n = \frac{11\text{g}}{16.04\,\text{g/mole}} = 0.688\text{moles}$$

$GMW_{N2} = 2(14.0067) = 28.013$ g/mole

$$n = \frac{1.5\text{g}}{28.013\,\text{g/mole}} = 0.054\text{moles}$$

$GMW_{CO2} = 12.011 + 2(15.9994) = 44.01$

$$n = \frac{16g}{44.01\,g/mole} = 0.364moles$$

7-15 Gram molecular weight of air

Given: 22.414 L volume of air at STP, $P_{O2} = 21.224$ kPa, $P_{N2} = 79.119$ kPa, $P_{Ar} = 0.946$ kPa, $P_{CO2} = 0.036$ kPa

Solution:

a. Compute number of moles of each gas

Oxygen

$$n = \frac{PV}{RT} = \frac{(21.224kPa)(10^3\ Pa/kPa)(22.414L)(10^{-3}\ m^3/L)}{(8.314\,J/K\cdot mole)(273.15K)}$$

n = 0.20947 moles

Nitrogen

$$n = \frac{PV}{RT} = \frac{(79.119kPa)(10^3\ Pa/kPa)(22.414L)(10^{-3}\ m^3/L)}{(8.314\,J/K\cdot mole)(273.15K)}$$

n = 0.78086 moles

Argon

$$n = \frac{PV}{RT} = \frac{(0.946kPa)(10^3\ Pa/kPa)(22.414L)(10^{-3}\ m^3/L)}{(8.314\,J/K\cdot mole)(273.15K)}$$

n = 0.00934 moles

Carbon dioxide

$$n = \frac{PV}{RT} = \frac{(0.036kPa)(10^3\ Pa/kPa)(22.414L)(10^{-3}\ m^3/L)}{(8.314\,J/K\cdot mole)(273.15K)}$$

n = 0.00036 moles

b. Compute mass of each gas

M_{O2} = (n)(GMW) = 0.209469(32.00) = 6.703

M_{N2} = 0.78086(28.02) = 21.880

M_{Ar} = 0.009336(39.95) = 0.37297

M_{CO2} = 0.000355(44.01) = 0.01562

c. Molecular weight of air

$M_{O2} + M_{N2} + M_{Ar} + M_{CO2}$ = 28.972 or 28.97 g/mole

7-16 GMW or air at 500 °C

Given: Temperature = 500 °C, Pressure = 101.325 kPa

Solution:

a. Compute the moles of each gas.

Note: P is standard pressure and T = 273.15 + 500 = 773.15 K

Oxygen

$$n = \frac{PV}{RT} = \frac{(21.224\text{kPa})(10^3\ \text{Pa/kPa})(22.414\text{L})(10^{-3}\ \text{m}^3/\text{L})}{(8.314\ \text{J/K}\cdot\text{mole})(773.15\text{K})}$$

n = 0.07401 moles

Nitrogen

$$n = \frac{PV}{RT} = \frac{(79.119\text{kPa})(10^3\ \text{Pa/kPa})(22.414\text{L})(10^{-3}\ \text{m}^3/\text{L})}{(8.314\ \text{J/K}\cdot\text{mole})(773.15\text{K})}$$

n = 0.27588 moles

Argon

$$n = \frac{PV}{RT} = \frac{(0.946\text{kPa})(10^3\ \text{Pa/kPa})(22.414\text{L})(10^{-3}\ \text{m}^3/\text{L})}{(8.314\ \text{J/K}\cdot\text{mole})(773.15\text{K})}$$

n = 0.00330 moles

Carbon dioxide

$$n = \frac{PV}{RT} = \frac{(0.036\text{kPa})(10^3\ \text{Pa/kPa})(22.414\text{L})(10^{-3}\ \text{m}^3/\text{L})}{(8.314\ \text{J/K}\cdot\text{mole})(773.15\text{K})}$$

n = 0.00013 moles

b. Compute mass of each gas

M_{O2} = (n)(GMW) = (0.07401)(32.00) = 2.368

M_{N2} = (0.27588)(28.02) = 7.7282

M_{Ar} = (0.00330)(39.95) = 0.1318

M_{CO2} = (0.00013)(44.01) = 0.0055189

c. Molecular weight of air

$M_{O2} + M_{N2} + M_{Ar} + M_{CO2}$ = 8.102 g/mole

7-17 Micrograms/m^3 to ppm for SO_2

Given: 80 μg/m^3 of SO_2, T = 25 °C, P = 101.325 kPa

Solution:

a. Compute GMW of SO_2

GMW = 32.06 + 32.00 = 64.06

b. Convert to ppm using Eqn. 7-7

$$\text{ppm} = \frac{\left(\frac{80}{64.06}\right)(22.414)\left(\frac{298}{273}\right)\left(\frac{101.325}{101.325}\right)}{(1.0)(1000)}$$

ppm = 0.030555 or 0.031

7-18 ppm to $\mu g/m^3$ for NO_2

Given: 0.55 ppm of NO_2, T = -17.7 °C = 255.45 K, P = 100.0 kPa

Solution:

a. Compute GMW of NO_2

GMW = 14.01 + 32.00 = 46.01

b. Convert to $\mu g/m^3$ using Eqn. 7-7
Note: Temperature = 273.15 – 17.7 = 255.45

$$M_p = \frac{(0.55)(1000)(46.01)}{(22.414)\left(\frac{255.45}{273.15}\right)\left(\frac{101.325}{100.0}\right)}$$

$M_p = 1191.45$ or 1191 $\mu g/m^3$

7-19 Convert ppm CO_2 to $\mu g/m^3$

Given: 370 ppm CO_2 at 20 °C and 101.325 kPa

Solution:

a. Compute GMW of CO_2

GMW = 12.01 + 2(16.00) = 44.01

b. Convert to $\mu g/m^3$

$$M_p = \frac{(370)(1000)(44.01)}{(22.414)\left(\frac{293.15}{273.15}\right)\left(\frac{101.325}{101.325}\right)}$$

$M_p = 676{,}932$ or 677,000 $\mu g/m^3$

7-20 Stability of atmosphere based on temperature profiles

Given: Elevations and temperatures

Solution:

Case a.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(-6.21^\circ C)-(-3.05^\circ C)}{318m - 2m} = -0.0100\ ^\circ C/m$$

Lapse rate per 100 m is -1.00 °C/100 m

Compare with neutral condition and find that the atmosphere is neutral.

Case b.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(3.09^\circ C)-(6.00^\circ C)}{202m - 10m} = -0.0152\ ^\circ C/m$$

Lapse rate per 100 m is -1.52 °C/100 m

Compare with neutral condition and find that the atmosphere is unstable.

Case c.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(16.71^\circ C)-(14.03^\circ C)}{286m - 18m} = +0.0100\ ^\circ C/m$$

Lapse rate per 100 m is +1.00 °C/100 m

Compare with neutral condition and find that the atmosphere is stable. In fact, it is an inversion.

7-21 Stability of atmosphere based on temperature profiles

Given: Elevations and temperatures

Solution:

Case a.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(0.10^\circ C) - (-4.49^\circ C)}{339m - 1.5m} = 0.0136\ ^\circ C/m$$

Lapse rate per 100 m is 1.36 °C/100 m

Compare with neutral condition and find that the atmosphere is stable. In fact, it is an inversion.

Case b.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(19.67^\circ C) - (28.05^\circ C)}{279m - 12m} = -0.0314\ ^\circ C/m$$

Lapse rate per 100 m is -3.14 °C/100 m

Compare with neutral condition and find that the atmosphere is unstable.

Case c.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(18.93^\circ C) - (19.55^\circ C)}{339m - 8m} = -0.00187\ ^\circ C/m$$

Lapse rate per 100 m is -0.187 °C/100 m

Compare with neutral condition and find that the atmosphere is stable.

7-22 Stability of atmosphere based on temperature profiles

Given: Elevations and temperatures

Solution:

Case a.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(4.52^\circ C) - (5.00^\circ C)}{50m - 2m} = -0.0100\ ^\circ C/m$$

Lapse rate per 100 m is -1.00 °C/100 m

Compare with neutral condition and find that the atmosphere is neutral.

Case b.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(5.00^\circ C)-(5.00^\circ C)}{50m-2m} = 0.00\ ^\circ C/m$$

Lapse rate is 0.00 °C/100 m

Compare with the neutral condition and find that the atmosphere is stable. It is also isothermal.

Case c.

Compute lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{(-25.17^\circ C)-(-21.01^\circ C)}{50m-2m} = -0.08667\ ^\circ C/m$$

Lapse rate is -8.67 °C/100 m

Compare with the neutral condition and find that the atmosphere is unstable.

7-23 Stability of atmosphere based on "Key"

Given: Time of year, time of day and wind speed

Solution:

Case a.

Because of late sunrise in winter, at 9:00 AM would expect solar insolation to be "slight." With wind speed of 5.5 m/s the stability class would be D.

Case b.

The neutral class (D) is selected for all overcast conditions. See footnote to Table 7-8.

Case c.

A clear winter night means < 3/8 cloud cover. With a wind speed of 2.8 m/s, select stability class F.

Case d.

At 11:30 AM in the summer we would expect the solar insolation to be strong. With a wind speed of 4.1 m/s, select stability class B.

7-24 Stability of atmosphere based on "Key"

Given: Time of year, time of day and wind speed

Solution:

Case a.

At 1:00 PM on a clear summer afternoon we would expect the solar insolation to be strong. With a wind speed of 1.6 m/s select stability class A.

Case b.

The neutral class (D) is selected for all overcast conditions. See footnote to Table 7-8.

Case c.

At 9:30 AM on a clear winter morning we would expect the solar insolation to be slight. With a wind speed of 6.6 m/s, select stability class D.

Case d.

Use the "thinly overcast" column and a wind speed of 2.4 m/s to select a stability class of E.

7-25 Stability of atmosphere based on "Key"

Given: Time of year, time of day, wind speed, and cloud cover

Solution:

Case a.

At 1:00 PM on a clear summer day we would expect solar insolation to be strong. With a wind speed of 5.6 m/s, select stability category C.

Case b.

A clear summer night means "≤ 3/8 cloud". With a wind speed of 2.1 m/s, select stability category F.

Case c.

Overcast conditions have a default stability category of D. See footnote to Table 7-8.

Case d.

See the notes below Table 7-8. For broken clouds "strong" solar insolation (as expected on a clear summer afternoon) is reduced to "moderate" with a wind speed of 5.2 m/s, select class C-D.

7-26 Downwind distance to inversion layer (xL)

Given: Time of year, time of day and wind speed, inversion base at 667 m

Solution:

a. Stability class

Because of late sunrise, solar insolation will be slight. With a wind speed of 2.6 m/s, select a stability class of C.

b. Compute S_z with Eqn. 7-24

$$S_z = 0.47(667) = 313.5 \text{ m}$$

c. Use Figure 7-23 with stability class C and $S_z = 313.5$ to locate x_L at 5.8 km. (Some allowance for graph reading should be given.)

7-27 Downwind distance to inversion layer (x_L)

Given: Time of year, time of day and wind speed, inversion base at 369 m

Solution:

a. Stability class

The neutral class (D) is selected for all overcast conditions. See footnote to Table 7-8.

b. Compute S_z with Eqn. 7-24

$$S_z = 0.47(369) = 173.43 \text{ m}$$

c. Use Figure 7-23 with stability class D and $S_z = 173.43$ to locate x_L at 14 km. (Some allowance for graph reading should be given.)

7-28 Distance downwind plume will begin mixing downward

Given: Time of year, time of day, wind speed, inversion base of 265 m, effective stack height of 85 m

Solution:

a. Stability class

For overcast conditions, pick stability class D. See footnote to Table 7-8

b. Compute S_z

$S_z = 0.47(265 - 85) = 84.6$ m

c. Using Figure 7-23, find $x_L = 4.5$ km
(Some allowance for graph reading should be given.)

7-29 Downwind concentration of SO_2

Given: Example 7-4, inversion base at 200 m, point downwind 4 km and 0.2 km perpendicular to plume

Solution:

a. First check to see if Eqn. 7-25 should be used. Stability class D is given in Example 7-4.

$S_z = 0.47(200) = 94.0$ m

Using Figure 7-23, we find $x_L = 5.5$ km and that the inversion form of the equation would apply beyond 2(5.5) = 11 km. Since the concentration is to be calculated at 4 km, use Eqn. 7-19.

b. Find plume standard deviations from Figures 7-22 and 7-23: $S_y = 230$ m, $S_z = 78$ m.

By Eqn 7-22, $S_y = 68(4)^{0.894} = 234.8$

By Eqn 7-23, $S_z = 44.5(4)^{0.516} - 13 = 77.99$.

c. Calculate concentration (using $S_y = 230$ m, $S_z = 78$ m)

$$\chi = \frac{1656.2}{(\pi)(230)(78)(4.50)}\exp\left[-\frac{1}{2}\left(\frac{200}{230}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{128}{78}\right)^2\right]$$

$$\chi = (0.00653)\exp[-0.378]\exp[-1.346] = 1.16\times10^{-3}\ \mathrm{g/m^3}$$

Slightly different answer will result if Eqns. 7-22 and 7-23 are used.

7-30 Emission rate of TSP

Given: Stack parameters, atmospheric conditions and downwind concentration of 1,520 $\mu g/m^3$

Solution:

a. Determine stability class (Table 7-8)

Solar insolation will be strong on a clear summer afternoon. With a wind speed of 3.2 m/s, select stability class B.

b. Select Eqn.7-19 because no inversion is specified.

c. Calculate plume rise (Eqn. 7-21)

$$\Delta H = \frac{(12.0)(1.50)}{3.20}\left[1.5 + \left(2.68\times10^{-2}(100.0)\left(\frac{595-301}{595}\right)(1.5)\right)\right] = 19.6\mathrm{m}$$

d. Calculate effective stack height (Eqn. 7-20)

H = 75.0 + 19.6 = 94.6 m

e. With stability class B and downwind distance of 2 km

By Eqn 7-22, $S_y = 156(2)^{0.894} = 289.898$

By Eqn 7-23, $S_z = 108.2(2)^{1.098} - 2 = 233.61$

f. Solve Eqn. 7-19 for E

$$E = \frac{(1520\times10^{-6})(\pi)(289.898)(233.61)(3.20)}{\exp\left[-\frac{1}{2}\left(\frac{500}{289.898}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{94.6}{233.61}\right)^2\right]}$$

E = 4,970.91 or 5,000 g/s

7-31 Downwind concentration of SO_2

Given: Stack parameters, emission rate, 1976 g/s of SO_2, wind speed = 2.5 m/s, 1:00 AM on clear winter night, effective stack height = 85 m, inversion layer at 185 m

Solution:

a. Determine stability class

Based on clear sky at night and wind speed = 2.5 m/s, select stability category F

b. Check x_L

$S_z = 0.47(185 - 85) = 47$ m

With stability class F and $S_z = 47$, find xL ≅ 10 km in Figure 7-23

$2x_L \cong 20$ km

Because 30 km > 20 km use Equation 7-25

c. Calculate S_y using Table 7-9 and Equation 7-22

$S_y = 34(30)^{0.894} = 711.26$

d. Calculate downwind concentration

$$\chi = \frac{1976}{\sqrt{2\pi}(711.26)(2.5)(185)} = 2.4\times10^{-3}\ \text{g/m}^3$$

7-32 Maximum SO_2 concentration

Given: Coal specifications, stack data and meteorological conditions

Solution:

a. Computations to set up spreadsheet

(1) Select stability class

From Key at “thinly overcast” and wind speed = 3.8 m/s, select category D

(2) Calculate emission rate

Note: 95% conversion efficiency (see Example 7-2)

$$S + O_2 \rightarrow SO_2$$

GMW: 32 32 64

Thus, 1 g of S in coal yields:

$$(1\text{g})\left(\frac{64}{32}\right) = 2\text{g } SO_2$$

From burning rate and 2.80% S in coal and 95% conversion efficiency:

$$E = \left(28.82\times10^{6}\ \text{g/h}\right)\left(\frac{1}{3600\,\text{s/h}}\right)(0.0280)\left(\frac{64}{32}\right)(0.95)$$

$$E = 425.90\ \text{g/s}$$

(3) Calculate effective stack height (Eqn. 7-21). Note T is absolute temp in K

$$\Delta H = \frac{(10.5)(1.8)}{3.8}\left[1.5 + \left(2.68\times10^{-2}\right)(103.285)\left(\frac{570-262}{570}\right)(1.8)\right] = 20.84\text{m}$$

$$H = 40.0\text{ m} + 20.84\text{ m} = 60.84\text{ m}$$

(4) Estimate downwind distance to switch from Eqn. 7-19 to Eqn. 7-25

(a) Calculate S_z

$$S_z = 0.47(170.0 - 60.84) = 51.3\text{ m}$$

(b) From Figure 7-23 at stability class D and S_z = 51.3 m, read

$$x_L = 2.1\text{ km}$$

(c) Switch from Eqn. 7-19 to Eqn. 7-25 at 2(2.1) = 4.2 km

b. See following spreadsheet calculations

Stability class	D
Emission rate	425.9 g/s
Effective stack height	60.84 m
Inversion base =	170 m
x_L	2.1 km
$2x_L$	4.2 km
Wind speed	3.8 m/s

continued on following page

Distance	s_y	s_z	First Term	Exponential	χ
0.1	8.679784	4.553715	0.902608	1.7316E-39	1.563E-39
0.2	16.12983	8.636769	0.25609	1.6776E-11	4.296E-12
0.3	23.1769	12.16919	0.12649	3.7357E-06	4.725E-07
0.4	29.9744	15.38565	0.077358	0.00040227	3.112E-05
0.5	36.59216	18.3859	0.053027	0.00419052	0.0002222
0.6	43.07012	21.22439	0.039027	0.01643321	0.0006413
0.7	49.43409	23.93505	0.030152	0.03953478	0.001192
0.8	55.70207	26.54089	0.024132	0.07226988	0.001744
0.9	61.88733	29.05841	0.019838	0.11171336	0.0022162
1	68	31.5	0.016655	0.15486397	0.0025793
1.5	97.70898	41.85587	0.008723	0.34769913	0.0030331
2	126.3659	50.63433	0.005576	0.48584348	0.0027089
3	181.5747	65.44307	0.003002	0.64912067	0.0019489
4	234.8284	77.99614	0.001948	0.73769109	0.0014369
5	286.6739	89.10066	0.001397		0.0009176
6	337.4241	99.17241	0.001066		0.0007796
7	387.2813	108.4593	0.000849		0.0006792
8	436.3866	117.1231	0.000698		0.0006028
9	484.8437	125.2767	0.000587		0.0005426
10	532.7322	133.0024	0.000504		0.0004938
20	989.9875	195.7812	0.000184		0.0002657
30	1422.51	244.368	0.000103		0.0001849
40	1839.715	285.554	6.79E-05		0.000143
50	2245.888	321.9874	4.93E-05		0.0001171
60	2643.481	355.0324	3.8E-05		9.951E-05
70	3034.077	385.5021	3.05E-05		8.67E-05
80	3418.782	413.9278	2.52E-05		7.695E-05
90	3798.409	440.6795	2.13E-05		6.926E-05
100	4173.582	466.027	1.83E-05		6.303E-05

c. Use highest value of χ on spreadsheet to calculate ppm using Eqn. 7-7

$$\text{ppm} = \frac{\left(\dfrac{0.0030331\,\text{g/m}^3\,(1000000\,\mu\text{g/g})}{64}\right)(22.414)\left(\dfrac{101.325}{103.285}\right)\left(\dfrac{262}{273}\right)}{1.0(1000)}$$

ppm = 1.00

7-33 Ventilation rate to reduce concentration to 0.05 ppm

Given: Steady-state conditions, CH_2O = 0.28 ppm, outdoor air = 0.0 ppm, $\forall = 148\ m^3$, k = $1.11 \times 10^{-4}\ s^{-1}$

Table 7-11 p. 598

Solution:

a. Calculate Q in m^3/h

$$Q = \text{ventilation rate} = (0.56\ \text{ach})(148\ m^3) = 82.88\ m^3/h$$

b. Estimate emission rate (E) in ppm/h

$$k = (1.1 \times 10^{-4}\ s^{-1})(3600\ s/h) = 0.3996\ h^{-1}$$

$$0.28 = \frac{(82.88\,m^3/h)(0.0) + E}{82.88\,m^3/h + (0.3996h^{-1})(148m^3)}$$

$$E = 39.77\ \text{ppm/h}$$

c. Estimate new ventilation rate

$$0.05 = \frac{0 + 39.77\text{ppm}}{Q + (0.3996h^{-1})(148m^3)}$$

50 x 75

$$Q = 736.11\ m^3/h$$

d. In air changes per hour

$$\text{ach} = \frac{736.11m^3/h}{148m^3} = 4.97 \text{ or } 5 \text{ ach}$$

7-34 Set point for CO alarm

Given: Furnace emits 3 mg/s of CO, $\forall = 540\ m^3$, C = 10 mg/m^3, k = 0.0, Q = 100 m^3/h

Solution:

Indoor Air Quality - Carbon Monoxide			
E	3	mg/s	
V	540	m^3	
C_a	10	mg/m^3	=NAAQS 8 hour std
Q	0.0278	m^3/s	=100 m^3/h
k	0.00E+00	s^{-1}	
C_0	1	mg/m^3	

General Equation	
E/V	0.005555556
C_aQ/V	0.000514815
Q/V	5.14815E-05
First term	117.9136691
Exp Pwr	5.14815E-05

$t_{allowed}$ [hours]	C_t [mg/m^3]	t [hours]	Safety factor
8	10	0.43	0.054027143
1	30	1.54	1.538204091
0.5	60	3.79	7.580744826
0.25	100	10.12	40.48644032

7-35 Slope of equilibrium curve for HCl

Given: Pressure and corresponding liquid concentrations

Solution:

a. Convert to mole fractions (example)

$$x^* = \frac{\dfrac{38.9}{36.46\text{GMW} \cdot \text{HCl}}}{\dfrac{38.9}{36.46} + \dfrac{100}{18.015}} = 0.1612$$

$$y^* = \frac{0.6533}{101.325} = 0.006477$$

b. The following table was calculated in a similar fashion

x*	y*
0.1612	0.006477
0.1351	0.000859
0.1099	0.000269

c. Perform a linear regression to find m = 0.120, b = 0.139 and y = 0.120x - 0.0139

7-36 Slope of equilibrium line for SO_2

Given: Pressures and water concentrations

Solution:

a. Convert to mole fractions as in Problem 7-35

b. Tabulation of mole fractions

x*	y*
0.0028	0.1039
0.0020	0.0684
0.0014	0.0474
0.0008	0.0259

c. By least squares linear regression

$$m = 39.71$$

7-37 Height of packed tower to remove H_2S

Given: Operating conditions for tower

Solution:

a. Compute mole fractions at inlet and outlet

Since operating temperature is 25 °C, the density of air is 1.185 kg/m^3.

$$y_1 = \frac{\dfrac{0.100\,\text{kg/m}^3}{34.07\text{GMW}\cdot H_2S}}{\dfrac{1.185\,\text{kg/m}^3}{28.97\text{GMW}\cdot \text{air}}} = 0.071755$$

$$y_2 = \frac{\dfrac{0.005\,\text{kg/m}^3}{34.07\text{GMW}\cdot H_2S}}{\dfrac{1.185\,\text{kg/m}^3}{28.97\text{GMW}\cdot \text{air}}} = 0.003587$$

$$x_2 = 0.0$$

b. Compute the value of A (see example 7-7)

$$A = \frac{5.522\left(\dfrac{5\,\text{kg/s air}}{28.97\text{GMW}\cdot\text{air}}\right)}{\dfrac{20\,\text{kg/s}\,H_2O}{18.015\text{GMW}\cdot H_2O}} = 0.858464$$

c. Number of gas transfer units (Eqn. 7-46)

$$N_{og} = \frac{\ln\left[\dfrac{0.071755 - 5.522(0)}{0.002587 - 5.522(0)}(1-0.8584)+0.8584\right]}{1-0.8584} = 9.233$$

d. Height of individual gas transfer unit (Eqn. 7-47)

$$H_{og} = 0.444 + 0.8584(0.325) = 0.723$$

e. Height of tower (Eqn. 7-45)

$$Z_t = (9.233)(0.723) = 6.6 \text{ or } 7 \text{ m}$$

7-38 Height of packed tower to reduce H_2S concentration to 0.0002 mg/L

Given: Problem 7-37, initial concentration = 0.100 kg/m^3, final concentration = 0.0002 mg/L

Solution:

a. Compute mole fractions at inlet and outlet with operation temp. = 25 °C, air density = 1.185 kg/m^3

Note: (0.0002 mg/L)(10^3 L/m^3)(10^{-6} kg/mg) = 2×10^{-7} kg/m^3

$$y_1 = \frac{\dfrac{0.100\,\text{kg/m}^3}{34.07\text{GMW}\cdot H_2S}}{\dfrac{1.185\,\text{kg/m}^3}{28.97\text{GMW}\cdot\text{air}}} = 0.071755$$

$$y_2 = \frac{\dfrac{2\times10^{-7}}{34.07\text{GMW}\cdot\text{H}_2\text{S}}}{\dfrac{1.185\,\text{kg/m}^3}{28.97\text{GMW}\cdot\text{air}}} = 1.4351\times10^{-7}$$

$x_2 = 0.0$

b. Compute the value of A

$$A = \frac{5.522\left[\dfrac{5\,\text{kg/s air}}{28.97\text{GMW}\cdot\text{air}}\right]}{\dfrac{20\,\text{kg/s}\,\text{H}_2\text{O}}{18.015\text{GMW}\cdot\text{H}_2\text{O}}} = 0.858464$$

c. Number of gas transfer units

$$N_{og} = \frac{\ln\left[\dfrac{0.071755 - 5.522(0)}{1.4351\times10^{-7} - 5.522(0)}(1-0.8584) + 0.8584\right]}{1-0.8584} = 78.87$$

d. Height of individual gas transfer unit

$H_{og} = 0.444 + (0.8584)(0.325) = 0.723$

e. Height of tower $Z_t = (78.87)(0.723) = 57.02$ or 57 m

Obviously an impractical solution!

7-39 Height of packed tower to remove Cl_2

Given: Operating conditions for tower

Solution:

a. Compute mole fractions at inlet and outlet

Since operating temperature is 20 °C, the density of air is 1.205 kg/m^3 (see example problem for calculation).

$$y_1 = \frac{\dfrac{10.0\,\text{mg/m}^3\left(10^{-6}\,\text{kg/mg}\right)}{70.906\text{GMW}\cdot\text{Cl}_2}}{\dfrac{1.205\,\text{kg/m}^3}{28.97\text{GMW}\cdot\text{air}}} = 3.39\times10^{-6}$$

$$y_2 = \frac{\dfrac{2.95\,\text{mg/m}^3\left(10^{-6}\,\text{kg/mg}\right)}{70.906\text{GMW}\cdot\text{Cl}_2}}{\dfrac{1.205\,\text{kg/m}^3}{28.97\text{GMW}\cdot\text{air}}} = 1.00\times10^{-6}$$

$x_2 = 0.0$

b. Compute the value of A

$$A = \frac{6.820\left[\dfrac{3\,\text{kg/s air}}{28.97\text{GMW}\cdot\text{air}}\right]}{\dfrac{15\,\text{kg/s}\,\text{H}_2\text{O}}{18.015\text{GMW}\cdot\text{H}_2\text{O}}} = 0.848203$$

c. Number of gas transfer units

$$N_{og} = \frac{\ln\left[\dfrac{3.39\times10^{-6} - 6.820(0)}{1.00\times10^{-6} - 6.820(0)}(1-0.8482)+0.8482\right]}{1-0.8482} = 2.039$$

d. Height of individual gas transfer unit

$H_{og} = 0.662 + 0.8482(0.285) = 0.9037$

e. Height of tower

$Z_t = (2.039)(0.9037) = 1.84$ or 2 m

7-40 Langmuir Constants for hydrogen sulfide (H_2S)

Given: Partial pressures and mass adsorption data

Solution:

a. Calculate equilibrium concentration of gas

Assume standard atmospheric pressure = 101.325 kPa

$$C^* = \left(\frac{P_{H_2S}}{101.325}\right)\left(\frac{GMW \cdot H_2S}{GMW \cdot air}\right)$$

$$C^* = \left(\frac{0.840}{101.325}\right)\left(\frac{34.08}{28.97}\right) = 0.009752$$

b. Complete table of C* and C*/W

P_{H2S}	C*	W	C*/W
0.840	0.009752	0.082	0.1189
1.667	0.01935	0.1065	0.1817
2.666	0.03095	0.118	0.2623
3.333	0.03869	0.122	0.3171

c. From plot on following page

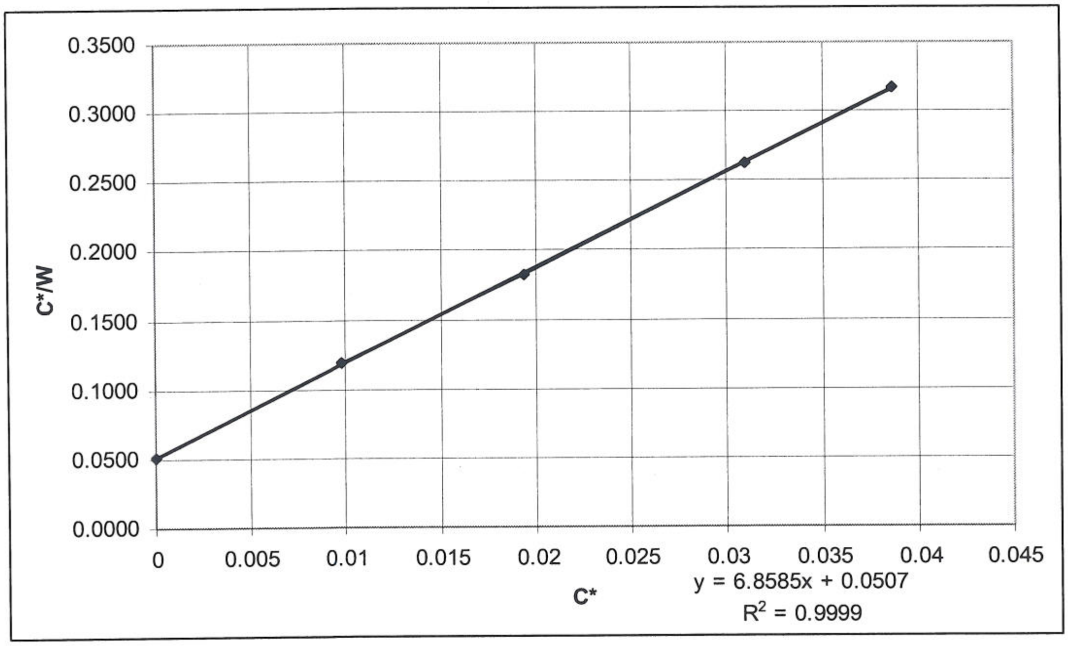


Figure S-7-40: Plot to determine Langmuir constants for H_2S on molecular sieve

$$\text{Intercept} = \frac{1}{a} = 0.0507$$

a = 19.72 or 20

$$\text{Slope} = \frac{b}{a} = 6.8583$$

$$b = (6.8583)(19.72) = 135.25 \text{ or } 135$$

7-41 Langmuir Constants for benzene (C_6H_6)

Given: Partial pressures and mass adsorption data

Solution:

a. Compute C* as in 7-40

P_{C6H6}	C*	W	C*/W
0.027	0.00072	0.129	0.00556
0.067	0.00178	0.170	0.01047
0.133	0.00354	0.204	0.01735
0.266	0.00708	0.240	0.02950

b. From plot

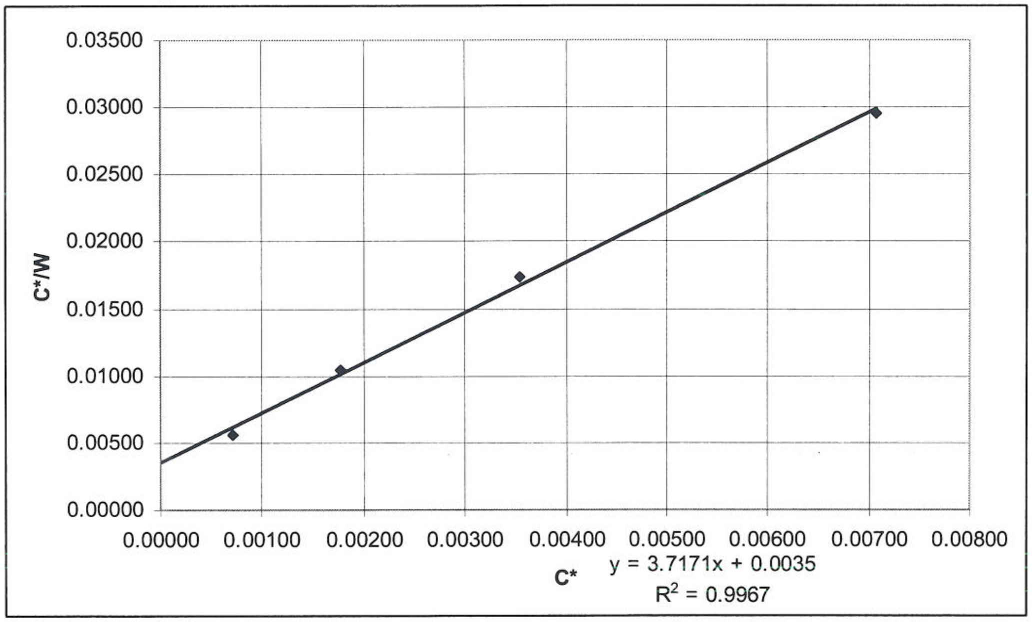


Figure S-7-41: Plot to determine Langmuir constants for C_6H_6

$$\text{Intercept} = \frac{1}{a} = 0.0035$$

$$a = 285.71 \text{ or } 286$$

$$\text{Slope} = \frac{b}{a} = 3.7171$$

$$b = (3.7171)(285.71) = 1062.03 \text{ or } 1060$$

7-42 Freundlich constants

Given: Table of q_e vs. C_e

Solution:

C_e	q_e
70	520
170	550
700	640
1750	690
4000	740
7000	780

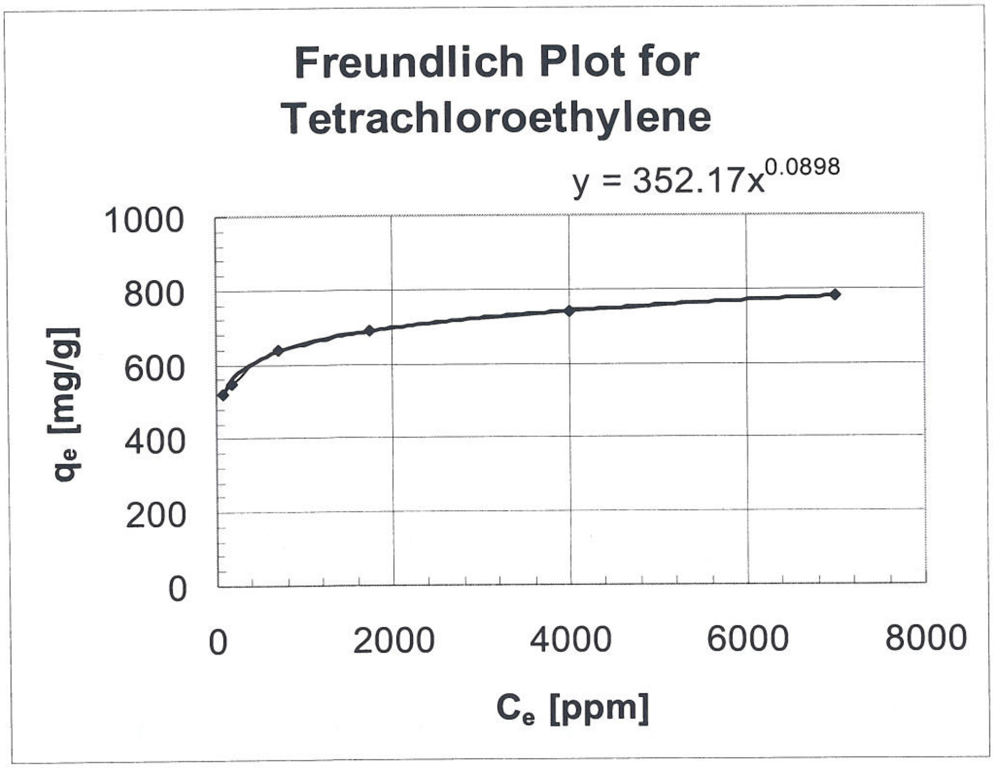


Figure S-7-42: Freundlich plot

From the curve fitting equation

K = 352.17

n = 0.0898

7-43 Breakthrough time

Given: Carbon column design and operating data

Solution:

a. From Appendix A, $\rho_g = 1.185\ \text{kg/m}^3$

b. Face velocity (Eqn. 7-52)

$$v_f = \frac{(1.185\,\text{kg/m}^3)(1+3000(0.00350))}{(465)(450)(1.185\,\text{kg/m}^3)(5.0)} = 1.1\times10^{-5}\ \text{m/s}$$

c. Breakthrough time

$$t_B = \frac{0.75\text{m} - 0.045\text{m}}{1.1\times10^{-5}\ \text{m/s}} = 6.409\times10^4\,\text{s}$$

$$t_B = \frac{6.409\times10^4\,\text{s}}{3600\,\text{s/h}} = 17.8\text{h}$$

7-44 Thickness of adsorption bed

Given: Carbon column operating data

Solution:

a. Gas density at 25 °C and 105 kPa from Appendix A.

Interpolate to find $\rho_g = 1.22685$

b. From Dalton's law, partial pressure may be determined from ratio of volumes.

Since pollutant concentration is 3000 ppm (V/V ratio): 3000 ppm = 0.30% = 0.003

$C^* = (0.003)(2.36\ \text{m}^3/\text{s})(1.22685\ \text{kg/m}^3) = 0.00869\ \text{kg/s}$

c. Calculate cross sectional area

$$A_c = \frac{\pi(3.00)^2}{4} = 7.0686\text{m}^2$$

d. Calculate face velocity

$$v_f = \frac{(2.36)(1.22685)(1+900(0.00869))}{(400)(390)(1.22685)(7.0686)} = 1.888\times10^{-5}\text{ m/s}$$

e. Solve for height of bed (Eqn. 7-50)

$Z_t = (t_B)(v_f) + \delta$

$Z_t = (8\text{ h})(3600\text{ s/h})(1.888 \text{ x } 10^{-5}\text{ m/s}) + 0.028$

$Z_t = 0.5717$ or 0.57 m

7-45 Catalyst dimensions to remove toluene

Given: $C_{in} = 1.87\text{ g/m}^3$, $C_{out} = 0.00187\text{ g/m}^3$, $Q_{in} = 16.33\text{ m}^3\text{/s}$, Combustion air = 1.80 $\text{m}^3\text{/s}$, $T_{in} = 20\ ^\circ\text{C}$, $T_{combustion} = 510\ ^\circ\text{C}$, bed gas velocity = 7.5 m/s, $k = 120\text{ s}^{-1}$

Solution:

a. Volumetric flow rate at 510 °C

$$Q_T = (16.33+1.80)\left(\frac{510+273}{20+273}\right) = 48.45\,\text{m}^3/\text{s}$$

b. Cross sectional area to obtain 7.5 m/s velocity

$$\text{Area} = \frac{48.54\,\text{m}^3/\text{s}}{7.5\,\text{m/s}} = 6.46 \text{ or } 6.5\text{ m}^2$$

c. Desired retention time (1st order kinetics)

$$\frac{C_t}{C_0} = \frac{0.00187}{1.87} = 0.0010$$

$0.0010 = \exp(-120(t))$

$\ln(0.0010) = -120(t)$

t = 0.0576 s

d. Depth of catalyst

D = (7.5 m/s)(0.0676 s) = 0.4317 or 0.43 m

7-46 Catalyst dimensions to remove hexane

Given: C_{in} = 454 g/min, C_{out} = 100 ppm at STP, Q_{in} = 7.1 m^3/s, T_{in} = 315 °C, $Q_{combustion}$ = 550 °C, bed gas velocity = 9.5 m/s, k = 55 s^{-1}

Solution:

a. Volumetric gas flow rate at 550 °C

$$Q_{in} = (7.1)\left(\frac{550+273}{315+273}\right) = 9.94\,\mathrm{m^3/s}$$

$$Q_{combustion} = (0.70)\left(\frac{550+273}{20+273}\right) = 1.97\,\mathrm{m^3/s}$$

Q_T = 9.94 + 1.97 = 11.91 m^3/s

b. Cross sectional area

$$\text{Area} = \frac{11.91\,\mathrm{m^3/s}}{9.5\,\mathrm{m/s}} = 1.25\mathrm{m^2}$$

c. Convert 454 g/min to g/m^3 at STP

Q_{gas} = (7.1 m^3/s)(60 s/min) = 426.0 m^3/min

At STP

$$(426.0\,\mathrm{m^3/min})\left(\frac{273}{315+273}\right) = 197.79\,\mathrm{m^3/min}$$

$$C_0 = \frac{454.0\,\mathrm{g/min}}{197.79\,\mathrm{m^3/min}} = 2.295\,\mathrm{g/m^3}$$

d. Convert 1.0 ppm to g/m^3

Solve Eqn. 7-7 for M_p

GMW Hexane (C_6H_{14})

$$6(12.01) + 14(1.008) = 86.172$$

$$M_P = \frac{(100\text{ppm})(1000)(86.172\text{ g/mole})}{(22.414)\left(\frac{273}{273}\right)\left(\frac{101.325}{101.325}\right)} = 3.845\times10^5\ \mu\text{g/m}^3$$

e. Desired retention time (1st order kinetics)

$$\frac{C_t}{C_0} = \frac{3.845\times10^{-1}\text{ g/m}^3}{2.295\text{ g/m}^3} = 0.168$$

$0.168 = \exp(-55(t))$

$\ln(0.168) = -55(t)$

$t = 0.032$ s

f. Depth of catalyst

$D = (9.5 \text{ m/s})(0.032 \text{ s}) = 0.309 \text{ m or } 0.3 \text{ m}$

7-47 Cyclone efficiency for 1.0 m barrel

Given: 2.50 μm diameter particle, $\rho = 1250$ kg/m^3, $Q_g = 2.80$ m^3/s, T = 25 °C

Solution:

a. Using Figure 7-35 with $D_2 = 1.0$ m

$B = 0.25(1.0) = 0.250$ m

$H = 0.5(1.0) = 0.50$ m

$L_1 = L_2 = 2(1.0) = 2.0$ m

b. The number of turns is

$$\theta = \frac{\pi}{0.50}[2(2.0)+2.0] = 37.7$$

c. From the gas temperature and Table A-3 the dynamic viscosity is 18.5 μPa-s

d. The cut diameter is

$$d_{0.5} = \left[\frac{9(18.5\times10^{-6}\,\text{Pa}\cdot\text{s})(0.250\text{m})^2(0.50\text{m})}{(1250\,\text{kg/m}^3)(2.80\,\text{m}^3/\text{s})(37.7)}\right]^{1/2} = 6.28\times10^{-6}\,\text{m}$$

$$= 6.28\ \mu\text{m}$$

e. The ratio of particle sizes is

$$\frac{d}{d_{0.5}} = \frac{2.50\mu\text{m}}{6.28\mu\text{m}} = 0.398 \text{ or } 0.4$$

f. From Figure 7-36 the efficiency is about 14%

7-48 Cyclone efficiency for multiclone

Given: Data in Problem 7-47 and $D_2 = 0.10$ m

Solution:

a. Using Figure 7-35 with $D_2 = 0.10$ m

$B = 0.25(0.10) = 0.025$

$H = 0.5(0.10) = 0.050$

$L_1 = L_2 = 2(0.10) = 0.20$ m

b. From the gas temperature and Table A-3 the dynamic viscosity is 18.5 μPa-s

c. The cut diameter (with $Q = \frac{2.80\,\text{m}^3/\text{s}}{10} = 0.280\,\text{m}^3/\text{s}$)

$$d_{0.5} = \left[\frac{9(18.5\times10^{-6}\,\text{Pa}\cdot\text{s})(0.025\text{m})^2(0.05\text{m})}{(1250\,\text{kg/m}^3)(0.280\,\text{m}^3/\text{s})(37.7)}\right]^{1/2} = 6.28\times10^{-7}\,\text{m}$$

= 0.628 μm

d. The ratio of particle sizes is

$$\frac{d}{d_{0.5}} = \frac{2.50\mu m}{0.628\mu m} = 3.98$$

e. From Figure 7-36 the efficiency is about 0.95 or 95%

7-49 Cyclone efficiency

Given: Cyclone in example 7-10; ρ_p = 1000 kg/m ; radii of 1.00, 5.00, 10.00, and 25.00 μm

Solution:

a. Determine cut diameter

$$d_{0.5} = \left[\frac{9(18.5\times10^{-6}\,Pa\cdot s)(0.125m)^2(0.25m)}{(1000\,kg/m^3)(4.0\,m^3/s)(37.7)}\right]^{1/2} = 2.08\times10^{-6}\,m$$

=2.08 μm

b. Ratio of particle sizes and efficiencies from Figure 7-36 remembering that d = 2r

Particle dia.[μm]	$d/d_{0.5}$	Efficiency
2	0.963026485	45
10	4.815132423	98
20	9.630264846	100
50	24.07566212	100

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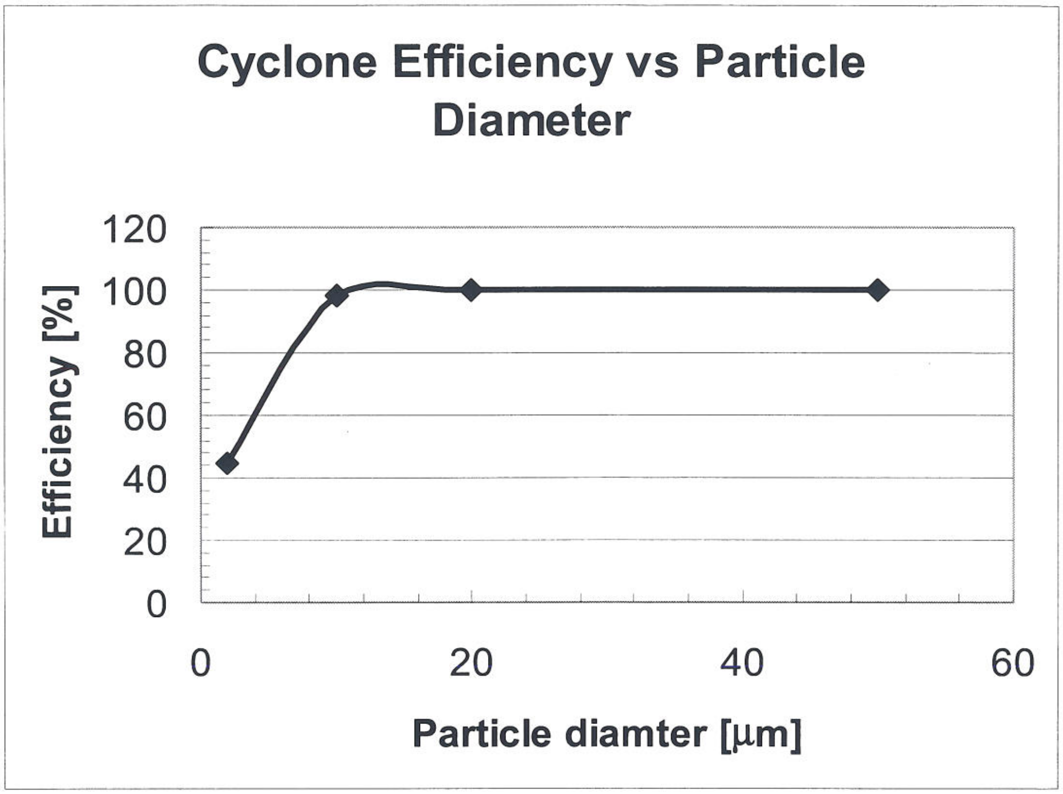


Figure S-7-49: Cyclone efficiency

7-50 Pulse-jet baghouse to replace mechanical shaker

Given: Example 7-11, 15 cm diameter x 5 m long bags, air to cloth ratio of 0.050 m/s

Solution:

a. Area required

$$A = \frac{20\,\text{m}^3/\text{s}}{0.050\,\text{m}^3/\text{s}\cdot\text{m}^2} = 400\text{m}^2$$

b. The net number of bags required is

$$\frac{400\text{m}^2}{\pi(0.15\text{m})(5\text{m})} = 169.77 \text{ or } 170 \text{ bags}$$

7-51 Reverse air baghouse for coffee bean screening

Given: Emission = 0.75 g/m^3, Q = 3.3 m^3/s, bag diameter = 20 cm, length = 12 m, A/C = 0.010, bag cleaning = 0.5

Solution:

a. Area required

$$A = \frac{3.3\,\mathrm{m^3/s}}{0.010\,\mathrm{m^3/s\cdot m^2}} = 330\mathrm{m}^2$$

b. Net number of bags

$$\frac{330\mathrm{m}^2}{\pi(0.20\mathrm{m})(12\mathrm{m})} = 43.77 \text{ or } 44 \text{ bags}$$

c. With 50% off-line for cleaning, the additional number of bags is

$$\frac{44}{2} = 22$$

And the total number of bags is 44 + 22 = 66 bags

d. Mass of particulate collected

M_p = (0.75 g/m^3)(3.3 m^3/s)(86400 s/d)(0.99) = 211,702 g or 210 kg/d

7-52 Overall efficiency of venturi

Given: Example 7-12 and particle size distribution

Solution:

a. Calculate Cunningham correction factor for smallest particle to see if d_p term can be ignored.

$$C = 1 + \frac{(6.21\times10^{-4})(1.50)}{2.5} = 1.04 \text{ or } 1.0$$

Therefore for all particles > 2.5 μm we can see that the term containing d_p will be small and can use the approximation C = 1.

b. Determine gas velocity at throat:

$$v_g = \frac{94.4\,\text{m}^3/\text{s}}{1.0\text{m}^2} = 94.4\,\text{m/s}$$

c. Calculating psi in terms of d

$$\Psi = \frac{(1)(700)(94.4)(d_p)^2(10^{-12})}{18(100\times10^{-6})(2.38\times10^{-5})} = 1.54(d_p)^2$$

d. Taking the square root of ψ and computing R as 0.13/94.40, the expression for efficiency as a function of diameter is then:

$$\eta = 1 - \exp[-0.342(d_p)]$$

e. Example calculation for diameter of 2.5 μm

$$\eta = 1 - \exp[-0.342(2.5)]\times100\% = 57.47\%$$

f. Therefore mass efficiency

25% total mass x 57.47% = 14.36%

g. Tabulated results:

Paricle Diameter [μm]	% of total mass	Efficiency	Mass Efficiency [%]
2.5	25	0.5747	14.37
7.5	20	0.9231	18.46
15	15	0.9941	14.91
25	15	0.9998	15.00
35	10	0.9999	10.00
50	15	0.9999	15.00
	100		87.74

h. Therefore the overall mass efficiency is = 88%

7-53 Venturi throat area to achieve efficiency = 99%

Given: $d_p = 2.50$ μm, $\rho_p = 1400$ kg/m^3, $Q_g = 10.0$ m^3/s, temperature = 180 °C, $Q_l = 0.100$ m^3/s, k = 200, droplet diameter = 100 μm

Solution:

a. Solve Eqn. 7-58 for ψ

$$R = \frac{Q_l}{Q_g} = \frac{0.100}{10.0} = 0.01$$

$$0.99 = 1 - \exp\left[-(200)(0.01)(\Psi)^{1/2}\right]$$

$$0.99 = 1 - \exp\left[-(2)(\Psi)^{1/2}\right]$$

$$-0.01 = -\exp\left[-(2)(\Psi)^{1/2}\right]$$

$$\ln(0.01) = \ln\left(\exp\left[-(2)(\Psi)^{1/2}\right]\right)$$

$$-4.6052 = -2.0(\Psi)^{1/2}$$

$$\Psi = 5.30$$

b. Cunningham correction factor (T = 180 + 273 = 453, d_p = 2(1.25) = 2.50 μm)

$$C = 1 + \frac{(6.21\times10^{-4})(453)}{2.5} = 1.11$$

c. Find μ from footnote in Table A-4 assuming p = 101.325

$$\mu = 17.11 + 0.0536(180) + 101.325/8280 = 26.77\ \mu\text{Pa-s}$$

d. Solve Eqn. 7-59 for v_g

$$v_g = \frac{(\Psi)(18)(d_d)(\mu)}{(C)(\rho_p)(d_p)^2}$$

$$v_g = \frac{(5.30)(18)(100\times10^{-6})(26.77\times10^{-6})}{(1.11)(1400)(2.50\times10^{-6})^2} = 26.3\,\text{m/s}$$

e. For Q_g = 10.0 m^3/s

$$A = \frac{10.0\,\text{m}^3/\text{s}}{26.3\,\text{m/s}} = 0.38\text{m}^2$$

Throat area = 0.38 m^2

7-54 Overall mass efficiency

Given: particle size distribution and data from Problem 7-53

Solution:

Gas temperature	180 °C =	453 K
ρ_p	1400 kg/m^3	
Gas velocity	26.3 m/s	
Droplet diameter	100 um	
μ	26.77024 μPa-s	See Table A-4 footnote
k	200	
Q_l	0.1 m^3/s	
Q_g	10 m^3/s	
R	0.01	

Particle dia.[μm]	C	ψ	Eta	Mass %	Mass Fraction	Mass Fraction Efficiency [%]
0.05	6.62626	0.0127	0.2014967	0.01	0.0001	0.00
0.3	1.93771	0.1333	0.5181334	0.21	0.0021	0.11
0.8	1.351641	0.661	0.8032923	0.78	0.0078	0.63
3	1.093771	7.5219	0.9958524	13	0.13	12.95
8	1.035164	50.623	0.9999993	16	0.16	16.00
13	1.021639	131.93	1	12	0.12	12.00
18	1.015629	251.44	1	8	0.08	8.00
80	1.003516	4907.5	1	50	0.5	50.00

Overall mass efficiency = 99.68 %

7-55 ESP Collection Efficiency

Given: Collection tube diameter = 0.300 m; L = 2.00 m; dp = 1.00 μm; Q_g = 0.150 m^3/s; E_p = 100,000 V/m; q = 0.300 fC; temp = 25.0 °C

Solution:

p. 980 A-4

a. From Appendix A, μ = 18.5 x 10^{-6} Pa s

b. Calculate Cunningham correction factor (Eqn. 7-60)

$$C = 1 + \frac{(6.21\times10^{-4})(298)}{1.00} = 1.19$$

c. Calculate migration velocity (Eqn. 7-62)

$$W = \frac{\left(0.300\times10^{-15}\right)\left(1.0\times10^{5}\right)\left(1.19\right)}{(6)(\pi)\left(0.50\times10^{-6}\right)\left(18.5\times10^{-6}\right)} = 0.205\,\text{m/s}$$

d. Area of collection surface

$$A = \pi(0.300\text{m})(2.00\text{m}) = 1.885\text{m}^2$$

e. Efficiency

$$\eta = 1 - \exp\left[\frac{-(1.885)(0.205)}{0.150}\right] = 0.924$$

Efficiency = 92.4%

7-56 ESP Collection Efficiency

Given: Problem 7-55

Solution:

a. All calculations from 7-55 remain same except last step

b. Efficiency

$$\eta = 1 - \exp\left[\frac{(1.885)(0.205)}{0.075}\right] = 0.9942$$

Efficiency = 99.42%

DISCUSSION QUESTIONS

7-1 Effect of change in pressure on ppm measurement

Given: Gas bag sample at 103.0 kPa with 0.02 ppm SO_2

Solution:

The concentration would remain the same because ppm in air pollution is a volume to volume measurement and the ratio of volumes would remain constant.

7-2 Strongest inversion conditions

Given: three choices

Solution:

Choice b - "Clear winter night with fresh snow cover." Because of snow cover radiative heating of the ground is minimized (the snow reflects the solar radiation). On a clear night, the radiative cooling of the ground is the greatest. This results in a very cold ground surface and, thus, the strongest inversion.

7-3 Selection of air pollution control device

Given: very hot cement kiln dust and three choices of control equipment

Solution:

Choice c - "Electrostatic precipitator." The nature of cement dust precludes wet collection, i.e. it will solidify the collection equipment. The very hot gas temperatures will damage the fabric of the bags in the bag house.

7-4 Photochemical oxidants and automobiles

Given: Photochemical oxidants are not directly attributable to people or natural sources. Why are autos singled out?

Solution:

Photochemical oxidants are the result of a reaction between volatile organic compounds and nitrogen dioxide in the presence of sunlight. Autos are singled out because, in major metropolitan areas, they are the major source of these two compounds.

7-5 Why PM2.5 standard is more appropriate then TSP

Solution:

The PM2.5 standard restricts the concentration of particulate matter smaller than 2.5 μm in diameter. Particles in the range below 2.5 μm in diameter have the greatest potential to penetrate to the lower respiratory tract and, thus, damage the alveoli. TSP restricts the concentration of all particles but because larger particles contribute more mass, the standard does not protect the lung from large concentrations of fine particles.

$10^6 \frac{N}{m^2} =$ [illegible]

$\frac{N}{m^2}\left(\frac{10^6\,mm^2}{m^2}\right)$

$\frac{kN}{m^2}$

$\frac{10^3 N}{m^2}$

$\frac{N}{m^2\left(\frac{10^6\,mm^2}{m^2}\right)}$

WASTE DECOMPOSITION PRODUCTS

Exist different uses of the waste decomposition in the wastewater treatment according to its type. The type of waste decomposition is determined by the type of the **electron acceptor** available:

- **Aerobic decomposition → O_2** (rapid, efficient and with low odor potential)
- **Anoxic decomposition** (Denitrification) **→ NO_3^-** (rate of decomposition is relatively high, although not as high as aerobic decomposition)
- **Anaerobic decomposition → SO_4^{2-}, CO_2, and some organic compounds** (low rate of decomposition)

TABLE 5-1 Waste decomposition end products

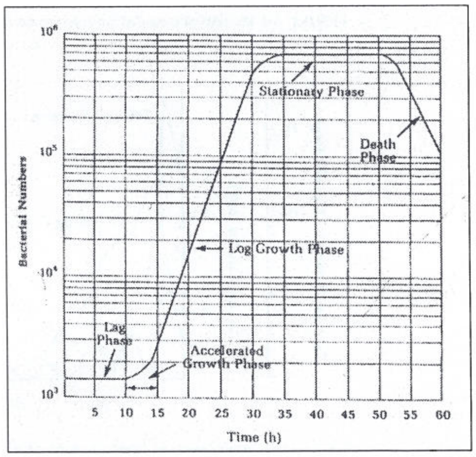
	Representative end products		
Substrates	**Aerobic decomposition**	**Anoxic decomposition**	**Anaerobic decomposition**
Proteins and other organic nitrogen compounds	Amino acids Ammonia → nitrites → nitrates Alcohols, Organic acids } → $CO_2 + H_2O$	Amino acids Nitrates → nitrites → N_2 Alcohols, Organic acids } → $CO_2 + H_2O$	Amino acids Ammonia Hydrogen sulfide Methane Carbon dioxide Alcohols Organic acids
Carbohydrates	Alcohols, Fatty acids } → $CO_2 + H_2O$	Alcohols, Fatty acids } → $CO_2 + H_2O$	Carbon dioxide Alcohols Fatty acids Methane
Fats and related substances	Fatty acids + glycerol Alcohols, Lower fatty acids } → $CO_2 + H_2O$	Fatty acids + glycerol Alcohols, Lower fatty acids } → $CO_2 + H_2O$	Fatty acids + glycerol Carbon dioxide Alcohols Lower fatty acids Methane

Microorganism Population Dynamics

Bacterial growth requirements:

1. **A terminal electron acceptor**
2. **Macronutrients**
   a. Carbon to build cells
   b. Nitrogen to build cells
   c. Phosphorus for ATP (energy carrier and DNA)
3. **Micronutrients**
   a. Trace Metals
   b. Vitamins (required by some bacteria)
4. **Appropriate environment**
   a. Moisture
   b. Temperature
   c. pH

FIGURE 5-3 Bacterial Growth in a pure culture (log-growth curve)



In the Log Growth Phase shown in the figure:

$$P = P_o(2)^n$$

$$\log P = \log P_o + n\log 2$$

Where:
P is the bacteria population after the n^{th} generation,
P_o is the initial population at the end of the accelerated growth phase

FIGURE 5-4 Microbial population dynamics in a closed system

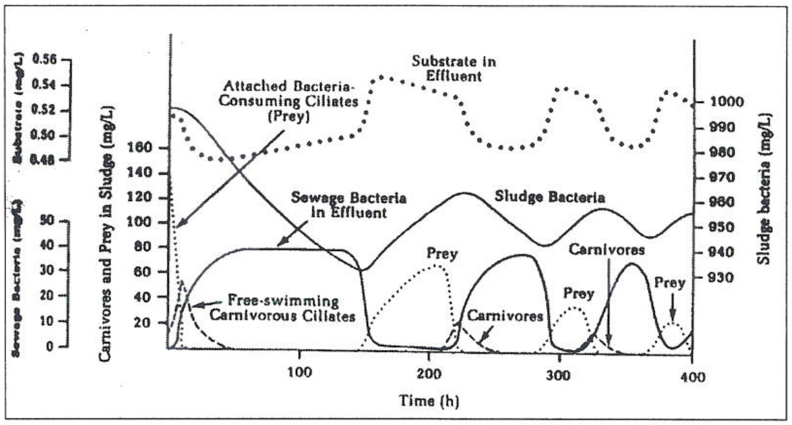
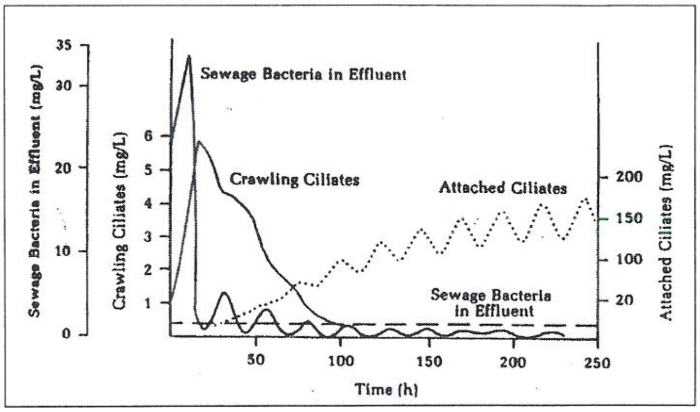


FIGURE 5-5 Microbial population dynamics in a open system



The Monod equation (measurement of biomass):

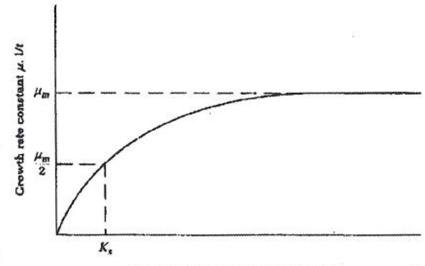
$$\underbrace{\frac{dX}{dt} = \mu X; \quad \mu = \frac{\mu_m S}{K_S + S}} \quad \& \quad -\frac{dS}{dt} = \frac{1}{Y}\frac{dX}{dt} \Longrightarrow -\frac{dS}{dt} = \frac{1}{Y}\frac{\mu_m SX}{K_S + S}$$

$$-\frac{dX}{dt} = \frac{\mu_m SX}{K_S + S} - K_d X$$

dX/dt: growth rate of biomass, mg/L . t
- μ: growth rate constant, t^{-1}
- X: concentration of biomass, mg/L
- μ_m: maximum growth rate constant, t^{-1}
- S: concentration of limiting food, mg/L
- K_S: half saturation constant, mg/L
  = concentration of limiting food when $\mu = 0.5\mu_m$
- K_d: endogenous decay rate constant, t^{-1}

dS/dt: rate of food utilization, mg/L
- Y: decimal fraction of food mass converted to biomass, (mg/L biomass)/(mg/L food utilized)

FIGURE 5-6 Monod growth rate constant as a function of limiting food concentration



CHARACTERISTIC OF DOMESTIC WASTEWATER

- Physical: 10-29°C, highly turbid ≈ 500g of solids. Fresh sewage: kerosene odor, gray color and septic sewage: rotten egg odor, black color.
- Chemical:

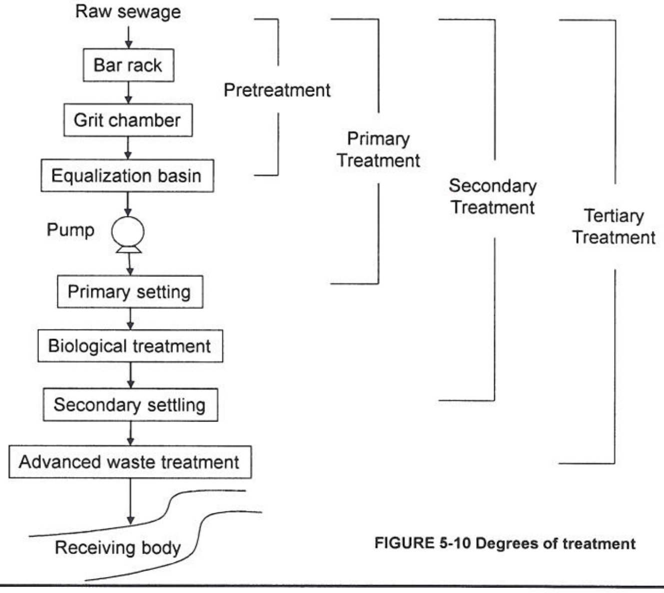
TABLE 5-2 TYPICAL COMPOSITION OF UNTREATED DOMESTIC WASTEWATER

Constituent	Weak	Medium	Strong
	(all mg/L except settleable solids)		
Alkalinity (as $CaCo_3$)[a]	50	100	200
BOD_5 (as O_2)	100	200	300
Chloride[a]	30	50	100
COD (as O_2)	250	500	1,000
Suspended solids (SS)	100	200	350
Settleable solids, mL/L	5	10	20
Total dissolved solids (TDS)	200	500	1,000
Total Kjeldahl nitrogen (TKN) (as N)	20	40	80
Total organic carbon (TOC) (as C)	75	150	300
Total phosphorus (as P)	5	10	20

[a] To be added to amount in domestic water supply. Chloride is exclusive of contribution from water-softener backwash.

Where:
BOD: Biochemical Oxygen Demand
COD: Chemical Oxygen Demand

MUNICIPAL WASTEWATER TREATMENT SYSTEMS



Raw sewage
Bar rack
Grit chamber
Equalization basin
Pump
Primary setting
Biological treatment
Secondary settling
Advanced waste treatment
Receiving body

Pretreatment
Primary Treatment
Secondary Treatment
Tertiary Treatment

FIGURE 5-10 Degrees of treatment

Purposes of the Municipal Wastewater Treatment

PRETREATMENT: to provide protection to the Waste Water Treatment Plant (WWTP) equipment that follows.

PRIMARY TREATMENT: to remove pollutants that will settle or float. Removes about 60% of suspended solids and 35% of BOD.

SECONDARY TREATMENT: to remove the soluble BOD and to provide added removal of suspended solids. Removes about 85% of the BOD and suspended solids that escape from the primary treatment.

TERCIARY TREATMENT: also called Advanced Wastewater Treatment (AWT) , can remove as much as 99% of phosphorus, suspended solids and bacteria, and 05% of nitrogen.

PRETREATMENT UNIT OPERATIONS

- **Bar Racks:** Remove large objects that would damage or foul pumps, valves, and other mechanical equipment. Trash racks with large openings (40-150mm) are normally followed by racks with smaller openings (25-50mm).
- **Grit Chambers:** Removes grit. Grit: inert dense material such as sand, broken glass, silt, and pebbles. Three devices:
  1. **Velocity Controlled:** also know as horizontal flow grit chamber. Sedimentation of particles takes place along the channels. Liquid velocity control is achieved by placing a specially designed weir at the end of the channel.
  2. **Aerated Grit Chambers:** The helical liquid flow pattern drives the grit into a hopper located at the bottom of the cannel. Diffusers are used for the bubbles to strip the inert grit of much of the organic material that adheres to its surface.
  3. **Constant Level Short-term Grit Chamber**.
- **Comminutors:** used to macerate wastewater solids (rags, paper, plastic) by revolving cutting bars.
- **Equalization:** Damping of the flow rate variations so that the wastewater can be treated at a nearly flow rate. Consist in large basins that collect and store the wastewater flow and from which the wastewater is pumped to the treatment plant at a constant rate.

Grit Chamber calculations:

$$\upsilon_s = \frac{g(\rho_s - \rho)d^2}{18\mu}$$

$$A_c = \frac{Q}{v}$$

$$h = \frac{A_c}{w}$$

Particle settling time:

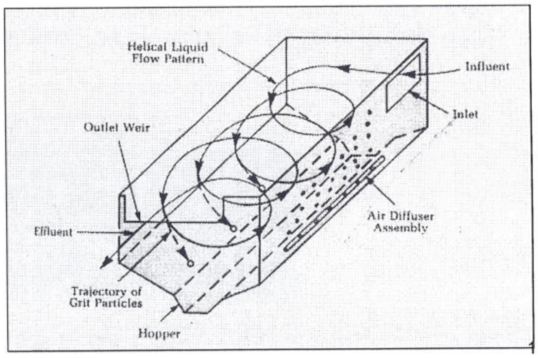
$$t_s = \frac{h}{\upsilon_s}$$

Detention time:

$$t = \frac{L}{v}$$

v_s: settling velocity
g: gravity
ρ: density of water
ρ: density of particle
μ: viscosity of water
A_c: cross sectional area
Q: volumetric flow
v: horizontal velocity
h: depth of flow
w: width of channel
t_s: settling time
t: detention time

FIGURE 5-12 Aerated Grit Chamber

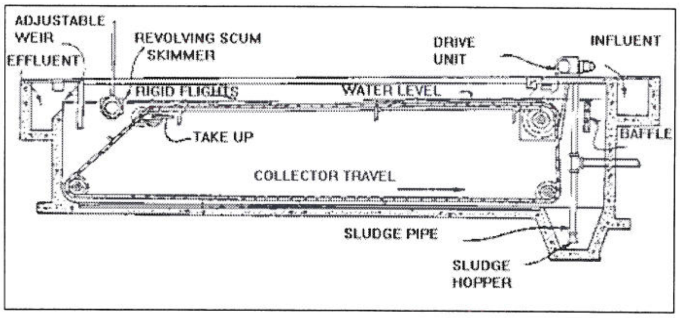


PRIMARY TREATMENT

Removal of the light organic suspended solids by gravity in a
Sedimentation or Settling tank

In the tank, the mass of settled solids (raw sludge) at the bottom of the tank is removed by mechanical scrapers or pumps; and the floating material such as oils and grease are collected by a surface skimming system and removed from the tank.
Approximately 50 – 60% of the raw sewage suspended solids and 30 – 35% of the raw sewage BOD may be removed.

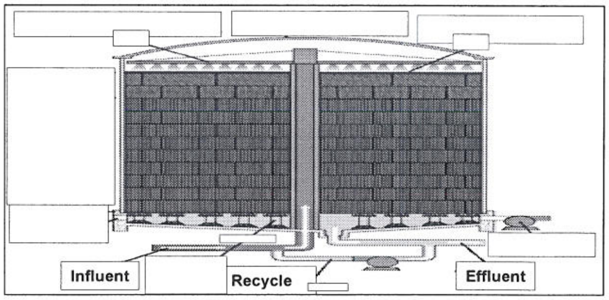
FIGURE 5-14 Primary Settling Tank



SECONDARY TREATMENT

Removal of the soluble BOD that escapes from primary treatment and to provide further removal of the suspended solids.

1. Trickling Filters: waste water is typically distributed by a rotating arm over a bed of coarse material such as stones, slats, or plastic. The media provides large amounts of surface area for the microbial film to be fixed and grow, and also provides the contact between the wastewater and microorganisms to feed on the organic matter. Air circulation through the media material void spaces provide the oxygen necessary for the microbial activity. Recirculation is used mainly to increase contact efficiency, to dilutes strong influent and supplements weak influents, and to rise the DO (dissolved oxygen) of the influent.



Effluent BOD concentration calculation:

$$F = \frac{1+R}{(1+0.1R)^2} \qquad E_T = E_{20}\theta^{(T-20)}$$

$$C_e = (1-E_1)Q$$

$$E_1 = \frac{1}{1+4.12\left(\frac{QC_{in}}{\forall F}\right)}$$

E_1: BOD fraction removal at 20°C
Q: wastewater flow rate, m^3/s
C_{in}: influent BOD concentration, mg/L
C_e: effluent BOD concentration, mg/L
$\forall$: volume of filter media, m^3
F: recirculation factor
Q_r: recirculation flow rate, m^3/s
R: recirculation ratio (Q_r/Q)
E_T: efficiency at T
E_{20}=efficiency at 20°C
Θ=1.035

Effluent BOD concentration as a function of depth calculation:

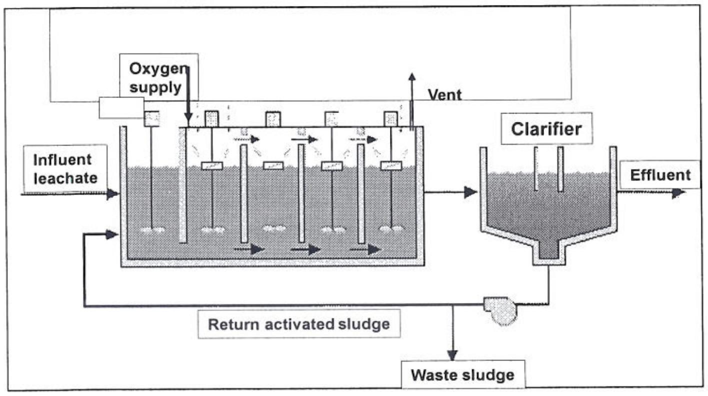
$$t = \frac{CD}{(Q/A)^n}$$

$$C \approx \frac{1}{D^m}$$

$$\frac{S_t}{S_o} = \exp\left[\frac{-KD}{(Q/A)^n}\right]$$

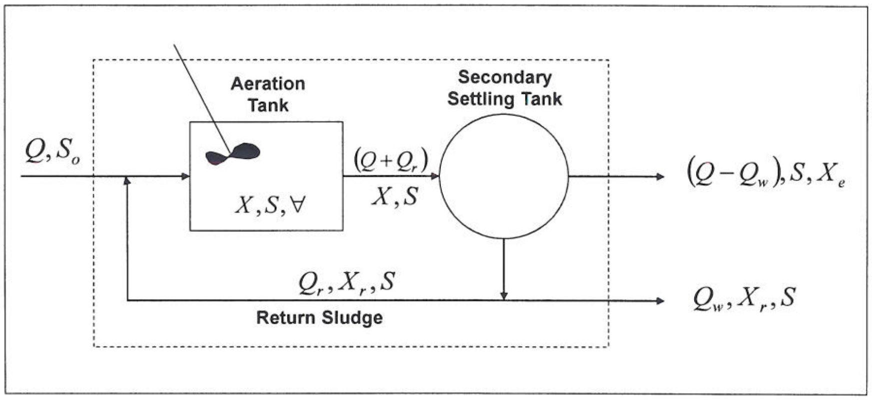
t: contact time, d
C: mean active film per unit volume
D: filter depth, m
Q: hydraulic loading, m^3/d
A: filter area, m^2
n: empirical constant based on filter media
m=1; empirical constant indicator of biological slime distribution
S_t: effluent BOD concentration, mg/L
S_o: influent BOD concentration, mg/L
K: empirical rate constant, $(m/d)^n/m$

2. Activated Sludge: wastewater flows continuously into an aeration tank where air is injected to mix the activated sludge with the wastewater (mixed liquor) and to supply the oxygen needed for the organisms to break down the organics. The microorganisms grow and are mixed by the agitation of the air, they clump together (flocculate) and form an active mass of microbes called activated sludge. The mixed liquor flows to a secondary clarifier where the activated sludge settled out. Most of the sludge is returned to the aeration tank to maintain the high population of microbes, the rest of the sludge is wasted for treatment and disposal.



Process variables for calculations:

FIGURE 5-21 Completely mixed biological reactor with recycle



Aeration tank volume calculation:

S= (Total BOD allowed) - (BOD in suspended solids)

$$S = \frac{K_S(1+k_d\theta_C)}{\theta_C(\mu_m - k_d) - 1}$$

$$X = \frac{\theta_C(Y)(S_o - S)}{\theta(1+k_d\theta_C)}$$

$$\theta = \frac{\forall}{Q}$$

S: soluble BOD concentration in effluent, mg/L (Table 5-11)
S_o: soluble BOD concentration in the influent, mg/L
X: microorganisms concentration (Mix Liquor Volatile Suspended Solids or MLVSS) in the aeration tank, mg/L
K_S: half velocity constant (soluble BOD concentration at one-half the maximum growth rate), mg/L
k_d: decay rate of microorganisms, d^{-1}
Y: yield coefficient (decimal fraction of food mass converted to biomass), (mg/L biomass)/(mg/L food utilized)
θ: hydraulic detention time, d
θ_C: mean cell residence time, d
μ_m: maximum growth rate constant, d^{-1}

Food to microorganisms ratio (F/M) calculation:

$$\frac{F}{M} = \frac{QS_o}{\forall X}$$

Expressed as: $\frac{mg\_BOD/d}{mg\_MLVSS}$

High F/M ratio indicates that microorganisms are saturated with food, which results in a poor efficiency of treatment. A low F/M ratio indicates that they are starving resulting in a more complete degradation. Typical range: 0.1-1.0mg/mg.d

TABLE 5-11 Values of growth constants for domestic wastewater

Parameter	Basis	Value[b]	
		Range	Typical
K_s	mg/L BOD_5	25–100	60
k_d	d^{-1}	0.025–0.075	0.06
μ_m	d^{-1}	2–10	5
Y	mg VSS/mg BOD_5	0.4–0.8	0.6

3. Oxidation Ponds:

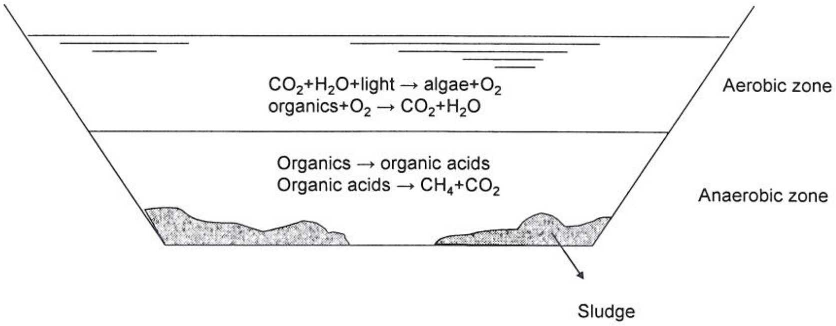
Classification:

a) **Aerobic ponds:** shallow ponds (less than 1m in depth) in which light penetrates to the bottom, and dissolved oxygen is maintained through the entire depth mainly by the action of the photosynthesis. In darkness hours oxygen is provided by the wind mixing action. Only aerobic bacteria accomplishes the organic material stabilization in these ponds.

b) **Anaerobic ponds:** deep ponds (1-2.5m) with smaller area that receive high organic loadings. Two stabilization stages are recognized according to the microbial activity products. In the firs stage (fermentation) complex organics materials are broken down mainly to short chain acids and alcohols; in the second stage (methane fermentation) these materials are converted to gases, primarily methane and carbon dioxide.

c) **Facultative ponds:** three zones characterized this ponds:
1) Anaerobic zone: suspended solid contained in the wastewater settle at the bottom where the microorganisms do not require molecular oxygen as an electron acceptor in energy metabolism. Both acid fermentation and methane fermentation occur.
2) Facultative zone: this zone is aerobic during daylight hours and anaerobic during darkness hours.
3) Aerobic zone: in this zone, oxygen is supplied from the diffusion across the pond surface, and trough algae photosynthesis.

FIGURE 5-28 Facultative pond relationships



4. Rotating Biological Contactors (RBCs):

RBCs consist of a series of closely spaced disc (3 to 3.5m in diameter) mounted on a horizontal shaft and rotated, while about one half of their surface area is immersed in the wastewater. The microorganisms adhere to the disc surface and cover them with a biological layer of slime (1-3mm thick). As the discs rotate, wastewater is oxygenated when carried into the with air and microorganisms absorb organics for breakdown when passing through the reservoir.

As the treated wastewater flows from the reservoir below the disc, it carries the suspended solids out to a down stream settling basing for removal.

Rotating Biological Contactor

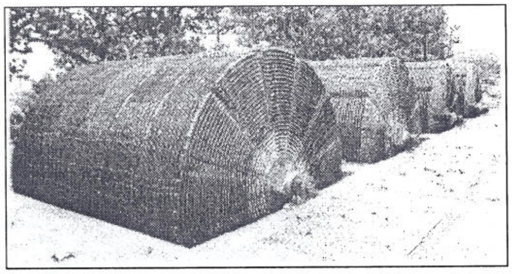
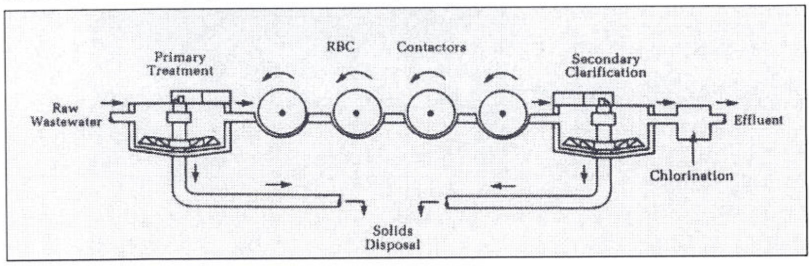


FIGURE 5-29 RBC and diagram of RBC treatment system



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DISINFECTION

The addition of chlorine gas or some other form of chlorine is perform to comply with the EPA rules calling for disinfection to achieve the required fecal coliforms quantities. Wastewater flows into a basing, where it is held for about 15 minutes to allow chlorine to react with the pathogens.

ADVANCED WASTEWATER TREATMENT OR TERTIARY TREATMENT

Processes capable of removing pollutant not adequately removed by the secondary treatment.

Filtration: used for the removal of the residual suspended solids, including the unsettled microorganisms (reducing residual BOD).

Filtration can reduce activated sludge effluent suspended solids from 25 to 10 mg/L; they can not be used directly after trickling filters, coagulation and sedimentation is required in between. Typically, filtration can achieve 80% of suspended solids reduction for activated sludge effluent and 70% reduction for trickling filters effluent.

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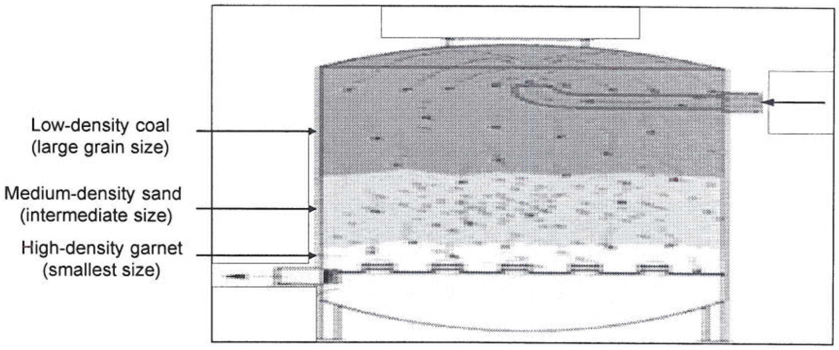
Multimedia filter



Low-density coal
(large grain size)

Medium-density sand
(intermediate size)

High-density garnet
(smallest size)

Carbon adsorption: activated carbon, adsorbs the soluble organics material persistent in the effluent after secondary treatment, coagulation, sedimentation and filtration (refractory organics), which are detected as soluble chemical oxygen demand or COD; the COD values are often 30 to 60 mg/L. In the adsorption process, the organic materials accumulate on the carbon surface due to physical binding of these molecules to the solid surface; thus, the greater the surface area of the carbon, the grater its capacity to hold organic material. After the adsorption capacity of the carbon has been exhausted, it can be resorted by an special process of heating.

Phosphorus removal: phosphorus is removed to prevent or reduce eutrophication through chemical precipitation:

Using ferric chloride: $FeCl_3 + HPO_4 \leftrightarrow FePO_4\downarrow + H^+ + 3Cl^-$

Using alum: $Al_2(SO_4)_3 + 2HPO_4 \leftrightarrow 2AlPO4\downarrow + 2H^+ + 3SO4^{2-}$

Using lime: $5Ca(OH)_2 + 3HPO_4^{2-} \leftrightarrow Ca_5(PO_4)_3OH\downarrow + 3H_2O + 6OH^-$

The precipitation of phosphorus requires of a reaction basing and a settling tank to remove the precipitate.

Nitrogen Control: to help control algal growth in the receiving water, nitrogen in any soluble form (NH_3, NH_4^+, NO_2^-, and NO_3^-) may need to be removed from the wastewater. It can be accomplished either biologically or chemically.

•Nitrification/Denitrification (biologically): nitrification can be force to occur in the activated sludge treatment by maintaining a cell detention time (θ_c) of 15 days and over 20 days in cold climates. Bacteria must be present for the next reaction to occur:

$$NH_4^+ + 2O_2 \leftrightarrow NO_3^- + H_2O + 2H^+$$

If nitrogen level is of concern for the receiving body, the nitrification step must be followed by anoxic denitrification by bacteria:

$$2NO_3^- + \text{organic matter} \rightarrow N_2 + CO_2 + H_2O$$

Organic matter is required for denitrification (energy source for the bacteria) and is obtained from within or outside the cell.

•Ammonia stripping (chemically): ammonia can be removed from water by raising the pH to convert the ammonium into ammonia, which can be stripped from the water using aeration and by adding lime as the source of hydroxide:

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O$$

LAND TREATMENT

Is an alternative to the advanced wastewater treatment processes for producing an extremely high-quality effluent.

The secondary effluent is irrigated on the land where treatment is provided by natural processes as the effluent moves through the natural filter provided by soil and plants. Part of the wastewater is lost by evapotranspiration, while the remainder returns to the hydrologic cycle through overland flow or groundwater system.

Land irrigation of the wastewater can provide moisture and nutrients (nitrogen, phosphorus, and potassium) necessary for crop growth.

SLUDGE TREATMENT

The sludge made of materials settled from the raw wastewater and solids generated in the wastewater treatment processes must be treated.
Basic sludge treatment processes:

Thickening: separation of water by gravity or flotation.

Stabilization: conversion of organic solids by biochemical oxidation processes (anaerobic and aerobic digestion) to refractory or inert forms, so they can be used as soil conditioners without causing a nuisance or health hazard.

Conditioning: treatment of sludge with chemicals or heat so that the water can be readily separated.

Dewatering: Separation of water by subjecting the sludge to vacuum, pressure or drying.

Reduction: conversion of the solids to a stable form by wet oxidation or incineration.

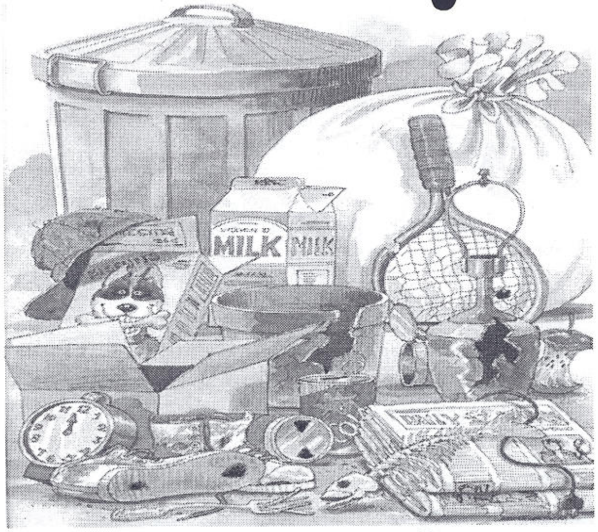
SLUDGE DISPOSAL

•Land Spreading:
in contrast with land disposal techniques, land spreading is land-use intensive. Is the application of WWTP residuals for the purposes of recovering nutrients, water, or reclaiming despoiled land such as trip mines spoils. The application rate is governed by the character of the soil and crops or forest on which sludge is spread to accommodate it.

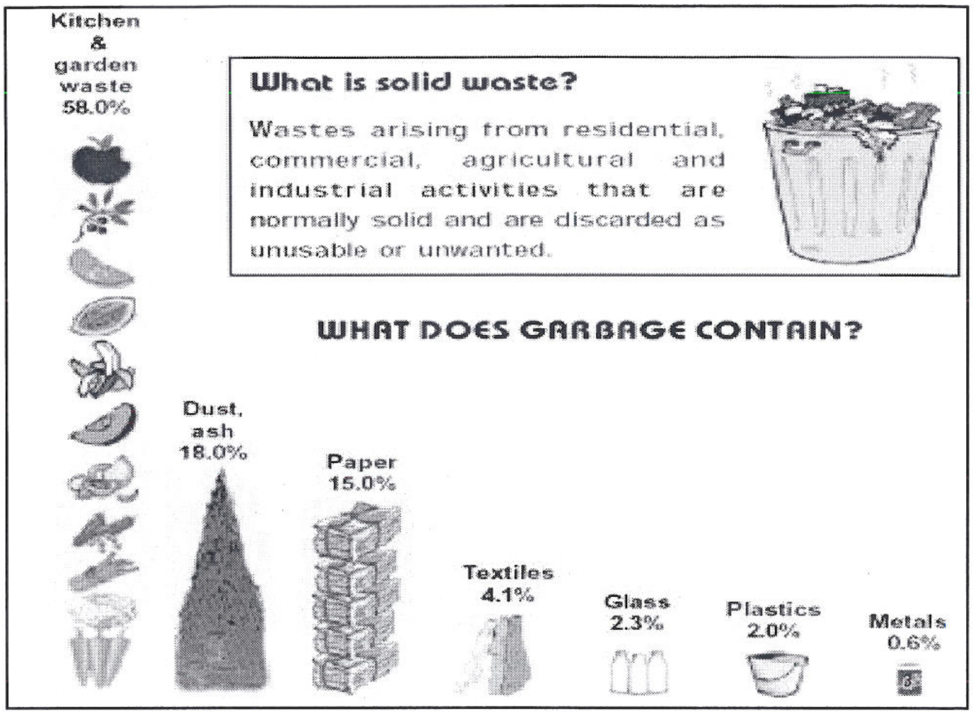
•Land filling:
the sludge is placed into a prepared site or excavated trench and covered with a more deeper layer of soil (0.2 – 0.25 m).

•Dedicated Land Disposal (DLD):
the application of heavy sludge loadings to some finite land area that has limited public access and has been set aside or dedicated fro all time to the disposal of wastewater sludge.

Solid Waste Management



Chapter - 8



What is solid waste?

Wastes arising from residential, commercial, agricultural and industrial activities that are normally solid and are discarded as unusable or unwanted.

WHAT DOES GARBAGE CONTAIN?

What is Solid Waste ??

- Includes things we commonly describe as garbage, refuse and trash
- USEPA Definition: any discarded item; things destined for reuse, recycle, or reclamation; sludges; and hazardous wastes.
- Doesn't include radioactive wastes and *insitu* mining wastes

Magnitude of the Problem

- 1990 – 1.95 kg per capita per day amounting to a total of 178 tetragrams
- 2000 – 200 tetragrams
- Solid wastes: 60 % from residential sources and the remaining from commercial sources.
- Differences in amounts are due to:
  - Climate
  - Living standards
  - Time of year
  - education
  - location
  - collection and disposal practices

Classification of Solid Wastes

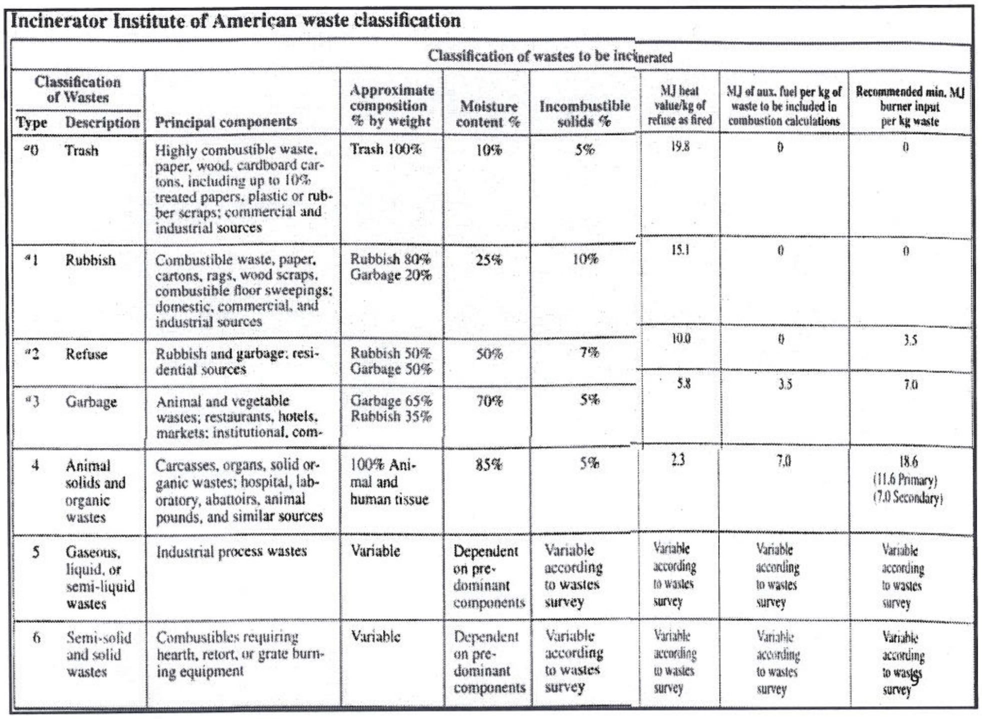
- Based on Point of Origin:
  - Domestic – household, residential
  - Institutional – schools, hospitals
  - Commercial – malls, offices, etc
  - Industrial Sources
  - Street wastes
  - Construction and Demolition wastes

Classification of Solid Wastes

- Based on nature of waste:
  - Organic
  - Inorganic
  - Combustible
  - Non-combustible
  - Putrescible and
  - Non - putrescible

TABLE 8-1
Refuse materials by kind, composition, and sources

Kind	Composition	Sources
Garbage	Wastes from preparation, cooking, and serving of food; market wastes; wastes from handling, storage, and sale of produce	Households, restaurants, institutions, stores, markets
Rubbish	Combustible: paper, cartons, boxes, barrels, wood, excelsior, tree branches, yard trimmings, wood furniture, bedding, dunnage	
	Noncombustible: metals, tin cans, metal furniture, dirt, glass, crockery, minerals	
Ashes	Residue from fires used for cooking and heating and from on-site incineration	
Street refuse	Sweepings, dirt, leaves, catch basin dirt, contents of litter receptacles	Streets, sidewalks, alleys, vacant lots
Dead animals	Cats, dogs, horses, cows	
Abandoned vehicles	Unwanted cars and trucks left on public property	
Industrial wastes	Food-processing wastes, boiler house cinders, lumber scraps, metal scraps, shavings	Factories, power plants
Demolition wastes	Lumber, pipes, brick, masonry, and other construction materials from razed buildings and other structures	Demolition sites to be used for new buildings, renewal projects, expressways
Construction wastes	Scrap lumber, pipe, other construction materials	New construction, remodeling
Special wastes	Hazardous solids and liquids; explosives, pathological wastes, radioactive materials	Households, hotels, hospitals, institutions, stores, industry
Sewage treatment residue	Solids from coarse screening and from grit chambers; septic tank sludge	Sewage treatment plants, septic tanks



Incinerator Institute of American waste classification

Classification of Wastes								
		Classification of wastes to be incinerated						
Type	Description	Principal components	Approximate composition % by weight	Moisture content %	Incombustible solids %	MJ heat value/kg of refuse as fired	MJ of aux. fuel per kg of waste to be included in combustion calculations	Recommended min. MJ burner input per kg waste
#0	Trash	Highly combustible waste, paper, wood, cardboard cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources	Trash 100%	10%	5%	19.8	0	0
#1	Rubbish	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources	Rubbish 80% Garbage 20%	25%	10%	15.1	0	0
#2	Refuse	Rubbish and garbage; residential sources	Rubbish 50% Garbage 50%	50%	7%	10.0	0	3.5
#3	Garbage	Animal and vegetable wastes; restaurants, hotels, markets; institutional, com-	Garbage 65% Rubbish 35%	70%	5%	5.8	3.5	7.0
4	Animal solids and organic wastes	Carcasses, organs, solid organic wastes; hospital, laboratory, abattoirs, animal pounds, and similar sources	100% Animal and human tissue	85%	5%	2.3	7.0	18.6 (11.6 Primary) (7.0 Secondary)
5	Gaseous, liquid, or semi-liquid wastes	Industrial process wastes	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey
6	Semi-solid and solid wastes	Combustibles requiring hearth, retort, or grate burning equipment	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey

Garbage

- Animal and vegetable waste resulting from the handling, cooking, and serving of food
- Composed largely of putrescible organic matter and moisture
- Originates from kitchens, stores, restaurants, etc
- Decomposes rapidly in warm weather and causes odor problems

Rubbish

- Variety of combustible & noncombustible solid wastes
- Trash: Combustible rubbish consisting of paper, rags, cartons, boxes, furniture, wood, tree branches, yard trimmings.
- Trash is not putrescible and can be stored for longer periods of time
- Density of combustible refuse is about 115 kg/m^3

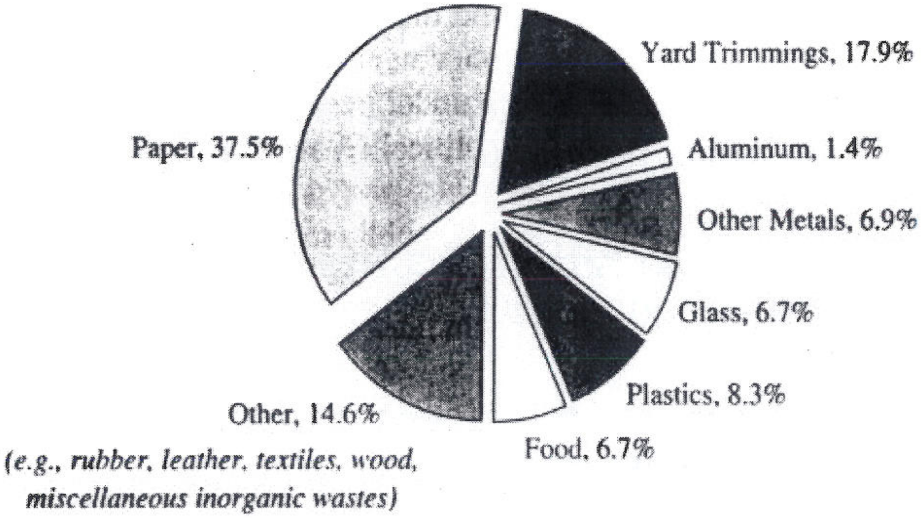
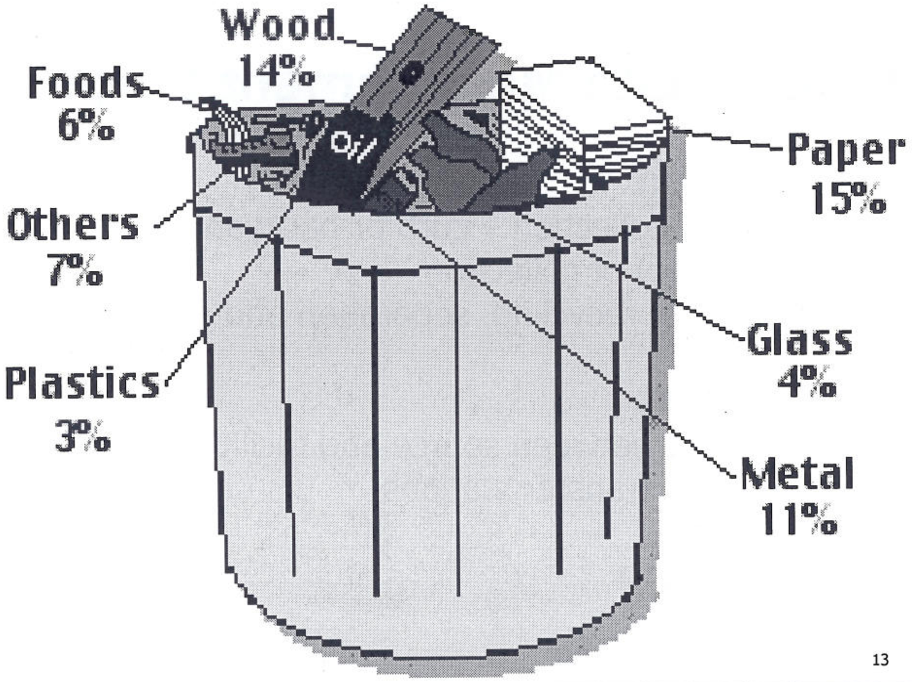


FIGURE 8-2

Materials generated in municipal solid waste (percent by mass), 1990. (*Source:* U.S. Environmental Protection Agency, "Characterization of Municipal Solid Waste in the United States," 1992 update.)



Solid Waste Management

- Objectives:
  - ➢Removal of discarded materials from inhabited places in a timely manner to prevent the spread of disease, minimize the likelihood of fires, and reducing aesthetic results
  - ➢Disposal of the discarded materials in a manner that is environmentally acceptable

Solid Waste Management Stages

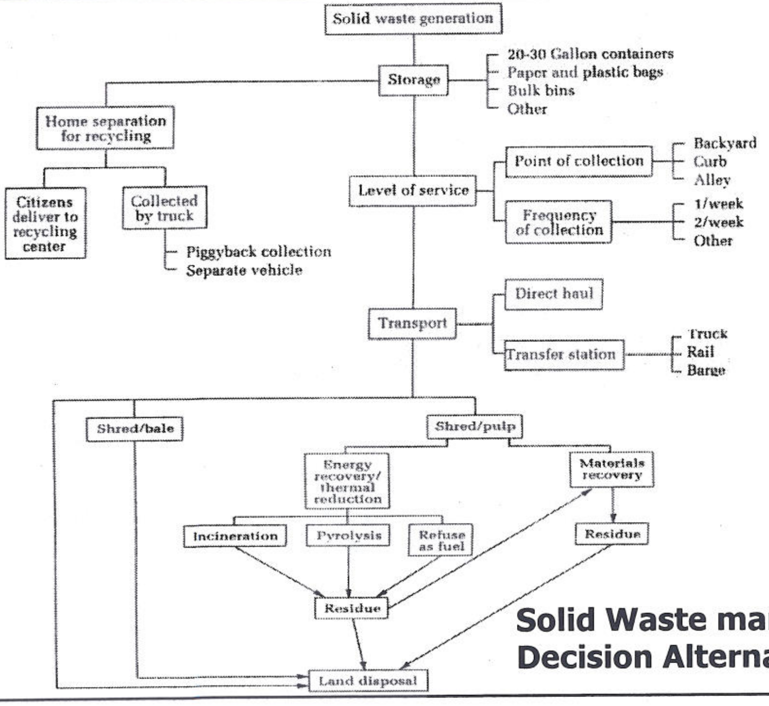
- **Collection**
  - – Point of collection – curb or backyard
  - – Frequency of collection
  - – Scope for recycling, separation and recovery
- **Transport**
  - – Distance between source and facility
  - – Need for transfer stations
- **Processing**

- **Disposal – Alternatives:**
  - – Direct disposal to sanitary landfill
  - – Processing of wastes followed by land disposal
    - Main aim is volume reduction
    - Reduction in hauling and ultimate disposal costs
    - Capital and operating costs of the volume reduction processes may be a concern
  - – Processing of wastes to recover resources (materials and/or energy) with subsequent disposal of the residues

- Incineration may be better owing to volume reduction
    - Reduces the volume going to the landfill
    - Beneficial from the point of view of increasing cost of landfill space.

INTEGRATED SOLID WASTE MANAGEMENT

"...Selection of a combination of techniques, Technologies, and management programs to Achieve waste management objectives..."



Solid Waste management Decision Alternatives

Collection

- Collection can be carried out by:
  - City employees (***Municipal Collection***)
  - Private firms that contract with city govt. (***Contract Collection***)
  - Private firms that contract with private residents (***Private Collection***)
- Policy decisions to be made:
  - Who has to collect?
  - What to collect?
  - Frequency of collection.

For Collection of Solid Waste, the Maximum Period should be less than:

- Normal time for the accumulation of the amount that can be placed in containers;
- Time taken for fresh garbage to putrefy and emit foul odors under average storage conditions;
- Length of the fly-breeding cycle, which, during summer is less than seven days.

Collection Methods

- Curb side collection or alley pick-up,
- Set-out, set-back collection, and
- Backyard pickup

- Curbside or Alley Pickup:
  - Using standard containers
  - Most economical – about half as expensive as backyard collection
  - Time limits: out by 7 am and back by 7 pm
  - Small crews are more efficient than large ones
  - Eliminates the need for collectors to enter the private property
- Set-out or Set-back Method:
  - Set-out crew carries full containers before vehicle arrives,
  - Loading into the vehicle, and
  - Return of empty cans
  - Not so economical than the backyard method

- Backyard Pickup:
  - Use of tote barrels
  - Collector enters property, dumps container into a tote barrel, carries to truck and dumps it
  - Advantage: Convenient to the home owner
  - Disadvantage: high costs

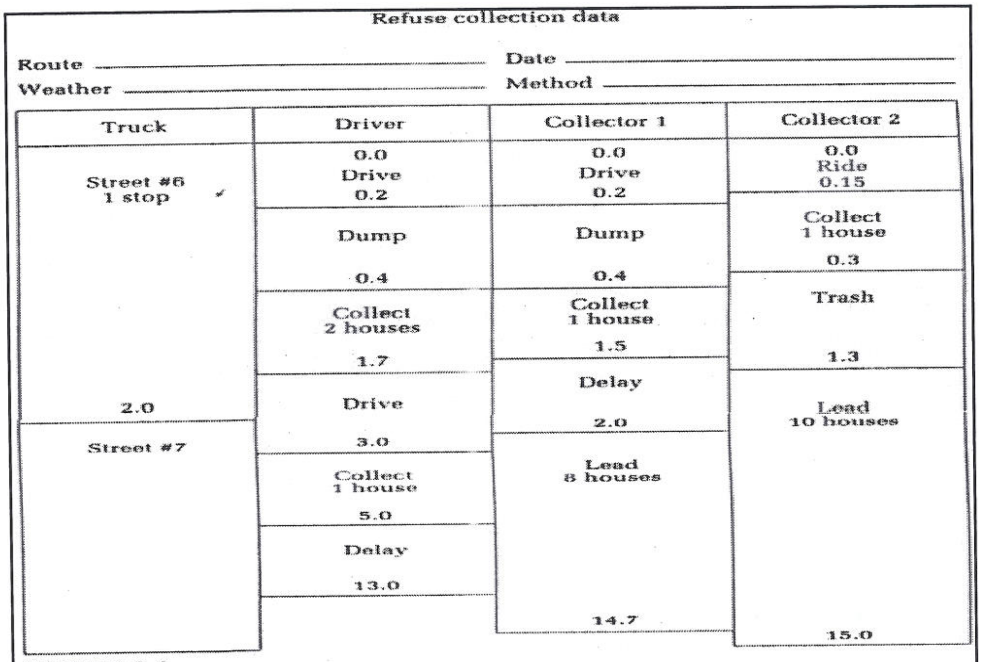
75 – 80% of the total cost of solid waste management can be attributed to the collection stage

Evaluation and optimization of collection systems

- "***Crew-machine***" chart: record time spent on each task
- Time is noted as a crew member leaves the collection truck or begins an operation
- Upon completion of the task, the time is noted and the next task begun
- A crew member must be doing the same task so that the whole day is accounted for

For meaningful results the tasks must be standardized. Typical tasks are

1. *Walk:* This is time spent by the workers in walking along the road from the truck to the next collection point. It is used only in the curb or alley collection method.
2. *Drive:* Time spent driving the truck from collection point to collection point.
3. *Trash:* Time spent placing yard wastes from the curb into the truck. Some crews accomplish this by use of a pitchfork.
4. *Ride:* Time the workers spend riding on the truck between collection points.
5. *Lead:* This is unique to some backyard collection procedures. It is when the worker leaves the truck with a tub and collects refuse from several houses. The collector stops ahead on the route and waits for the truck to catch up.
6. *Collect:* Time spent collecting from houses in the traditional way in backyard pickup. It includes the time from when the collector leaves the truck, walks to the backyard, dumps the cans into a tub, returns to the truck, and dumps the tub. The collector may collect from more than one house before returning.
7. *Dump:* Time spent dumping cans or bags from the curb into the truck.
8. *Delay:* Time spent on any operation other than these listed.



Refuse collection data

Route ____________________ Date ____________________

Weather ____________________ Method ____________________

Truck	Driver	Collector 1	Collector 2
Street #6 1 stop ✓ 2.0	0.0 Drive 0.2	0.0 Drive 0.2	0.0 Ride 0.15
Street #7	Dump 0.4	Dump 0.4	Collect 1 house 0.3
	Collect 2 houses 1.7	Collect 1 house 1.5	Trash 1.3
	Drive 3.0	Delay 2.0	Lead 10 houses 15.0
	Collect 1 house 5.0	Lead 8 houses 14.7	
	Delay 13.0		

FIGURE 8-4
Sample data collection form. (*Note:* "Crew-Machine" chart time is recorded in minutes from a start time of 0.0.)

Estimating truck capacity. Given that you are able to estimate a large number of factors, the following equation will allow you to estimate the volume of solid waste a truck must be able to carry.

$$\forall_T = \frac{\forall_p}{rt_p}\left[\frac{H}{N_d} - \frac{2x}{s} - 2t_d - t_u - \frac{B}{N_d}\right] \tag{8-1}$$

where $\forall_T$ = volume of solid waste carried per trip by truck at a mean density, D_T, m^3
$\forall_p$ = volume of solid waste per pickup location or stop, m^3/stop
r = compaction ratio
t_p = mean time per collection stop plus the mean time to reach the next stop, h
H = length of working day,[10] h
N_d = number of trips to the disposal site per day
x = one-way distance to disposal site, km
s = average haul speed to and from disposal site, km/h
t_d = one-way delay time, h/trip
t_u = unloading time at disposal site, h/trip
B = off route time per day, h

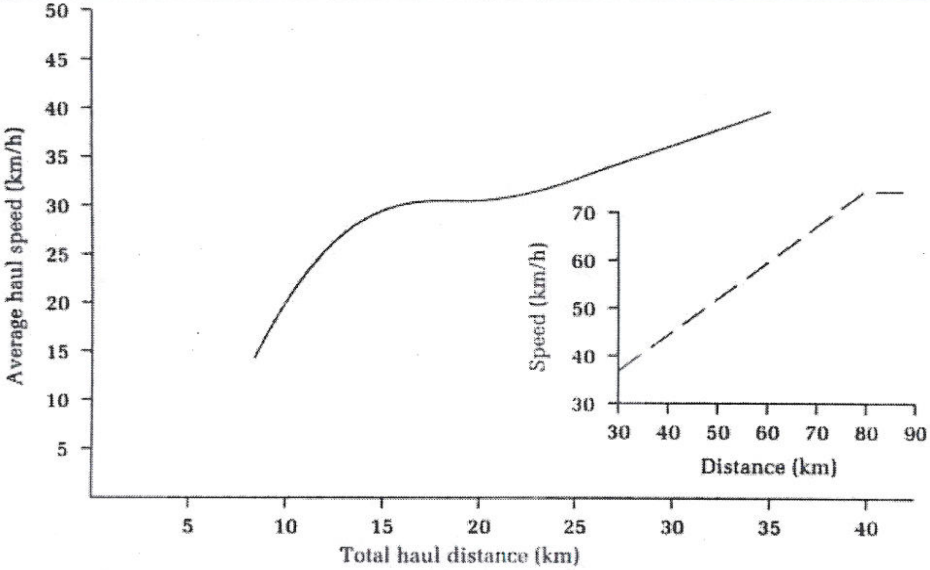
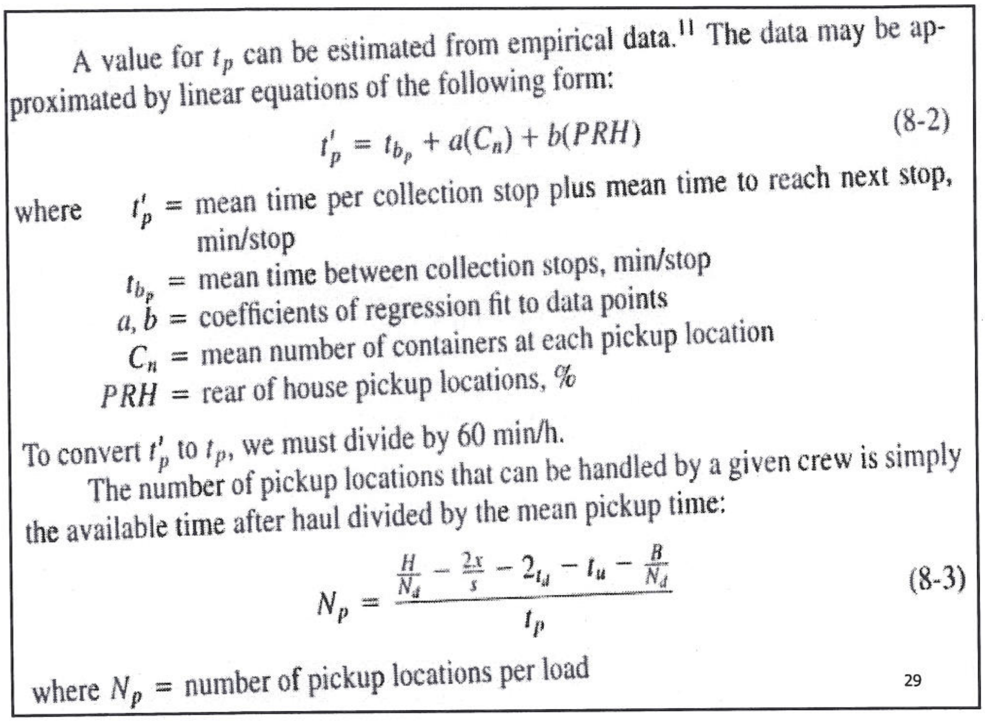


FIGURE 8-7
Effect of haul distance on average haul speed. [Adapted from *An Analysis of Refuse Collection and Sanitary Landfill Disposal* (University of California Technical Bulletin No. 8), 1952.]



A value for t_p can be estimated from empirical data.[11] The data may be approximated by linear equations of the following form:

$$t'_p = t_{b_p} + a(C_n) + b(PRH) \qquad (8\text{-}2)$$

where t'_p = mean time per collection stop plus mean time to reach next stop, min/stop

t_{b_p} = mean time between collection stops, min/stop

a, b = coefficients of regression fit to data points

C_n = mean number of containers at each pickup location

PRH = rear of house pickup locations, %

To convert t'_p to t_p, we must divide by 60 min/h.

The number of pickup locations that can be handled by a given crew is simply the available time after haul divided by the mean pickup time:

$$N_p = \frac{\frac{H}{N_d} - \frac{2x}{s} - 2_{t_d} - t_u - \frac{B}{N_d}}{t_p} \qquad (8\text{-}3)$$

where N_p = number of pickup locations per load

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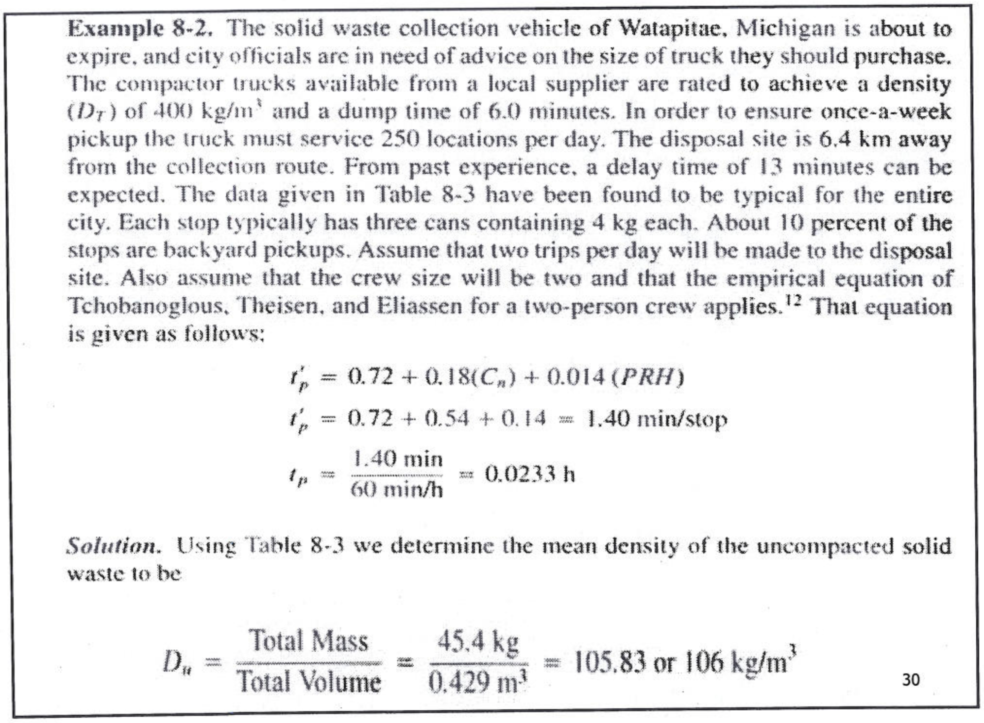


Example 8-2. The solid waste collection vehicle of Watapitae, Michigan is about to expire, and city officials are in need of advice on the size of truck they should purchase. The compactor trucks available from a local supplier are rated to achieve a density (D_T) of 400 kg/m^3 and a dump time of 6.0 minutes. In order to ensure once-a-week pickup the truck must service 250 locations per day. The disposal site is 6.4 km away from the collection route. From past experience, a delay time of 13 minutes can be expected. The data given in Table 8-3 have been found to be typical for the entire city. Each stop typically has three cans containing 4 kg each. About 10 percent of the stops are backyard pickups. Assume that two trips per day will be made to the disposal site. Also assume that the crew size will be two and that the empirical equation of Tchobanoglous, Theisen, and Eliassen for a two-person crew applies.[12] That equation is given as follows:

$$t'_p = 0.72 + 0.18(C_n) + 0.014\,(PRH)$$

$$t'_p = 0.72 + 0.54 + 0.14 = 1.40 \text{ min/stop}$$

$$t_p = \frac{1.40 \text{ min}}{60 \text{ min/h}} = 0.0233 \text{ h}$$

Solution. Using Table 8-3 we determine the mean density of the uncompacted solid waste to be

$$D_u = \frac{\text{Total Mass}}{\text{Total Volume}} = \frac{45.4 \text{ kg}}{0.429 \text{ m}^3} = 105.83 \text{ or } 106 \text{ kg/m}^3$$

30

The volume per pickup is then

$$\forall_p = \frac{(3\text{ cans})(4\text{ kg/can})}{106\text{ kg/m}^3} = 0.11\text{ m}^3$$

The compaction ratio is determined from the densities.

$$r = \frac{D_T}{D_w} = \frac{400\text{ kg/m}^3}{106\text{ kg/m}^3} = 3.77$$

The average haul speed is determined from Figure 8-7. Since the graph is for total haul distance, we enter with (2)(6.4) = 12.8 km and determine that $s = 27$ km/h. All of the other required data were given; thus, we can now use Equation 8-1. The factor of 60 is to convert minutes to hours. For two 15-minute breaks, $B = 0.50$.

$$\forall_t = \frac{0.11}{(3.77)(0.0233)}\left[\frac{8}{2} - \frac{(2)(6.4)}{27} - 2\,\frac{13\text{ min}}{60\text{ min/h}} - \frac{6\text{ min}}{60\text{ min/h}} - \frac{0.50}{2}\right]$$

$$= (1.25)(2.74) = 3.43\text{ m}^3$$

The number of stops that can be handled is given by Equation 8-3.

$$N_p = \frac{2.74}{0.0233} = 117.60 \text{ or } 118 \text{ pickups per load}$$

Estimating costs. Most of the decisions involved in the collection of solid waste are based on economic considerations rather than technical ones. The costs are considered on the basis of a unit mass of solid waste to facilitate comparison between different size vehicles, crews, and the like. Furthermore, truck costs are considered separately from labor costs.

Truck costs include depreciation of the initial capital investment plus the *operating and maintenance (O & M)* costs.[13]

The following equation may be used to estimate the annual cost per Mg:[14]

$$A_T = \frac{1{,}000(F)}{\forall_T D_T N_T Y}\left[1 + \frac{i(Y+1)}{2}\right] + \frac{1{,}000(X_t)(OM)}{\forall_T D_T} \qquad (8\text{-}4)$$

where A_T = annual truck cost, \$/Mg
F = initial (first) cost of truck, \$
D_T = mean density of solid waste in truck, kg/m^3
N_T = number of trips per year
Y = useful life of truck, y
i = interest rate on capital
X_t = distance per trip, pickup plus haul, km
OM = operating and maintenance cost, \$/km

The factor of 1,000 is to convert kg to Mg.

Labor costs consist of direct wages plus some overhead costs for such things as supervision, secretarial support, phone, utilities, insurance, and fringe benefits. Equation 8-5 can be used to estimate the annual labor cost per Mg:

$$A_L = \frac{1{,}000(CS)(W)(H)}{\forall_T D_T N_d}[1 + (OH)] \tag{8-5}$$

where A_L = annual labor cost, \$/Mg
CS = average crew size
W = average hourly wage rate, \$/h
OH = overhead as a fraction of wages

Again, the factor of 1,000 is to convert kg to Mg.

Example 8-3. Estimate the customer service charge for the situation of Example 8-2. The initial truck cost of a 4.0 m^3 compactor truck is \$104,000, and the average O & M cost over the five-year life of the truck is expected to be \$5.50/km. The interest rate is 8.25 percent. The average route length is 6.3 km. The average hourly wage rate is \$13.50 per hour with time and a half for overtime. The overhead rate is 125 percent of the hourly wage rate.

Solution. Assuming a five-day work week and ignoring holidays, the number of trips per year would be

$$N_t = N_d(5)(52) = 2(5)(52) = 520$$

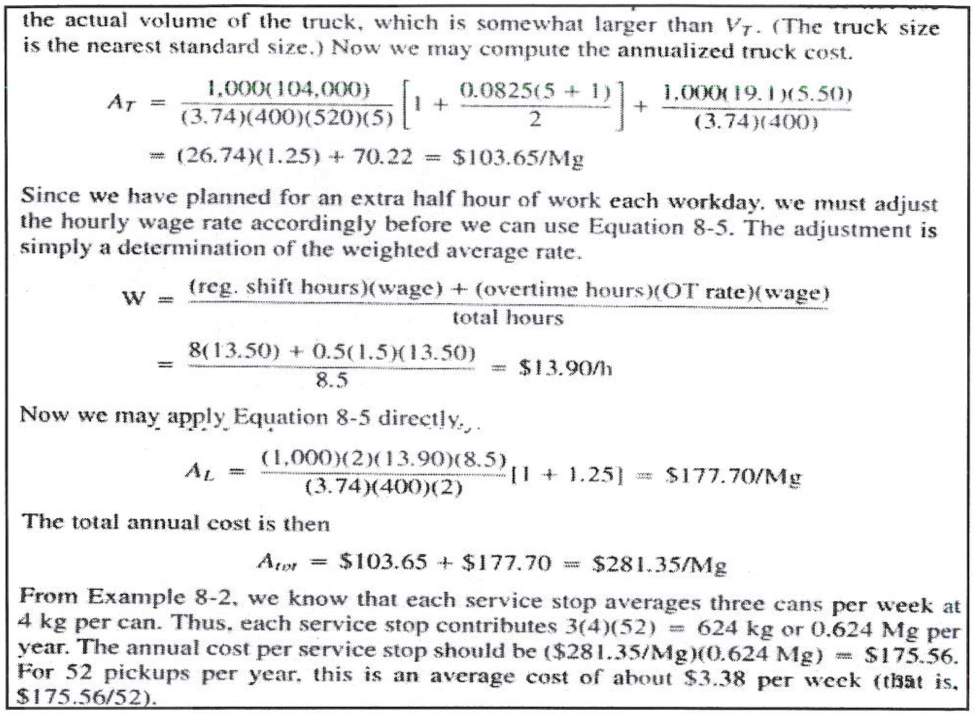
Since the average route length is 6.3 km and the average haul distance from Example 8-2 is 2(6.4) = 12.8 km, then

$$X_t = 6.3 + 12.8 = 19.1 \text{ km}$$

For the extended workday proposed at the end of Example 8-2, the volume of solid waste per trip would be

$$V_T = (1.25)(2.74 + 1/2(0.5)) = 3.74 \text{ m}^3$$

The factor of one-half times the extra half hour was selected because we assumed the time to be equally divided between each of the two trips. Note that we do not use



the actual volume of the truck, which is somewhat larger than V_T. (The truck size is the nearest standard size.) Now we may compute the annualized truck cost.

$$A_T = \frac{1{,}000(104{,}000)}{(3.74)(400)(520)(5)}\left[1 + \frac{0.0825(5+1)}{2}\right] + \frac{1{,}000(19.1)(5.50)}{(3.74)(400)}$$

$$= (26.74)(1.25) + 70.22 = \$103.65/\text{Mg}$$

Since we have planned for an extra half hour of work each workday, we must adjust the hourly wage rate accordingly before we can use Equation 8-5. The adjustment is simply a determination of the weighted average rate.

$$W = \frac{(\text{reg. shift hours})(\text{wage}) + (\text{overtime hours})(\text{OT rate})(\text{wage})}{\text{total hours}}$$

$$= \frac{8(13.50) + 0.5(1.5)(13.50)}{8.5} = \$13.90/\text{h}$$

Now we may apply Equation 8-5 directly.

$$A_L = \frac{(1{,}000)(2)(13.90)(8.5)}{(3.74)(400)(2)}[1 + 1.25] = \$177.70/\text{Mg}$$

The total annual cost is then

$$A_{tot} = \$103.65 + \$177.70 = \$281.35/\text{Mg}$$

From Example 8-2, we know that each service stop averages three cans per week at 4 kg per can. Thus, each service stop contributes 3(4)(52) = 624 kg or 0.624 Mg per year. The annual cost per service stop should be ($281.35/Mg)(0.624 Mg) = $175.56. For 52 pickups per year, this is an average cost of about $3.38 per week (that is, $175.56/52).

Truck Routing

1 Daily Routing:

- Definite route to be finished before going home
- Advantages:
  - Homeowner knows when the refuse will be picked up
  - Route sizes can be adjusted for the load to maximize
  - Crew likes the method because it provides an incentive to get done early

- Disadvantages:
  - **If route is not finished, crew has to work overtime, which will increase the costs**
  - **Crew may be careless to finish the job soon**
  - **Underutilization of the crew and equipment due to the increased incentive of the crew**
  - **Breakdown seriously affects operations**
  - **Hard to plans route if the loads are variable, because of disposal of yard wastes, etc**

2 Large Method:

- **Crew has enough work to last for the entire week**
- **It's the crew's discretion to chose when to pick up the route.**
- **Best for backyard pickup since the residents don't know when the pickup will be.**

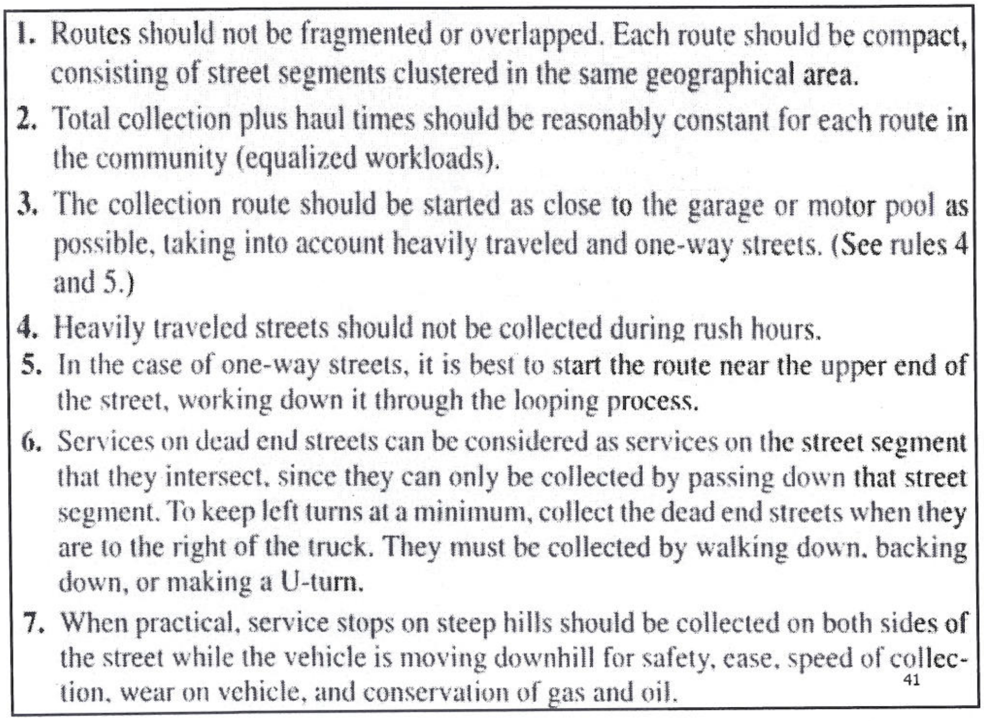
3 Single Route Method:

- Routes planned to get a full truck
- Each crew is assigned as many loads as it can collect per day
- Biggest advantage of this method is that it can minimize travel time
- Must consider crew size, truck capacity, length of travel, refuse generated, etc
- Enables maximum utilization of crew and equipment capacity
- Can be used for any type of pickup
- Disadvantage: hard to predict the number of homes that can be serviced before the truck is filled.

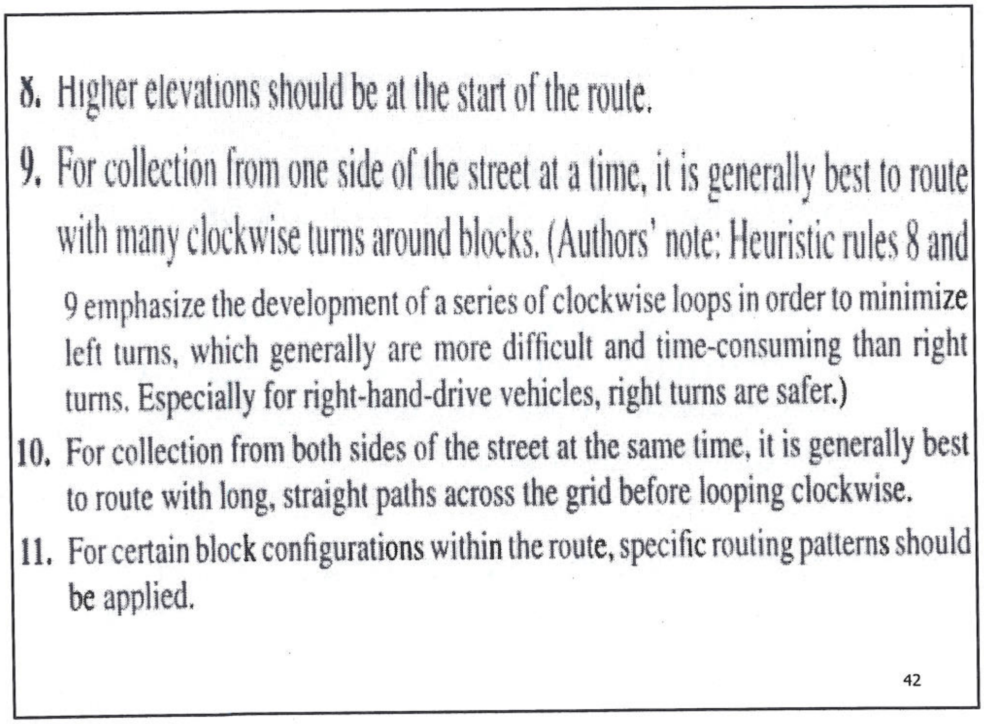
4 Definite Working Day Method:

- Crew works for assigned number of hours
- Predominates in areas where Unions are strong
- Enables the maximum utilization of crew and equipment
- Regularity is sacrificed
- Residents have little idea when pickup will occur

Office of the Solid Waste Management of USEPA has developed a "*heuristic*" approach to routing to minimize deadheading, delay and left turns.



1. Routes should not be fragmented or overlapped. Each route should be compact, consisting of street segments clustered in the same geographical area.
2. Total collection plus haul times should be reasonably constant for each route in the community (equalized workloads).
3. The collection route should be started as close to the garage or motor pool as possible, taking into account heavily traveled and one-way streets. (See rules 4 and 5.)
4. Heavily traveled streets should not be collected during rush hours.
5. In the case of one-way streets, it is best to start the route near the upper end of the street, working down it through the looping process.
6. Services on dead end streets can be considered as services on the street segment that they intersect, since they can only be collected by passing down that street segment. To keep left turns at a minimum, collect the dead end streets when they are to the right of the truck. They must be collected by walking down, backing down, or making a U-turn.
7. When practical, service stops on steep hills should be collected on both sides of the street while the vehicle is moving downhill for safety, ease, speed of collection, wear on vehicle, and conservation of gas and oil.



8. Higher elevations should be at the start of the route.
9. For collection from one side of the street at a time, it is generally best to route with many clockwise turns around blocks. (Authors' note: Heuristic rules 8 and 9 emphasize the development of a series of clockwise loops in order to minimize left turns, which generally are more difficult and time-consuming than right turns. Especially for right-hand-drive vehicles, right turns are safer.)
10. For collection from both sides of the street at the same time, it is generally best to route with long, straight paths across the grid before looping clockwise.
11. For certain block configurations within the route, specific routing patterns should be applied.

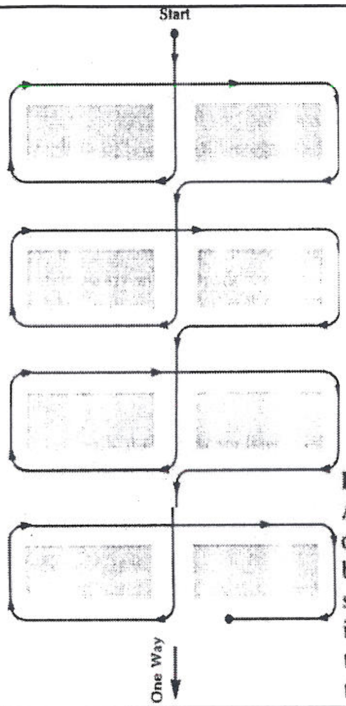


FIGURE 8-8
Arrows show heuristic routing pattern developed for a north-south, one-way street combined with east-west, two-way streets. If both sides of the one-way street cannot be collected in one pass, it is necessary to loop back to the upper end and make a straight pass down the other side. [*Source:* K. A. Shuster and

Inter-route Transfer

- It may not be possible at times to haul the entire waste collected to the disposal site.
- <u>Transfer Vehicles:</u> larger vehicle like tractor-trailer, barge, etc to transfer from several small collection vehicles to the ultimate disposal site.
- <u>Transfer Station:</u> special facility to permit this exchange in a rapid and sanitary way.

$$T_H = \frac{H}{N_d} - t_p N_p - 2t_d - t_u - \frac{B}{N_d} \qquad (8\text{-}6)$$

where T_H = maximum available haul time, h

If the maximum available haul time is less than the round trip distance divided by the average route speed ($2x/s$), then you have a problem. Up to a point, changes in t_d, t_u, B, and/or H may alleviate the situation.[16]

Economical Haul Time

The travel time in and of itself is not usually the prime consideration. Cost is usually the prime consideration. Costs are saved when a transfer operation is used because

1. The nonproductive time of collectors is reduced, since they no longer ride to and from the disposal site. It may be possible to reduce the number of collection crews needed because of increased productive collection time.
2. Any reduction in mileage traveled by the collection trucks results in a savings in operating costs.
3. The maintenance requirements for collection trucks can be reduced when these vehicles are no longer required to drive into the landfill site. Much of the damage to suspensions, drive trains, and tires occurs at landfills.
4. The capital cost of collection equipment may be reduced; since the trucks will be traveling only on improved roads, lighter duty, less expensive models can be used.[17]

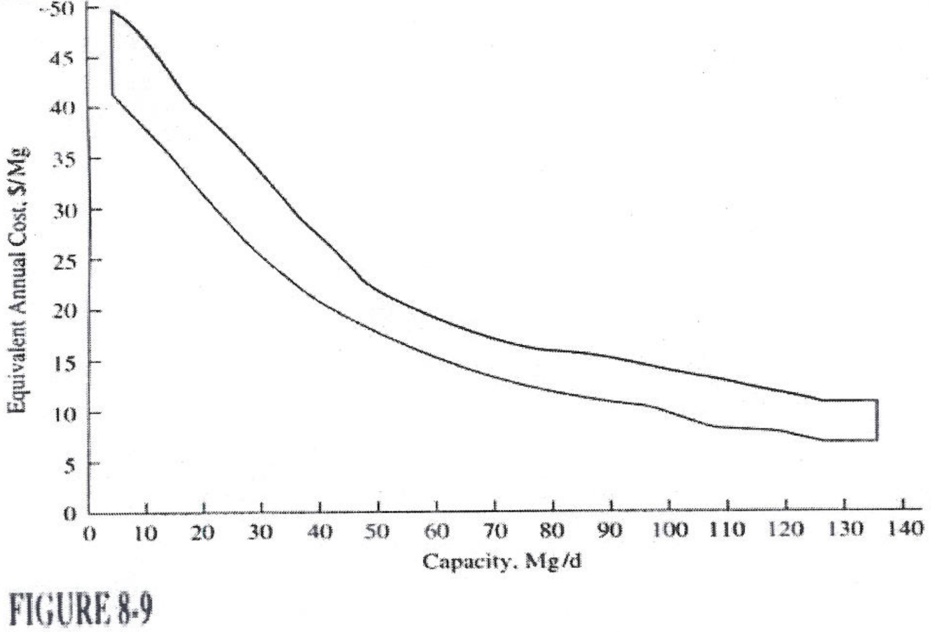
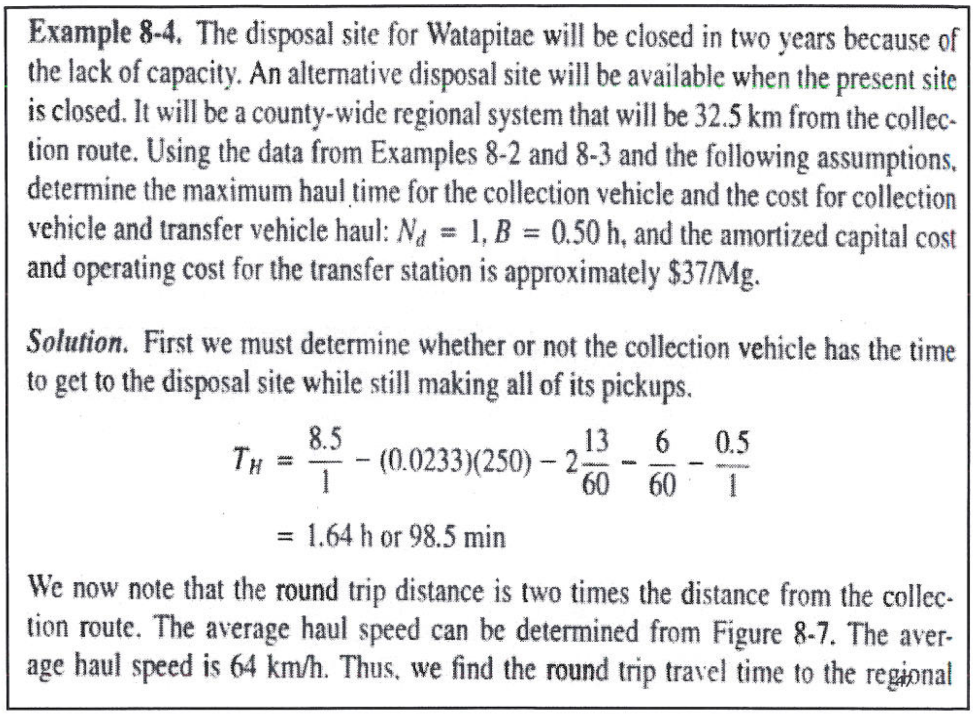


FIGURE 8-9

Transfer station equivalent annual cost as a function of capacity. Costs adjusted to 1996.



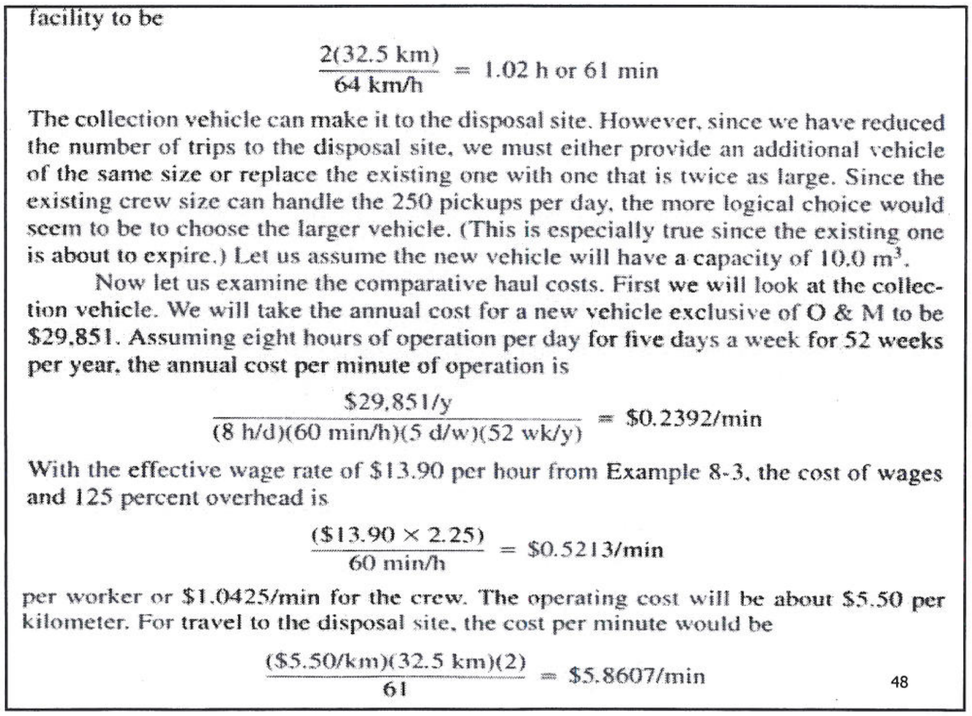
Example 8-4. The disposal site for Watapitae will be closed in two years because of the lack of capacity. An alternative disposal site will be available when the present site is closed. It will be a county-wide regional system that will be 32.5 km from the collection route. Using the data from Examples 8-2 and 8-3 and the following assumptions, determine the maximum haul time for the collection vehicle and the cost for collection vehicle and transfer vehicle haul: $N_d = 1$, $B = 0.50$ h, and the amortized capital cost and operating cost for the transfer station is approximately \$37/Mg.

Solution. First we must determine whether or not the collection vehicle has the time to get to the disposal site while still making all of its pickups.

$$T_H = \frac{8.5}{1} - (0.0233)(250) - 2\frac{13}{60} - \frac{6}{60} - \frac{0.5}{1}$$

$$= 1.64 \text{ h or } 98.5 \text{ min}$$

We now note that the round trip distance is two times the distance from the collection route. The average haul speed can be determined from Figure 8-7. The average haul speed is 64 km/h. Thus, we find the round trip travel time to the regional



facility to be

$$\frac{2(32.5 \text{ km})}{64 \text{ km/h}} = 1.02 \text{ h or } 61 \text{ min}$$

The collection vehicle can make it to the disposal site. However, since we have reduced the number of trips to the disposal site, we must either provide an additional vehicle of the same size or replace the existing one with one that is twice as large. Since the existing crew size can handle the 250 pickups per day, the more logical choice would seem to be to choose the larger vehicle. (This is especially true since the existing one is about to expire.) Let us assume the new vehicle will have a capacity of 10.0 m^3.

Now let us examine the comparative haul costs. First we will look at the collection vehicle. We will take the annual cost for a new vehicle exclusive of O & M to be \$29,851. Assuming eight hours of operation per day for five days a week for 52 weeks per year, the annual cost per minute of operation is

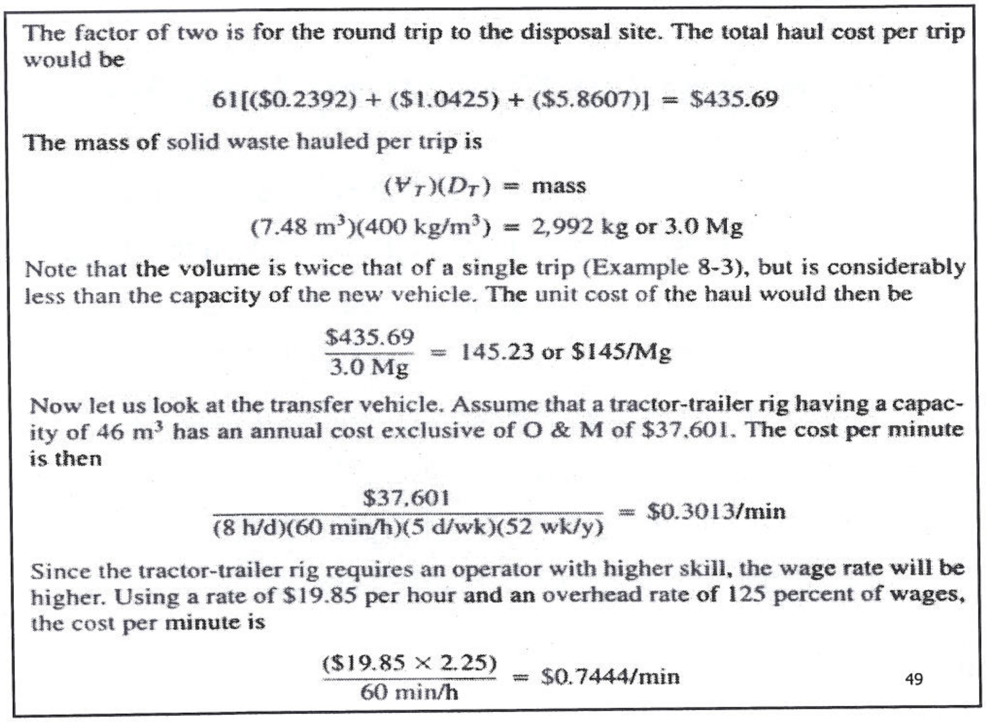
$$\frac{\$29{,}851/\text{y}}{(8 \text{ h/d})(60 \text{ min/h})(5 \text{ d/w})(52 \text{ wk/y})} = \$0.2392/\text{min}$$

With the effective wage rate of \$13.90 per hour from Example 8-3, the cost of wages and 125 percent overhead is

$$\frac{(\$13.90 \times 2.25)}{60 \text{ min/h}} = \$0.5213/\text{min}$$

per worker or \$1.0425/min for the crew. The operating cost will be about \$5.50 per kilometer. For travel to the disposal site, the cost per minute would be

$$\frac{(\$5.50/\text{km})(32.5 \text{ km})(2)}{61} = \$5.8607/\text{min}$$



The factor of two is for the round trip to the disposal site. The total haul cost per trip would be

$$61[(\$0.2392) + (\$1.0425) + (\$5.8607)] = \$435.69$$

The mass of solid waste hauled per trip is

$$(\mathcal{V}_T)(D_T) = \text{mass}$$

$$(7.48\ \text{m}^3)(400\ \text{kg/m}^3) = 2{,}992\ \text{kg or } 3.0\ \text{Mg}$$

Note that the volume is twice that of a single trip (Example 8-3), but is considerably less than the capacity of the new vehicle. The unit cost of the haul would then be

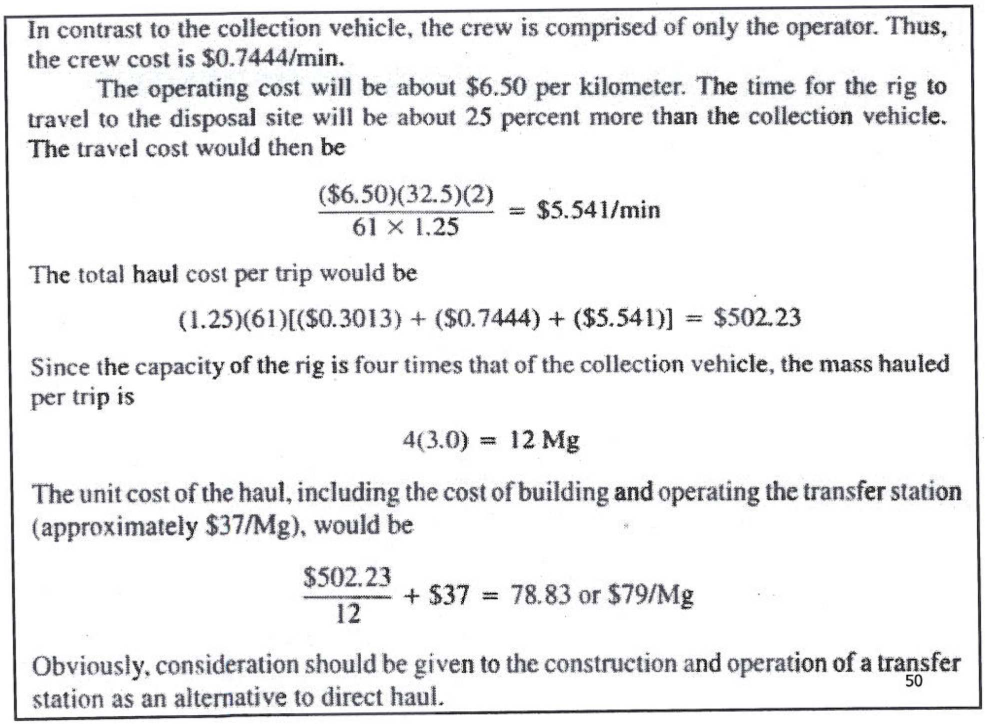
$$\frac{\$435.69}{3.0\ \text{Mg}} = 145.23 \text{ or } \$145/\text{Mg}$$

Now let us look at the transfer vehicle. Assume that a tractor-trailer rig having a capacity of 46 m³ has an annual cost exclusive of O & M of $37,601. The cost per minute is then

$$\frac{\$37{,}601}{(8\ \text{h/d})(60\ \text{min/h})(5\ \text{d/wk})(52\ \text{wk/y})} = \$0.3013/\text{min}$$

Since the tractor-trailer rig requires an operator with higher skill, the wage rate will be higher. Using a rate of $19.85 per hour and an overhead rate of 125 percent of wages, the cost per minute is

$$\frac{(\$19.85 \times 2.25)}{60\ \text{min/h}} = \$0.7444/\text{min}$$



In contrast to the collection vehicle, the crew is comprised of only the operator. Thus, the crew cost is $0.7444/min.

The operating cost will be about $6.50 per kilometer. The time for the rig to travel to the disposal site will be about 25 percent more than the collection vehicle. The travel cost would then be

$$\frac{(\$6.50)(32.5)(2)}{61 \times 1.25} = \$5.541/\text{min}$$

The total haul cost per trip would be

$$(1.25)(61)[(\$0.3013) + (\$0.7444) + (\$5.541)] = \$502.23$$

Since the capacity of the rig is four times that of the collection vehicle, the mass hauled per trip is

$$4(3.0) = 12\ \text{Mg}$$

The unit cost of the haul, including the cost of building and operating the transfer station (approximately $37/Mg), would be

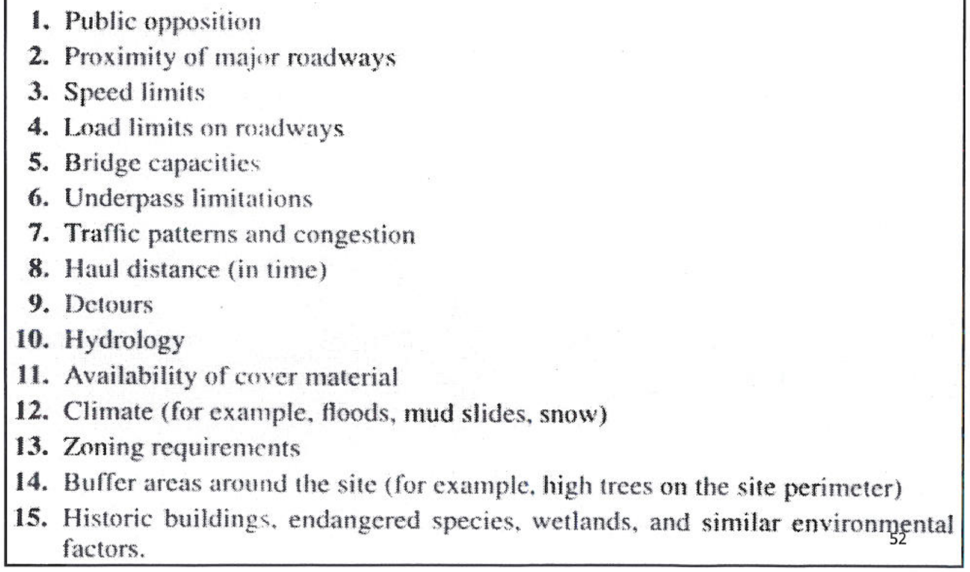
$$\frac{\$502.23}{12} + \$37 = 78.83 \text{ or } \$79/\text{Mg}$$

Obviously, consideration should be given to the construction and operation of a transfer station as an alternative to direct haul.

Disposal by Sanitary Landfill

- Sanitary Landfill is defined as a land disposal site employing an engineered method of disposing of solid wastes on land in a manner that minimizes environmental hazards by spreading the solid wastes to the smallest practical volume, and applying and compacting cover material at the end of each day.

Site Selection Considerations



1. Public opposition
2. Proximity of major roadways
3. Speed limits
4. Load limits on roadways
5. Bridge capacities
6. Underpass limitations
7. Traffic patterns and congestion
8. Haul distance (in time)
9. Detours
10. Hydrology
11. Availability of cover material
12. Climate (for example, floods, mud slides, snow)
13. Zoning requirements
14. Buffer areas around the site (for example, high trees on the site perimeter)
15. Historic buildings, endangered species, wetlands, and similar environmental factors.

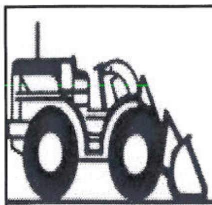
Site Preparation Steps

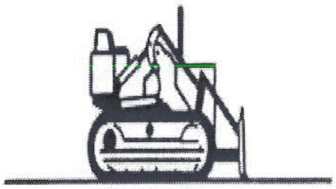
- Grading the site area
- Constructing access roads and fences
- Installing signs
- Installing utilities
- Installing operating facilities
- Telephone or radio communication facilities

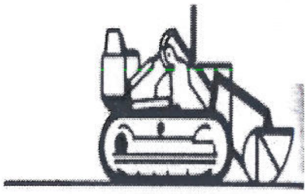
Equipment

- Size, type and number depends on size and method of operation, quantities & time of solid waste deliveries and the experience of the operators.

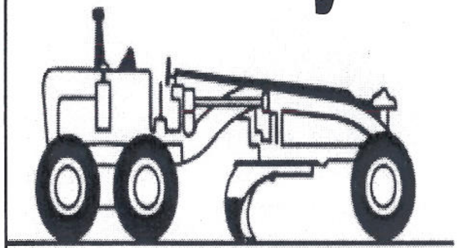
- Commonly used equipment:
    - Crawlers,
    - Tractors,
    - Scrapers,
    - Water wagons,
    - Drag liners,
    - Graders.

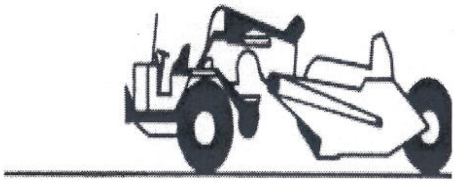

Rubber-Tired Front End Loader


Crawler Tractor


Front-End Loader — Tracke
With Bullclam

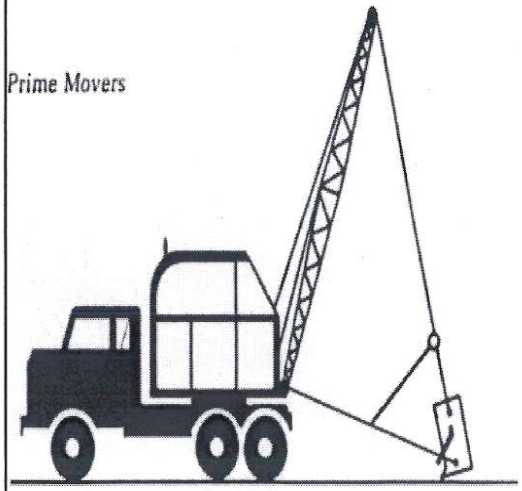
Sanitary Landfill Equipment

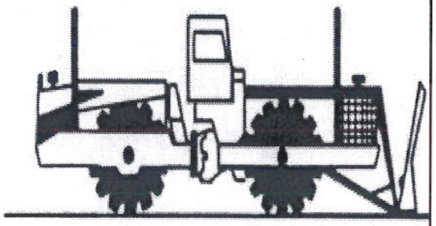

Motor Grader


Earth Mover (Scraper)

Sanitary Landfill Equipment

Prime Movers


Drag Line


Steel-Wheeled Compactor

Operation : Area Method

- Solid waste deposited on the surface, compacted, then covered with a layer of compacted soil at the end of the working day
- Seldom restricted by topography; flat or rolling terrain, canyons, and other types of depressions are all acceptable
- Cover material may come from on or off site

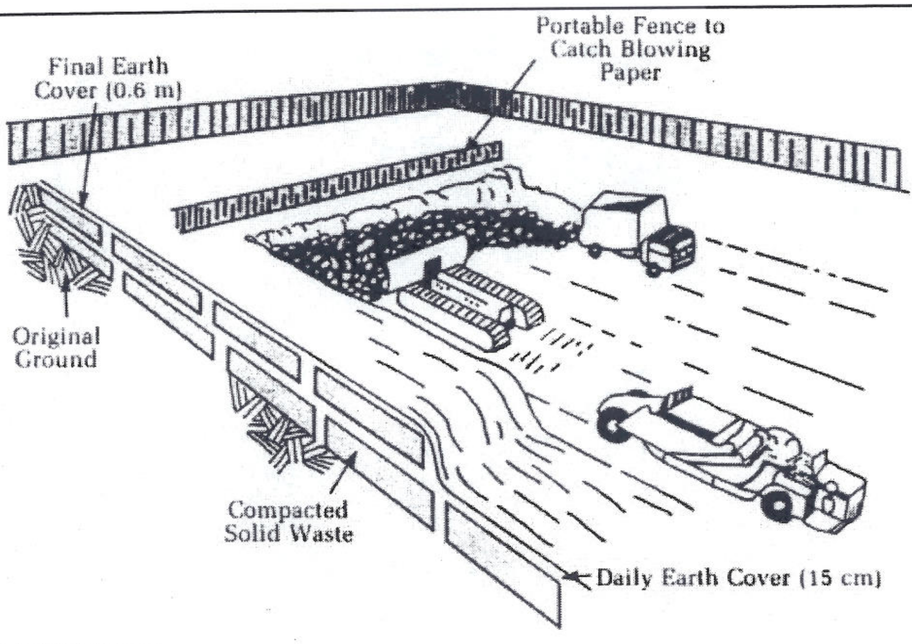


FIGURE 8-11
The area method.

Operation : Trench Method

- Used on level or gently sloping land where the water table is low
- A trench is excavated; solid waste is placed in it and compacted; and the soil that was taken from the trench is then laid on the waste and compacted.
- Advantage: cover material is readily available as a result of excavation
- Width must be atleast twice the compacting equipment so that the treads or wheels can compact all the material in the work area.

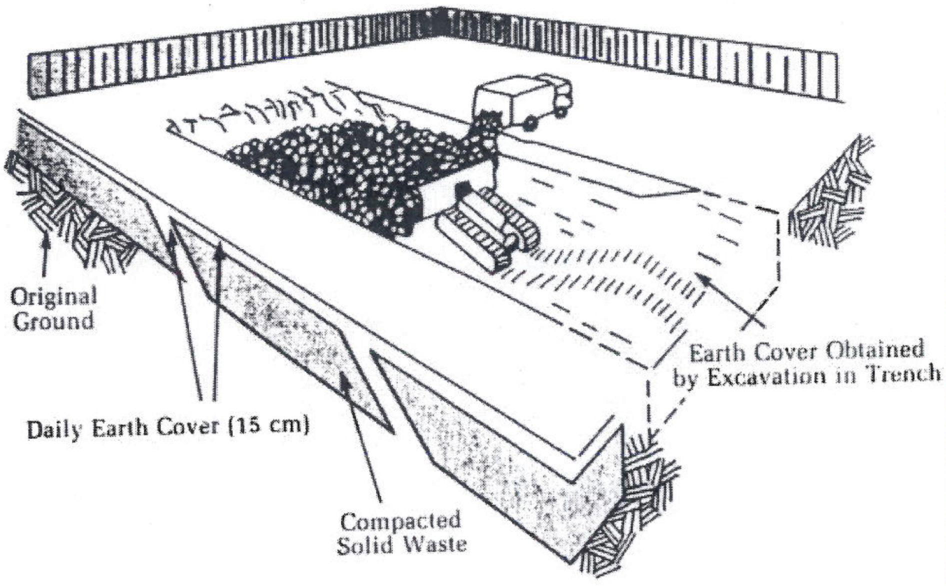


FIGURE 8-12
The trench method.

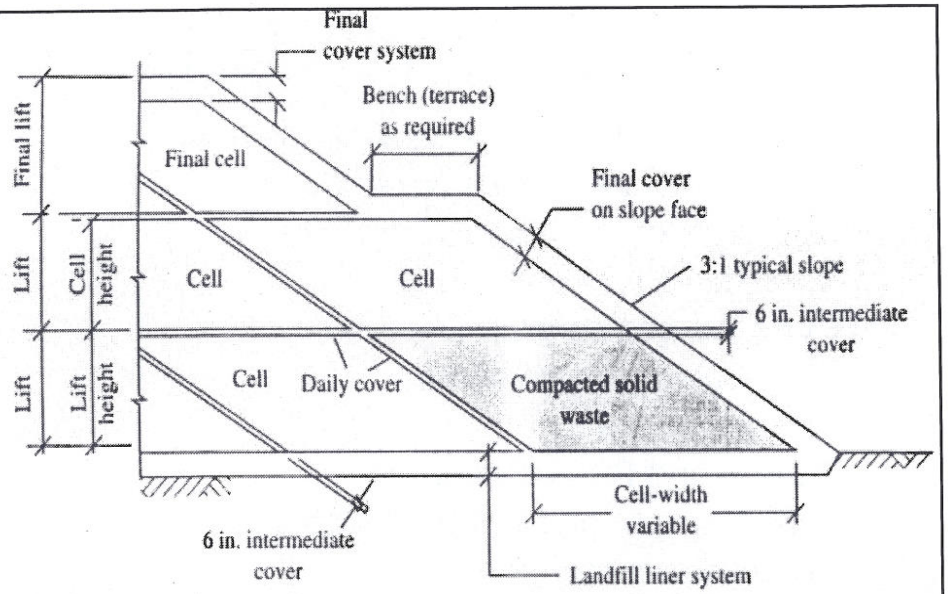


FIGURE 8-13
Sectional view through a sanitary landfill. (*Source:* G. Tchobanoglous, H. Theisen, and S. Vigil, *Integrated Solid Waste Management*, New York: McGraw-Hill, 1993. Reprinted by permission.)

Components of a Landfill

- Cell
- Face
- Cover
- Lift
- Benches
- Final Cover

Operational Considerations

- Required by 1991 Subtitle D regulations
- Exclusion of hazardous wastes
- Use of cover materials
- Disease vector control
- Explosive gas control
- Air quality measurements
- Access Control
- Run-on and Run-off controls
- Surface water and liquids restrictions
- Groundwater monitoring
- Record Keeping
- Landfill Fires

Landfill Gases

- Result of microbial decomposition of the wastes
- Constituents: CO_2 (carbon-di-oxide) in earlier stages and equal amounts of CH_4 (methane) as the landfill matures
- Heat Content of landfill gas: 16,000 to 20,000 kJ/m^3

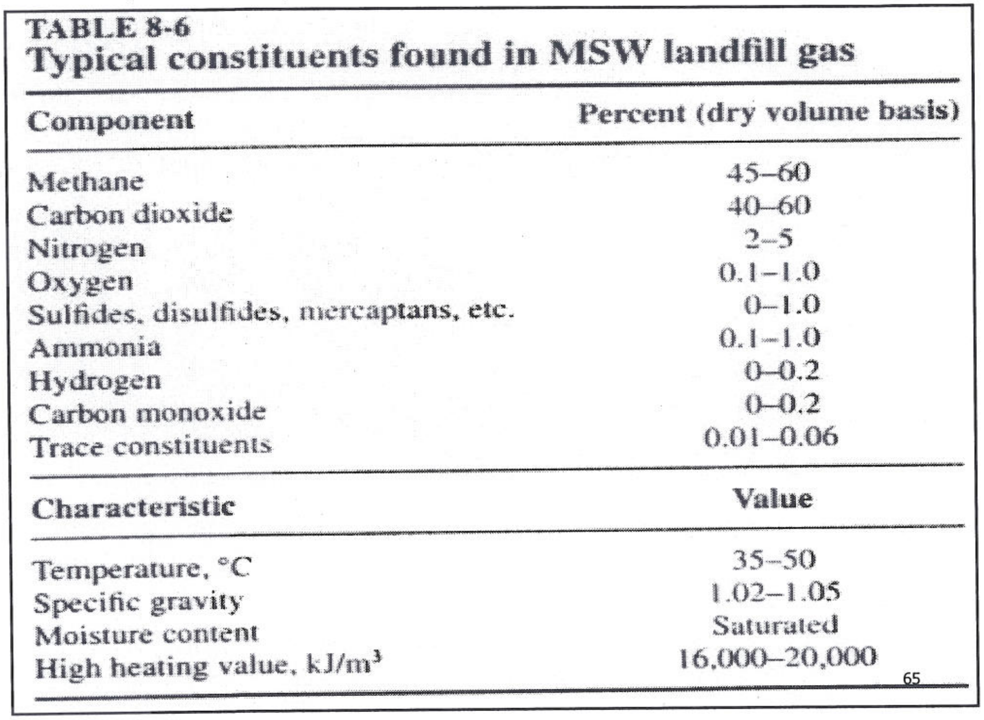


TABLE 8-6
Typical constituents found in MSW landfill gas

Component	Percent (dry volume basis)
Methane	45–60
Carbon dioxide	40–60
Nitrogen	2–5
Oxygen	0.1–1.0
Sulfides, disulfides, mercaptans, etc.	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Carbon monoxide	0–0.2
Trace constituents	0.01–0.06

Characteristic	Value
Temperature, °C	35–50
Specific gravity	1.02–1.05
Moisture content	Saturated
High heating value, kJ/m³	16,000–20,000

Landfill Leachate

- Liquid that passes through the landfill and that has extracted dissolved and suspended matter from it is ***LEACHATE***
- Liquid enters through external sources such as rainfall, surface drainage, groundwater, and the liquid in and produced from decomposition of the waste.

6-32 Activated sludge tanks at Turkey Run

Given: size and operating characteristics

Solution:

a. Aeration period (Eqn. 6-18)

$$\theta = \frac{(7.0\text{m})(30.0\text{m})(4.3\text{m})(2\text{ tanks})}{0.0796\,\text{m}^3/\text{s}} = 22688\text{s} \text{ or } 6.3\text{ h}$$

b. F/M ratio (Eqn. 6-26 and note that mg/L = g/m^3)

$$\frac{F}{M} = \frac{(0.0796\,\text{m}^3/\text{s})(86400\,\text{s}/\text{d})(130\,\text{g}/\text{m}^3)}{(1806\text{m}^3)(1500\,\text{g}/\text{m}^3)} = 0.33\,\text{mg}/\text{mg}\cdot\text{d}$$

c. SVI (Eqn. 6-27)

$$\text{SVI} = \frac{230.0\,\text{mL}/\text{L}}{(1.40)(1500\,\text{mg}/\text{L})}(1000\,\text{mg}/\text{g}) = 109.52 \text{ or } 110\text{ mL/g}$$

d. Solids concentration in return sludge (Eqn. 6-20)

$$X_r = \frac{10^6}{109.5} = 9132.4 \text{ or } 9130\text{ mg/L}$$

6-35 Sludge age and wastage at Turkey Run

Given: Data from Problem 6-32 and operating assumptions

Solution:

a. Sludge age (Eqn. 6-23; θ = 6.3 h or 0.2625 d from Prob. 6-32

$$1500 = \frac{\theta_c(0.40)(130 - 5.0)}{(0.2625)(1 + 0.040 \cdot \theta_c)}$$

$\theta_c = 11.5$ d

b. Sludge wasting (Eqn. 6-19)

Recognize that wasting from aeration tank means that $X_r = X$ so Eqn 6-19 reduces to

$$\theta_c = \frac{V}{Q_W}$$

and

$$Q_W = \frac{V}{\theta_c} = \frac{(7.0\text{m})(30.0\text{m})(4.3\text{m})(2\ \text{tanks})}{11.5\text{d}}$$

$Q_W = 157.04\ \text{m}^3/\text{d}$ or $0.00182\ \text{m}^3/\text{s}$

c. Return sludge flow rate (Eqn. 6-30)

From Problem 6-32

$X' = \text{MLSS} = (1.40)(1{,}500) = 2100$ mg/L
$X_r' = 9132.4$ mg/L
$Q = 0.0796\ \text{m}^3/\text{s}$

Then

$$Q_r = \frac{(0.0796)(2100) - (0.00182)(9132.4)}{9132.4 - 2100}$$

$Q_r = 0.02141$ or $0.0214\ \text{m}^3/\text{s}$

6-38 Evaluation of secondary settling tanks at Turkey Run

Given: Problem 6-32; tanks are 16.0 m diameter and 4.0 m deep at side wall.

Solution:

a. Overflow rate

The design standard is 33 m/d. The overflow Q = Q of wastewater into the plant = 0.0796 m^3/s from Prob. 6-32. The radius of the tank is 16.0/2 = 8.0 m.

$$v_o = \frac{(0.0796\,m^3/s)(86400\,s/d)}{\pi(8.0m)^2(2\tan ks)} = 17.1\,m/d$$

This is less than 33 m/d, therefore okay.

b. Side water depth

Check Table 6-12: Recommended depth for 16.0 m diameter is 3.7 m. Therefore, side water depth of 4.0 m is okay.

c. Solids loading

$$SL = \frac{(1+r)(Q)(X)(86400\,s/d)}{(A_s)(1000\,g/kg)}$$

where r = recycle ratio; X = MLSS = (1.40)(MLVSS)

From Prob. 6-35, $Q_r = 0.0214$ m^3/s and then

$$r = \frac{Q_r}{Q} = \frac{0.0214}{0.0796} = 0.2688$$

So

$$SL = \frac{(1+0.2668)(0.0796)(1.40)(1500)(86400)}{(402.12)(1000)} = \frac{1.833\times10^7}{4.021\times10^5} = 45.57\,kg/m^2\cdot d$$

Checking with Figure 6-28, we find this is much less than the 253 kg/m^2-d allowed.

d. Weir loading

$$WL = \frac{(0.0796m^3/s)(86400\,s/d)}{\pi(16.0m)(2\tan ks)} = 68.4\,m^3/d\cdot m$$

This is less than the design standard of 125 m^3/d-m to 250 m^3/d-m.

6-46 Diameter of single stage rock filter

Given: Applied BOD_5 = 125 mg/L, effluent BOD_5 = 25 mg/L, Q = 0.14 m^3/s, R = 12.0 and depth = 1.83 m. Assume NRC equations apply and the wastewater temperature is 20 °C. NOTE: In the first printing of the 3rd edition, a hydraulic loading rate rather than the flow rate was given and no temperature was given.

Solution:

a. Calculate E_1

$$E_1 = \frac{125 - 25}{125} = 0.80$$

b. Calculate recirculation factor

$$F = \frac{1 + 12.0}{[1 + 0.1(12.0)]^2} = 2.686$$

c. Solve Eqn 6-39 for volume

$$0.80 = \frac{1}{1 + 4.12\left(\frac{(0.14)(125)}{V(2.686)}\right)^{0.5}}$$

$$0.80 = \frac{1}{1 + 4.12(2.5525)\left(\frac{1}{V}\right)^{0.5}} = \frac{1}{1 + 10.5163\left(\frac{1}{V}\right)^{0.5}}$$

$$0.80\left[1 + 10.5163\left(\frac{1}{V}\right)^{0.5}\right] = 1$$

$$10.5613\left(\frac{1}{V}\right)^{0.5} = \frac{1}{0.80} - 1 = 0.25$$

$$\left(\frac{1}{V}\right)^{0.5} = \frac{0.25}{10.5163} = 0.0238$$

$$\frac{1}{V} = (0.0238)^2 = 5.65 \times 10^{-4}$$

$$V = 1769.48\ \mathrm{m}^3$$

d. The area of the filter is then

$$A = \frac{1769.48\mathrm{m}^3}{1.83\mathrm{m}} = 966.93\mathrm{m}^2$$

e. The diameter of the filter is

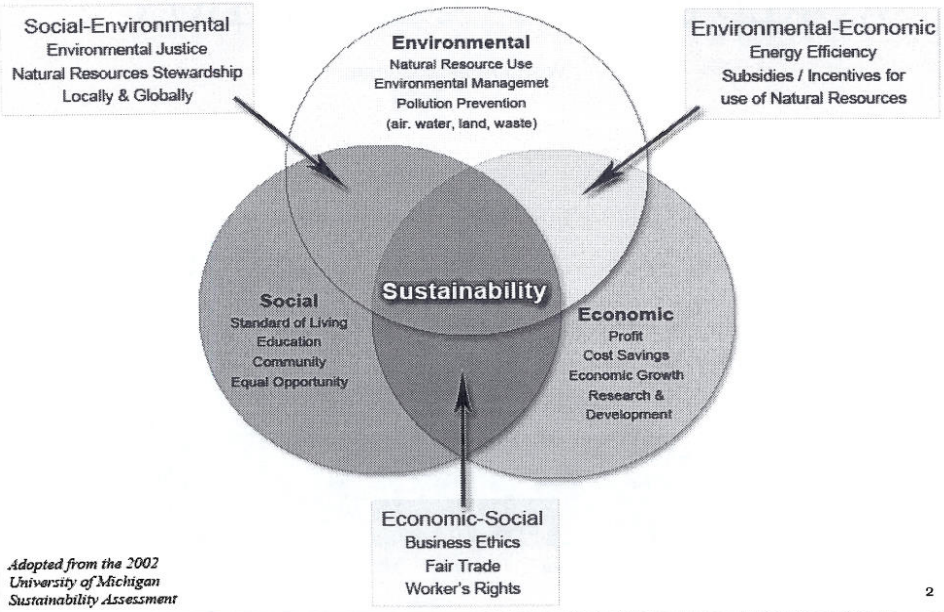
$$\frac{\pi D^2}{4} = 966.93\mathrm{m}^2$$

$$D = \left[\frac{(966.93\mathrm{m}^2)(4)}{\pi}\right]^{0.5} = 35\mathrm{m}$$

Presented by:
Suruchi Verma and Bhaskar Kura

PROMOTING SUSTAINABILITY: LFG-TO-ENERGY?

The Three Spheres of Sustainability



Social-Environmental
Environmental Justice
Natural Resources Stewardship
Locally & Globally

Environmental
Natural Resource Use
Environmental Managemet
Pollution Prevention
(air, water, land, waste)

Environmental-Economic
Energy Efficiency
Subsidies / Incentives for
use of Natural Resources

Social
Standard of Living
Education
Community
Equal Opportunity

Sustainability

Economic
Profit
Cost Savings
Economic Growth
Research &
Development

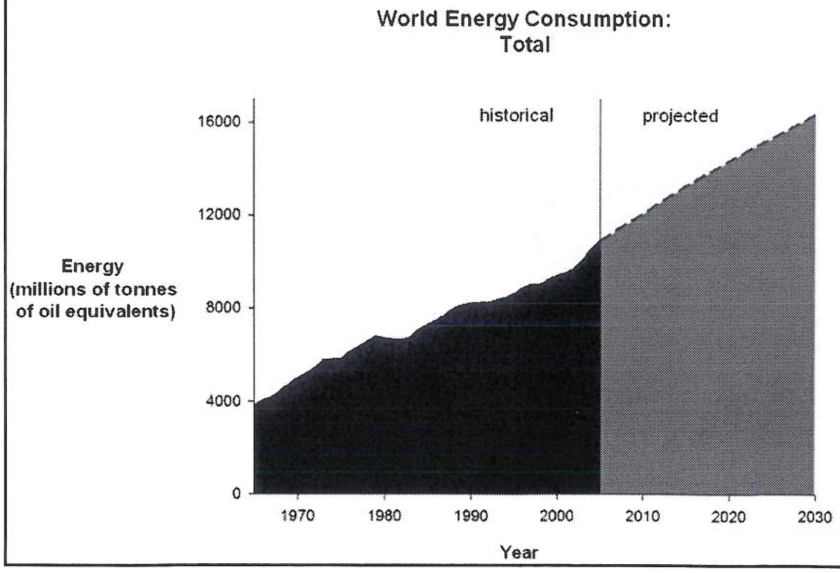
Economic-Social
Business Ethics
Fair Trade
Worker's Rights

Adopted from the 2002
University of Michigan
Sustainability Assessment

INTRODUCTION

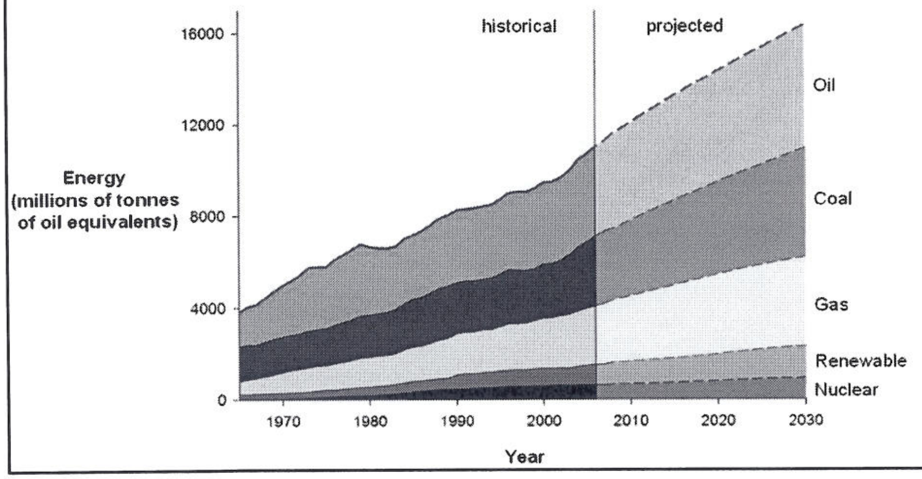
- 80% of U.S. residents were living in urban environments in 2000 and that proportion is continuing to grow.
- Buildings account for more than 40 percent of total energy consumption.
- About 93% of the energy consumed in the United States comes from non-renewable energy sources, which include uranium ore and the fossil fuels — coal, natural gas, and petroleum.

WORLD ENERGY CONSUMPTION

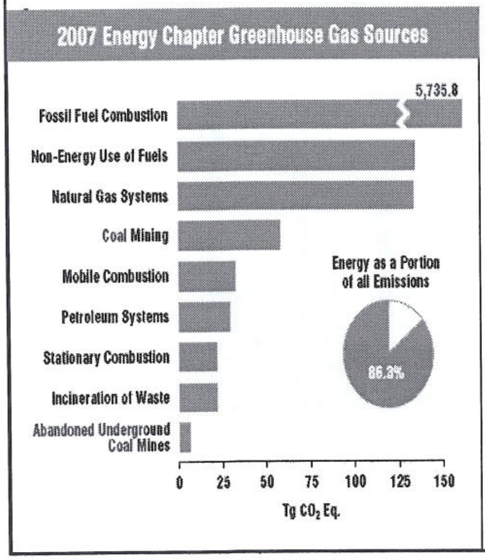


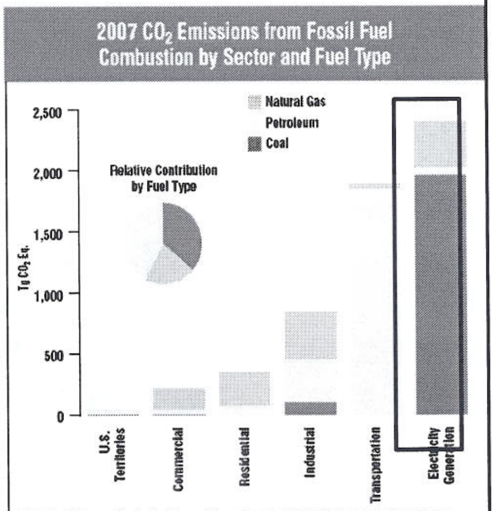
ENERGY SOURCES

Energy Demand by Fuel Type

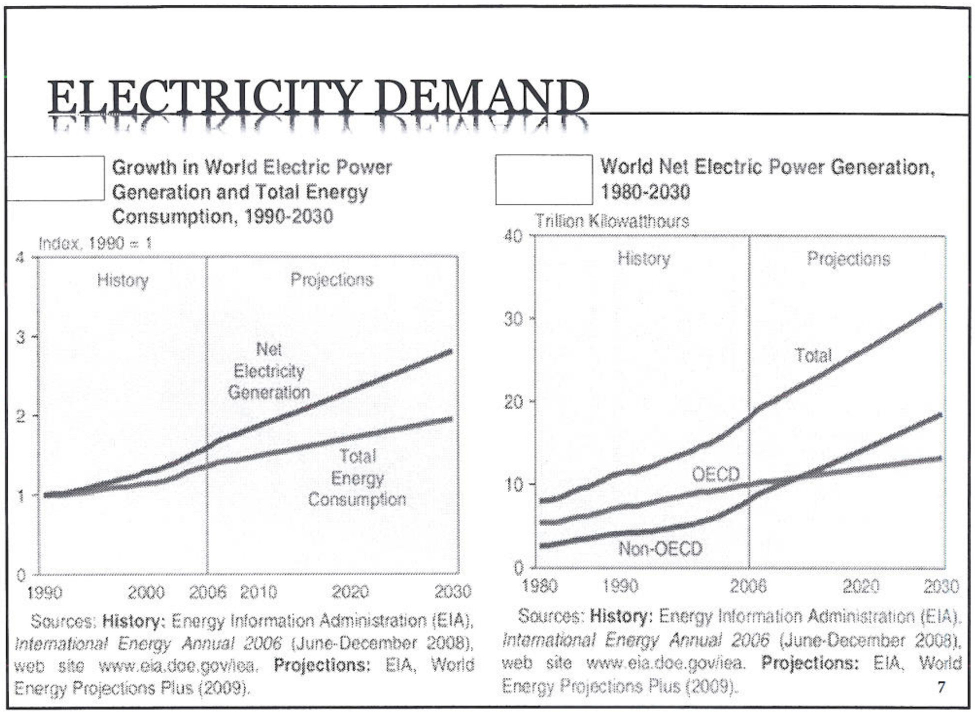


GHG SOURCES – ENERGY & ELECTRICITY


2007 Energy Chapter Greenhouse Gas Sources


2007 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.



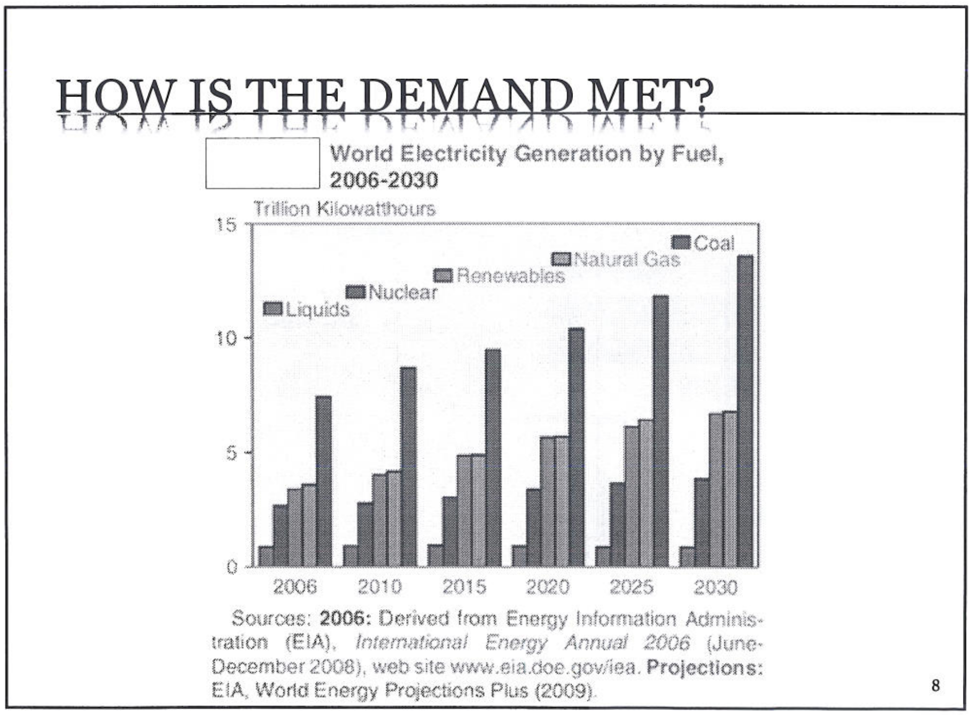
ELECTRICITY DEMAND

Growth in World Electric Power Generation and Total Energy Consumption, 1990-2030

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2006* (June-December 2008), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2009).

World Net Electric Power Generation, 1980-2030

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2006* (June-December 2008), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2009).



HOW IS THE DEMAND MET?

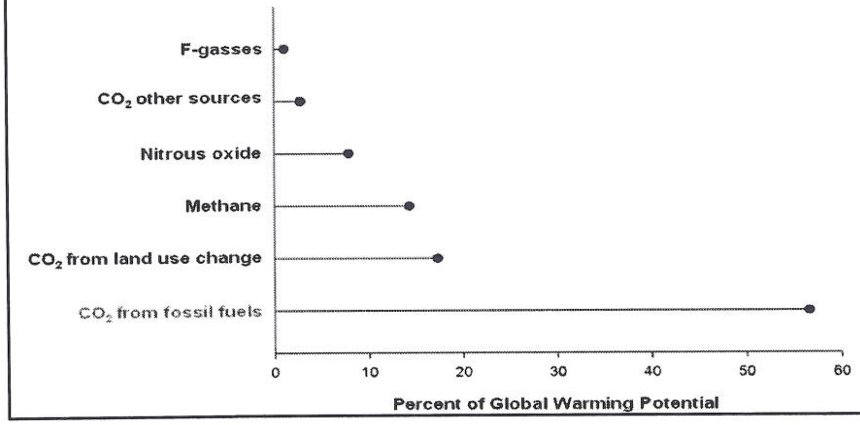
World Electricity Generation by Fuel, 2006-2030

Sources: **2006:** Derived from Energy Information Administration (EIA), *International Energy Annual 2006* (June-December 2008), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2009).

CLIMATE CHANGE DUE TO FOSSIL FUELS

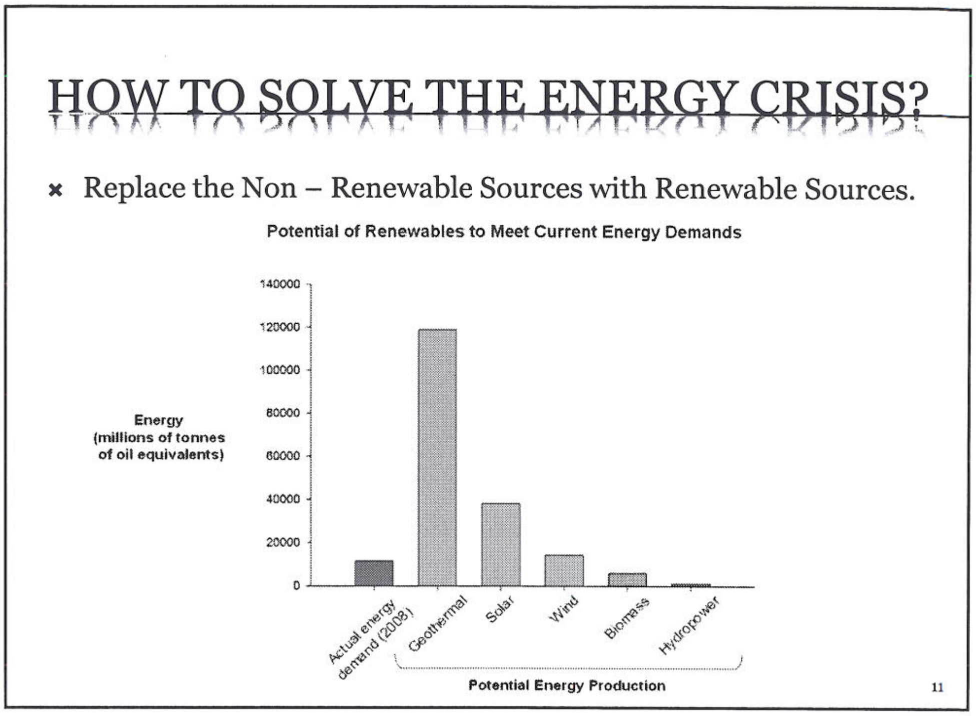
Fossil fuel combustion accounts for 62% of the global warming potential of all anthropogenic greenhouse gases.

Contribution of Fossil Fuels to Climate Change



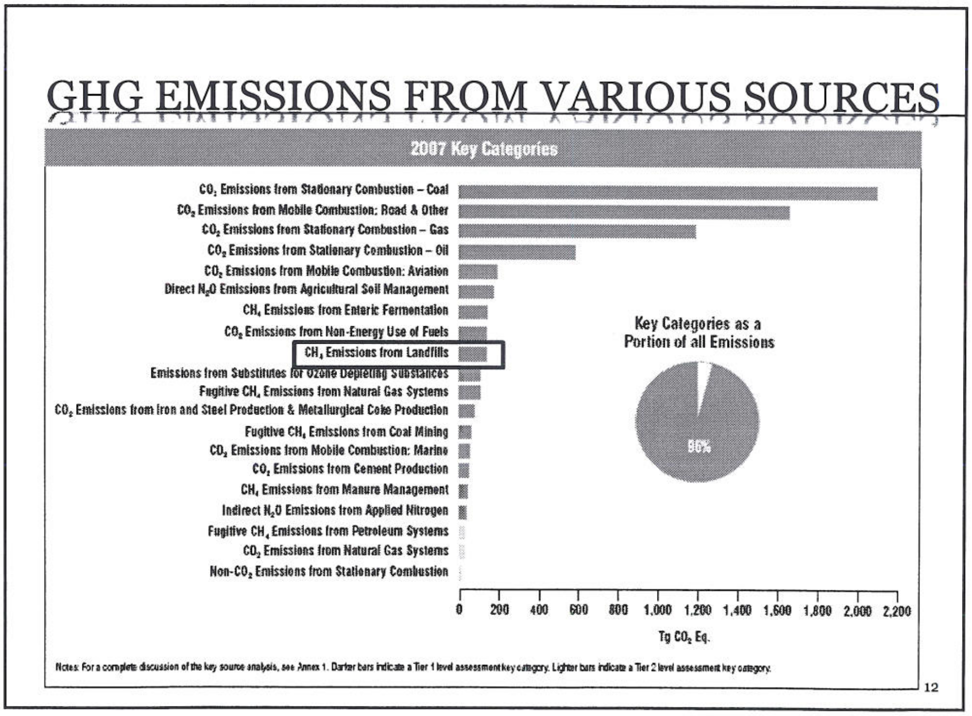
GREENHOUSE GAS EQUIVALENTS

- 25,000 metric tons CO_{2e} =
  - 1/6th of annual GHG from an average size landfill
  - 1/100th annual CO_2 from a coal fired power plant
  - 131 railcars' worth of coal CO_2
  - 3,467 homes annual *electricity* use CO_2
  - 2,275 homes annual *energy* use CO_2
  - 4,579 passenger vehicles' annual GHG



HOW TO SOLVE THE ENERGY CRISIS?

- Replace the Non – Renewable Sources with Renewable Sources.



GHG EMISSIONS FROM VARIOUS SOURCES

Notes: For a complete discussion of the key source analysis, see Annex 1. Darker bars indicate a Tier 1 level assessment key category. Lighter bars indicate a Tier 2 level assessment key category.

LANDFILLS

- Landfills are the second largest man made source of methane emissions.

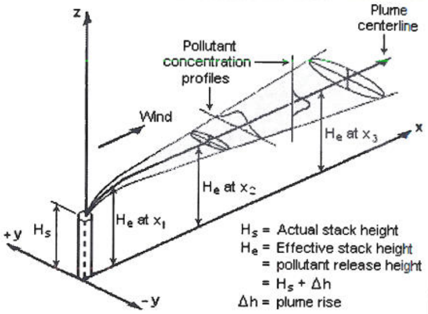
- Municipal Solid Waste Landfills receive
  - household waste,
  - non-hazardous sludge,
  - industrial solid waste, and
  - construction and demolition debris.

LANDFILL GASES

- Landfill gas (LFG) is a by-product of the anaerobic decomposition of municipal solid waste (MSW):
  - ~50% methane (CH_4)
  - ~50% carbon dioxide (CO_2)
  - <1% non-methane organic compounds (NMOCs) Gas Collection System

- Methane is **21 times** potent than Carbon dioxide for global warming.

GAUSSIAN DISPERSION MODEL



- **C**= steady-state concentration at a point (x,y,z), gm/m³
- **Q**= emission rate, gm/s
- **z**= vertical distance from ground level, m
- **y**= horizontal distance from plume centerline, m
- **u**= average wind speed at the physical stack height, m/s
- $\boldsymbol{\sigma_y}$, $\boldsymbol{\sigma_z}$ = horizontal and vertical dispersion coefficients (in m) which are function of distance x and atmospheric stability
- $\mathbf{H_e}$= effective stack height [physical stack height (h) + plume rise (h)], m

$$C=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-H_e)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H_e)^2}{2\sigma_z^2}\right)\right\}$$

15

INVERSE DISPERSION METHOD

$$C_{i,j} = f(x,y)_{i,j} * Q_j$$

Generally, we know Q and F. So, we can compute C. Here, we know C and F. Hence we invert F to compute Q.

$$\mathbf{q} = \mathbf{F}^{-1}\mathbf{c}_{\mathbf{measured}}$$

F is not a square matrix, so we perform the following to invert it.

$$\mathbf{F}^{+} = \left(\mathbf{F}^{\mathrm{T}}\mathbf{F}\right)^{-1}\mathbf{F}^{\mathrm{T}}$$

16

LFG TO ENERGY

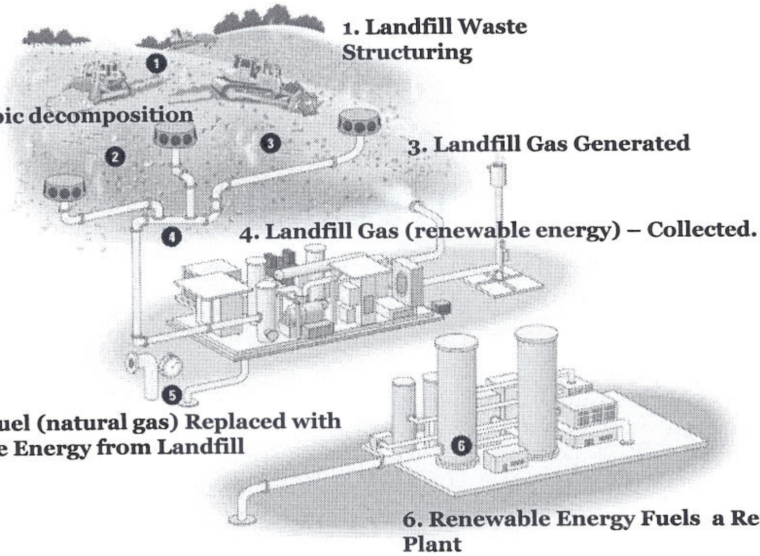
- The gases produced within the landfill can be collected and flared off or used to produce heat or electricity.
- For every 1million tons of MSW:
  - ~0.8 megawatts (MW) of electricity
  - ~432,000 cubic feet per day of LFG

Diversity of Project Types (Electricity Generation):

- Internal Combustion Engine (Range: 100kW to 3 MW)
- Gas Turbine (Range: 800kW to 10.5 MW)
- Microturbine (Range: 30kW to 250kW)

The gas can then be used as a power source.

THE COMPLETE PROCESS



1. Landfill Waste Structuring

2. Anaerobic decomposition of MSW

3. Landfill Gas Generated

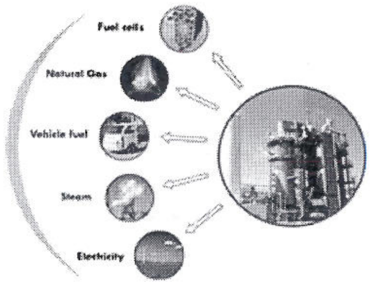
4. Landfill Gas (renewable energy) – Collected.

5. Fossil Fuel (natural gas) Replaced with Renewable Energy from Landfill

6. Renewable Energy Fuels a Remote Plant

USES OF LFG TO ENERGY

- **Direct Use:** Directly use LFG to offset another Fuel. This direct use of LFG can be in a boiler, dryer, kiln, greenhouse, or other thermal application or for evaporation of leachate.
- **Cogeneration:** LFG generate can both electricity and thermal energy in the form of hot water or steam
- **Alternate Fuels :**Natural gas, High Btu or Medium Btu



THANKS!

Donald Jerolleman | CHAP 6

$\frac{40}{40}$

6-32) $\Theta = 7(30)(4.3)(2_{\text{TANKS}})\left(\frac{1}{0.0796}\right) = 22688\text{ s} = \underline{6.3\text{ hrs}}$

$\frac{F}{M} = \frac{0.0796(86400)(130)}{1806(1500)} = \underline{0.33\ \text{mg/mg}\cdot\text{day}}$

10

$SV_1 = \frac{270\ (1000\ \text{mg/g})}{1.4(15000)} = \underline{109.5\ \text{mL/g}}$

$x_f = \frac{10^6}{109.5} = \boxed{9132\ \text{mg/L}}$

6-35) $6.3\text{ hr} \rightarrow 0.2625\text{ d}$ $\qquad 1500 = \frac{\Theta_c\ (0.4)(130-5)}{0.2625(1.04\,\Theta_c)} \rightarrow \Theta = \underline{11.5\text{d}}$

$Q_w = \frac{7(3)(4.3)(2)}{11.4964\text{d}} = 15.7093\ \text{m}^3/\text{d} = 0.000182\ \text{m}^3/\text{s}$

10

$X' = 1.4(1500) = 2100\ \text{mg/L}$
$X_f' = 9132.42\ \text{mg/L}$
$Q = 0.0796\ \text{m}^3/\text{s}$
$Q_r = \frac{0.0796(2100) - 0.00182(9132.42)}{9132.42 - 2100} = 0.021406\ \text{m}^3/\text{s}$

6-38) $V_0 = \frac{0.0796(86400)}{\pi\ (8^2)(2_{\text{TANKS}})} = \underline{17.1\ \text{m/d}}$

$SL = \frac{1.2668(0.0796)(1.4)(1500)(86400)}{402.12\ (1000)} = \underline{45.5\ \text{kg/m}^2\text{d}}$

10

$wL = \frac{0.0796\ (86400)}{\pi(16)(2)} = \underline{68.4112\ \text{m}^3/\text{d}\,\text{m}} < 125\text{-}250$

6-46) $E_1 = \frac{100}{125} = 0.8$ $\qquad F = \frac{13}{2.2^2} = 2.69$

$0.8 = \frac{1}{5.12\left[\frac{0.14(125)}{V(2.646)}\right]^{1/2}} \rightarrow V = \underline{1769\ \text{m}^3}$

$A = \frac{1769.}{1.83} = 967\ \text{m}^2$

10

$\text{diameter} = \left(\frac{967(4)}{\pi}\right)^{1/2} = 35\ \text{m}$

Donald Scrolleman

Solid Waste Characteristics
(With correct BTU values)

Component	Weight %	Moisture %	Inert %	Energy BTU/lb	Moisture lb	Dry Waste lb	Inert Res. lb	Discarded BTU	Dry Basis BTU	Dry and Excluding Residue BTU
Food Wastes										
Paper										
Cardboard										
Plastics										
Yard Wastes										
Wood										
Glass										
Metal										
Total	**0**				**0.00**	**0.00**	**0.00**	**0**	**0**	**0**

Avg. Moisture Content (%)
Avg. Inert Residue (%)

Avg. BTU/100 lb; (Dry Basis) (BTU/100 lb As Discarded) * (100 / (100-Moisture %))
0

Avg. BTU/100 lb; (Dry Basis Excluding Inert) BTU/lb As Discarded * (100 / (100 - Moisture % - Inert Residue %)
0

Solid Waste Characteristics
(With correct BTU values)

Component	Weight %	Moisture %	Inert %	Energy BTU/lb	Moisture lb	Dry Waste lb	Inert Res. lb	Discarded BTU	Dry Basis BTU	Dry and Excluding Residue BTU
Food Wastes	15	75	5	2500	11.25	3.75	0.75	37500	150000	187500
Paper	35	5	5	7500	1.75	33.25	1.75	262500	276316	291667
Cardboard	5	5	5	6500	0.25	4.75	0.25	32500	34211	36111
Plastics	5	2	15	15000	0.10	4.90	0.75	75000	76531	90361
Yard Wastes	20	70	5	4000	14.00	6.00	1.00	80000	266667	320000
Wood	2	25	2	8000	0.50	1.50	0.04	16000	21333	21918
Glass	10	2	90	75	0.20	9.80	9.00	750	765	9375
Metal	8	2	90	200	0.16	7.84	7.20	1600	1633	20000
Total	**100**				**28.21**	**71.79**	**20.74**	**505850**	**827455**	**976932**

Avg. Moisture Content (%) 28.21
Avg. Inert Residue (%) 20.74

Avg. BTU/100 lb; (Dry Basis) (BTU/100 lb As Discarded) * (100 / (100-Moisture %))
704625

Avg. BTU/100 lb; (Dry Basis Excluding Inert) BTU/lb As Discarded * (100 / (100 - Moisture % - Inert Residue %)
990891

28

ENCE 3323: Introduction to Environmental Engineering
Spring 2009; Test 3
Part II: Long/Design Questions
Time: 1 hr 45 Minutes (1.00 – 2.45 PM); Total Points: 60

Note: Answer any five questions. Open book/open notes. Some questions are straight from the chapter-end listing/example problems but may have different data, so please read carefully! Please return the question paper with your answer sheet.

NAME: JEREMY PAGUADA

1. Calculate the volume of an aeration tank of an activated sludge plant for the following data:

Average flow	-	$0.0978\ m^3/s$
BOD Average	-	93.16 mg/l
Effluent soluble BOD desired	-	11.1 mg/l
K_s	-	100 mg/l
k_d	-	$0.05\ d^{-1}$
μ_m	-	$2.5\ d^{-1}$
Y, yield coefficient	-	0.5 mg VSS/mg BOD_5
MLVSS	-	2000 mg/l

2. A lagoon having three cells, each $110{,}000\ m^2$ in area, a minimum operating depth of 0.6 m, and a maximum operating depth of 1.5 m, receives $1{,}800\ m^3/d$ of wastewater having an average BOD_5 of 100 mg/l. What is the BOD_5 and loading and what is the detention time? If the first order kinetics and plug flow conditions apply with a rate constant of $0.3\ d^{-1}$ (k), calculate the expected effluent BOD_5.

3. Determine the diameter of a single-stage, rock media filter (Trickling Filter) to reduce an applied BOD_5 of 125 mg/l to 25 mg/l. Use a hydraulic loading rate of $14\ m^3/(m^2.d)$, a recirculation ratio of 12.0, and a filter depth of 1.83 m. Assume NRC equation apply and that the wastewater temperature is 20 ^{0}C.

4. Calculate the efficiency of removal of a 7 μm diameter particle having a density of $1{,}250\ kg/m^3$ in a cyclone with 0.4 m barrel diameter. The gas flow rate is $2.8\ m^3/s$ and the gas temperature is 25 °C. Give the cyclone design dimensions.

Cyclone D = 0.4 m
B = 0.25 x 0.4 = 0.1 m
H = 0.5 x 0.4 = 0.2 m
L1 = L2 = 2 x 0.4 = 0.8 m
De = 0.5 x 0.4 = 0.2 m
Dd = 0.25 x 0.4 = 0.1 m
L3 = 0.125 x 0.4 = 0.05 m

5. Determine the efficiency of an ESP for a particle of 80 μm in diameter having a drift velocity of 0.2 m/s. Collection plate height is 8 m, length is 5 m, and there are a total of 5 plates with a spacing of 0.3 m. Consider all sides of 5 plates (total of 10 sides) collecting particles. Gas flow rate is $23\ m^3/s$.

5. Write typical values of BOD_5, COD, SS, TDS of untreated domestic wastewater (range: weak to strong values). [4]

6. A two stage treatment system has two units, systems A and B in series. System A has 70% removal efficiency and System B has 90% removal efficiency for BOD reduction. What is the overall efficiency? [3]

7. Two wastewater treatment systems, System A and System B are in parallel with the following flow and efficiencies:

	System A	**System B**
Flow (percent of total):	30%	70%
BOD removal efficiency:	70%	90%

Estimate the overall combined BOD removal efficiency. [3]

8. Define "criteria pollutants" and list them. [2]

9. Define "emission factor" and give two examples. [2]

10. Define atmospheric inversion and illustrate with DALR and ELR using temperature on x-axis and altitude on y-axis. [2]

Project Title: ______________________________

Subject: ____________________ Job No: __________

By: _______ Date: _______ Checked By: _______ Date: _______

EUSTIS
Metairie, Louisiana
Lafayette, Louisiana
Gulfport, Mississippi

Page: __________

Reason for deduction?

$\frac{74}{100}$

$\frac{90}{100}$ → $\frac{80}{100}$

Donald Jerolleman
Intro. to Environmental Engineering
Spring 2010
Lab 1: Air Quality - Particle Types, Concentration, and Sizes

$\frac{74}{80} \approx 92.5\%$

Objective:

Our experiment will take an air sample during the process of cutting masonry block and indentify the concentrations, types, and size of some of the dust particles present. The particles tested for are heavy metals which include, transition metals, metalloids, lanthanides, and actinides (also called toxic metals). The data will then be used to create a particle size distribution (PSD) chart, mass of pollutant chart, particle size (ECD) verse cumulative percent less than size range graphs, and particle size (ECD) verse mass of pollutant graphs.

Equipment Used:

10

- Innovex X-Ray Fluorescence Spectrometer
- Laptop and Spectrometer Software
- Masonry Block
- Masonry Circular Saw
- Small, Unventilated room
- Ambient Cascade Impactor

Procedure:

10

- Set up sample, saw, and Ambient Cascade Impactor
- Observe safety precautions for personnel (eg. masks, goggles, etc.)
- Cut sample while taking air samples (10 min)
- Clean up area to prevent possible exposure to individuals who may enter area later
- Carefully remove filters and fold in half twice to crate a cone look (this prevents loss of contaminants
- Carry out X-ray analysis (5-8 times per filter)
- Log data and perform calculation

Discussion:

Based on the results, the particles are composed of very dangerous metals. The highest concentrations appear to be Zn (Zinc - by far the largest), Ba (Barium), and Fe (Iron) respectively.

6

Unfortunately, I do not have the knowledge or the information to make any claims as to the risks posed by these concentrations found.

+4

10

Stage	Size Range	Initial Weight (g)	Final Weight (g)	Net Weight (g)	% in size Range	Cumulative % Less than size range	ECD (µm)
Pre-Separator	10 & above					100%	10
0	9 -10	0.307	0.418	0.111	70.70%	29%	9
1	5.8 - 9	0.335	0.339	0.004	2.55%	27%	5.8
2	4.7 - 5.8	0.336	0.345	0.009	5.73%	21%	4.7
3	3.3 - 4.7	0.335	0.349	0.014	8.92%	12%	3.3
4	2.1 - 3.3	0.333	0.341	0.008	5.10%	7%	2.1
5	1.1 -2.1	0.331	0.336	0.005	3.18%	4%	1.1
6	0.7 - 1.1	0.336	0.339	0.003	1.91%	2%	0.7
7	0.4 - 0.7	0.31	0.313	0.003	1.91%	0%	0.4
			SUM:	0.157	100.00%		

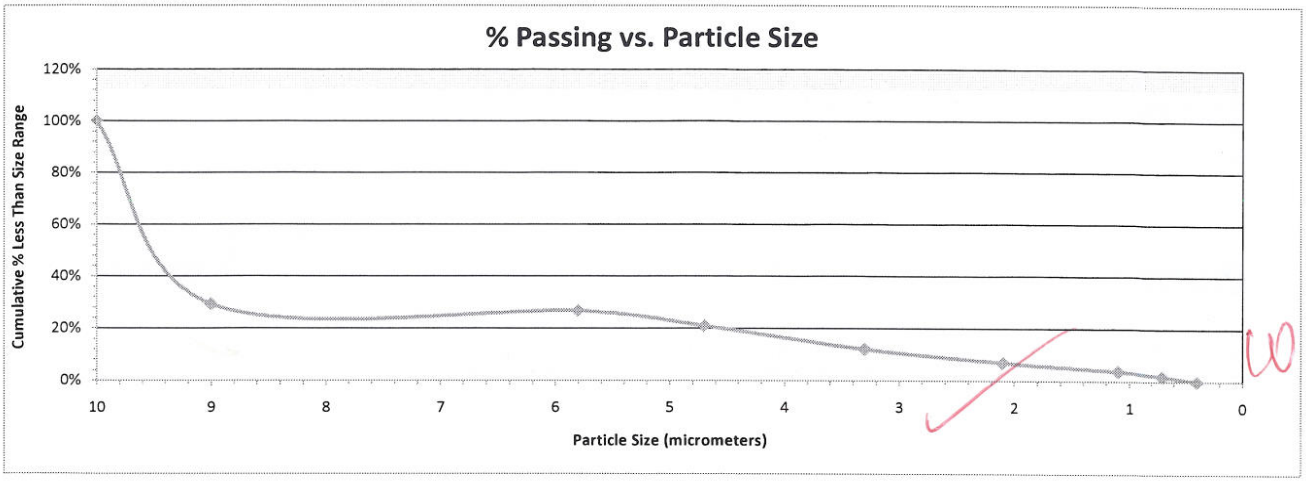
Miscellaneous Notes		
Run Time	:	10 min
Dia. of filter (cm)	:	9.5
Area (sq.cm.)	:	70.88
1/4 of A (sq.cm.)	:	17.72

Microgram per sq.cm.		Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
Filter 1	avg	16.54	0.60	1.87	6.79	16.89	0.88	1.97	54.85	1.01	2.96
Filter 2	avg	19.14	0.60	0.64	2.72	9.44	0.74	1.64	62.14	0.69	2.46
Filter 3	avg	18.75	0.47	0.00	1.10	6.49	0.58	1.61	61.22	0.55	2.18
Filter 4	avg	19.03	0.54	0.00	1.39	7.21	0.53	1.58	60.38	0.61	2.26
Filter 5	avg	19.60	0.52	0.00	0.86	6.04	0.53	1.55	61.63	0.54	2.09
Filter 6	avg	20.32	0.46	0.00	0.51	5.91	0.56	1.51	62.85	0.59	2.14
Filter 7	avg	20.70	0.49	0.00	0.00	4.45	0.00	1.59	62.78	0.49	2.07
Filter 8	avg	18.79	0.53	0.00	0.00	4.61	0.67	1.50	62.39	0.54	2.12
Mass of Pollutant	**in µg**	**Ba**	**Pb**	**Co**	**Cu**	**Fe**	**Mn**	**Mo**	**Zn**	**Rb**	**Sr**
Filter 1	avg	293.1	10.6	33.1	120.3	299.3	15.6	34.9	972.0	17.9	52.5
Filter 2	avg	339.2	10.6	11.3	48.2	167.3	13.1	29.1	1101.2	12.2	43.6
Filter 3	avg	332.3	8.3	0.0	19.5	115.0	10.3	28.5	1084.9	9.7	38.6
Filter 4	avg	337.2	9.6	0.0	24.6	127.8	9.4	28.0	1070.0	10.8	40.0
Filter 5	avg	347.3	9.2	0.0	15.2	107.0	9.4	27.5	1092.1	9.6	37.0
Filter 6	avg	360.1	8.2	0.0	9.0	104.7	9.9	26.8	1113.7	10.5	37.9
Filter 7	avg	366.8	8.7	0.0	0.0	78.9	0.0	28.2	1112.5	8.7	36.7
Filter 8	avg	333.0	9.4	0.0	0.0	81.7	11.9	26.6	1105.6	9.6	37.6
	Sum	2708.9	74.6	44.5	236.9	1081.7	79.6	229.5	8651.9	89.0	323.9

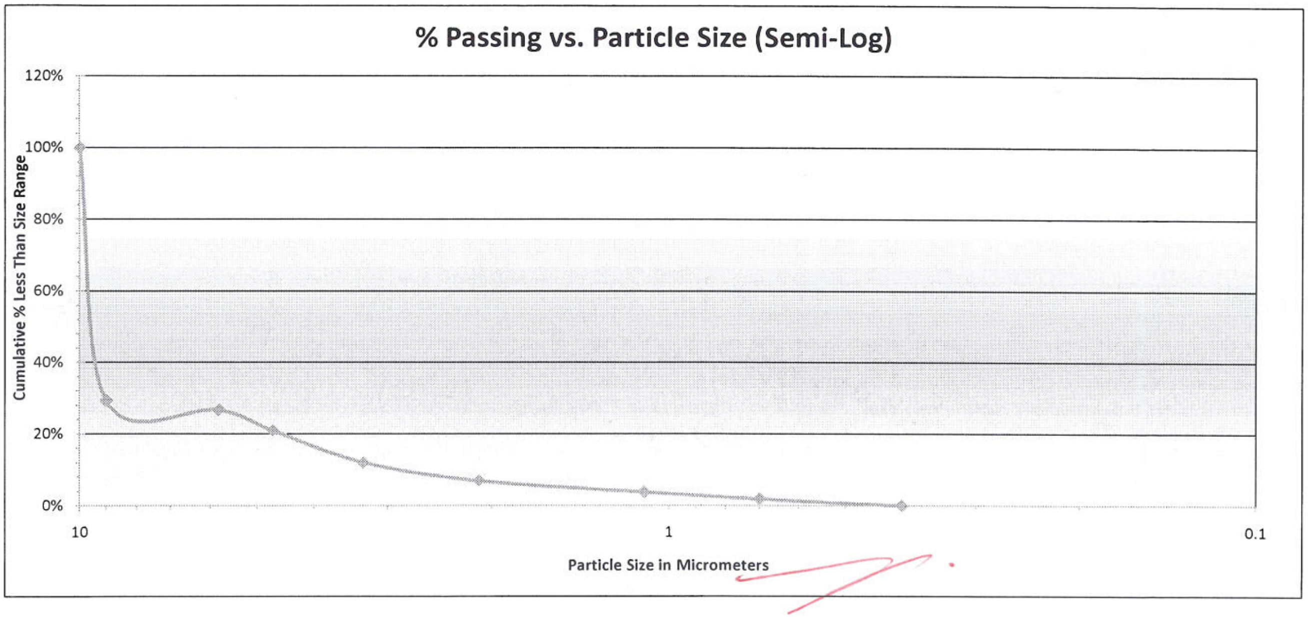
10

10

Emission Rates => ? . Table (-10)


% Passing vs. Particle Size
Cumulative % Less Than Size Range
120%
100%
80%
60%
40%
20%
0%
10
9
8
7
6
5
4
3
2
1
0
Particle Size (micrometers)

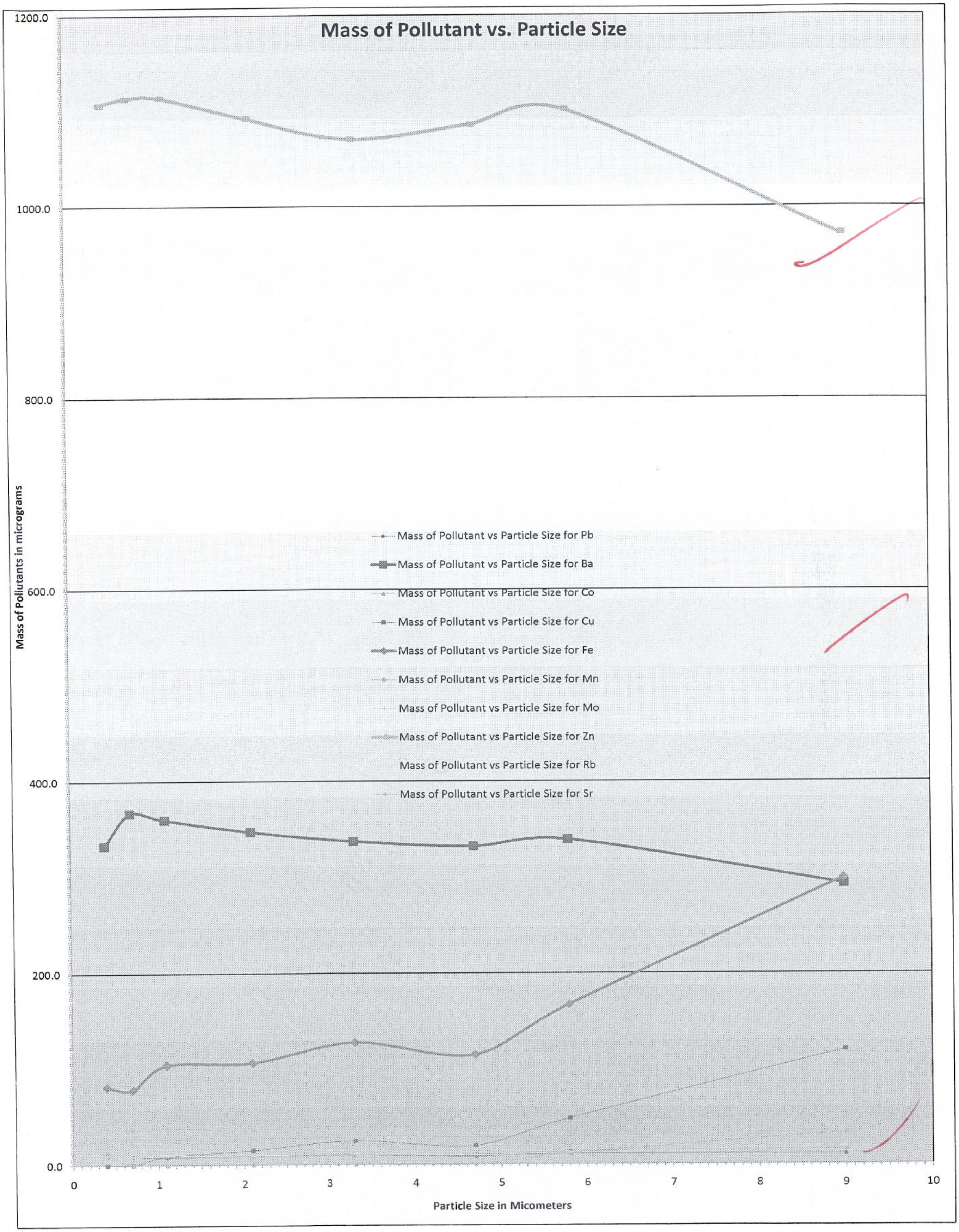
10


% Passing vs. Particle Size (Semi-Log)
Cumulative % Less Than Size Range
120%
100%
80%
60%
40%
20%
0%
10
1
0.1
Particle Size in Micrometers

8

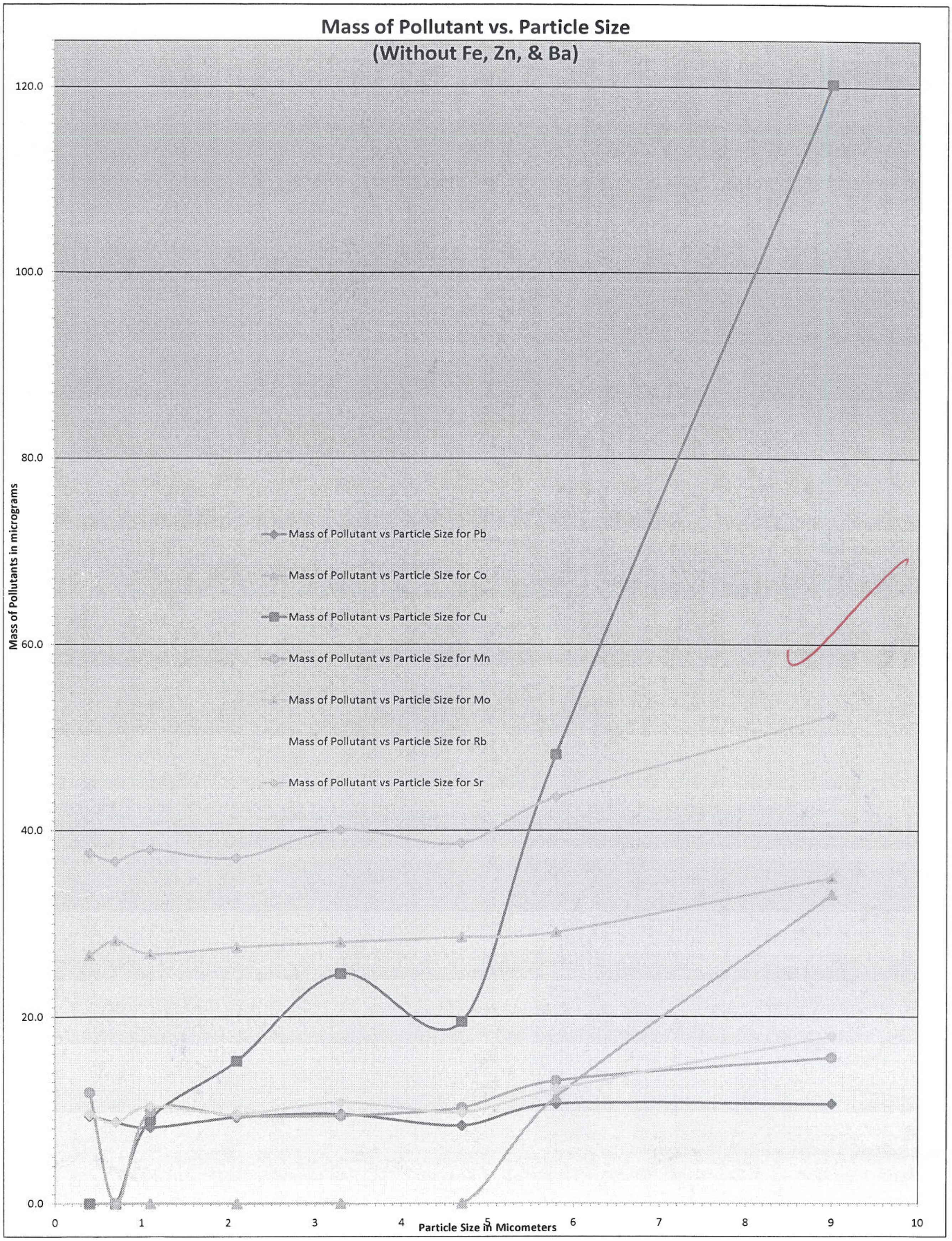
+2

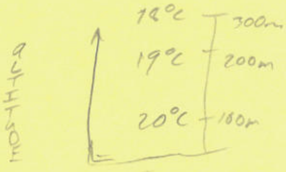
log?


Mass of Pollutant vs. Particle Size
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Mass of Pollutants in micrograms
0
1
2
3
4
5
6
7
8
9
10
Particle Size in Micometers
Mass of Pollutant vs Particle Size for Pb
Mass of Pollutant vs Particle Size for Ba
Mass of Pollutant vs Particle Size for Co
Mass of Pollutant vs Particle Size for Cu
Mass of Pollutant vs Particle Size for Fe
Mass of Pollutant vs Particle Size for Mn
Mass of Pollutant vs Particle Size for Mo
Mass of Pollutant vs Particle Size for Zn
Mass of Pollutant vs Particle Size for Rb
Mass of Pollutant vs Particle Size for Sr

10

Sample Calculation?





$\approx \frac{1°C}{100m}$

Air Pollution

Sources < natural / manmade

Class. of Areas - Ambient (EPA) / state Agencies
- Indoors (Resedential / Commercial)
- Occupational / workspace (OSHA) Tend to be high pollution level

Attainment

Non-Attainment
- Area does not meet NAAQS
- AKA violating the limit

NATIONAL AMBIENT AIR QUALITY STANDARDS (NAAQS)

CRITERIA POLLUTANTS
- Those that have NAAQS
- PM_{10} / $PM_{2.5}$; SO_2 , NO_x ; CO, Particulate Pb , O_3
  - NAAQS → Concentration limits $\left[\frac{\mu g}{m^3}\right]$ or [ppm]

particulate matter

Hazardous Air Pollutants (HAPs)
- No National Air quality standards b/c there is no safe limit (goal is none)

$PV = nrT$ $\qquad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

SO_2 $\qquad \frac{\mu g \text{ (mass)}}{m^3 \text{ (vol)}} \xrightarrow{\text{convert}} \frac{Vol}{10^6 Vol}$ SO_2 ppm

1 gram-mole → 22.4 liters

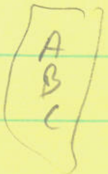
SO_2 → 64g → 22.4 liters

64 kg → 22.4 m^3

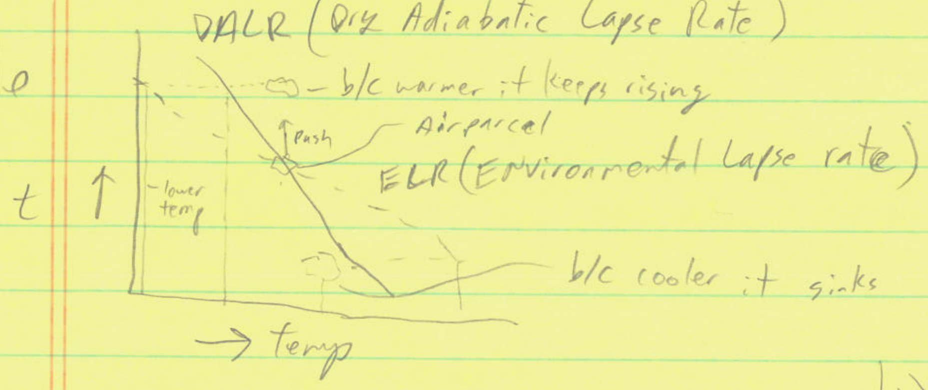
Mass Emisson Risk → $\frac{\text{ton } SO_2}{yr}$ [Air Permit]

- Nat Amb. Air Quality Standards Averaging time 9.5 in book

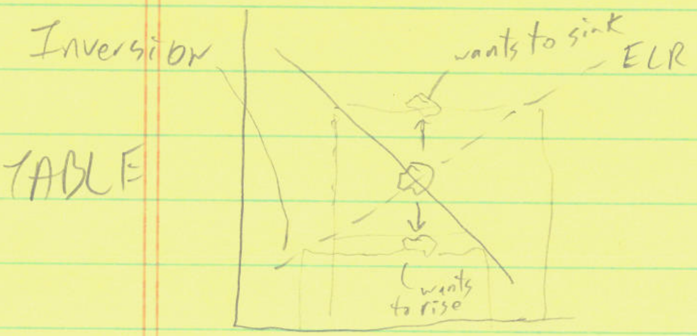
Pascel Classifications



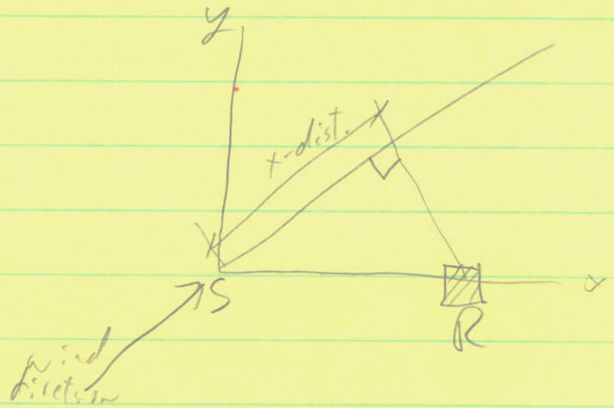
UNSTABLE



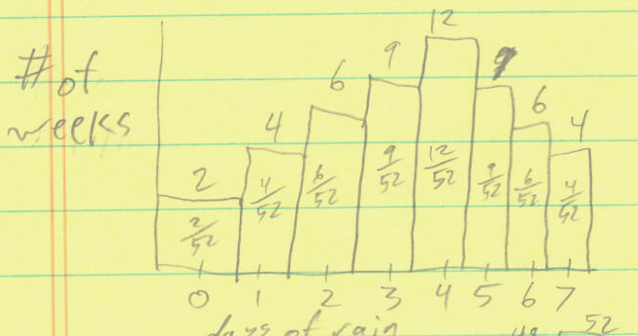
STABLE



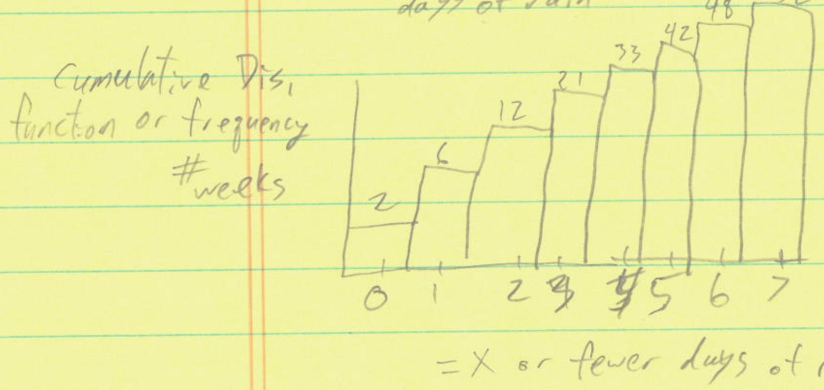
Gaussian Model

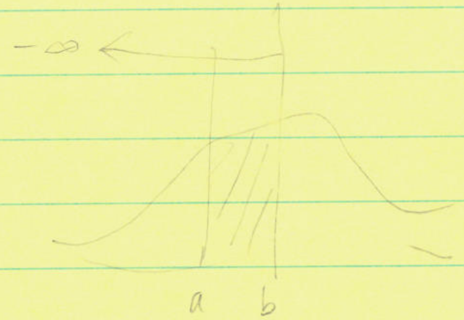


frequency of occur of frequency distribution



$P(x=3) = \frac{9}{52}$





CDF most useful form of analysis

Moments of a Distribution

Discrete : $M^{r}_{a/b\,a} = \Sigma(x_i - a)\, P(x_i)$

Continuous : $M^{r}_{a} = \int (x-a)^{r} f(x)\,dx$

Discrete $M^{1}_{0} = \sum_{-\infty}^{\infty} (x_i)(P(x_i)) = \mu\,(\text{mean}) = E(x)$ (expected value)

Continuous $M^{1}_{0} = \int_{-\infty}^{\infty} x\, f(x)\, dx = \mu = E(x)$

PDF

Second Moment a/b the mean $M^{2}_{\mu} = \Sigma(x_i - \mu)^2 P(x_i) = Var(x)$

$M^{2}_{\mu} = \int_{-\infty}^{\infty} (x-\mu) f(x)\, dx = Var(x)$

$E(x) = \Sigma x\, P(x)$

$E(x^2) = \Sigma x^2 P(x)$

$E(x) = \int x f(x) dx$

$E(x^2) = \int x^2 f(x) dx$

Problem 20.1

class

C

Gaussian Model $X = \left(\frac{E}{\pi S_y S_z u}\right) \exp\left(-\frac{1}{2}\left(\frac{y}{S_y}\right)^2\right) \exp\left(-\frac{1}{2}\left(\frac{H}{S_z}\right)^2\right)$

$H = 80m$ E (emission rate) $= 200\ g/s$ $u = 8\ m/s$

$X(1000, 0, 0) = ?$

concentration @ point $y=0$ $z=0$

$X(5000, 0, 0) = ?$

p. 592-3 charts for S_y, S_z

or eq. on p. 594 (Martin's Eq.)

$S_y = a\ x^{0.894}$
$S_z = c\ x^{d} + f$
x in kilometers

a, c, d, f p. 594-595

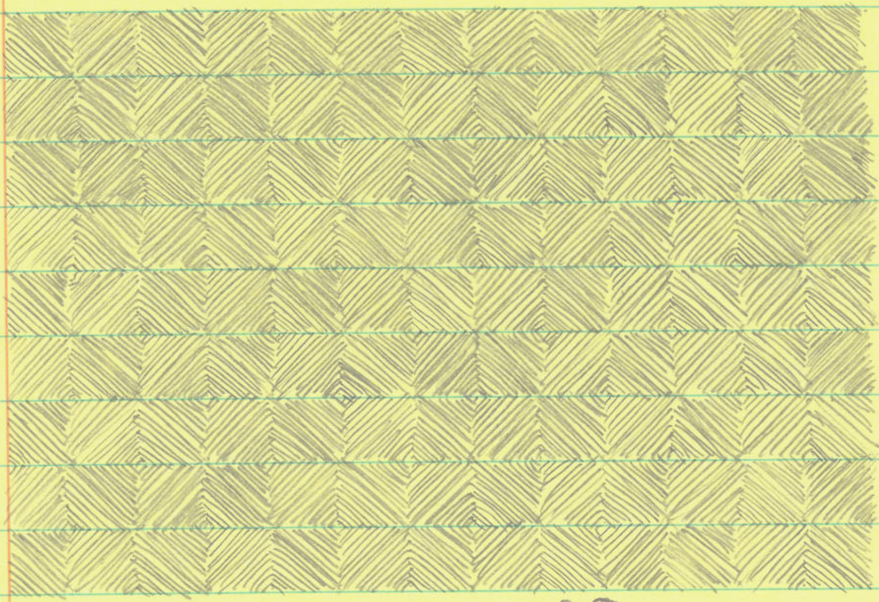
$X = 1000m$, stab C

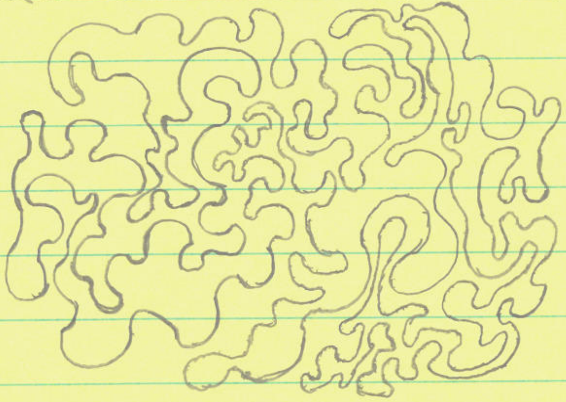
$\rightarrow S_y = 104_m$ $S_z = 61\ m$

$X_{(1000,0,0)} = 526\ \mu g/m^3$

$X = 5000m$, stab C $\rightarrow S_y = 438m$ $S_z = 264m$

$X_{(5000,0,0)} = 66\ \mu g/m^3$





Stage	Size Range	Initial Weight (g)	Final Weight (g)	Net Weight (g)	% in size Range	Cumulative % Lesstan size range	ECD (micrometers)
Pre- Seperator	10.0 & Above	-					10.0
0	9.0- 10.0	0.307	0.418	0.111			9.0
1	5.8-9.0	0.335	0.339	0.004			5.8
2	4.7-5.8	0.336	0.345	0.009			4.7
3	3.3-4.7	0.335	0.349	0.014			3.3
4	2.1-3.3	0.333	0.341	0.008			2.1
5	1.1-2.1	0.331	0.336	0.005			1.1
6	0.7-1.1	0.336	0.339	0.003			0.7
7	0.4-0.7	0.31	0.313	0.003		0	0.4
Back up Filter	0.0-0.4	-	SUM:	0.157			0.0

Time of Run = 10 minutes

		Barrium	Lead	Cobalt	Copper	Iron			Zinc		
		Ba	Pb	Co	Cu	Fe	Mn	Mo	Zn	Rb	Sr
FILTER 1	AVG	16.54	0.60	1.87	6.79	16.89	0.88	1.97	54.85	1.01	2.96
FILTER 2	AVG	19.14	0.60	0.64	2.72	9.44	0.74	1.64	62.14	0.69	2.46
FILTER 3	AVG	18.75	0.47		1.10	6.49	0.58	1.61	61.22	0.55	2.18
FILTER 4	AVG	19.03	0.54		1.39	7.21	0.53	1.58	60.38	0.61	2.26
FILTER 5	AVG	19.60	0.52		0.86	6.04	0.53	1.55	61.63	0.54	2.09
FILTER 6	AVG	20.32	0.46		0.51	5.91	0.56	1.51	62.85	0.59	2.14
FILTER 7	AVG	20.70	0.49			4.45		1.59	62.78	0.49	2.07
FILTER 8	AVG	18.79	0.53			4.61	0.67	1.50	62.39	0.54	2.12

Table 4 - mult. concentrations by Area of Filter to get mass of pollutants

Units: microgram per square centimeter

Diameter of filter = 9.5 centimeters

- Compute emission rate of each pollutant (t=10min)
- Plot PSD (Particle Sizedistribution) graphs

+ aslo on semi-log graph

- Plot Particle Size vs. mass of Pollutants (one line for ea. pollutant)

ENVIRON Apr 20

ISSUES

NPDES - National Pollutant Discharge Elimination System.
LDEQ - Louisiana Department of Environmental Quality
EPA - Eviromental Protection Agency
LPDES - Louisiana Pollutant Discharge Elimination System

Permit/
Contract

BOD - Biochemical Oxygen Demand
- suspended
- desolved

Chap 8 H.W.
32, 35, 38, 46

Know Trickling Filter
" Calc. size if E=80% Desired what should size be given other parameters
- what if 2 in series
Know mass balance of act$\overset{?}{i}$ve sluge
" sluge Volume index SVI
" Food / micro organism ratio

$$n=\frac{C_3}{C_1}=\frac{C_2-63}{C_2+1941}$$

$$n=\frac{C_2}{C_1}\quad n=\frac{C_3}{C_2}$$

$$C_2=C_1-1941$$

$$\frac{63}{n}=\frac{1941}{n}-1941$$

Power Point 1 - chap 1

AIR REGULATION

- New source performance standards (NSPS) [1970]
- Title V – Comprehensive air permit system
- National ambient air quality standards (NAAQS)
- Prevention of significant deterioration (PSD)
  - For attainment areas; to prevent rapid air quality degradation

$$n=\frac{C_2-63}{C_2}=1-\frac{63}{C_2}$$

$$n=\frac{(C_1-1941)-63}{C_1-1941}$$

$$=1-\frac{63}{C_1-1941}$$

$$n=\frac{C_1-1941}{C_1}$$

$$=1-\frac{1941}{C_1}$$

$$C_2=\frac{C_3}{n}$$

$$C_1-1941=\frac{C_2-63}{n}$$

$$C_1=\frac{C_2}{n}=\frac{C_1-1941}{n}$$

$$\frac{C_2-63}{n}+1941=\frac{C_1-1941}{n}$$

$$\cancel{C_1}-\cancel{1941}-63+1941n=\cancel{C_1}-\cancel{1941}$$

$$1941n=63$$

$$n=$$

- Water pollution control
  - BPT - Best practical treatment
  - BAT - Best available treatment
  - NPDES - National pollutant discharge elimination system
  - BCT - Best conventional treatment
- EPA's priority pollutant list (Table 1-6/Pg. 21)

$$1-\frac{63}{C_1-1941}=1-\frac{1941}{C_1}$$

$$\frac{63}{C_1-1941}=\frac{1941}{C_1}$$

Power Point 2 Mass Balance
(chap 2 part 1 of 2)

- Mass Balance Approach to Solving Environmental Engineering Problems

Conservation of mass

- Balance = Deposit - Withdrawal
- Accumulation = $\text{Input}_{(\text{eg mass})}$ - $\text{Output}_{(\text{eg mass})}$

Example Calculation of Mass

a. Flow

Mass = (Flow) (Density) (Time)
1 m^3/d = ? kg

Mass = (1 m^3/d) (1000 kg/m^3) (1 d)
= 1,000kg

Compounds in Water

Mass = (Concentration) (Volume)
1 mg/L in 1 m^3 = ? mg

Mass = (1 mg/L) (1 m^3) (1,000 L/m^3)
= 1,000mg

Verify That System "Closes" or Balances

Input of mass - Accumulation of Mass - Output of Mass = 0

"Rate" Means "Change With Respect to Time" so,

(Rate of Accumulation of Mass)
= (rate of Input of mass)
- (rate of Output of mass)

$$\frac{dM}{dT} = \frac{d(In)}{dT} - \frac{d(Out)}{dT}$$

Softening Water

a. Input $Ca(HCO_3)^2$
b. Reaction $CaCO_3$

Change of O_2 in Stream

a. Input → O_2
b. Microorganisms Use O_2 → CO_2

IN THESE INSTANCES, THE PREVIOUS EXPRESSION SHOWS ONLY THAT Ca(HCO3)2 OR O2 "DISAPPEARED"!

(Rate of Accumulation of Mass)
= (rate of Input of mass)
- (rate of Output of mass)
± (rate of Transformation)

- Time Dependent Reactions are called "**Kinetic Reactions**"
- "**Stoichiometric Reactions**" are those that have achieved equilibrium.

Transformation rate is described by the "Reaction Rate" (r)

$$\frac{dM}{dT} = \frac{d(In)}{dT} - \frac{d(Out)}{dT} \pm r$$

Reaction rate is function of

r = f (Temperature,
Pressure,
Reacting components
or Products)

Power Point 3 Mass Balance
(chap 2 part 2 of 2)

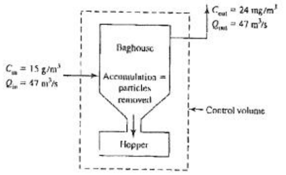
Efficiency

- Often removal of contaminants / pollutants is measured in terms of mass removal efficiency.
  - η (Eta) = [(mass in – mass out) / (mass in)] *100
  - $= [(C_{in} * Q_{in} - C_{out} * Q_{out}) / (C_{in} * Q_{in})] * 100$

Example 2-4. The air pollution control equipment on a municipal waste incinerator includes a fabric filter particle collector (known as a baghouse). The baghouse contains 424 cloth bags arranged in parallel, that is 1/424 of the flow goes through each bag. The gas flow rate into and out of the baghouse is 47 m^3/s, and the concentration of particles entering the baghouse is 15 g/m^3. In normal operation the baghouse particulate discharge meets the regulatory limit of 24 mg/m^3. During preventive maintenance replacement of the bags, one bag is inadvertently not replaced, so only 423 bags are in place.

Calculate the fraction of particulate matter removed and the efficiency of particulate removal when all 424 bags are in place and the emissions comply with the regulatory requirements. Estimate the mass emission rate when one of the bags is missing and recalculate the efficiency of the baghouse. Assume the efficiency for each individual bag is the same as the overall efficiency for the baghouse.

Solution. The mass balance diagram for the baghouse in normal operation is shown here.



In concentration and flow rate terms, the mass balance equation is

$$\frac{dM}{dt} = C_{in}Q_{in} - C_{out}Q_{out}$$

The mass rate of accumulation in the baghouse is

$$\frac{dM}{dt} = (15{,}000\ mg/m^3)(47\ m^3/s) - (24\ mg/m^3)(47\ m^3/s) = 703{,}872\ mg/s$$

The fraction of particulates removed is

$$\frac{703{,}872\ mg/s}{(15{,}000\ mg/m^3)(47\ mg/s)} = \frac{703{,}872\ mg/s}{705{,}000\ mg/s} = 0.9984$$

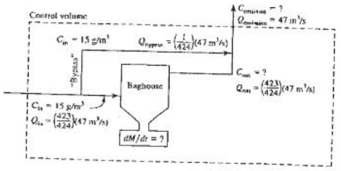
The efficiency of the baghouse is

$$\eta = \frac{15{,}000\ mg/m^3 - 24\ mg/m^3}{15{,}000\ mg/m^3}(100\%)$$
$$= 99.84\%$$

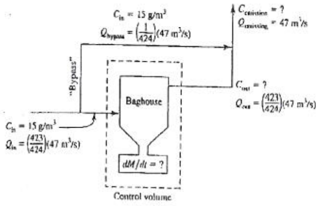
Note that the fraction of particulate matter removed is the decimal equivalent of the efficiency.

Note that the fraction of particulate matter removed is the decimal equivalent of the efficiency.

To determine the mass emission rate with one bag missing, we begin by drawing a mass balance diagram. Because one bag is missing, a portion of the flow (1/424 of Q_{out}) effectively bypasses the baghouse. The "Bypass" line around the baghouse is drawn to show this.



A judicious selection of the control volume aids in the solution of this problem. As shown in the diagram, a control volume around the overall baghouse and bypass flow yields three unknowns: the mass flow rate out of the baghouse, the rate of mass accumulation in the baghouse hopper, and the mass flow rate of the mixture. A control volume around the baghouse alone reduces the number of unknowns to two:



Because we know the efficiency and the influent mass flow rate, we can solve the mass balance equation for the mass flow rate out of the filter.

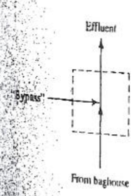
$$\eta = \frac{C_{in}Q_{in} - C_{out}Q_{out}}{C_{in}Q_{in}}$$

Solving for $C_{out}Q_{out}$

$$\begin{aligned} C_{out}Q_{out} &= (1 - \eta)C_{in}Q_{in} \\ &= (1 - 0.9984)(15{,}000\ mg/m^3)(47\ m^3/s)(423/424) = 1{,}125\ mg/s \end{aligned}$$

1.

This value can be used as an input for a control volume around the junction of the bypass, the effluent from the baghouse and the final effluent.



A mass balance for the control volume around the junction may be written as

$$\frac{dM}{dt} = C_{\text{in}}Q_{\text{in from bypass}} + C_{\text{in}}Q_{\text{in from baghouse}} - C_{\text{emission}}Q_{\text{emission}}$$

Because there is no accumulation in the junction

$$\frac{dM}{dt} = 0$$

and the mass balance equation is

$$\begin{aligned} C_{\text{out}}Q_{\text{out}} &= C_{\text{in}}Q_{\text{in from bypass}} + C_{\text{in}}Q_{\text{in from baghouse}} \\ &= (15{,}000 \text{ mg/m}^3)(47 \text{ m}^3\text{/s})(1/424) + 1{,}125 = 2788 \text{ mg/s} \end{aligned}$$

The concentration in the effluent is

$$\frac{C_{\text{out}}Q_{\text{out}}}{Q_{\text{out}}} = \frac{2{,}788 \text{ mg/s}}{47 \text{ m}^3\text{/s}} = 59 \text{ mg/m}^3$$

The overall efficiency of the baghouse with the missing bag is

$$\begin{aligned} \eta &= \frac{15{,}000 \text{ mg/m}^3 - 59 \text{ mg/m}^3}{15{,}000 \text{ mg/m}^3}(100\%) \\ &= 99.61\% \end{aligned}$$

The efficiency is still very high but the control equipment does not meet the allowable emission rate of 24 mg/m^3. It is not likely that a baghouse would ever operate with a missing bag because the unbalanced gas flows would be immediately apparent. However, many small holes in a number of bags could yield an effluent that did not meet the discharge standards but would otherwise appear to be functioning correctly. To prevent this situation, the bags undergo periodic inspection and maintenance and the effluent stream is monitored continuously.

State of Mixing

- Plug flow systems
  - No mixing of constituents (pollutants / elements) within the system / boundary
  - Concentration is variable within the system (Pulse change?)

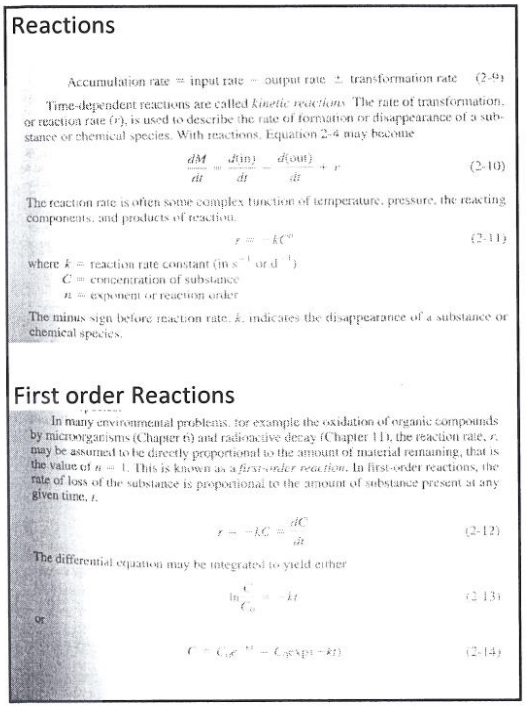
- Completely mixed systems
  - Constituents are well mixed
  - Concentration of constituents (pollutants / elements) within the system are identical

State of Mixing (Contd..)

- Also related terms are :

- Stead State: $dM/dt = 0$

- Unsteady State: $dM/dt \neq 0$



Reactions

$$\text{Accumulation rate} = \text{input rate} - \text{output rate} \pm \text{transformation rate} \qquad (2\text{-}9)$$

Time-dependent reactions are called *kinetic reactions*. The rate of transformation, or reaction rate (r), is used to describe the rate of formation or disappearance of a substance or chemical species. With reactions, Equation 2-4 may become

$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} + r \qquad (2\text{-}10)$$

The reaction rate is often some complex function of temperature, pressure, the reacting components, and products of reaction.

$$r = -kC^n \qquad (2\text{-}11)$$

where k = reaction rate constant (in s^{-1} or d^{-1})
C = concentration of substance
n = exponent or reaction order

The minus sign before reaction rate, k, indicates the disappearance of a substance or chemical species.

First order Reactions

In many environmental problems, for example the oxidation of organic compounds by microorganisms (Chapter 6) and radioactive decay (Chapter 11), the reaction rate, r, may be assumed to be directly proportional to the amount of material remaining, that is the value of $n = 1$. This is known as a *first-order reaction*. In first-order reactions, the rate of loss of the substance is proportional to the amount of substance present at any given time, t.

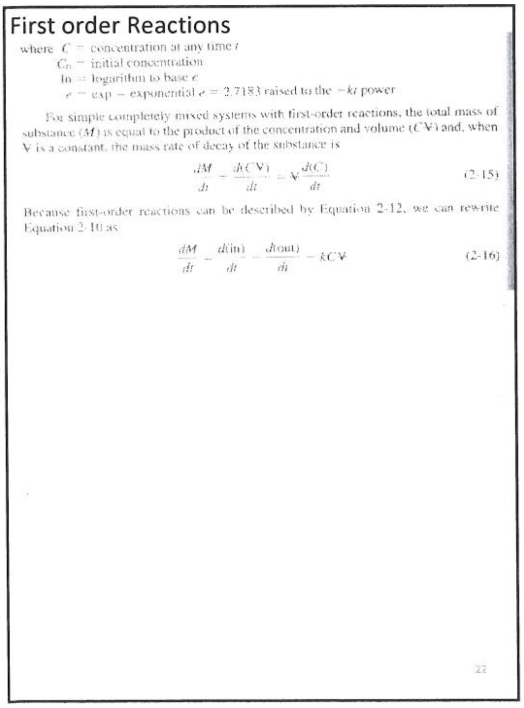
$$r = -kC = \frac{dC}{dt} \qquad (2\text{-}12)$$

The differential equation may be integrated to yield either

$$\ln\frac{C}{C_0} = -kt \qquad (2\text{-}13)$$

or

$$C = C_0e^{-kt} = C_0\exp(-kt) \qquad (2\text{-}14)$$



First order Reactions

where C = concentration at any time t
C_0 = initial concentration
ln = logarithm to base e
e = exp = exponential e = 2.7183 raised to the $-kt$ power

For simple completely mixed systems with first-order reactions, the total mass of substance (M) is equal to the product of the concentration and volume (CV) and, when V is a constant, the mass rate of decay of the substance is

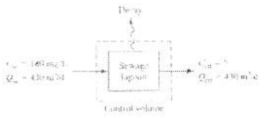
$$\frac{dM}{dt} = \frac{d(CV)}{dt} = V\frac{d(C)}{dt} \qquad (2\text{-}15)$$

Because first-order reactions can be described by Equation 2-12, we can rewrite Equation 2-10 as

$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} - kCV \qquad (2\text{-}16)$$

Example 2-6. A well-mixed sewage lagoon (a shallow pond) is receiving 430 m^3/d of sewage out of a sewer pipe. The lagoon has a surface area of 10 ha (hectares) and a depth of 1.0 m. The pollutant concentration in the raw sewage discharging into the lagoon is 180 mg/L. The organic matter in the sewage degrades biologically (decays) in the lagoon according to first-order kinetics. The reaction rate constant (decay coefficient) is 0.70 d^{-1}. Assuming no other water losses or gains (evaporation, seepage, or rainfall) and that the lagoon is completely mixed, find the steady-state concentration of the pollutant in the lagoon effluent.

Solution. We begin by drawing the mass-balance diagram.



The mass-balance equation may be written as

$$\text{Accumulation} = \text{input rate} - \text{output rate} - \text{decay rate}$$

Assuming steady-state conditions, that is, accumulation = 0, then

$$\text{Input rate} = \text{output rate} + \text{decay rate}$$

This may be written in terms of the notation in the figure as

$$C_{in}Q_{in} = C_{eff}Q_{eff} + kC_{lagoon}\forall$$

Solving for C_{eff}, we have

$$C_{eff} = \frac{C_{in}Q_{in} - kC_{lagoon}\forall}{Q_{eff}}$$

Now calculate the values for terms in the equation. The input mass rate ($C_{in}Q_{in}$) is

$$(180 \text{ mg/L})(430 \text{ m}^3/\text{d})(1{,}000 \text{ L/m}^3) = 77{,}400{,}000 \text{ mg/d}$$

With a lagoon volume of

$$(10 \text{ ha})(10^4 \text{ m}^2/\text{ha})(1 \text{ m}) = 100{,}000 \text{ m}^3$$

and the decay coefficient of 0.70 d^{-1}, the decay rate is

$$kC\forall = (0.70 \text{ d}^{-1})(100{,}000 \text{ m}^3)(1{,}000 \text{ L/m}^3)(C_{lagoon}) = (70{,}000{,}000 \text{ L/d})(C_{lagoon})$$

Now using the assumption that the lagoon is completely mixed, we assume that $C_{eff} = C_{lagoon}$. Thus,

$$kC\forall = (70{,}000{,}000 \text{ L/d})(C_{eff})$$

Substituting into the mass-balance equation

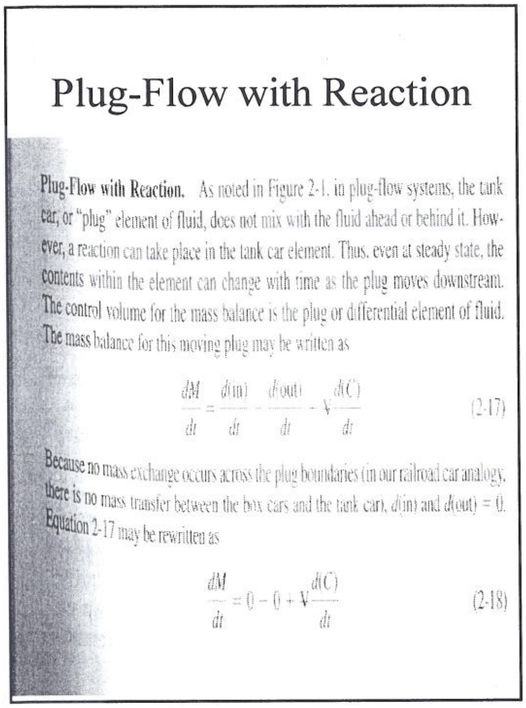
$$\text{Output rate} = 77{,}400{,}000 \text{ mg/d} - 70{,}000{,}000 \text{ L/d} \times C_{eff}$$

or

$$C_{eff}(430 \text{ m}^3/\text{d})(1{,}000 \text{ L/m}^3) = 77{,}400{,}000 \text{ mg/d} - 70{,}000{,}000 \text{ L/d} \times C_{eff}$$

Solving for C_{eff}, we have

$$C_{eff} = \frac{77{,}400{,}000 \text{ mg/d}}{70{,}430{,}000 \text{ L/d}} = 1.10 \text{ mg/L}$$



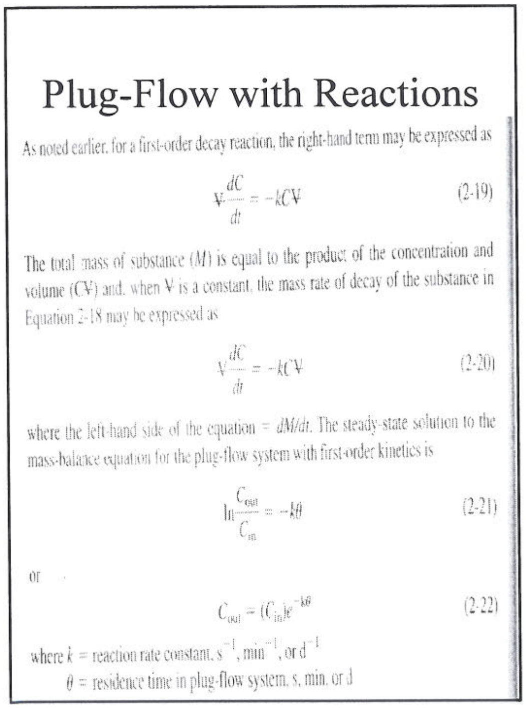
Plug-Flow with Reaction

Plug-Flow with Reaction. As noted in Figure 2-1, in plug-flow systems, the tank car, or "plug" element of fluid, does not mix with the fluid ahead or behind it. However, a reaction can take place in the tank car element. Thus, even at steady state, the contents within the element can change with time as the plug moves downstream. The control volume for the mass balance is the plug or differential element of fluid. The mass balance for this moving plug may be written as

$$\frac{dM}{dt} = \frac{d(\text{in})}{dt} - \frac{d(\text{out})}{dt} + \yen\frac{d(C)}{dt} \qquad (2\text{-}17)$$

Because no mass exchange occurs across the plug boundaries (in our railroad car analogy, there is no mass transfer between the box cars and the tank car), *d*(in) and *d*(out) = 0. Equation 2-17 may be rewritten as

$$\frac{dM}{dt} = 0 - 0 + \yen\frac{d(C)}{dt} \qquad (2\text{-}18)$$



Plug-Flow with Reactions

As noted earlier, for a first-order decay reaction, the right-hand term may be expressed as

$$\yen\frac{dC}{dt} = -kC\yen \qquad (2\text{-}19)$$

The total mass of substance (*M*) is equal to the product of the concentration and volume ($C\yen$) and, when ¥ is a constant, the mass rate of decay of the substance in Equation 2-18 may be expressed as

$$\yen\frac{dC}{dt} = -kC\yen \qquad (2\text{-}20)$$

where the left-hand side of the equation = *dM/dt*. The steady-state solution to the mass-balance equation for the plug-flow system with first-order kinetics is

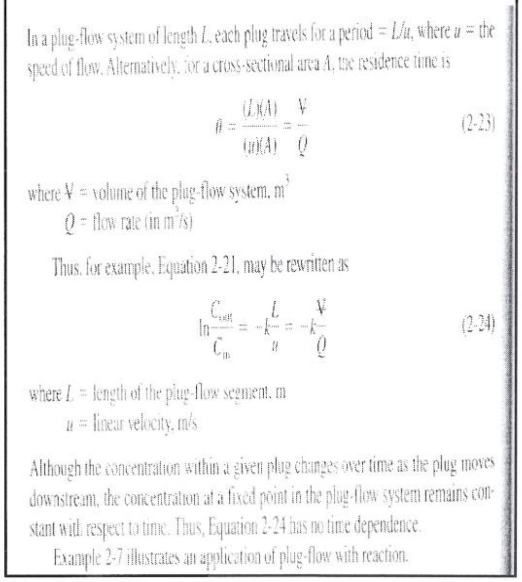
$$\ln\frac{C_{\text{out}}}{C_{\text{in}}} = -k\theta \qquad (2\text{-}21)$$

or

$$C_{\text{out}} = (C_{\text{in}})e^{-k\theta} \qquad (2\text{-}22)$$

where k = reaction rate constant, s^{-1}, min^{-1}, or d^{-1}
θ = residence time in plug-flow system, s, min, or d

Plug-Flow with Reactions



In a plug-flow system of length L, each plug travels for a period = L/u, where u = the speed of flow. Alternatively, for a cross-sectional area A, the residence time is

$$\theta = \frac{(L)(A)}{(u)(A)} = \frac{V}{Q} \qquad (2\text{-}23)$$

where V = volume of the plug-flow system, m^3

Q = flow rate (in m^3/s)

Thus, for example, Equation 2-21, may be rewritten as

$$\ln\frac{C_{out}}{C_{in}} = -k\frac{L}{u} = -k\frac{V}{Q} \qquad (2\text{-}24)$$

where L = length of the plug-flow segment, m

u = linear velocity, m/s

Although the concentration within a given plug changes over time as the plug moves downstream, the concentration at a fixed point in the plug-flow system remains constant with respect to time. Thus, Equation 2-24 has no time dependence.

Example 2-7 illustrates an application of plug-flow with reaction.

Reactors

- Reactors: Tanks in which physical, chemical, and biochemical reactions occur
- Types: Two, Batch and Continuous
- Batch Reactors:
  - Fill-and-draw type
  - Materials added, mixed, allowed to stay in for the reaction to occur, and then drained

Reactors

- Completely Mixed Flow Reactor (CMFR) or Continuous-flow Stirred Tank Reactor (CSTR)
  - Material flows in and out of the tank on a continuous, uninterrupted, basis

Plug Flow Reactors

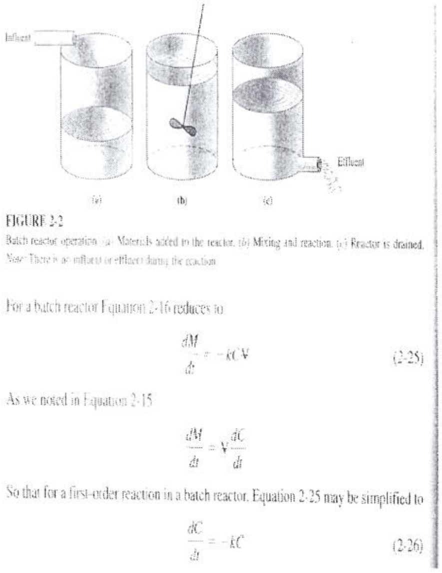


FIGURE 2-2

Batch reactor operation (a) Materials added to the reactor. (b) Mixing and reaction. (c) Reactor is drained. Note: There is no influent or effluent during the reaction.

For a batch reactor Equation 2-16 reduces to

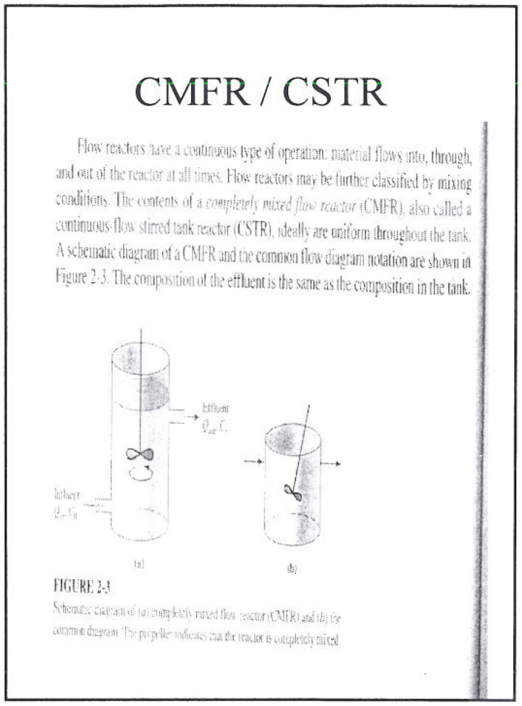
$$\frac{dM}{dt} = -kCV \qquad (2\text{-}25)$$

As we noted in Equation 2-15

$$\frac{dM}{dt} = V\frac{dC}{dt}$$

So that for a first-order reaction in a batch reactor, Equation 2-25 may be simplified to

$$\frac{dC}{dt} = -kC \qquad (2\text{-}26)$$

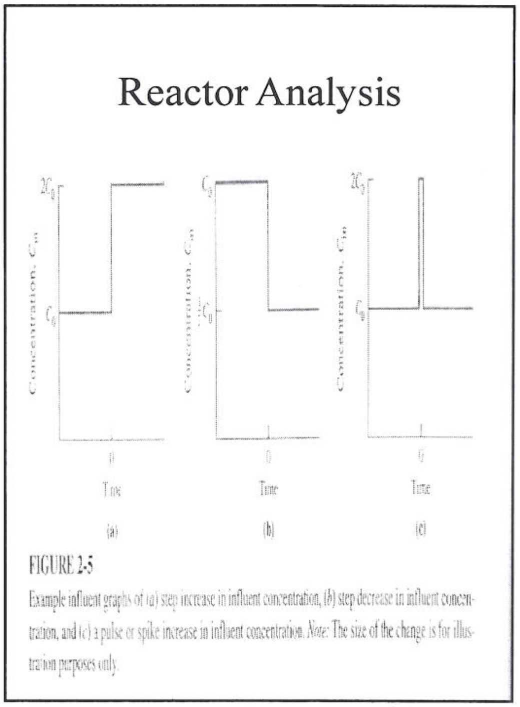


CMFR / CSTR

Flow reactors have a continuous type of operation: material flows into, through, and out of the reactor at all times. Flow reactors may be further classified by mixing conditions. The contents of a *completely mixed flow reactor* (CMFR), also called a continuous-flow stirred tank reactor (CSTR), ideally are uniform throughout the tank. A schematic diagram of a CMFR and the common flow diagram notation are shown in Figure 2-3. The composition of the effluent is the same as the composition in the tank.

FIGURE 2-3

Schematic diagram of (a) completely mixed flow reactor (CMFR) and (b) the common diagram. The propeller indicates that the reactor is completely mixed.



Reactor Analysis

FIGURE 2-5

Example influent graphs of (*a*) step increase in influent concentration, (*b*) step decrease in influent concentration, and (*c*) a pulse or spike increase in influent concentration. *Note:* The size of the change is for illustration purposes only.

Reactor Analysis – Batch Reactor

Batch Reactor. Laboratory experiments are often conducted in batch reactors because they are inexpensive and easy to build. Industries that generate small quantities of wastewater (less than 150 m^3/d) use batch reactors because they are easy to operate and provide an opportunity to check the wastewater for regulatory compliance before discharging it.

Because there is no influent to or effluent from a batch reactor, the introduction of a conservative substance into the reactor either as a step increase or a pulse results in an instantaneous increase in concentration of the conservative substance in the reactor. The concentration plot is shown in Figure 2-6.

Because there is no influent or effluent, for a nonconservative substance that decays as a first-order reaction, the mass balance is described by Equation 2-26. Integration yields

$$\frac{C_t}{C_0} = e^{-kt} \qquad (2\text{-}28)$$

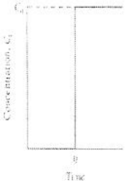


FIGURE 2-6
Batch reactor response to a step or pulse increase in concentration of a conservative substance. C_0 = mass of conservative substance/volume of reactor.

Reactor Analysis – Batch Reactor

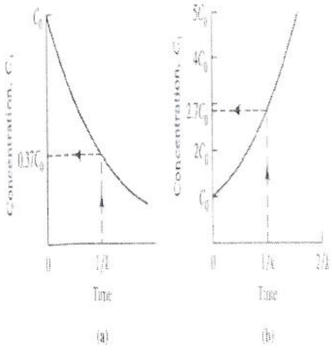
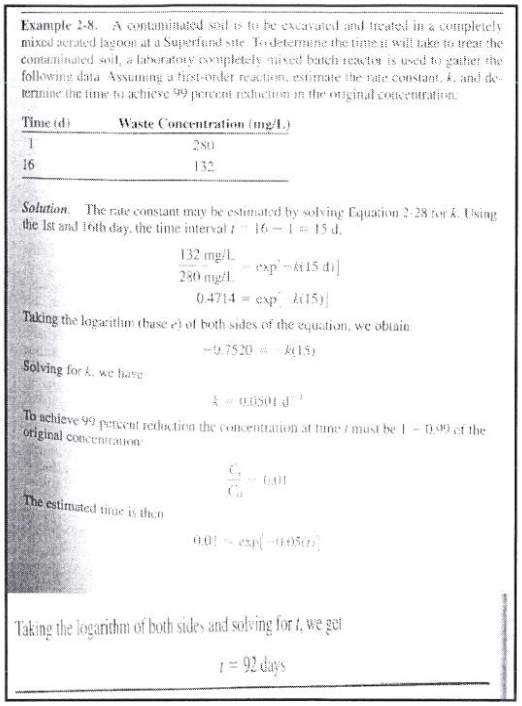


FIGURE 2-7
Batch reactor response for (*a*) decay of a non-conservative substance and (*b*) for a formation reaction.

The final concentration plot is shown in Figure 2-7*a*. For the formation reaction, where the sign in Equation 2-28 is positive, the concentration plot is shown in Figure 2-7*b*.



Example 2-8. A contaminated soil is to be excavated and treated in a completely mixed aerated lagoon at a Superfund site. To determine the time it will take to treat the contaminated soil, a laboratory completely mixed batch reactor is used to gather the following data. Assuming a first-order reaction, estimate the rate constant, k, and determine the time to achieve 99 percent reduction in the original concentration.

Time (d)	Waste Concentration (mg/L)
1	280
16	132

Solution. The rate constant may be estimated by solving Equation 2-28 for k. Using the 1st and 16th day, the time interval $t = 16 - 1 = 15$ d.

$$\frac{132 \text{ mg/L}}{280 \text{ mg/L}} = \exp[-k(15 \text{ d})]$$

$$0.4714 = \exp[-k(15)]$$

Taking the logarithm (base e) of both sides of the equation, we obtain

$$-0.7520 = -k(15)$$

Solving for k, we have

$$k = 0.0501 \text{ d}^{-1}$$

To achieve 99 percent reduction the concentration at time t must be $1 - 0.99$ of the original concentration:

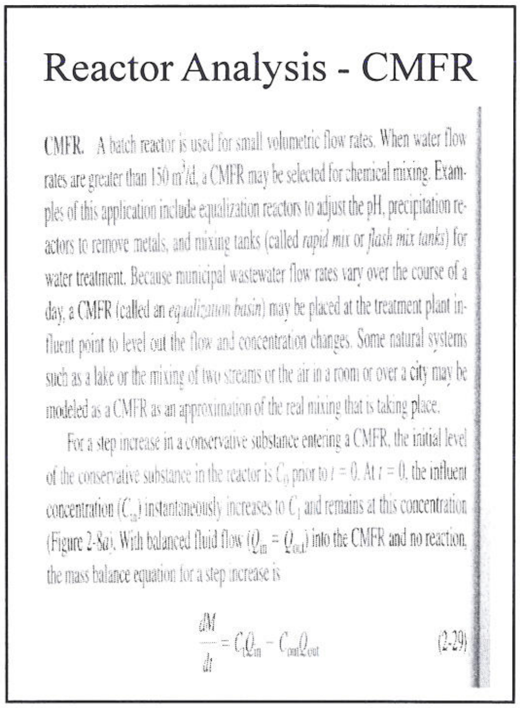
$$\frac{C_t}{C_0} = 0.01$$

The estimated time is then

$$0.01 = \exp[-0.05(t)]$$

Taking the logarithm of both sides and solving for t, we get

$$t = 92 \text{ days}$$

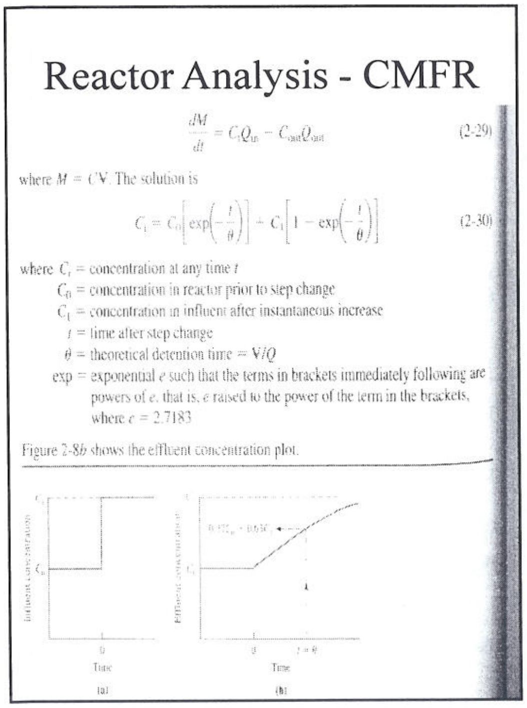


Reactor Analysis - CMFR

CMFR. A batch reactor is used for small volumetric flow rates. When water flow rates are greater than 150 m^3/d, a CMFR may be selected for chemical mixing. Examples of this application include equalization reactors to adjust the pH, precipitation reactors to remove metals, and mixing tanks (called *rapid mix* or *flash mix tanks*) for water treatment. Because municipal wastewater flow rates vary over the course of a day, a CMFR (called an *equalization basin*) may be placed at the treatment plant influent point to level out the flow and concentration changes. Some natural systems such as a lake or the mixing of two streams or the air in a room or over a city may be modeled as a CMFR as an approximation of the real mixing that is taking place.

For a step increase in a conservative substance entering a CMFR, the initial level of the conservative substance in the reactor is C_0 prior to $t = 0$. At $t = 0$, the influent concentration (C_{in}) instantaneously increases to C_1 and remains at this concentration (Figure 2-8*a*). With balanced fluid flow ($Q_{in} = Q_{out}$) into the CMFR and no reaction, the mass balance equation for a step increase is

$$\frac{dM}{dt} = C_1Q_{in} - C_{out}Q_{out} \qquad (2\text{-}29)$$



Reactor Analysis - CMFR

$$\frac{dM}{dt} = C_i Q_{in} - C_{out} Q_{out} \tag{2-29}$$

where $M = C\forall$. The solution is

$$C_t = C_0\left[\exp\left(-\frac{t}{\theta}\right)\right] + C_1\left[1 - \exp\left(-\frac{t}{\theta}\right)\right] \tag{2-30}$$

where C_t = concentration at any time t

C_0 = concentration in reactor prior to step change

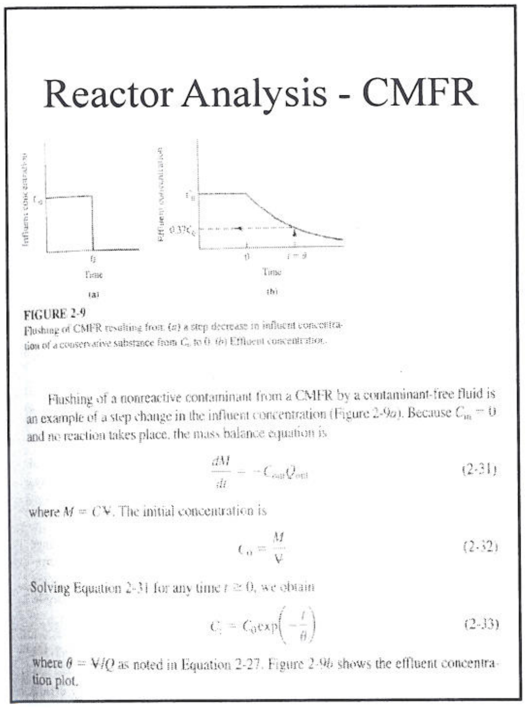
C_1 = concentration in influent after instantaneous increase

t = time after step change

θ = theoretical detention time = $\forall/Q$

exp = exponential e such that the terms in brackets immediately following are powers of e, that is, e raised to the power of the term in the brackets, where $e = 2.7183$

Figure 2-8*b* shows the effluent concentration plot.



Reactor Analysis - CMFR

FIGURE 2-9

Flushing of CMFR resulting from: (*a*) a step decrease in influent concentration of a conservative substance from C_0 to 0. (*b*) Effluent concentration.

Flushing of a nonreactive contaminant from a CMFR by a contaminant-free fluid is an example of a step change in the influent concentration (Figure 2-9*a*). Because $C_{in} = 0$ and no reaction takes place, the mass balance equation is

$$\frac{dM}{dt} = -C_{out} Q_{out} \tag{2-31}$$

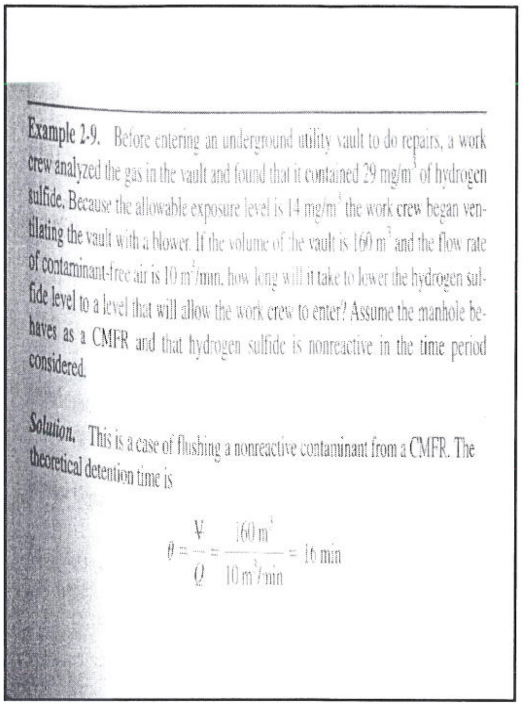
where $M = C\forall$. The initial concentration is

$$C_0 = \frac{M}{\forall} \tag{2-32}$$

Solving Equation 2-31 for any time $t \geq 0$, we obtain

$$C_t = C_0 \exp\left(-\frac{t}{\theta}\right) \tag{2-33}$$

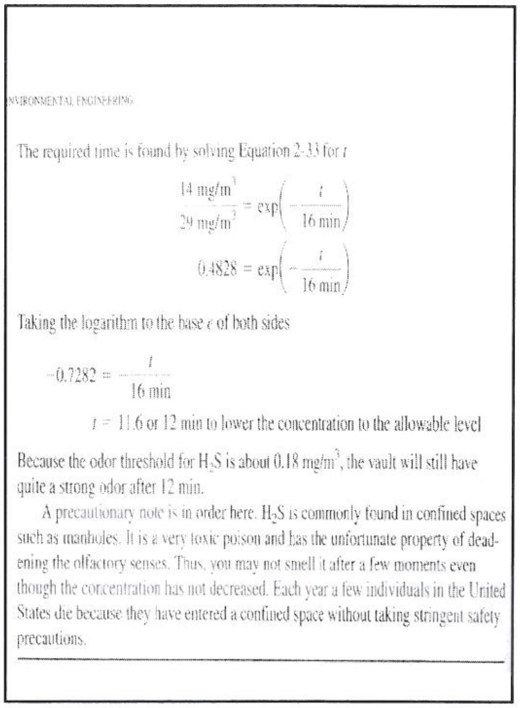
where $\theta = \forall/Q$ as noted in Equation 2-27. Figure 2-9*b* shows the effluent concentration plot.



Example 2-9. Before entering an underground utility vault to do repairs, a work crew analyzed the gas in the vault and found that it contained 29 mg/m³ of hydrogen sulfide. Because the allowable exposure level is 14 mg/m³ the work crew began ventilating the vault with a blower. If the volume of the vault is 160 m³ and the flow rate of contaminant-free air is 10 m³/min, how long will it take to lower the hydrogen sulfide level to a level that will allow the work crew to enter? Assume the manhole behaves as a CMFR and that hydrogen sulfide is nonreactive in the time period considered.

Solution. This is a case of flushing a nonreactive contaminant from a CMFR. The theoretical detention time is

$$\theta = \frac{\forall}{Q} = \frac{160\ \text{m}^3}{10\ \text{m}^3/\text{min}} = 16\ \text{min}$$



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The required time is found by solving Equation 2-33 for *t*

$$\frac{14\ \text{mg/m}^3}{29\ \text{mg/m}^3} = \exp\left(-\frac{t}{16\ \text{min}}\right)$$

$$0.4828 = \exp\left(-\frac{t}{16\ \text{min}}\right)$$

Taking the logarithm to the base *e* of both sides

$$-0.7282 = -\frac{t}{16\ \text{min}}$$

$$t = 11.6 \text{ or } 12 \text{ min to lower the concentration to the allowable level}$$

Because the odor threshold for H_2S is about 0.18 mg/m³, the vault will still have quite a strong odor after 12 min.

A precautionary note is in order here. H_2S is commonly found in confined spaces such as manholes. It is a very toxic poison and has the unfortunate property of deadening the olfactory senses. Thus, you may not smell it after a few moments even though the concentration has not decreased. Each year a few individuals in the United States die because they have entered a confined space without taking stringent safety precautions.

Power Point 3 Hydrology (Chap 3 part 1 of 3)

Hydrologic Cycle

- The global system that supplies and removes water from the earth's surface
- Three things to know:
  - Evaporation (-)
  - Transpiration (-)
  - Precipitation (+)

Surface Water Hydrology

- Precipitation
  - Precipitation forms (rain, sleet, hail, or snow)
  - Precipitation factors (extent/area covered, duration, and intensity)
- Things that happen after precipitation:
  - Evaporation
  - Infiltration (in to the ground)
  - Interception (by leaves, grass, and other objects)
  - Trapping
- Abstractions (Evaporation, infiltration, interception, and trapping) – four factors that reduce direct runoff

Surface Water Hydrology
Streamflow

- Stream receives water from two main sources
  - Direct runoff from precipitation
  - Groundwater exfiltration (reverse of infiltration)
    - This is also known as base flow / dry weather flow
    - Occurs as a result of seepage of groundwater out of stream banks
- Amount of water in a stream depends on:
  - Watershed feeding the stream (+)
  - Abstractions (-)

Surface Water Hydrology
Streamflow

- Stream receives water from two main sources
  - Direct runoff from precipitation
  - Groundwater exfiltration (reverse of infiltration)
    - This is also known as base flow / dry weather flow
    - Occurs as a result of seepage of groundwater out of stream banks
- Amount of water in a stream depends on:
  - Watershed feeding the stream (+)
  - Abstractions (-)

Groundwater Hydrology

- Water table
  - A surface connecting the piezometric levels of water in wells
- Aquifer – The geological formation that bears water
  - Unconfined (Water is not under pressure)
  - Confined / Artesian (Water is under pressure)
  - Perched (Situated above the water table; water is not under pressure)
- Aquicludes (impermeable) < Aquitards (intermediate permeability) < Aquifers (permeable)

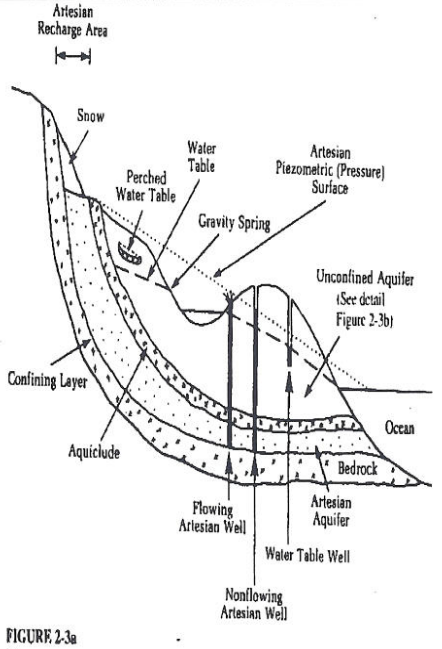


FIGURE 2-3a

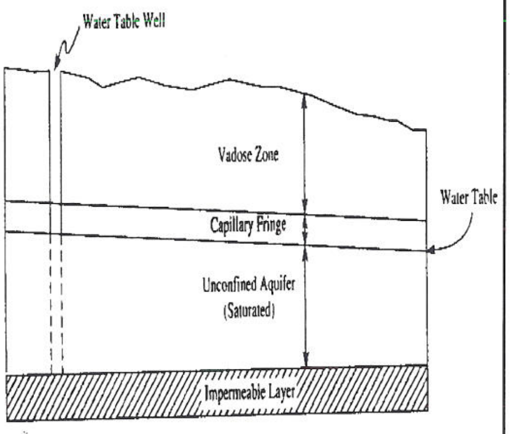


FIGURE 2-3b
Detail of the unconfined aquifer.

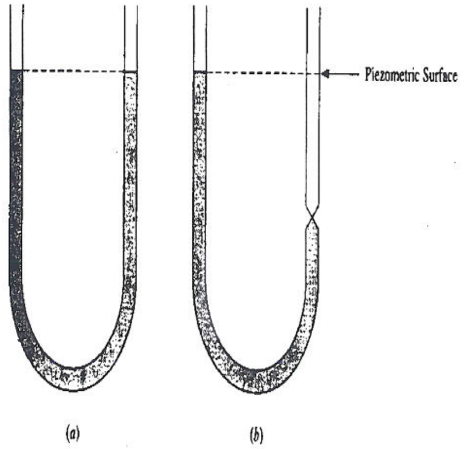
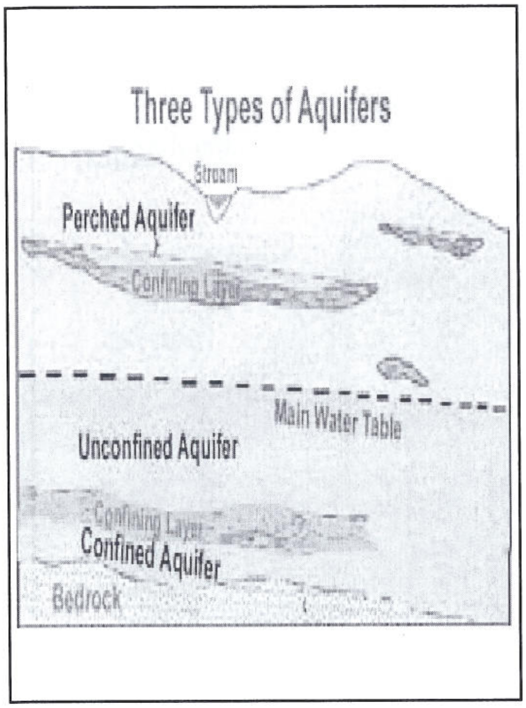
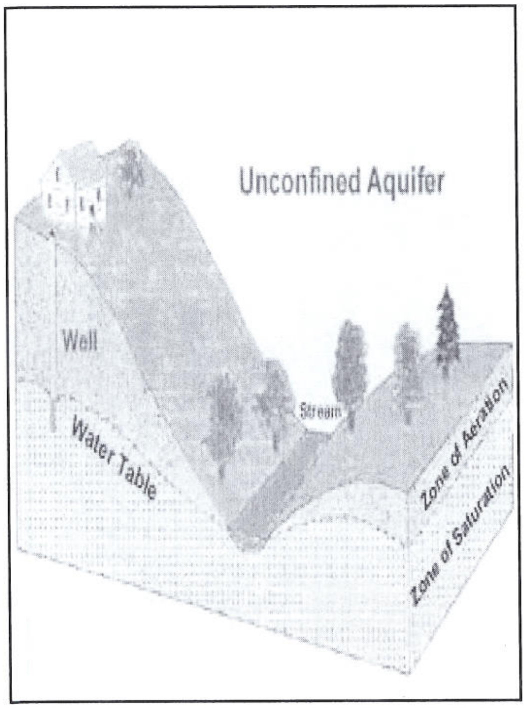


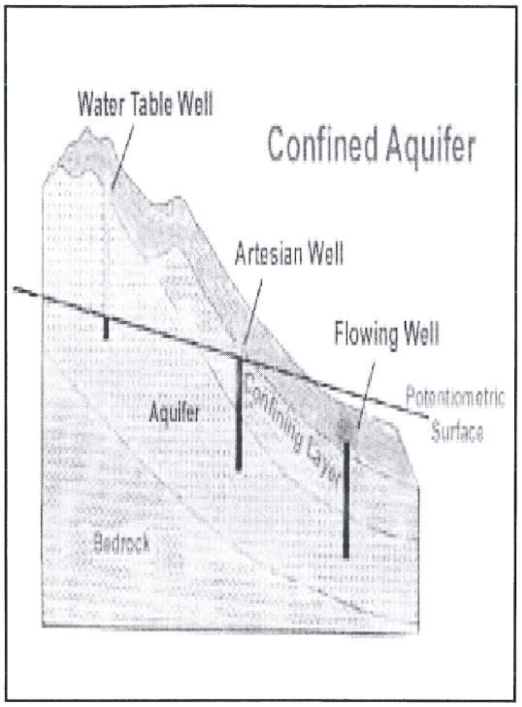
FIGURE 2-4
Manometer analogy to water in an aquifer. Manometer "a" is analogous to an unconfined aquifer. Manometer "b" is analogous to a confined aquifer.

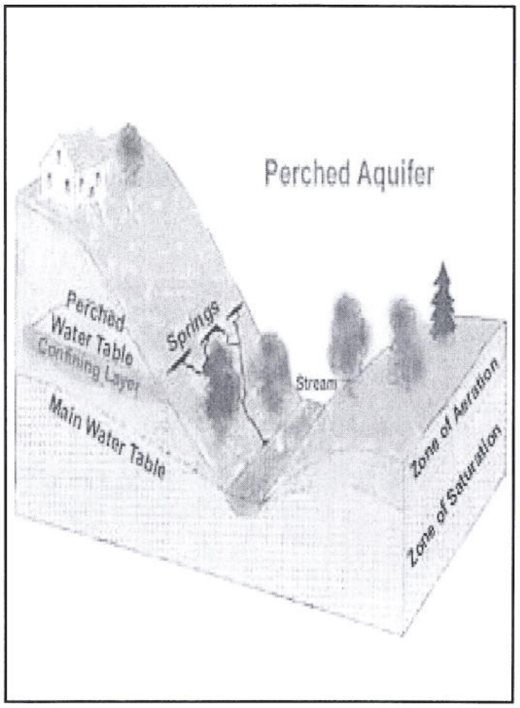


Three Types of Aquifers



Unconfined Aquifer


Water Table Well
Confined Aquifer
Artesian Well
Flowing Well
Potentiometric Surface
Aquifer
Confining Layer
Bedrock


Perched Aquifer
Perched Water Table
Confining Layer
Springs
Stream
Main Water Table
Zone of Aeration
Zone of Saturation

Common Units of Measurement

- Precipitation (mm); Rate (mm/hr)
- Evaporation (mm); Rate (mm/hr)
- Transpiration (mm); Rate (mm/hr)
- Stream speed (m/s) and stream flow (m^3/d)
- Volume (m^3)

The Hydrologic Equation

- Mass balance equation (global basis):

$$V_P(\rho) - V_S(\rho) - V_R(\rho) - V_G(\rho)$$
$$- V_E(\rho) - V_T(\rho) = 0$$

(Eq. 2.1)

$$V_P - V_S - V_R - V_G - V_E - V_T = 0$$

Where:

ρ - Water density
P - Precipitation
S - Storage
R - Runoff
G - Groundwater infiltration
E - Evaporation
T - Transpiration

Hydrologic Subsystem

- Rate of accumulation = Rate of input – Rate of out put

  $dS/dt = d(In)/dt - d(Out)/dt$ *(Eq. 2.2)*

Infiltration

- Horton's Equation

  $f = f_c + (f_o - f_c) * e^{-kt}$ *(Eq. 2.3)*

  Where:

  f - infiltration rate, mm/h

  f_o - equilibrium or final infiltration rate

  f_c - initial infiltration rate, mm/h

  k - empirical constant, 1/h

  t - time, h
- Infiltration rates and 'k' are function of soil type
- Integration of Eq. 2.3 yields Volume

  $V = f_c . t + (f_o - f_c) . (1 - e^{-kt}) / k$ *(Eq. 2.4)*

Evaporation

- Evaporation,

  E = $(e_s - e_a) * (a + b * u)$ (Eq. 2.5)

  Where:

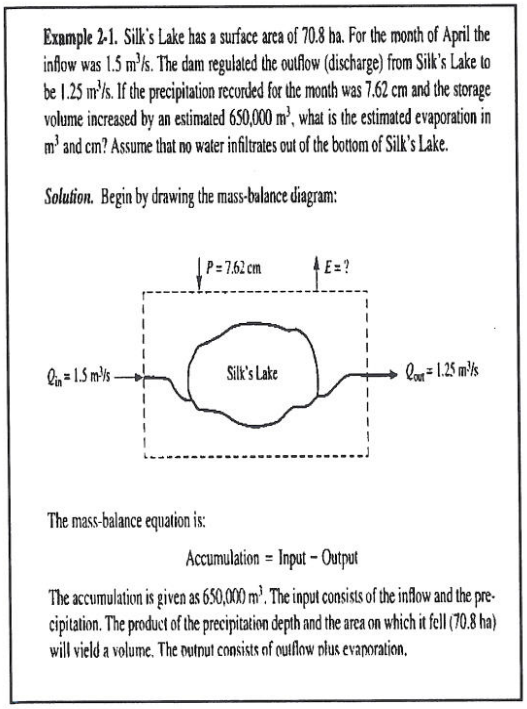
  E - *evaporation rate, mm/d*

  e_s - *saturation vapor pressure, kPa*

  e_a - *vapor pressures in overlaying air, kPa*

  a & b - empirical constants

  u - *wind speed, m/s*



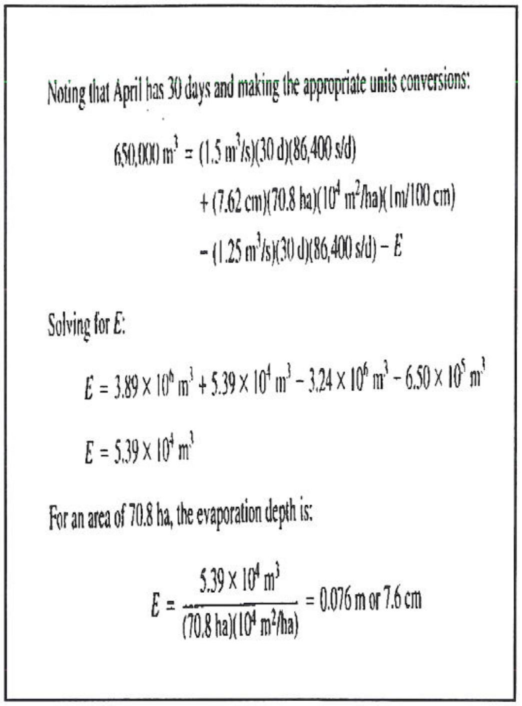
Example 2-1. Silk's Lake has a surface area of 70.8 ha. For the month of April the inflow was 1.5 m^3/s. The dam regulated the outflow (discharge) from Silk's Lake to be 1.25 m^3/s. If the precipitation recorded for the month was 7.62 cm and the storage volume increased by an estimated 650,000 m^3, what is the estimated evaporation in m^3 and cm? Assume that no water infiltrates out of the bottom of Silk's Lake.

Solution. Begin by drawing the mass-balance diagram:

The mass-balance equation is:

$$\text{Accumulation} = \text{Input} - \text{Output}$$

The accumulation is given as 650,000 m^3. The input consists of the inflow and the precipitation. The product of the precipitation depth and the area on which it fell (70.8 ha) will yield a volume. The output consists of outflow plus evaporation.



Noting that April has 30 days and making the appropriate units conversions:

$$\begin{aligned} 650{,}000\ \text{m}^3 &= (1.5\ \text{m}^3/\text{s})(30\ \text{d})(86{,}400\ \text{s/d}) \\ &\quad + (7.62\ \text{cm})(70.8\ \text{ha})(10^4\ \text{m}^2/\text{ha})(1\ \text{m}/100\ \text{cm}) \\ &\quad - (1.25\ \text{m}^3/\text{s})(30\ \text{d})(86{,}400\ \text{s/d}) - E \end{aligned}$$

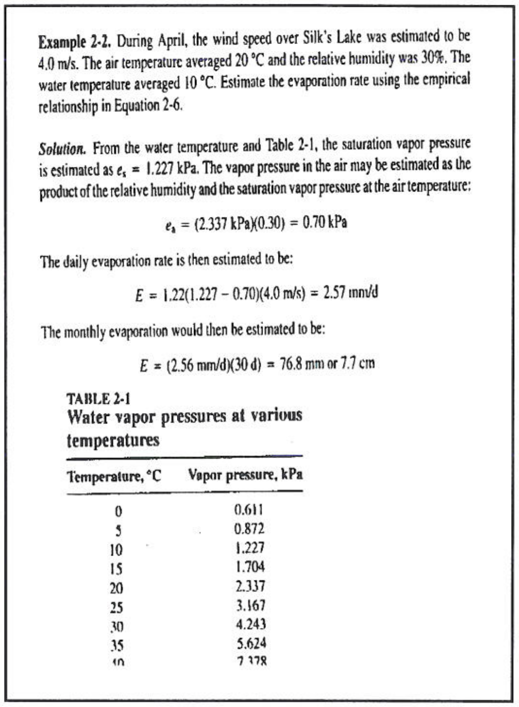
Solving for E:

$$E = 3.89 \times 10^6\ \text{m}^3 + 5.39 \times 10^4\ \text{m}^3 - 3.24 \times 10^6\ \text{m}^3 - 6.50 \times 10^5\ \text{m}^3$$

$$E = 5.39 \times 10^4\ \text{m}^3$$

For an area of 70.8 ha, the evaporation depth is:

$$E = \frac{5.39 \times 10^4\ \text{m}^3}{(70.8\ \text{ha})(10^4\ \text{m}^2/\text{ha})} = 0.076\ \text{m or } 7.6\ \text{cm}$$



Example 2-2. During April, the wind speed over Silk's Lake was estimated to be 4.0 m/s. The air temperature averaged 20 °C and the relative humidity was 30%. The water temperature averaged 10 °C. Estimate the evaporation rate using the empirical relationship in Equation 2-6.

Solution. From the water temperature and Table 2-1, the saturation vapor pressure is estimated as $e_s = 1.227$ kPa. The vapor pressure in the air may be estimated as the product of the relative humidity and the saturation vapor pressure at the air temperature:

$$e_a = (2.337\ \text{kPa})(0.30) = 0.70\ \text{kPa}$$

The daily evaporation rate is then estimated to be:

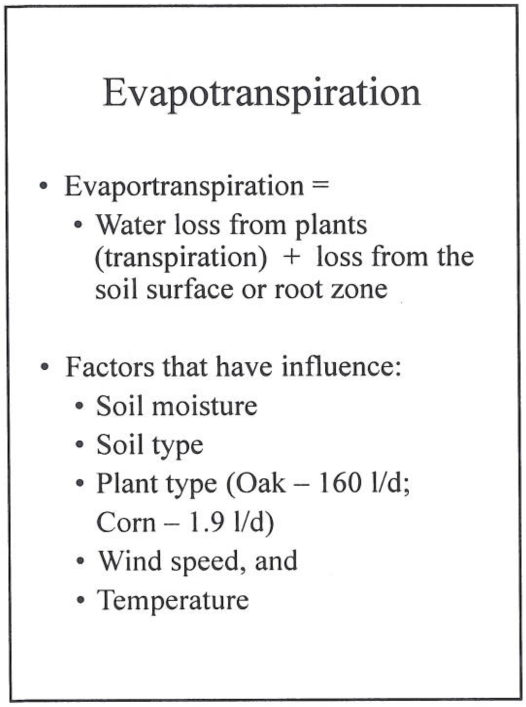
$$E = 1.22(1.227 - 0.70)(4.0\ \text{m/s}) = 2.57\ \text{mm/d}$$

The monthly evaporation would then be estimated to be:

$$E = (2.56\ \text{mm/d})(30\ \text{d}) = 76.8\ \text{mm or } 7.7\ \text{cm}$$

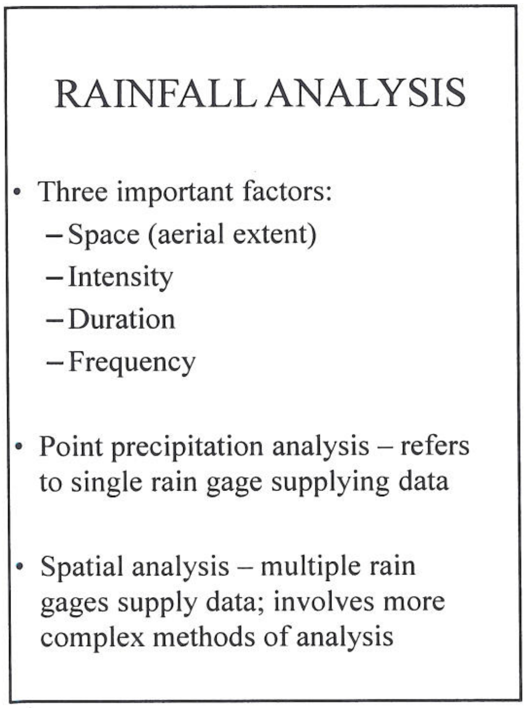
TABLE 2-1
Water vapor pressures at various temperatures

Temperature, °C	Vapor pressure, kPa
0	0.611
5	0.872
10	1.227
15	1.704
20	2.337
25	3.167
30	4.243
35	5.624
40	7.378



Evapotranspiration

- Evaportranspiration =
  - Water loss from plants (transpiration) + loss from the soil surface or root zone
- Factors that have influence:
  - Soil moisture
  - Soil type
  - Plant type (Oak – 160 l/d; Corn – 1.9 l/d)
  - Wind speed, and
  - Temperature



RAINFALL ANALYSIS

- Three important factors:
  - Space (aerial extent)
  - Intensity
  - Duration
  - Frequency
- Point precipitation analysis – refers to single rain gage supplying data
- Spatial analysis – multiple rain gages supply data; involves more complex methods of analysis

RAINFALL ANALYSIS
Types of Rain Gages

- Standard (manual recording over 24-hr period)
- Weighing Bucket (Continuous strip chart records the rainfall)
- Tipping Bucket (cup tips for every 0.25 mm precipitation)

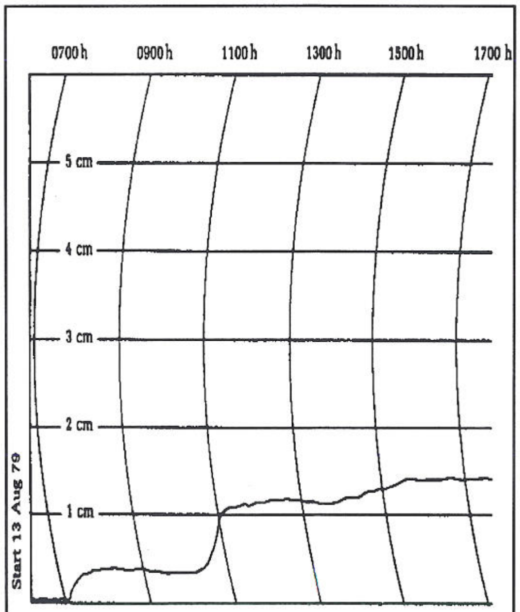


FIGURE 2-6

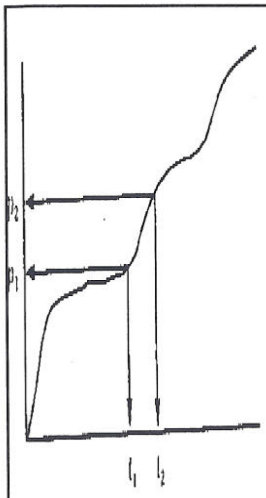


FIGURE 2-7

Computation of rainfall intensity from weighing-bucket strip chart record.

RAINFALL ANALYSIS
Intensity-duration-frequency (IDF) Curves

- IDF curves are essential for rational designing of storm drainage system.

- Avg. return period of a storm or avg. recurrence interval in yrs (T)
  T = 1 / Annual Avg. Probability

- Weibull's formula for Storm Return Period (T) = (n + 1)/m
  Where,
  T – average return period in years
  n – number of years on record
  m – rank of storm, with most intense storm given a rank of 1

TABLE 2-2

Rainfall record for the Dismal Swamp (1 Oct. 1923–30 Sep. 1968)

Duration (min)	Number of storms of stated intensity or more Intensity (mm/h) 20.0	30.0	40.0	60.0	80.0	100.0	120.0	140.0	160.0	180.0	200.0
5						245	49	16	7	3	2
10					256	64	15	7	4	1	
15				241	94	18	6	3	2		
20		240	80	36	10	4	2	1			
30	202	44	17	9	2	2	1				
40	76	31	8	1							
50	30	12	3								
60	9	2									

Example 2-3. Prepare a table of plotting points for an IDF curve for a 5-year storm at the Dismal Swamp. Compute points for each duration given in Table 2-2.

Solution. Since Table 2-2 is a table of ranks, we need to determine the rank of the 5-year storm. First, we rearrange Weibull's formula:

$$m = \frac{n+1}{T}$$

where

$$n = 1968 - 1923 = 45 \text{ y}$$

$$T = 5 \text{ y}$$

thus

$$m = \frac{46}{5} = 9.2$$

Starting with the 5-minute duration, we note that the 9.2-ranked storm lies between the 16th- and 7th-ranked storm; that is,

Intensity (mm/h)		
140.0		160.0
16	9.2	7

We also note that the ranks increase from right to left while the intensities increase from left to right. Keeping this in mind, and recalling that we assume a linear relationship between intensity and rank, we may interpolate by simple proportions:

$$\frac{9.2-7}{16-7}(160.0 - 140.0) = 4.89$$

Thus, the 9.2-ranked storm is 4.89 mm/h less than 160.0 mm/h:

$$160.0 - 4.89 = 155.11 \text{ or } 155.1 \text{ mm/h}$$

The completed table would appear as follows:

Intensity and duration values for a five-year storm at Dismal Swamp

Duration (min)	Intensity (mm/h)
5	155.1
10	134.5
15	114.7
20	82.7
30	59.5
40	39.5
50	33.1
60	—

Note that a similar table could be constructed for each intensity given in Table

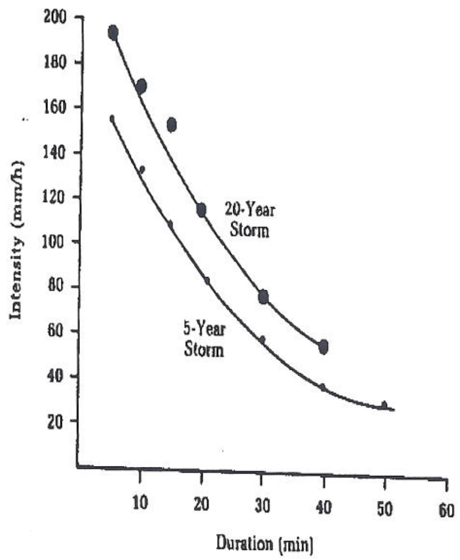


FIGURE 2-8
Intensity-duration-frequency curves for the Dismal Swamp.

Power Point 4 Hydrology (chap 3- part 2of 3)

Example 2-4. Determine the unit hydrograph ordinates for the Triangle River hydrograph shown in Figure 2-14. The area of the watershed is 16.2 square kilometers.

Solution. The first step is to determine the depth of the storm precipitation spread over the watershed. The depth is equivalent to the volume of water divided by the area. The volume is equal to the area under the hydrograph. Because of the rather symmetrical shape of this particular hydrograph, it would be easy to find the area from the principles of geometry. However, in the interest of developing a technique that will also be applicable to more customary hydrographs, we will numerically integrate the area under the curve. We do this by taking a convenient slice or *dt* and multiplying it by

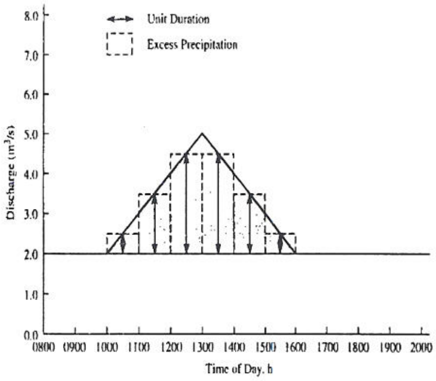
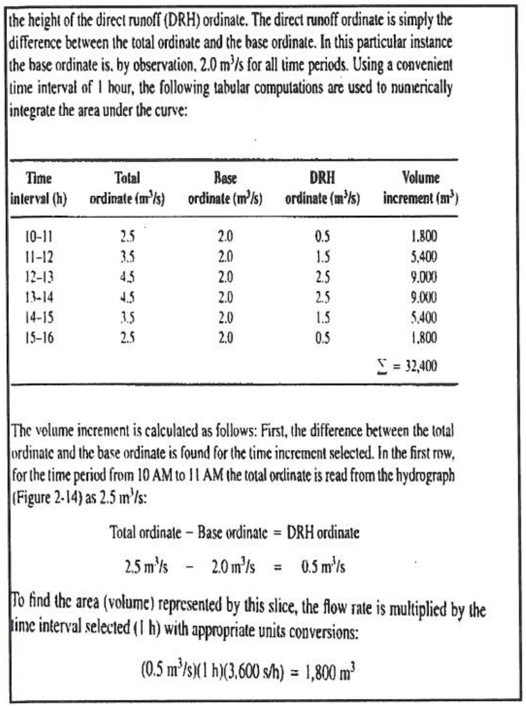


FIGURE 2-14
Triangle River hydrograph.



the height of the direct runoff (DRH) ordinate. The direct runoff ordinate is simply the difference between the total ordinate and the base ordinate. In this particular instance the base ordinate is, by observation, 2.0 m^3/s for all time periods. Using a convenient time interval of 1 hour, the following tabular computations are used to numerically integrate the area under the curve:

Time interval (h)	Total ordinate (m^3/s)	Base ordinate (m^3/s)	DRH ordinate (m^3/s)	Volume increment (m^3)
10–11	2.5	2.0	0.5	1.800
11–12	3.5	2.0	1.5	5,400
12–13	4.5	2.0	2.5	9.000
13–14	4.5	2.0	2.5	9.000
14–15	3.5	2.0	1.5	5,400
15–16	2.5	2.0	0.5	1,800
				$\sum = 32{,}400$

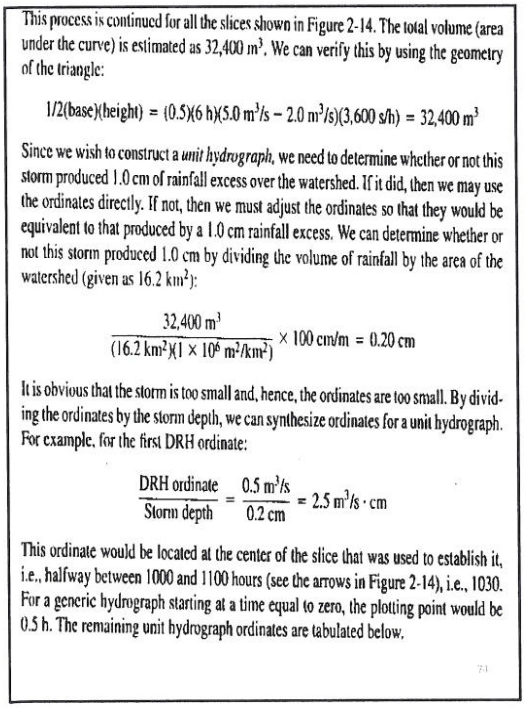
The volume increment is calculated as follows: First, the difference between the total ordinate and the base ordinate is found for the time increment selected. In the first row, for the time period from 10 AM to 11 AM the total ordinate is read from the hydrograph (Figure 2-14) as 2.5 m^3/s:

$$\text{Total ordinate} - \text{Base ordinate} = \text{DRH ordinate}$$

$$2.5\ m^3/s \quad - \quad 2.0\ m^3/s \quad = \quad 0.5\ m^3/s$$

To find the area (volume) represented by this slice, the flow rate is multiplied by the time interval selected (1 h) with appropriate units conversions:

$$(0.5\ m^3/s)(1\ h)(3{,}600\ s/h) = 1{,}800\ m^3$$



This process is continued for all the slices shown in Figure 2-14. The total volume (area under the curve) is estimated as 32,400 m^3. We can verify this by using the geometry of the triangle:

$$1/2(\text{base})(\text{height}) = (0.5)(6\ h)(5.0\ m^3/s - 2.0\ m^3/s)(3{,}600\ s/h) = 32{,}400\ m^3$$

Since we wish to construct a *unit hydrograph,* we need to determine whether or not this storm produced 1.0 cm of rainfall excess over the watershed. If it did, then we may use the ordinates directly. If not, then we must adjust the ordinates so that they would be equivalent to that produced by a 1.0 cm rainfall excess. We can determine whether or not this storm produced 1.0 cm by dividing the volume of rainfall by the area of the watershed (given as 16.2 km^2):

$$\frac{32{,}400\ m^3}{(16.2\ km^2)(1 \times 10^6\ m^2/km^2)} \times 100\ cm/m = 0.20\ cm$$

It is obvious that the storm is too small and, hence, the ordinates are too small. By dividing the ordinates by the storm depth, we can synthesize ordinates for a unit hydrograph. For example, for the first DRH ordinate:

$$\frac{\text{DRH ordinate}}{\text{Storm depth}} = \frac{0.5\ m^3/s}{0.2\ cm} = 2.5\ m^3/s \cdot cm$$

This ordinate would be located at the center of the slice that was used to establish it, i.e., halfway between 1000 and 1100 hours (see the arrows in Figure 2-14), i.e., 1030. For a generic hydrograph starting at a time equal to zero, the plotting point would be 0.5 h. The remaining unit hydrograph ordinates are tabulated below.

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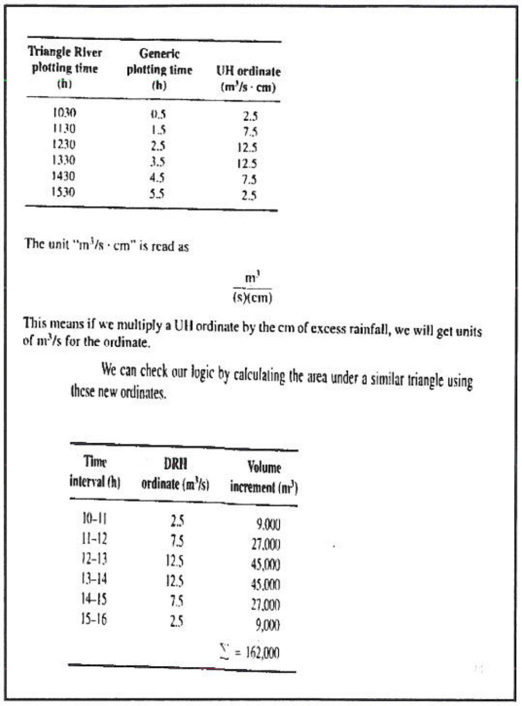


Triangle River plotting time (h)	Generic plotting time (h)	UH ordinate ($m^3/s \cdot cm$)
1030	0.5	2.5
1130	1.5	7.5
1230	2.5	12.5
1330	3.5	12.5
1430	4.5	7.5
1530	5.5	2.5

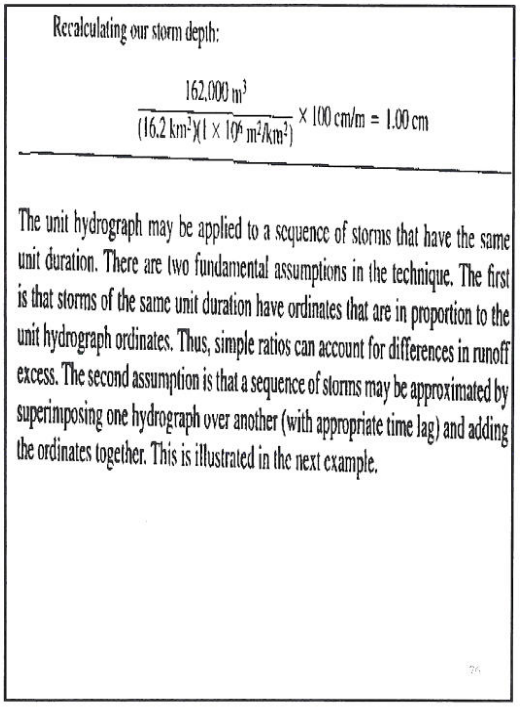
The unit "$m^3/s \cdot cm$" is read as

$$\frac{m^3}{(s)(cm)}$$

This means if we multiply a UH ordinate by the cm of excess rainfall, we will get units of m^3/s for the ordinate.

We can check our logic by calculating the area under a similar triangle using these new ordinates.

Time interval (h)	DRH ordinate (m^3/s)	Volume increment (m^3)
10–11	2.5	9,000
11–12	7.5	27,000
12–13	12.5	45,000
13–14	12.5	45,000
14–15	7.5	27,000
15–16	2.5	9,000
		$\sum$ = 162,000



Recalculating our storm depth:

$$\frac{162{,}000\ m^3}{(16.2\ km^2)(1 \times 10^6\ m^2/km^2)} \times 100\ cm/m = 1.00\ cm$$

The unit hydrograph may be applied to a sequence of storms that have the same unit duration. There are two fundamental assumptions in the technique. The first is that storms of the same unit duration have ordinates that are in proportion to the unit hydrograph ordinates. Thus, simple ratios can account for differences in runoff excess. The second assumption is that a sequence of storms may be approximated by superimposing one hydrograph over another (with appropriate time lag) and adding the ordinates together. This is illustrated in the next example.

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Unit Hydrograph Method

- Hyetograph / Definition
  - A plot between rainfall excess (cm) vs. time (h)
- Figure 2.15 shows three sequential storms that have the same durations of 1 hour

Example 2-5. Using the hyetograph in Figure 2-15, and the unit hydrograph ordinates from Example 2-4, determine the DRH ordinates and compound runoff.

Solution. The tabular computations are shown below. The explanation follows the table.

Time interval	Time (h)	Rainfall excess (cm)	DRH ordinates 1	2	3	Compound runoff (m^3/s)
1	0–1	0.5	1.25	N/A	N/A	1.25
2	1–2	2.0	3.75	5.0	N/A	8.75
3	2–3	1.0	6.25	15.0	2.5	23.75
4	3–4	0.0	6.25	25.0	7.5	38.75
5	4–5	0.0	3.75	25.0	12.5	41.25
6	5–6	0.0	1.25	15.0	12.5	28.75
7	6–7	0.0	0.0	5.0	7.5	12.5
8	7–8	0.0	0.0	0.0	2.5	2.5

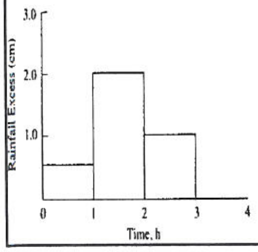
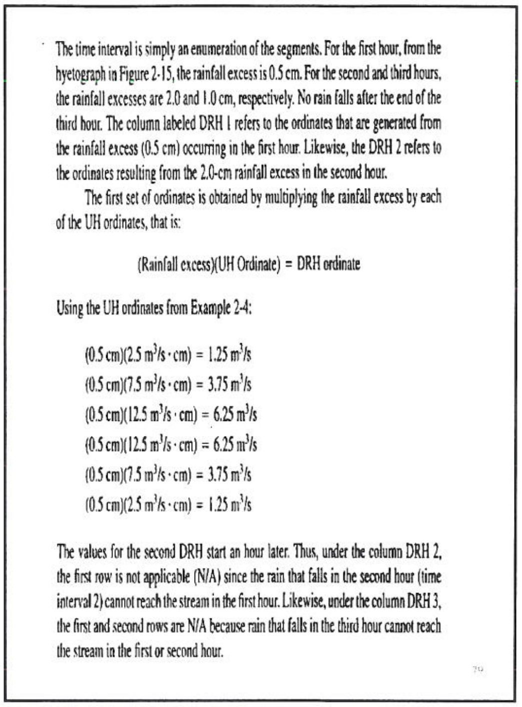


FIGURE 2-15
Hyetograph for Triangle River basin.



The time interval is simply an enumeration of the segments. For the first hour, from the hyetograph in Figure 2-15, the rainfall excess is 0.5 cm. For the second and third hours, the rainfall excesses are 2.0 and 1.0 cm, respectively. No rain falls after the end of the third hour. The column labeled DRH 1 refers to the ordinates that are generated from the rainfall excess (0.5 cm) occurring in the first hour. Likewise, the DRH 2 refers to the ordinates resulting from the 2.0-cm rainfall excess in the second hour.

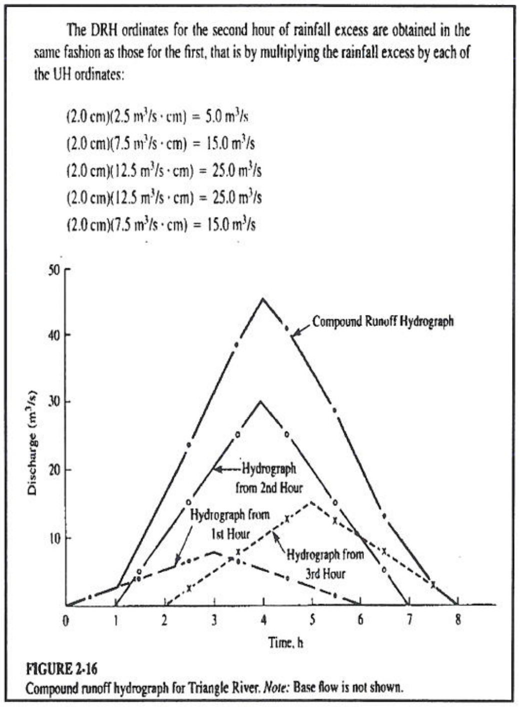
The first set of ordinates is obtained by multiplying the rainfall excess by each of the UH ordinates, that is:

$$(\text{Rainfall excess})(\text{UH Ordinate}) = \text{DRH ordinate}$$

Using the UH ordinates from Example 2-4:

$$(0.5\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 1.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 3.75\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 6.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 6.25\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 3.75\ \text{m}^3/\text{s}$$
$$(0.5\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 1.25\ \text{m}^3/\text{s}$$

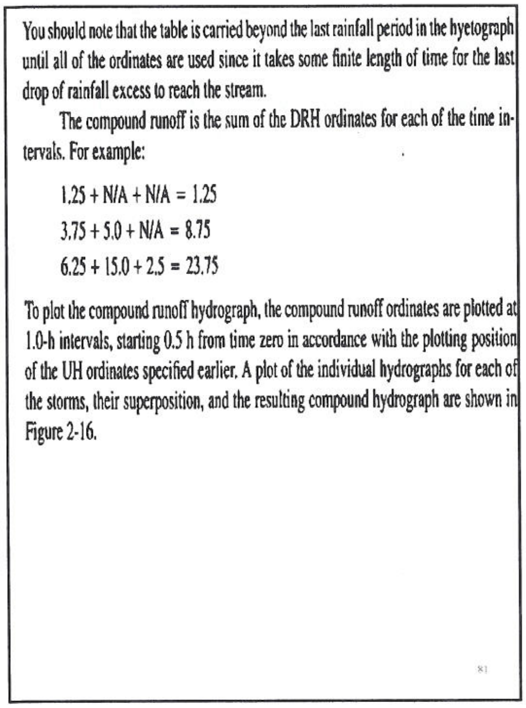
The values for the second DRH start an hour later. Thus, under the column DRH 2, the first row is not applicable (N/A) since the rain that falls in the second hour (time interval 2) cannot reach the stream in the first hour. Likewise, under the column DRH 3, the first and second rows are N/A because rain that falls in the third hour cannot reach the stream in the first or second hour.



The DRH ordinates for the second hour of rainfall excess are obtained in the same fashion as those for the first, that is by multiplying the rainfall excess by each of the UH ordinates:

$$(2.0\ \text{cm})(2.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 5.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 15.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 25.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(12.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 25.0\ \text{m}^3/\text{s}$$
$$(2.0\ \text{cm})(7.5\ \text{m}^3/\text{s}\cdot\text{cm}) = 15.0\ \text{m}^3/\text{s}$$

FIGURE 2-16
Compound runoff hydrograph for Triangle River. *Note:* Base flow is not shown.



You should note that the table is carried beyond the last rainfall period in the hyetograph until all of the ordinates are used since it takes some finite length of time for the last drop of rainfall excess to reach the stream.

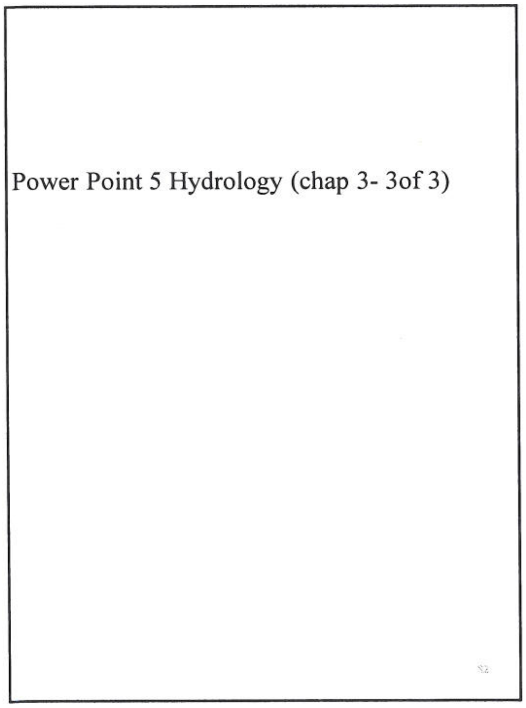
The compound runoff is the sum of the DRH ordinates for each of the time intervals. For example:

1.25 + N/A + N/A = 1.25

3.75 + 5.0 + N/A = 8.75

6.25 + 15.0 + 2.5 = 23.75

To plot the compound runoff hydrograph, the compound runoff ordinates are plotted at 1.0-h intervals, starting 0.5 h from time zero in accordance with the plotting position of the UH ordinates specified earlier. A plot of the individual hydrographs for each of the storms, their superposition, and the resulting compound hydrograph are shown in Figure 2-16.



Power Point 5 Hydrology (chap 3- 3of 3)

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

$$\frac{Storage}{Unit\ of\ Time} =$$

$$\frac{Volume\ of\ \text{Precipitation}}{Unit\ of\ Time} - \frac{Volume\ of\ Runoff}{Unit\ of\ Time}$$

$$\frac{dS}{dt} = \frac{\forall_P}{dt} - \frac{\forall_R}{dt}$$

(2-10)

$$\frac{\forall_P}{dt} = \frac{\forall_R}{dt}$$

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

$$\boxed{\frac{\forall_P}{dt} = iA}$$ (2-11)

$$Q = 0.0028\,CiA$$ (2-12)

Q = peak runoff rate, m^3/s
C = runoff coefficient
i = average rainfall intensity, mm/h
A = area of watershed, ha
0.0028 = conversion factor, $m^3{*}h/mm{*}ha{*}s$

RUNOFF ANALYSIS
Estimation of Runoff Quantity
Rational Method

- Why is it called Rational Method?
- In "English Units" system, the relationship does not require any conversion factor

$$Q = CiA$$

Q = peak runoff rate, ft^3/s
C = runoff coefficient
i = average rainfall intensity, in/h
A = area of watershed, acres

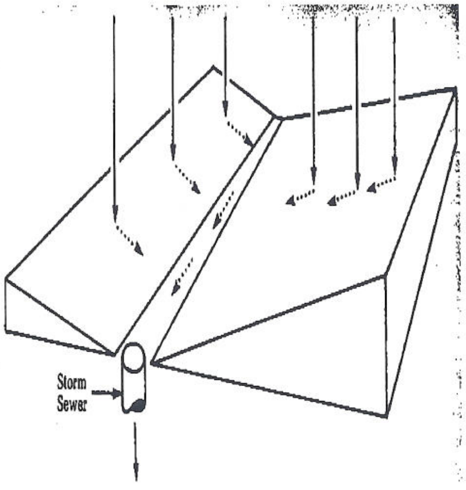


FIGURE 2-17
The application of the hydrologic equation to a parking lot having area = A.

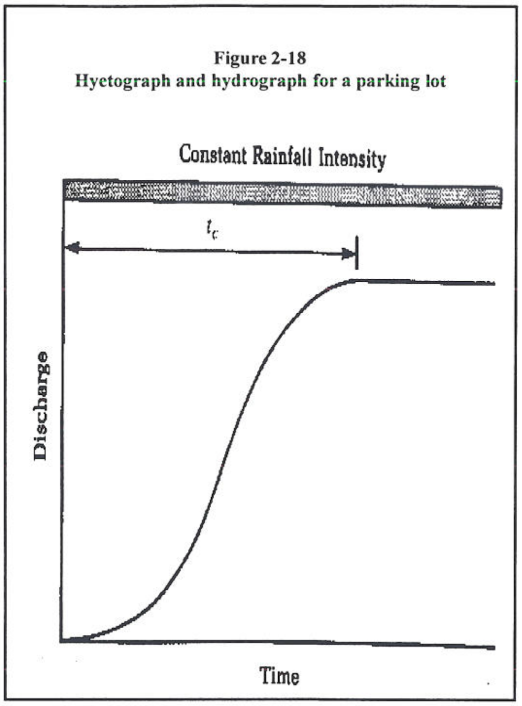
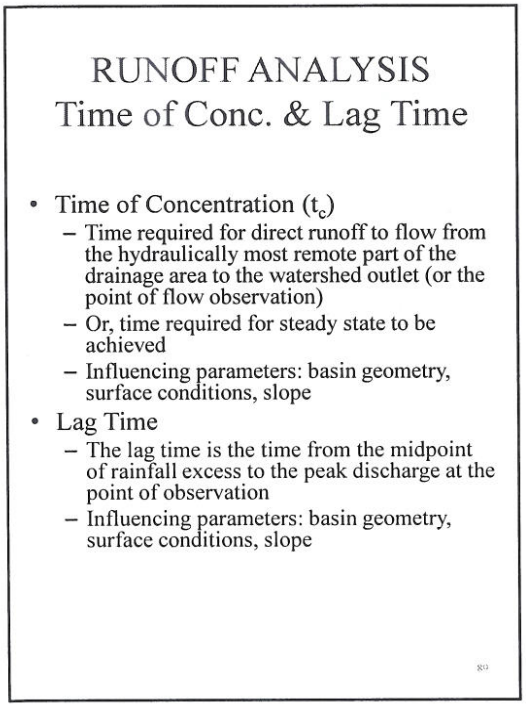


Figure 2-18
Hyetograph and hydrograph for a parking lot

RUNOFF ANALYSIS
Importance of Time of Concentration in Rational Method

- Important assumption in Rational Method
  - The average rainfall intensity used in Rational Method (Eq. 2-12) has continued for a period long enough to establish direct runoff
  - and that the rainfall has continued long enough to equal or exceed 't_c'



RUNOFF ANALYSIS
Time of Conc. & Lag Time

- Time of Concentration (t_c)
  - Time required for direct runoff to flow from the hydraulically most remote part of the drainage area to the watershed outlet (or the point of flow observation)
  - Or, time required for steady state to be achieved
  - Influencing parameters: basin geometry, surface conditions, slope
- Lag Time
  - The lag time is the time from the midpoint of rainfall excess to the peak discharge at the point of observation
  - Influencing parameters: basin geometry, surface conditions, slope

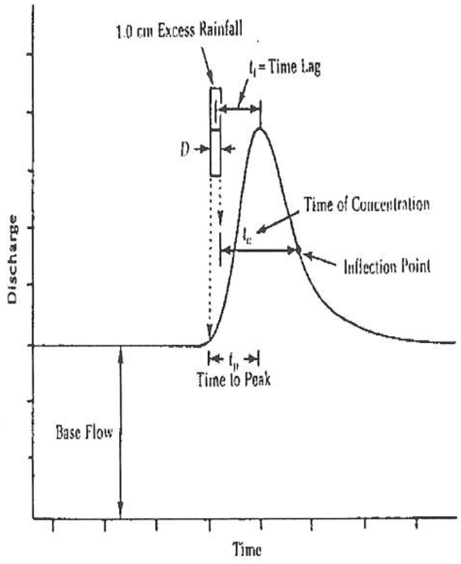


FIGURE 2-13
An idealized hydrograph showing a uniform base flow and a superimposed direct runoff hydrograph resulting from 1.0 cm of rainfall excess.

Example 2.6

- Review Example 2.6

RUNOFF ANALYSIS Estimation of Time of Concentration

$$t_c = \frac{1.8(1.1 - C)\sqrt{3.28D}}{\sqrt[3]{S}} \qquad \text{(2-13)}$$

t_c = time of concentration, min
C = runoff coefficient
D = overland flow distance, m
S = slope, %

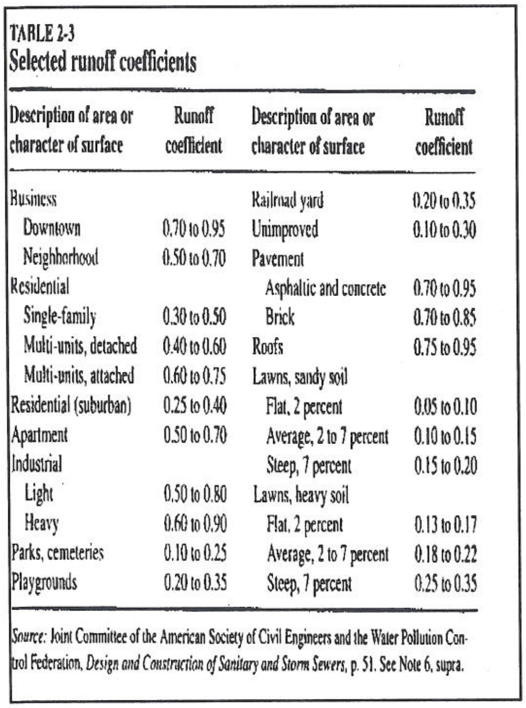
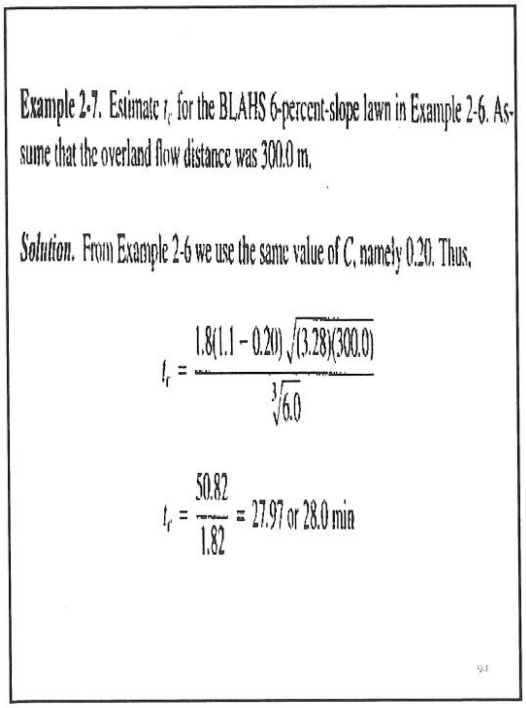


TABLE 2-3
Selected runoff coefficients

Description of area or character of surface	Runoff coefficient	Description of area or character of surface	Runoff coefficient
Business		Railroad yard	0.20 to 0.35
Downtown	0.70 to 0.95	Unimproved	0.10 to 0.30
Neighborhood	0.50 to 0.70	Pavement	
Residential		Asphaltic and concrete	0.70 to 0.95
Single-family	0.30 to 0.50	Brick	0.70 to 0.85
Multi-units, detached	0.40 to 0.60	Roofs	0.75 to 0.95
Multi-units, attached	0.60 to 0.75	Lawns, sandy soil	
Residential (suburban)	0.25 to 0.40	Flat, 2 percent	0.05 to 0.10
Apartment	0.50 to 0.70	Average, 2 to 7 percent	0.10 to 0.15
Industrial		Steep, 7 percent	0.15 to 0.20
Light	0.50 to 0.80	Lawns, heavy soil	
Heavy	0.60 to 0.90	Flat, 2 percent	0.13 to 0.17
Parks, cemeteries	0.10 to 0.25	Average, 2 to 7 percent	0.18 to 0.22
Playgrounds	0.20 to 0.35	Steep, 7 percent	0.25 to 0.35

Source: Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation, *Design and Construction of Sanitary and Storm Sewers*, p. 51. See Note 6, supra.



Example 2-7. Estimate t_c for the BLAHS 6-percent-slope lawn in Example 2-6. Assume that the overland flow distance was 300.0 m.

Solution. From Example 2-6 we use the same value of C, namely 0.20. Thus,

$$t_c = \frac{1.8(1.1 - 0.20)\sqrt{(3.28)(300.0)}}{\sqrt[3]{6.0}}$$

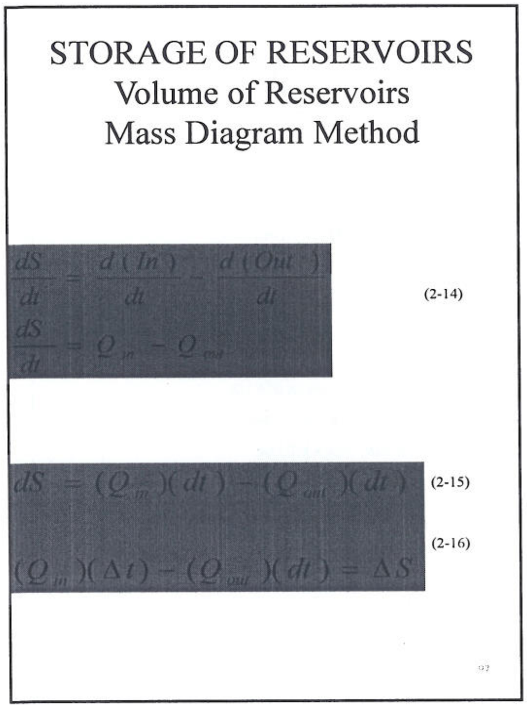
$$t_c = \frac{50.82}{1.82} = 27.97 \text{ or } 28.0 \text{ min}$$

Storms of Different Frequencies: Which One to Use?

- Which storm should be used for design?
  - 50 year storm
  - 100 year storm
- Cost-benefit-analysis should be employed
- Storm sewer design (Typical)
  - Residential area - 2 to 15 years
  - Commercial area - 10 to 50 years
- Various other factors should be considered as appropriate

STORAGE OF RESERVOIRS
Classification of Reservoirs

- Major reservoirs (> $6x10^7$ m^3)
  - Designed to withstand maximum probable flood
- Intermediate-sized reservoirs ($1x10^6$ m^3 to $6x10^7$ m^3)
  - Designed to withstand most severe storm
- Minor reservoirs (< $1x10^6$ m^3)
  - Designed to withstand 50-100 year storm
- Benefits: Hydroelectric power, irrigation, water supply, navigation, etc.



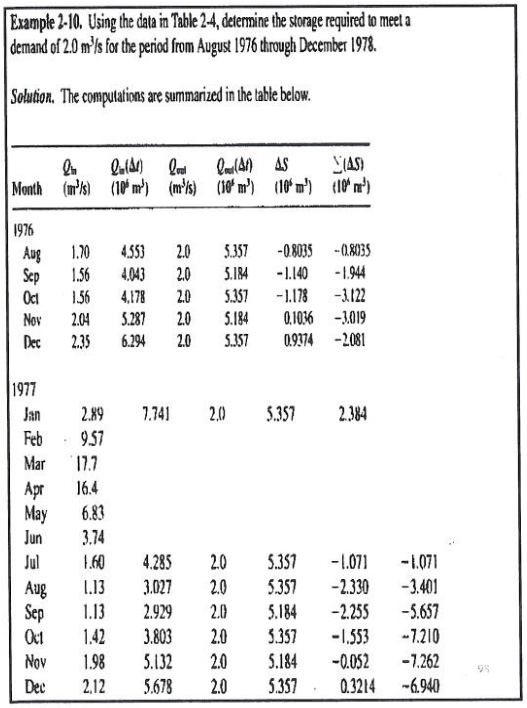
STORAGE OF RESERVOIRS
Volume of Reservoirs
Mass Diagram Method

$$\frac{dS}{dt} = \frac{d(In)}{dt} - \frac{d(Out)}{dt} \qquad (2\text{-}14)$$

$$\frac{dS}{dt} = Q_{in} - Q_{out}$$

$$dS = (Q_{in})(dt) - (Q_{out})(dt) \qquad (2\text{-}15)$$

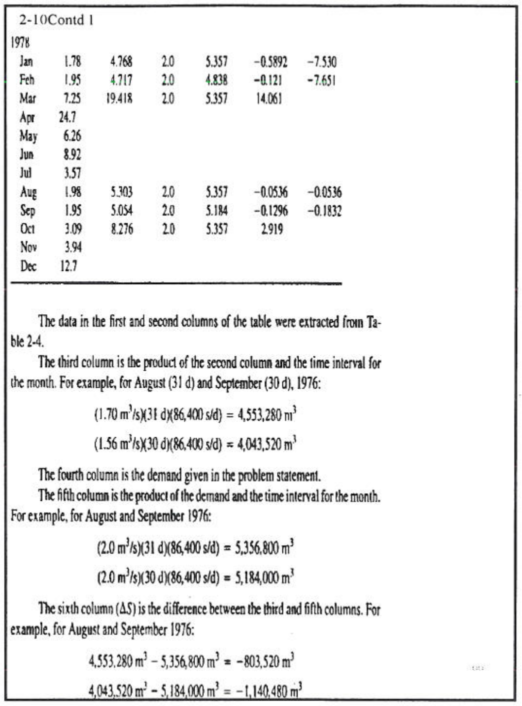
$$(Q_{in})(\Delta t) - (Q_{out})(dt) = \Delta S \qquad (2\text{-}16)$$



Example 2-10. Using the data in Table 2-4, determine the storage required to meet a demand of 2.0 m³/s for the period from August 1976 through December 1978.

Solution. The computations are summarized in the table below.

Month	Q_{in} (m³/s)	$Q_{in}(\Delta t)$ (10⁶ m³)	Q_{out} (m³/s)	$Q_{out}(\Delta t)$ (10⁶ m³)	ΔS (10⁶ m³)	$\sum(\Delta S)$ (10⁶ m³)
1976						
Aug	1.70	4.553	2.0	5.357	−0.8035	−0.8035
Sep	1.56	4.043	2.0	5.184	−1.140	−1.944
Oct	1.56	4.178	2.0	5.357	−1.178	−3.122
Nov	2.04	5.287	2.0	5.184	0.1036	−3.019
Dec	2.35	6.294	2.0	5.357	0.9374	−2.081
1977						
Jan	2.89	7.741	2.0	5.357	2.384	
Feb	9.57					
Mar	17.7					
Apr	16.4					
May	6.83					
Jun	3.74					
Jul	1.60	4.285	2.0	5.357	−1.071	−1.071
Aug	1.13	3.027	2.0	5.357	−2.330	−3.401
Sep	1.13	2.929	2.0	5.184	−2.255	−5.657
Oct	1.42	3.803	2.0	5.357	−1.553	−7.210
Nov	1.98	5.132	2.0	5.184	−0.052	−7.262
Dec	2.12	5.678	2.0	5.357	0.3214	−6.940



2-10Contd 1

1978						
Jan	1.78	4.768	2.0	5.357	−0.5892	−7.530
Feb	1.95	4.717	2.0	4.838	−0.121	−7.651
Mar	7.25	19.418	2.0	5.357	14.061	
Apr	24.7					
May	6.26					
Jun	8.92					
Jul	3.57					
Aug	1.98	5.303	2.0	5.357	−0.0536	−0.0536
Sep	1.95	5.054	2.0	5.184	−0.1296	−0.1832
Oct	3.09	8.276	2.0	5.357	2.919	
Nov	3.94					
Dec	12.7					

The data in the first and second columns of the table were extracted from Table 2-4.

The third column is the product of the second column and the time interval for the month. For example, for August (31 d) and September (30 d), 1976:

$$(1.70\ \text{m}^3/\text{s})(31\ \text{d})(86{,}400\ \text{s/d}) = 4{,}553{,}280\ \text{m}^3$$

$$(1.56\ \text{m}^3/\text{s})(30\ \text{d})(86{,}400\ \text{s/d}) = 4{,}043{,}520\ \text{m}^3$$

The fourth column is the demand given in the problem statement.

The fifth column is the product of the demand and the time interval for the month. For example, for August and September 1976:

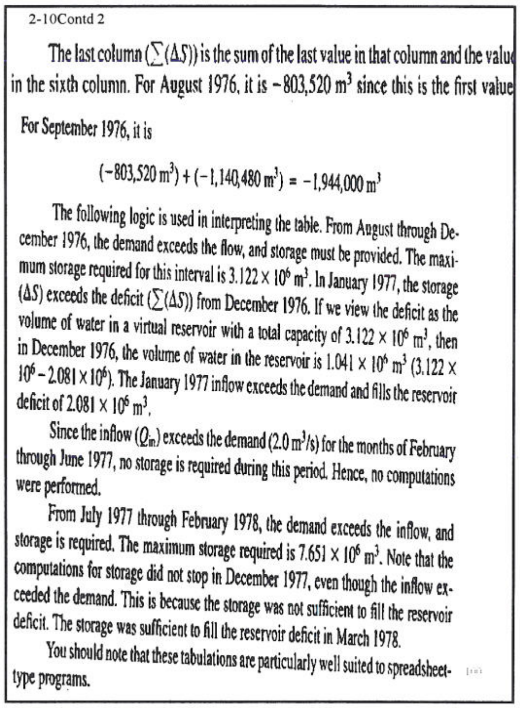
$$(2.0\ \text{m}^3/\text{s})(31\ \text{d})(86{,}400\ \text{s/d}) = 5{,}356{,}800\ \text{m}^3$$

$$(2.0\ \text{m}^3/\text{s})(30\ \text{d})(86{,}400\ \text{s/d}) = 5{,}184{,}000\ \text{m}^3$$

The sixth column (ΔS) is the difference between the third and fifth columns. For example, for August and September 1976:

$$4{,}553{,}280\ \text{m}^3 - 5{,}356{,}800\ \text{m}^3 = -803{,}520\ \text{m}^3$$

$$4{,}043{,}520\ \text{m}^3 - 5{,}184{,}000\ \text{m}^3 = -1{,}140{,}480\ \text{m}^3$$



2-10Contd 2

The last column ($\sum(\Delta S)$) is the sum of the last value in that column and the valu in the sixth column. For August 1976, it is $-803{,}520\ \text{m}^3$ since this is the first value

For September 1976, it is

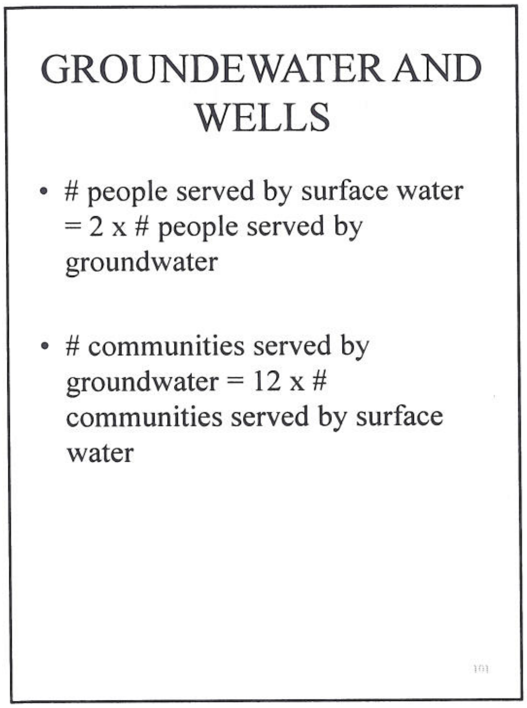
$$(-803{,}520\ \text{m}^3) + (-1{,}140{,}480\ \text{m}^3) = -1{,}944{,}000\ \text{m}^3$$

The following logic is used in interpreting the table. From August through December 1976, the demand exceeds the flow, and storage must be provided. The maximum storage required for this interval is $3.122 \times 10^6\ \text{m}^3$. In January 1977, the storage (ΔS) exceeds the deficit ($\sum(\Delta S)$) from December 1976. If we view the deficit as the volume of water in a virtual reservoir with a total capacity of $3.122 \times 10^6\ \text{m}^3$, then in December 1976, the volume of water in the reservoir is $1.041 \times 10^6\ \text{m}^3$ ($3.122 \times 10^6 - 2.081 \times 10^6$). The January 1977 inflow exceeds the demand and fills the reservoir deficit of $2.081 \times 10^6\ \text{m}^3$.

Since the inflow (Q_{in}) exceeds the demand ($2.0\ \text{m}^3/\text{s}$) for the months of February through June 1977, no storage is required during this period. Hence, no computations were performed.

From July 1977 through February 1978, the demand exceeds the inflow, and storage is required. The maximum storage required is $7.651 \times 10^6\ \text{m}^3$. Note that the computations for storage did not stop in December 1977, even though the inflow exceeded the demand. This is because the storage was not sufficient to fill the reservoir deficit. The storage was sufficient to fill the reservoir deficit in March 1978.

You should note that these tabulations are particularly well suited to spreadsheet-type programs.



GROUNDEWATER AND WELLS

- # people served by surface water = 2 x # people served by groundwater
- # communities served by groundwater = 12 x # communities served by surface water

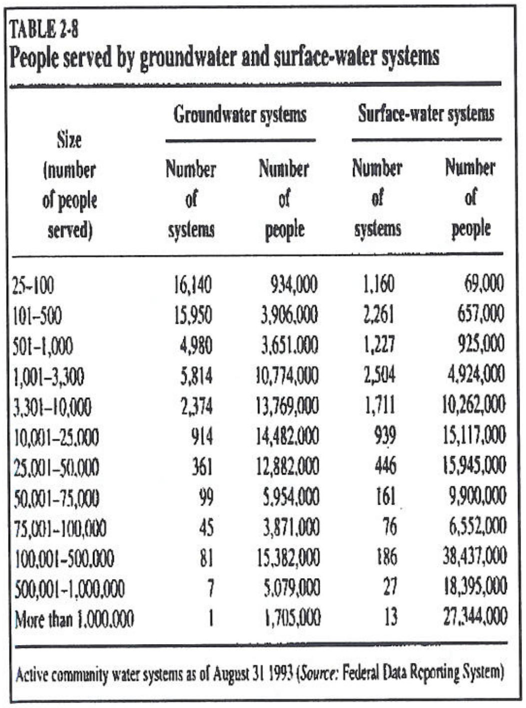


TABLE 2-8
People served by groundwater and surface-water systems

Size (number of people served)	Groundwater systems		Surface-water systems	
	Number of systems	Number of people	Number of systems	Number of people
25–100	16,140	934,000	1,160	69,000
101–500	15,950	3,906,000	2,261	657,000
501–1,000	4,980	3,651,000	1,227	925,000
1,001–3,300	5,814	10,774,000	2,504	4,924,000
3,301–10,000	2,374	13,769,000	1,711	10,262,000
10,001–25,000	914	14,482,000	939	15,117,000
25,001–50,000	361	12,882,000	446	15,945,000
50,001–75,000	99	5,954,000	161	9,900,000
75,001–100,000	45	3,871,000	76	6,552,000
100,001–500,000	81	15,382,000	186	38,437,000
500,001–1,000,000	7	5,079,000	27	18,395,000
More than 1,000,000	1	1,705,000	13	27,344,000

Active community water systems as of August 31 1993 (*Source:* Federal Data Reporting System)

Construction of Wells

- Sanitary Considerations
- Well Covers and Seals
- Disinfection of Wells
- Pump Housing

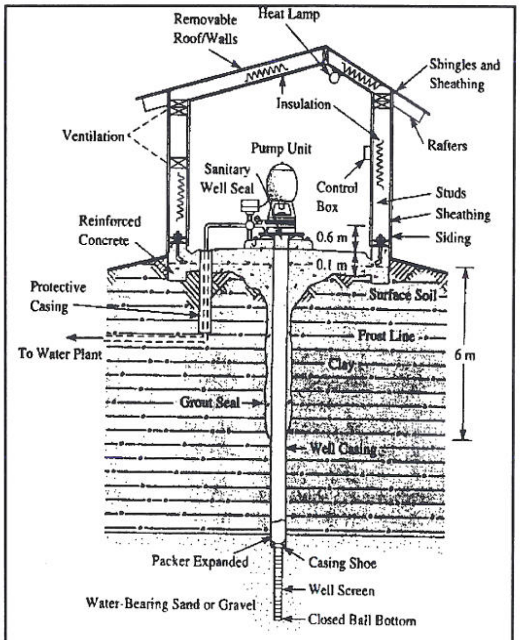


FIGURE 2-22
Pumphouse. [*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems*, (Publication No. EPA-430-9-73-003), Washington, DC: U.S.

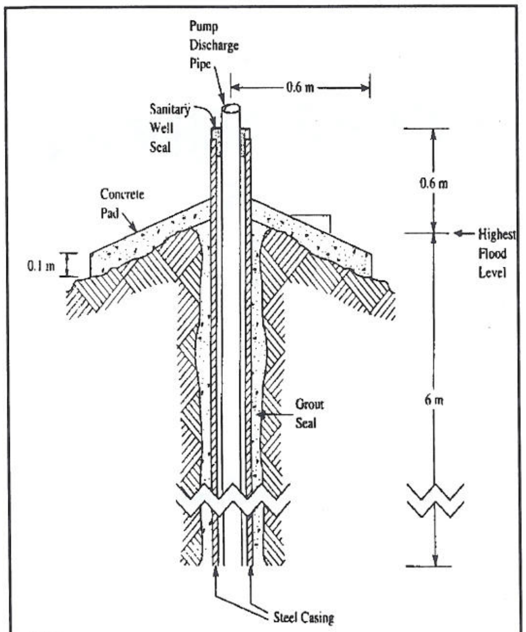


FIGURE 2-23
Sanitary considerations in well construction.

Cone of Depression

- Drawdown
- Radius of influence
- Pumping costs
  - Aquifer composition (clay, coarse sand, gravel)
  - Water table (deep and shallow)
  - Spacing of wells (closer and farther)

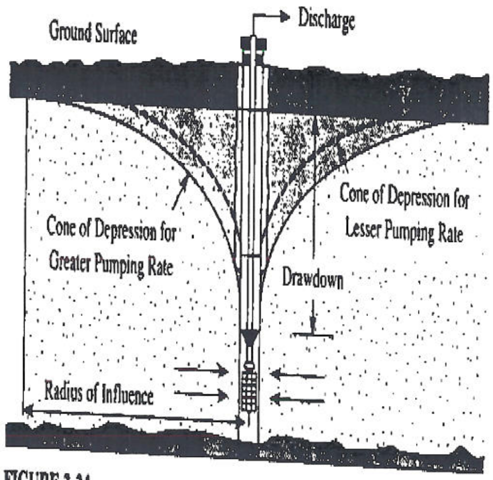


FIGURE 2-24

Effect of pumping rate on cone of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

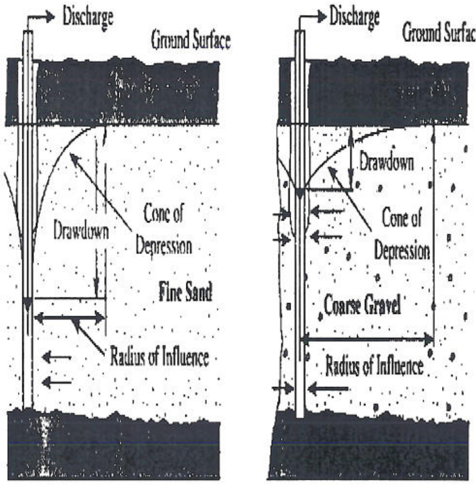


FIGURE 2-25

Effect of aquifer material on cone of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

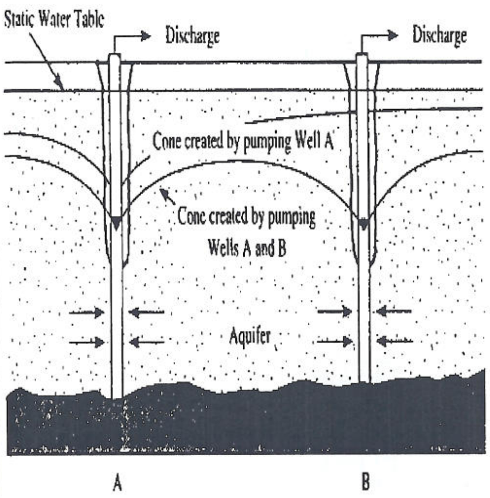


FIGURE 2-26
Effect of overlapping cones of depression. (*Source:* U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems.* See Note 20, supra.)

Groundwater and Wells Definition of Terms

- Porosity: Volume of voids to total volume. Units – No units
- Specific Yield: % water that is free to drain under the influence of gravity. Units – No units
  - What holds water inside aquifer? (surface tension, molecular attraction)
- Storage Coefficient: Volume of available water resulting from a unit decline in the piezometric surface over a unit horizontal cross-sectional area. Units – No units; m^3 of water / m^3 of aquifer

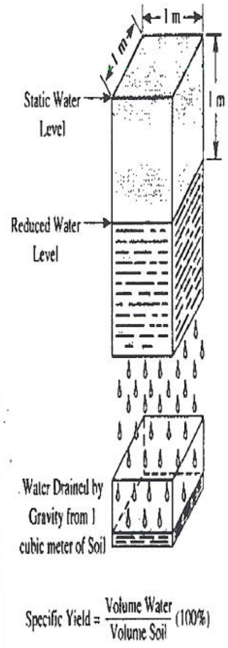


FIGURE 2-27
Specific yield. (*Source:* Johnson Division, UOP, *Ground Water and Wells*, St. Paul, MN: Johnson Division, UOP, 1975. Reprinted by permission.)

Groundwater and Wells Definition of Terms

- Hydraulic Gradient: The slope of the piezometric surface
- Change in head / horizontal distance
- dh/dr

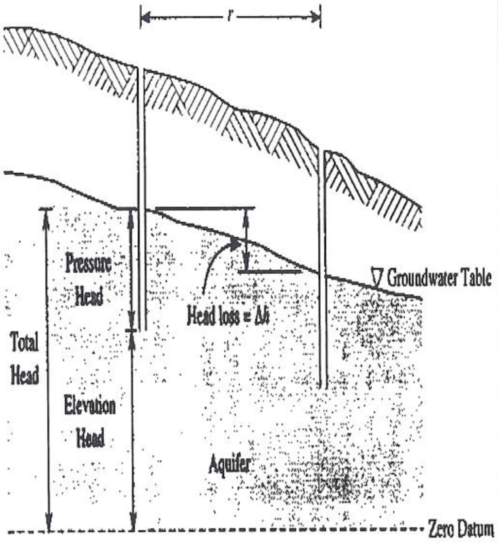
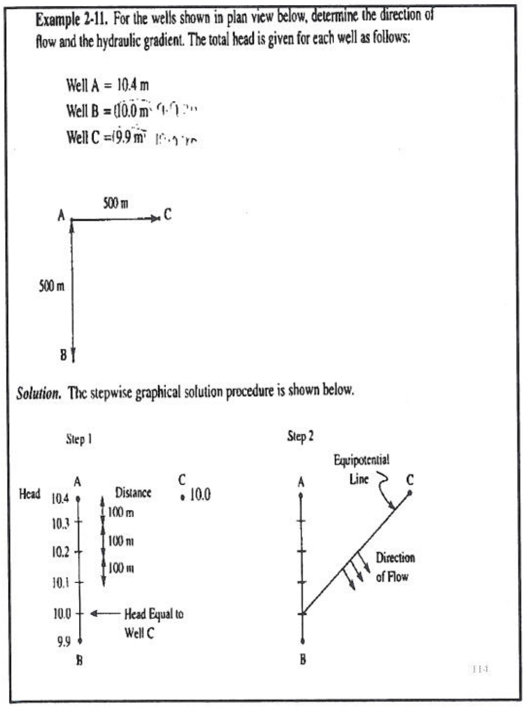


FIGURE 2-28

Geometry for definition of head and hydraulic gradient.



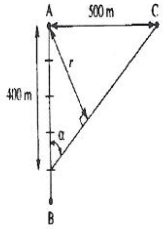
Example 2-11. For the wells shown in plan view below, determine the direction of flow and the hydraulic gradient. The total head is given for each well as follows:

Well A = 10.4 m
Well B = 10.0 m 9.9 m
Well C = 9.9 m 10.0 m

Solution. The stepwise graphical solution procedure is shown below.

2-11Contd 1

Step 3



The distance r must be determined in order to calculate the hydraulic gradient. From the plan view, we may note that the wells form a right triangle with legs of 400 m and 500 m. The angle α may be computed as:

$$\tan^{-1}(\alpha) = \frac{500}{400}$$

and $\alpha = 51.34°$

The distance r is

$$r = (400)\sin\alpha = 400 \sin 51.34 = 312.35 \text{ m}$$

The hydraulic gradient is then:

$$\text{Hydraulic gradient} = \frac{10.4 \text{ m} - 10.0 \text{ m}}{312.35 \text{ m}} = 0.00128$$

Note that the hydraulic gradient has no units.

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Groundwater and Wells Definition of Terms

- Hydraulic Conductivity: Property of an aquifer that is a measure of its ability to transmit water under a sloping piezometric surface
- Also, the discharge that occurs through a unit cross section of aquifer under a hydraulic gradient of ‘1’
- Units – m/sec

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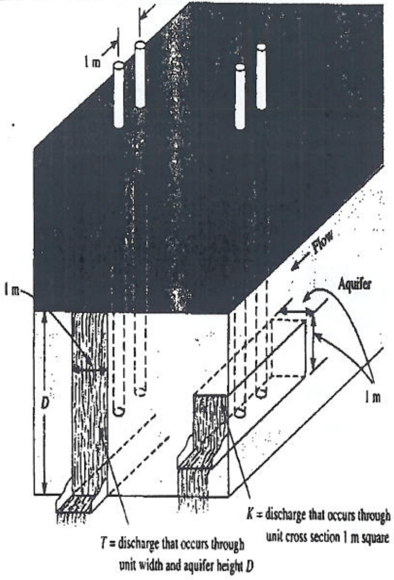


FIGURE 2-29
Illustration of definition of hydraulic conductivity (*K*) and transmissibility (*T*). (*Source:* Johnson Division, UOP, *Ground Water and Wells*. Reprinted by permission. See source note for Figure 2-26, supra.)

Groundwater and Wells Definition of Terms

- Transmissibility (T): A measure of the rate at which water will flow through a unit width of aquifer extending through its full saturated thickness under a unit hydraulic gradient
- Units – m^2/s

Well Hydraulics

- Darcy’s Equation

$$v = K \frac{dh}{dr} \quad (2\text{-}19)$$

$$A'v' = Av = Q \quad (2\text{-}20)$$

$$v' = \frac{Av}{A'} \quad (2\text{-}21)$$

- Darcy’s Equation

$$v' = \frac{ALv}{A'L} \quad (2\text{-}23)$$

$$v' = \frac{DarcyVeloc\ ity}{Porosity} = \frac{v}{\eta} \quad (2\text{-}24)$$

$$Q = vA = KA \frac{dh}{dr} \quad (2\text{-}25)$$

Well Hydraulics

- Darcy's Equation (2-25) has been solved for steady and non-steady (transient) flows.
- Assumptions:
  - Pumping at constant rate
  - Flow towards the well is radial and uniform
  - Initially piezometric surface is horizontal
  - Well penetrates the entire depth of aquifer
  - Aquifer is homogeneous and is of infinite length
  - Water is released from aquifer in immediate response to a drop in the piezometric surface

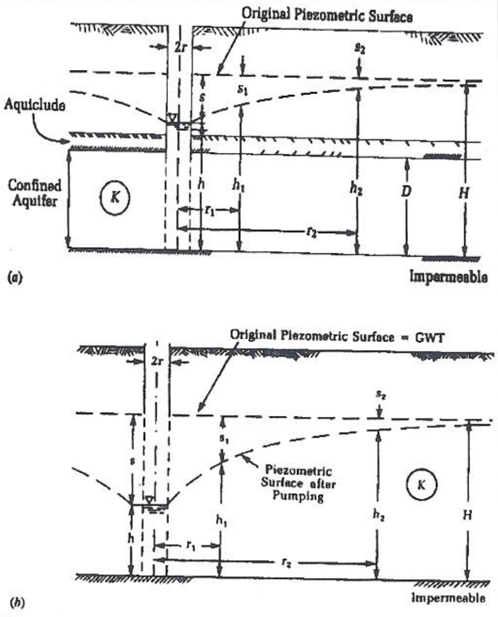


FIGURE 2-30
Geometry and symbols for a pumped well in (*a*) confined aquifer and (*b*) unconfined aquifer. (*Source:* H. Bouwer, *Groundwater Hydrology,* New York: McGraw-Hill, 1978. Reprinted by permission.)

Stead-flow
Confined or Artisan Aquifer

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2/r_1)} \quad (2\text{-}26)$$

- Q, discharge, m^3/s
- T – transmissibility, m^3/s (K x D)
- D - thickness of aquifer, m
- h_1, h_2 – heights of piezometric surfaces above the bottom of aquifer, m
- r_1, r_2 – radii of influence, m

Example 2-12. An artesian aquifer 10.0 m thick with a piezometric surface 40.0 m above the bottom confining layer is being pumped by a fully penetrating well. The aquifer is a medium sand with a hydraulic conductivity of 1.50×10^{-4} m/s. Steady state drawdowns of 5.00 m and 1.00 m are observed at two nonpumping wells located 20.0 m and 200.0 m, respectively, from the pumped well. Determine the discharge at the pumped well.

Solution. First we determine h_1 and h_2:

$$h_1 = 40.0 - 5.00 = 35.0 \text{ m}$$

$$h_2 = 40.0 - 1.00 = 39.0 \text{ m}$$

so

$$Q = \frac{(2\pi)(1.50 \times 10^{-4})(10.0)(39.0 - 35.0)}{\ln(200/20)}$$

$$Q = 0.0164 \text{ or } 0.016 \text{ m}^3/\text{s}$$

Steady-flow Unconfined Aquifer

$$Q = \frac{\pi K (h_2^2 - h_1^2)}{\ln(r_2/r_1)} \quad (2\text{-}27)$$

- Q, discharge, m^3/s
- T – transmissibility, m^3/s (K x D)
- D - thickness of aquifer, m
- h_1, h_2 – heights of piezometric surfaces above the bottom of aquifer, m
- r_1, r_2 – radii of influence, m

Example 2-13. A 0.50 m diameter well fully penetrates an unconfined aquifer which is 30.0 m thick. The drawdown at the pumped well is 10.0 m and the hydraulic conductivity of the gravel aquifer is 6.4×10^{-3} m/s. If the flow is steady and the discharge is 0.014 m^3/s, determine the drawdown at a site 100.0 m from the well.

Solution. First we calculate h_1

$$h_1 = 30.0 - 10.0 = 20.0 \text{ m}$$

Then we apply Equation 2-27 and solve for h_2. Note that $r_1 = 0.50 \text{ m}/2 = 0.25$ m.

$$0.014 = \frac{\pi(6.4 \times 10^{-3})(h_2^2 - (20.0)^2)}{\ln(100/0.25)}$$

$$h_2^2 - 400.0 = \frac{(0.014)(5.99)}{\pi(6.4 \times 10^{-3})}$$

$$h_2 = (4.17 + 400.0)^{1/2}$$

$$h_2 = 20.10 \text{ m}$$

The drawdown is then

$$s_2 = H - h_2 = 30.0 - 20.10 = 9.90 \text{ m}$$

Unsteady-flow
Confined or Artisan Aquifer

$$s = \frac{Q}{4\pi T}\int_u^{\infty}\left(\frac{e^{-u}}{u}\right)du \quad (2\text{-}28)$$

s = drawdown (H-h), m

$$u = \frac{r^2 S}{4Tt}$$

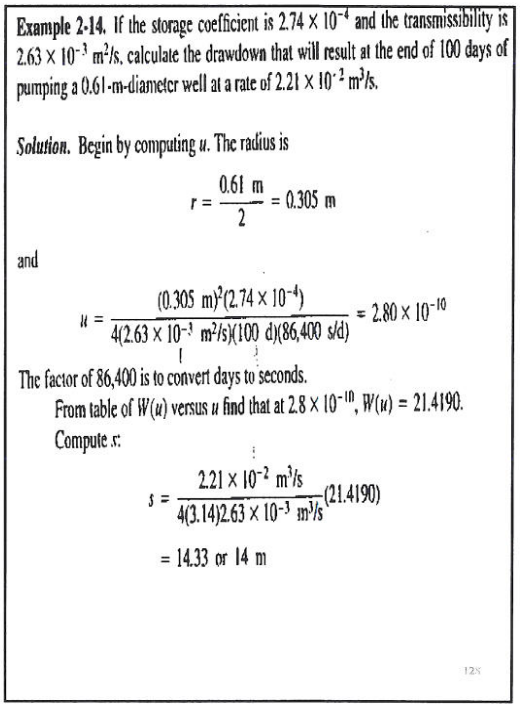
r = distance between pumping well and observation well, or radius of pumping well, m

S = storage coefficient

T = transmissibility, m2/s

t = time since pumping began, s

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \ldots \quad (2\text{-}29)$$



Example 2-14. If the storage coefficient is 2.74×10^{-4} and the transmissibility is 2.63×10^{-3} m^2/s, calculate the drawdown that will result at the end of 100 days of pumping a 0.61-m-diameter well at a rate of 2.21×10^{-2} m^3/s.

Solution. Begin by computing u. The radius is

$$r = \frac{0.61 \text{ m}}{2} = 0.305 \text{ m}$$

and

$$u = \frac{(0.305 \text{ m})^2(2.74 \times 10^{-4})}{4(2.63 \times 10^{-3} \text{ m}^2/\text{s})(100 \text{ d})(86{,}400 \text{ s/d})} = 2.80 \times 10^{-10}$$

The factor of 86,400 is to convert days to seconds.

From table of $W(u)$ versus u find that at 2.8×10^{-10}, $W(u) = 21.4190$.

Compute s:

$$s = \frac{2.21 \times 10^{-2} \text{ m}^3/\text{s}}{4(3.14)2.63 \times 10^{-3} \text{ m}^3/\text{s}}(21.4190)$$

$$= 14.33 \text{ or } 14 \text{ m}$$

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Unsteady flow in Unconfined Aquifer

- No reliable solution has been developed so far

Hydraulic Properties of a Confined Aquifer – Steady State

$$T = \frac{Q \ln(r_2 / r_1)}{2\pi(s_1 - s_2)} \quad (2\text{-}30)$$

where s_1=drawdown at radius r_1
s_2=drawdown at radius r_2

Hydraulic Properties of a Confined Aquifer – Transient/Unsteady

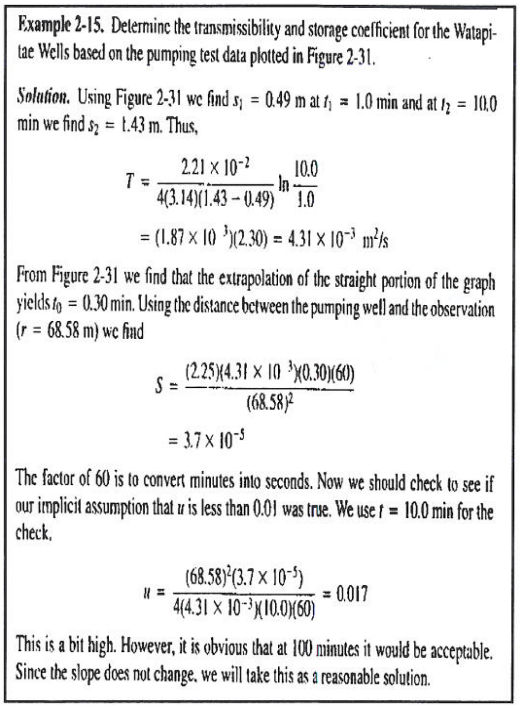
$$s = \frac{Q}{4\pi T} \ln \frac{2.25Tt}{r^2 S} \qquad (2\text{-}31)$$

Solving for T, we find

$$s_2 - s_1 = \frac{Q}{4\pi T} \ln \frac{t_2}{t_1} \qquad (2\text{-}32)$$

$$T = \frac{Q}{4\pi (s_2 - s_1)} \ln \frac{t_2}{t_1} \qquad (2\text{-}33)$$

$$S = \frac{2.25\,Tt_0}{r^2} \qquad (2\text{-}34)$$



Example 2-15. Determine the transmissibility and storage coefficient for the Watapitae Wells based on the pumping test data plotted in Figure 2-31.

Solution. Using Figure 2-31 we find $s_1 = 0.49$ m at $t_1 = 1.0$ min and at $t_2 = 10.0$ min we find $s_2 = 1.43$ m. Thus,

$$T = \frac{2.21 \times 10^{-2}}{4(3.14)(1.43 - 0.49)} \ln \frac{10.0}{1.0}$$

$$= (1.87 \times 10^{\ 3})(2.30) = 4.31 \times 10^{-3}\ \text{m}^2/\text{s}$$

From Figure 2-31 we find that the extrapolation of the straight portion of the graph yields $t_0 = 0.30$ min. Using the distance between the pumping well and the observation ($r = 68.58$ m) we find

$$S = \frac{(2.25)(4.31 \times 10^{\ 3})(0.30)(60)}{(68.58)^2}$$

$$= 3.7 \times 10^{-5}$$

The factor of 60 is to convert minutes into seconds. Now we should check to see if our implicit assumption that u is less than 0.01 was true. We use $t = 10.0$ min for the check,

$$u = \frac{(68.58)^2(3.7 \times 10^{-5})}{4(4.31 \times 10^{-3})(10.0)(60)} = 0.017$$

This is a bit high. However, it is obvious that at 100 minutes it would be acceptable. Since the slope does not change, we will take this as a reasonable solution.

1. What are combined sewers? -- expected to accommodate both municipal wastewater and stormwater. (page 11)
2. What is a lift station? -- location of a sewage pump that pumps vertically to discharge into a higher-elevation gravity sewer. (page 11)
3. What is a unit hydrograph? -- it is a direct runoff hydrograph (drh) that results from a unit precipitation excess (say 1 cm) over a watershed for a unit period of time
4. Time Dependant Reactions are called Kinetic Reactions.
5. Know how to graph a IDF curve. It is in the slides (chapter 3 part 2), something like 5 yr storm, which will be under 10 yr storm, which will be under 20 yr storm, etc. like in the slide

these are the questions chad marked and told me he remembered. also something with the variables: Ct, C0, k, theta. which i think is the zero order equation on page 70 in chapter 2.

ENCE 3323: Introduction to Environmental Engineering
Quiz 1: Chapter 1 through 3

Name: ______________________________

1. Define "steady state."
   Steady state is a condition when there is no accumulation, and/or there is no change with respect to time.

✓ 2. Explain and/or define reactors
   The tanks and/or containers in which physical, chemical, and biological reactions occur are called reactors.

3. Explain about plug-flow reactors
   If fluid particles pass through a tank in sequence, that tank is called as a plug-flow reactor.

✓ 4. What are the two processes through which water is transferred to the earth's atmosphere?
   Evaporation and Transpiration

5. How much snow ("mm of snow") makes the equivalent of "1 mm of rain?"
   10 mm of snow fall make the equivalent of 1 mm of rain

✓ 6. If abstractions are those that reduce the amount of direct runoff, list those four abstractions.
   Evaporation, infiltration, interception, and trapping

✓ 7. Which type of the aquifer listed below is under hydraulic pressure?
   (a) Confined aquifer
   (b) Unconfined aquifer
   (a) Confined aquifer

✓ 8. List the two main sources of water for a stream.
   Direct Runoff
   Exfiltration (opposite of infiltration)

9. What is exfiltration?
Exfiltration is the reverse of infiltration. Seepage of groundwater out of stream banks is called exfiltration. This is also known as the base flow or dry weather flow.

✓10. Arrange the following three geological formations based on their permeability (low to high):

Aquicludes; Aquitards; Aquifers
Aquicludes (impermeable) < Aquitards (intermediate permeability) < Aquifers (permeable)

✓11. List the three types of aquifers.
Confined aquifers
Unconfined aquifers
Perched aquifers

✓12. Evaporation rate (mm/d) increases with wind speed; True or False?
True

✓13. Evaporation rate (mm/d) increases during the days of high relative humidity; True or False?
False

✓14. List the three most important factors in rainfall analysis.
Intensity; Duration; and Frequency

15. What is the difference between "point precipitation analysis" and "spatial analysis?"
In point precipitation analysis, the rain fall data is supplied by single gauge and in spatial analysis the data comes from multiple rain gauges.

16. What is evapotranspiration?
Water loss from plants plus the water loss from the soil surface or root zone

17. What is transpiration?
Water loss from plants is called transpiration

✓18. Intensity and duration of rain fall are directly proportional. Is it true or false?
False

✓19. Storm A and B have the same duration, but Strom A is more intensive. Which storm has the high frequency of occurrence, Storm A or Storm B?
Strom B

✓20. Storm C and D have the same duration, but Strom C is more intensive. Which storm has higher value for "average storm return period (T)," Storm C or Storm D?
Strom C

✓21. List three important factors in "runoff analysis."
What portion of the storm/rain reaches the stream/storm drain?
How long does it take to reach the stream/storm drain?
How often the runoff causes a flooding?

22. What is a hydrograph?
A hydrograph represents the discharge of a stream at a single gauging station

23. Explain the base flow in a hydrograph.
Base flow is due to exfiltration of groundwater from the banks of stream

24. Write the rational equation to estimate runoff quantity and identify the units of each parameter in the equation
$Q = C.i.A;$
Q – *cubic feet/second;* i – *inch/hour;* C – *runoff coefficient;* A – *acres*

✓25. Define "time of concentration."
Time required for direct runoff to flow from the hydraulically most remote part of the drainage area to the watershed outlet (or the point of flow observation)

CHAPTER 3
SOLUTIONS

3-3 Mass balance on storage reservoir and runoff coefficient

Given: watershed area = 4,000 km^2; precipitation = 102 cm/y; flow of river = 34.2 m^3/s; infiltration = 5.5 x 10^{-7} cm/s; evapotranspiration = 40 cm/y

Solution:

a. The mass balance diagram is shown below.

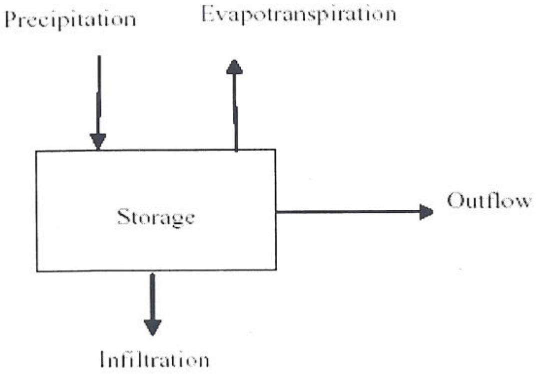


Figure S-3-3 Mass Balance Diagram

b. The mass balance equation is:

ΔStorage = Precipitation - Outflow - Evapotranspiration - Infiltration.

c. It is convenient to solve the mass balance equation in units of cm/y, so converting flow and infiltration:

$$\text{Flow} = \frac{(34.2\ \text{m}^3/\text{s})(86400\ \text{s/d})(365\ \text{d/y})(100\ \text{cm/m})}{(4000\text{km}^2)(1\times10^6\ \text{m}^2/\text{km}^2)} = 26.96\ \text{cm/y}$$

Infiltration = (5.5 x 10^{-7} cm/s)(86,400 s/d)(365 d/y) = 17.34 cm/y

d. Compute the change in storage.

ΔStorage = 102 cm/y - 26.96 cm/y - 40 cm/y - 17.34 cm/y = 17.70 cm/y

The volume for the 4,000 km^2 area,

Volume = (17.70 cm/y)(10^{-2} m/cm)(4,000 km^2)(1 x 10^6 m^2/km^2)

Volume = 7.08 x 10^8 m^3 or 7 x 10^8 m^3

e. The runoff coefficient is

$$C = \frac{\text{runoff}}{\text{precipitation}} = \frac{26.96\text{cm}}{102\text{cm}} = 0.26$$

3-10 IDF curve for 10 y storm

Given: T = 2 y ; n = 45; Table 3-1

Solution:

$$m = \frac{46}{10} = 4.60$$

By interpolation find intensities for selected durations:

Duration (min)	Intensity (mm/h)
5	172.0
10	156.0
15	129.3
20	98.0
30	72.6
40	49.7
50	38.2
60	26.3

3-11 IDF curve for 5 y storm

Given: T = 5 y; n = 10; Annual max data

Solution:

$$m = \frac{11}{5} = 2.20$$

Under each duration find intensity of 2.20 ranked storm by interpolation:

Duration (min)	Intensity (mm/h)
30	118.8
60	96.8
90	77.8
120	52.2

3-13 Parking lot configuration

Given: Vertical and horizontal configurations
For "a" D = 830 m, S = 6.00 %
For "b" D = 600 m, S = 6.00 %

Solution:

a. From Table 3-3 under pavement select C = 0.95 for "asphaltic"

b. For configuration "a"

$$t_c = \frac{1.8(1.1 - 0.95)[(3.28)(830)]^{1/2}}{6.00^{1/3}} = \frac{14.08}{1.817} = 7.75 \text{ min or } 7.8 \text{ min}$$

c. For configuration "b"

$$t_c = \frac{1.8(1.1 - 0.95)[(3.28)(600.00)]^{1/2}}{6.00^{1/3}} = \frac{11.977}{1.817} = 6.59 \text{ min or } 6.6 \text{ min}$$

3-28 Compound runoff hydrograph for Isoceles River

Given: Rainfall excess for 1st hour = 0.1 cm; for 2nd hour R.E. = 0.20 cm; for 3rd ho
R.E. = 0.05 cm; U.H. ordinates from Prob. 3-23.

Solution:

Time	R.E. (cm)	DRH Ordinates			Compound Runoff (m^3/s)
		1	2	3	
1	0.10	1.0	N/A	N/A	1.0
2	0.20	2.0	2.0	N/A	4.0
3	0.05	1.0	4.0	0.5	5.5
4	0.0	0.0	2.0	1.0	3.0
5	0.0	0.0	0.0	0.5	0.5

2-31 Compare efficiency of CMFR and PRF

Given: $\forall = 280\ \text{m}^3$, $Q = 14\ \text{m}^3/\text{d}$, $k = 0.05\ \text{d}^{-1}$

Solution:

a. CMFR

From Table 2-2

$$C_t = \frac{C_o}{1 + k\theta}$$

$$\theta = \frac{\forall}{Q} = \frac{280\text{m}^3}{14\text{m}^3/\text{d}} = 20\text{d}$$

$$\frac{C_t}{C_o} = \left(\frac{1}{1 + (0.05)(20)}\right) = 0.50$$

Using Eqn 2-8

$$\eta = \frac{C_o - 0.50C_o}{C_o} \times 100\% = 50\%$$

b. PFR

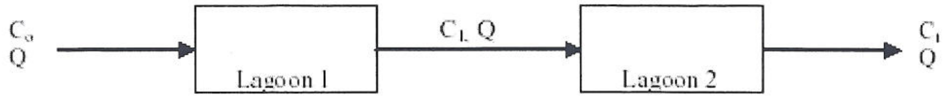
From Table 2-2

2-27 Rate constant for two lagoons in series

Given: Data from Problem 2-26, two lagoons in series, area of each lagoon = 5 ha, depth = 1 m

Solution:

a. Mass balance diagram



Thus, the output from the 1st lagoon is the input to the 2nd lagoon. Solve the problem sequentially.

b. Calculate volume and hydraulic retention time

$$\forall = (5\text{ ha})(10{,}000\text{ m}^2/\text{ha})(1\text{ m}) = 5.0 \times 10^4\text{ m}^3$$

$$\theta = \frac{\forall}{Q} = \frac{5.0\times10^4\text{ m}^3}{8640\text{ m}^3/\text{d}} = 5.787\text{d}$$

c. Using Table 2-2

$$C_1 = \frac{C_o}{1+k\theta}$$

d. Because $C_1 = C_o$ for the second lagoon and the second lagoon has the same relationship

$$C_1 = \frac{C_1}{1+k\theta}$$

Substituting for C_1

$$C_1 = \left(\frac{1}{1+k\theta}\right)\left(\frac{C_o}{1+k\theta}\right)$$

$$\frac{C_1}{C_o} = \left(\frac{1}{1+k\theta}\right)^2$$

$$\left(\frac{C_1}{C_o}\right)^{1/2} = \frac{1}{1+k\theta}$$

$$1+k\theta = \left(\frac{C_o}{C_1}\right)^{1/2}$$

$$k = 0.2136\text{ or }0.21\text{ d}^{-1}$$

$C_t = C_o \exp(-k\theta)$

$$\frac{C_{out}}{C_o} = \exp(-k\theta)$$

$$\frac{C_{out}}{C_o} = \exp(-(0.05)(20))$$

$$\frac{C_{out}}{C_o} = 0.37$$

Using Eqn 2-8

$$\eta = \frac{C_o - 0.37C_o}{C_o} \times 100\% = 63\%$$

2-32 Volume required to achieve 95% efficiency

Given: $Q = 14\ m^3/d$, $k = 0.05$

Solution:

a. Solve Eqn 2-8 for fraction of C_o

$$\eta = 0.95 = \frac{C_o - (X)C_o}{C_o}$$

$$1 - X = 0.95$$

$$X = 0.05$$

Therefore

$$\frac{C_t}{C_o} = 0.05$$

b. CMFR

From Table 2-2

$$C_t = \frac{C_o}{1 + k\theta}$$

Solve for θ

$$\frac{1}{1+k\theta}=\frac{C_i}{C_o}$$

$$\frac{C_o}{C_i}=1+k\theta$$

$$k\theta=\frac{C_o}{C_i}-1$$

$$\theta=\frac{\frac{C_o}{C_i}-1}{k}$$

Substituting values,

$$\theta=\frac{20-1}{0.05}=380\text{d}$$

Solve for the volume

$$\theta=\frac{\forall}{Q}$$

$\forall = (\theta)(Q) = (380\text{ d})(14\text{ m}^3/\text{d}) = 5{,}320\text{ m}^3$

c. PFR

From Table 2-2

$$\frac{C_i}{C_o}=\exp[-k\theta]$$

As in (a.) above

$0.05 = \exp(- 0.05\theta)$

Take the natural log of both sides

$-2.9957 = -0.05\theta$

2-36 Temperature of river after cooling water discharge

Given: River flow rate = 40 m^3/s, river temperature = 18° C, power plant discharge = 2 m^3/s, cooling water temperature = 80° C

Solution:

This is a simple energy balance as in Example 2-12. Assume the density of water is 1000 kg/m^3. The balance equation would be:

$$Q_{river}(\rho)(C_p)(\Delta T) = Q_{cooling\ water}(\rho)(C_p)(\Delta T)$$

Because the density is assumed constant and the specific heat is the same the equivalence reduces to:

$$Q_{river}(T - (273.15 + 18)) = Q_{cooling\ water}((273.15 + 80) - T)$$

Or,

$$40(T - 291.15) = 2(353.15 - T)$$

$$40T - 11{,}646 = 706.30 - 2T$$

$$42T = 12{,}352.30$$

T = 294.10 K or 20.95°C or 21° C

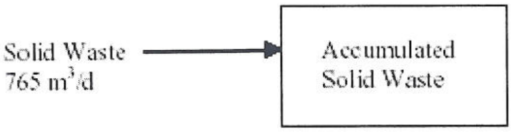
CHAPTER 2
SOLUTIONS

2-1 Expected life of landfill

Given: 16.2 ha at depth of 10 m, 765 m^3 dumped 5 days per week, compacted to twice delivered density

Solution:

a. Mass balance diagram



b. Total volume of landfill

$$(16.2\ \text{ha})(10^4\ \text{m}^2/\text{ha})(10\ \text{m}) = 1.620 \times 10^6\ \text{m}^3 \quad \textcircled{1}$$

c. Volume of solid waste is ½ delivered volume after it is compacted to 2 times its delivered density

$$(765\ \text{m}^3)(0.5) = 382.5\ \text{m}^3$$

d. Annual volume of solid waste placed in landfill

$$(382.5\ \text{m}^3)(5\ \text{d/wk})(52\ \text{wk/y}) = 9.945 \times 10^4\ \text{m}^3/\text{y} \quad \textcircled{2}$$

e. Estimated expected life

$$\frac{\textcircled{1}}{\textcircled{2}} \qquad \frac{1.620\times10^6\ \text{m}^3}{9.945\times10^4\ \text{m}^3/\text{y}} = 16.29 \text{ or } 16 \text{ years}$$

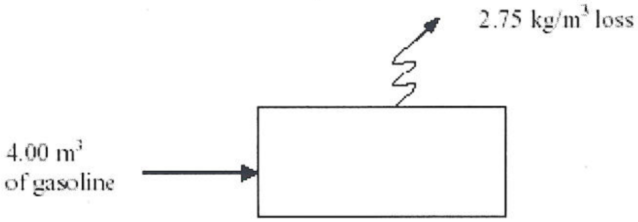
NOTE: the actual life will be somewhat less due to the need to cover the waste with soil each day.

2-4 Annual loss of gasoline

Given: Uncontrolled loss = 2.75 kg/m^3 of gasoline
Controlled loss = 0.095 kg/m^3 of gasoline
Refill tank once a week
Tank volume = 4.00 m^3
Specific gravity of gasoline is 0.80
Condensed vapor density = 0.80 g/mL
Cost of gasoline = \$0.80/L

Solution:

a. Mass balance diagram



b. Annual loss with splash fill method

Loss = (4.00 m^3/wk)(2.75 kg/m^3)(52 wk/y) = 572 kg/y

c. Value of fuel captured with vapor control

Mass captured = (4.00 m^3/wk)(2.75 kg/m^3 – 0.095 kg/m^3)(52 wk/y) = 552.24 kg/y

Value (note: 1.0 g/mL = 1000 kg/m³)

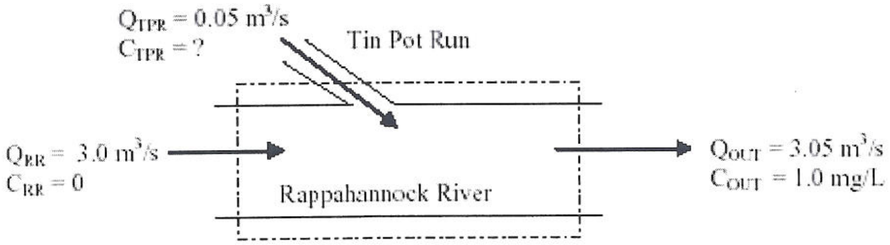
$$\frac{(552.24\,\text{kg/y})(1000\,\text{L/m}^3)}{800\,\text{kg/m}^3}(\$1.06/\text{L}) = \$731.72 \text{ or } \$732/\text{y}$$

2-5 Mass rate of tracer addition

Given: $Q_{RR} = 3.00\ \text{m}^3/\text{s}$, $Q_{TPR} = 0.05\ \text{m}^3/\text{s}$, detection limit = 1.0 mg/L

Solution:

a. Mass balance diagram (NOTE: $Q_{out} = Q_{RR} + Q_{TPR} = 3.05\ \text{m}^3/\text{s}$)



b. Mass balance equation

$$C_{RR}Q_{RR} + C_{TRP}Q_{TPR} = C_{out}Q_{out}$$

Because C_{RR} in = 0 this equation reduces to:

$$C_{TPR}Q_{TPR} = C_{out}Q_{out}$$

c. Note that the quantity $C_{TPR}Q_{TPR}$ is the mass flow rate of the tracer into TPR and substitute values

$$C_{TPR}Q_{TPR} = \frac{1.0\,\text{mg}}{\text{L}} \times \frac{3.05\,\text{m}^3}{\text{s}} \times \frac{1000\,\text{L}}{\text{m}^3} \times \frac{1\text{kg}}{10^6\,\text{mg}} \times \frac{86400\,\text{s}}{\text{d}} = 264\,\text{kg/d}$$

d. Concentration in Tin Pot Run

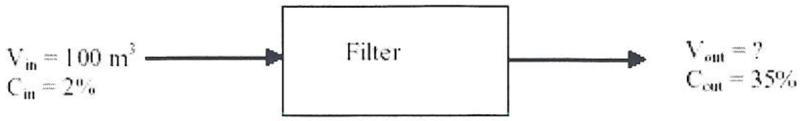
$$C_{TPR} = \frac{C_{TPR}Q_{TPR}}{Q_{TPR}} = \frac{(264\,\text{kg/d})(10^6\ \text{mg/kg})}{(0.05\,\text{m}^3/\text{s})(86400\,\text{s/d})(1000\,\text{L/m}^3)} = 61 \text{ or } 60\ \text{mg/L}$$

2-8 Volume of sludge after filtration

Given: Sludge concentration of 2%, sludge volume = 100 m³, sludge concentration after filtration = 35%

Solution:

a. Mass balance diagram



b. Mass balance equation

$$C_{in}\forall_{in} = C_{out}\forall_{out}$$

c. Solve for $\forall_{out}$

$$V_{out} = \frac{C_{in}\forall_{in}}{C_{out}}$$

d. Substituting values

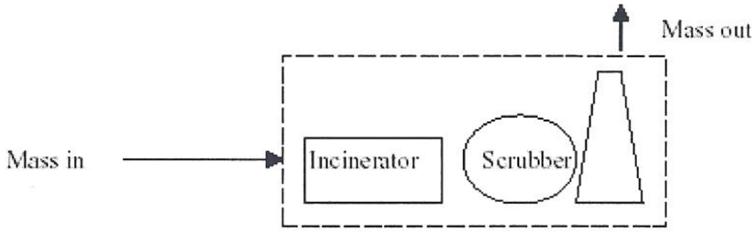
$$V_{out} = \frac{(0.02)(100m^3)}{0.35} = 5.71m^3$$

2-9 Hazardous waste incinerator emission

Given: Four nines DRE
Mass flow rate in = 1.0000 g/s
Incinerator is 90% efficient

Solution:

a. Mass balance diagram



b. Allowable quantity in exit stream

Mass out = (1 - DRE)(Mass in)

= (1 – 0.9999)(1.0000 g/s) = 0.00010 g/s

c. Scrubber efficiency

Mass out of incinerator $= (1 - 0.90)(1.000 \text{ g/s}) = 0.10000$ g/s

Mass out of scrubber must be 0.00010 g/s from "b", therefore

$$\eta = \frac{0.1000\,\text{g/s} - 0.00010\,\text{g/s}}{0.1000\,\text{g/s}} = 0.999 \text{ or } 99.9\%$$

2-10 Sampling filter efficiency

Given: First filter captures 1941 particles
Second filter captures 63 particles
Figure P-2-10
Each filter has same efficiency

Solution:

a. Note that

$$\eta = \frac{C_2}{C_1} \text{ and } \eta = \frac{C_3}{C_2}$$

b. The concentration C_2 is

$$C_2 = C_1 - 1{,}941$$

c. Substitute efficiency for C_1 and C_2

$$\frac{63}{\eta} = \frac{1941}{\eta} - 1941$$

d. Solve for η

$$63 = 1{,}941 - 1941\eta$$

$$-1{,}941\eta = 63 - 1941 = -1{,}878$$

$$\eta = \frac{1878}{1941} = 0.9675$$

e. The efficiency of the sampling filters is 96.75%

~~As~~ $C_1 = \frac{C_2}{n} = \frac{C_1 - 1941}{n}$

$$n = \frac{C_1 - 1941}{C_1} = 1 - \frac{1941}{C_1}$$

$$n = \frac{C_2 - 63}{C_2} = 1 - \frac{63}{C_2} = 1 - \frac{63}{C_1 - 1941}$$

$$1 - \frac{1941}{C_1} = 1 - \frac{63}{C_1 - 1941}$$

$$n = -\frac{63}{C_1 - 1941} + \frac{1941}{C_1}$$

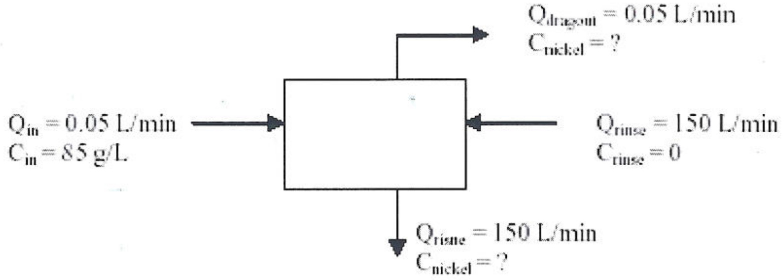
$$\frac{C_1 - 1941}{C_1} = \frac{C_1 - 1941 - 63}{C_1 - 1941}$$

2-11 Concentration of nickel in wastewater stream

Given: Figure P – 2-11, concentration of plating solution = 85 g/L, drag-out rate = 0.05 L/min, flow into rinse tank = 150 L/min, assume no accumulation in tank.

Solution:

a. Mass balance diagram



b. Mass balance equation

$$Q_{in}C_{in} + Q_{rinse}C_{rinse} - Q_{dragout}C_{nickel} - Q_{rinse}C_{nickel} = 0$$

c. Because $C_{rinse} = 0$ this reduces to

$$Q_{in}C_{in} = Q_{dragout}C_{nickel} + Q_{rinse}C_{nickel}$$

d. Solving for C_{nickel}

$$C_{nickel} = \frac{Q_{in}C_{in}}{Q_{dragout} + Q_{rinse}}$$

e. Substituting values

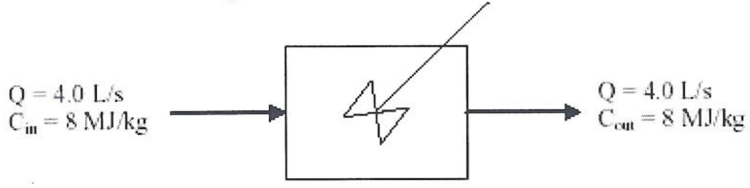
$$C_{nickel} = \frac{(0.05\,L/min)(85\,g/L)}{0.05\,L/min + 150\,L/min} = 28\,mg/L$$

2-19 Mixing time to achieve desired energy content

Given: CMFR, current waste energy content = 8.0 MJ/kg, new waste energy content = 10.0 MJ/kg, volume of CMFR = 0.20 m^3, flow rate into and out of CMFR = 4.0 L/s, effluent energy content = 9 MJ/kg.

Solution:

a. Mass balance diagram at $t < 0$



b. Step change in influent concentration at $t \geq 0$

C_{in} = 8 MJ/kg increases to C_{in} = 10 MJ/kg

c. Assuming this is non-reactive then the behavior is as shown in Figure 2-8 and Eqn 2-30 applies. Using the given values:

$$9\frac{\text{MJ}}{\text{kg}} = 8\frac{\text{MJ}}{\text{kg}}e^{-t/\theta} + 10\frac{\text{MJ}}{\text{kg}}\left(1 - e^{-t/\theta}\right)$$

Compute theoretical detention time:

$$\theta = \frac{0.20\text{m}^3}{(4.0\,\text{L/s})(10^{-3}\ \text{m}^3/\text{L})} = 50\text{s}$$

Solving for the exponential term:

$$9 = 8e^{-t/50} + 10 - 10e^{-t/50}$$

$$-1 = (8 - 10)e^{-t/50}$$

$$0.50 = e^{-t/50}$$

Taking the natural log of both sides

$$-0.693 = \frac{-t}{50}$$

$t = 34.66$ or 35 s

2-14 Oxygen concentration in bottle

Given: Starting O_2 concentration = 8 mg/L, rate constant of 0.35 d^{-1}

Solution:

a. General mass balance equation for the bottle is Eqn 2-28

$$C_t = C_o e^{-kt}$$

b. With C_o = 8.0 mg/L and k = 0.35, the plotting points for oxygen remaining are:

Day	Oxygen Remaining, mg/L
1	5.64
2	3.97
3	2.79
4	1.97
5	1.39

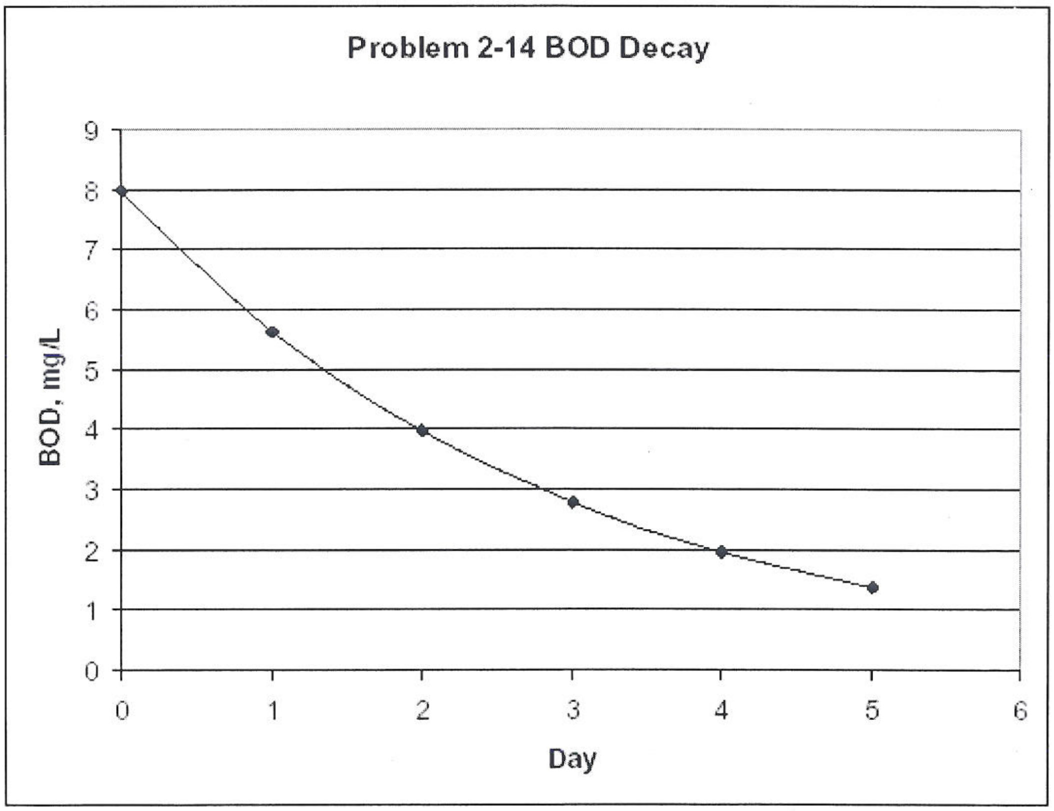


Figure S-2-14: BOD decay

2-22 Brine pond dilution

Given: Pond volume = 20,000 m^3, salt concentration = 25,000 mg/L, Atlantic ocean salt concentration = 30,000 mg/L, final salt concentration = 500 mg/L, time to achieve final concentration = 1 year.

Solution:

a. Assuming the pond is completely mixed, treat as a step decrease in CMFR and use Eqn 2-33 and solve for θ.

$$500 = 25000\exp\left(-\frac{1\text{year}}{\theta}\right)$$

$$0.020 = \exp\left(\frac{-1\text{y}}{\theta}\right)$$

Take the natural log of both sides

$$-3.912 = \left(\frac{-1\text{y}}{\theta}\right)$$

$$\theta = \frac{1}{3.912} = 0.2556\text{y}$$

b. Recognize that

$$\theta = \frac{\forall}{Q}$$

and solve for Q

$$0.2556\text{y} = \frac{20000\text{m}^3}{Q}$$

$$Q = \frac{20000\text{m}^3}{0.2556\text{y}} = 78{,}240\,\text{m}^3/\text{y}$$

c. Convert to units of m^3/s

$$78{,}240\,\text{m}^3/\text{y} \times \frac{1}{365\,\text{d}/\text{y}} \times \frac{1}{86400\,\text{s}/\text{d}} = 0.0025\,\text{m}^3/\text{s}$$

2-23 Venting water tower after disinfection

Given: Volume = 1,900 m^3, chlorine concentration = 15 mg/m^3, allowable concentration = 0.0015 mg/L, air flow = 2.35 m^3/s.

Solution:

a. Assume the water tower behaves as CMFR and apply Eqn 2-33

$$\theta = \frac{1900\text{m}^3}{2.35\text{m}^3/\text{s}} = 808.51\text{s}$$

Convert concentration to similar units

(0.0015 mg/L)(1,000 L/m^3) = 1.5 mg/m^3

Now solve Eqn 2-33

$$1.5\,\text{mg}/\text{m}^3 = 15\,\text{mg}/\text{m}^3 \exp\left(-\frac{t}{808.51\text{s}}\right)$$

$$0.10 = \exp\left(\frac{-t}{808.51\text{s}}\right)$$

Take the natural log of both sides

$$-2.303 = \left(\frac{-t}{808.51\text{s}}\right)$$

t = 1,861.66 s or 31 min or 30 min

2-26 Rate constant for sewage lagoon

Given: Area = 10 ha, depth = 1 m, flow into lagoon = 8,640 m^3/d, biodegradable material = 100 mg/L, effluent must meet = 20 mg/L, assume 1st order reaction.

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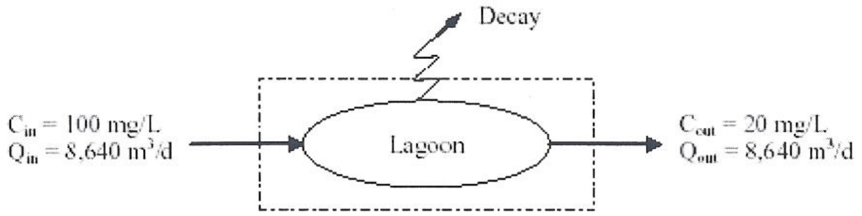
Solution:

a. There are two methods to solve this problem: (1) by using mass balance, (2) using equation from Table 2-2

b. First by mass balance



The mass balance equation is

$$\frac{dM}{dt} = C_{in}Q_{in} - C_{out}Q_{out} - kC_{lagoon}\forall$$

Assuming steady state, CMFR then

$$\frac{dM}{dt} = 0 \text{ and } C_{lagoon} = C_{out}$$

So,

$$C_{in}Q_{in} - C_{out}Q_{out} - kC_{out}\forall = 0$$

Solving for k

$$C_{in}Q_{in} - C_{out}Q_{out} = kC_{out}\forall$$

$$k = \frac{C_{in}Q_{in} - C_{out}Q_{out}}{C_{out}\forall}$$

Note that 1 mg/L = 1 g/m^3

$$k = \frac{(100\,g/m^3)(8640\,m^3/d) - (20\,g/m^3)(8640\,m^3/d)}{(20\,g/m^3)(10ha)(10000\,m^2/ha)(1m)}$$

$k = 0.3456\ d^{-1}$

c. Repeat using Table 2-2 equation for CMFR and 1st order reaction

$$C_t = \frac{C_o}{1 + k\theta}$$

$$\theta = \frac{\forall}{Q} = \frac{(10ha)(10000\,m^2/ha)(1m)}{8640\,m^3/d} = 11.574d$$

$$20\,mg/L = \frac{100\,mg/L}{1 + k(11.574d)}$$

Solve for k

$$0.20 = \frac{1}{1 + k(11.574d)}$$

$5.00 = 1 + k(11.574\ d)$

$$k = \frac{4.00}{11.574d} = 0.3456d^{-1}$$