

ENVIRONMENTAL ENGINEERING

AIR POLLUTION

Nomenclature

$$\frac{\mu\text{g}}{\text{m}^3} = \text{ppb} \times \frac{P(\text{MW})}{RT}$$

ppb = parts per billion

P = pressure (atm)

R = ideal gas law constant
= 0.0821 L·atm/(mole·K)

T = absolute temperature, K = 273.15 + °C

MW = molecular weight (g/mole)

Atmospheric Dispersion Modeling (Gaussian)

σ_y and σ_z as a function of downwind distance and stability class, see following figures.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \left[\exp\left(-\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2}\right) \right]$$

where

C = steady-state concentration at a point (x, y, z) ($\mu\text{g}/\text{m}^3$)

Q = emissions rate ($\mu\text{g}/\text{s}$)

σ_y = horizontal dispersion parameter (m)

σ_z = vertical dispersion parameter (m)

u = average wind speed at stack height (m/s)

y = horizontal distance from plume centerline (m)

z = vertical distance from ground level (m)

H = effective stack height (m) = $h + \Delta h$

where h = physical stack height

Δh = plume rise

x = downwind distance along plume centerline (m)

Maximum concentration at ground level and directly downwind from an elevated source.

$$C_{\max} = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2} \frac{(H^2)}{\sigma_z^2}\right)$$

where variables are as above except

C_{\max} = maximum ground-level concentration

$\sigma_z = \frac{H}{\sqrt{2}}$ for neutral atmospheric conditions

Selected Properties of Air

Nitrogen (N ₂) by volume	78.09%
Oxygen (O ₂) by volume	20.94%
Argon (Ar) by volume	0.93%
Molecular weight of air	28.966 g/mol
Absolute viscosity, μ	
at 80°F	0.045 lbm/(hr-ft)
at 100°F	0.047 lbm/(hr-ft)
Density	
at 80°F	0.0734 lbm/ft ³
at 100°F	0.0708 lbm/ft ³

The dry adiabatic lapse rate Γ_{AD} is 0.98°C per 100 m (5.4°F per 1,000 ft). This is the rate at which dry air cools adiabatically with altitude. The actual (environmental) lapse rate Γ is compared to Γ_{AD} to determine stability as follows:

Lapse Rate	Stability Condition
$\Gamma > \Gamma_{AD}$	Unstable
$\Gamma = \Gamma_{AD}$	Neutral
$\Gamma < \Gamma_{AD}$	Stable

Atmospheric Stability Under Various Conditions

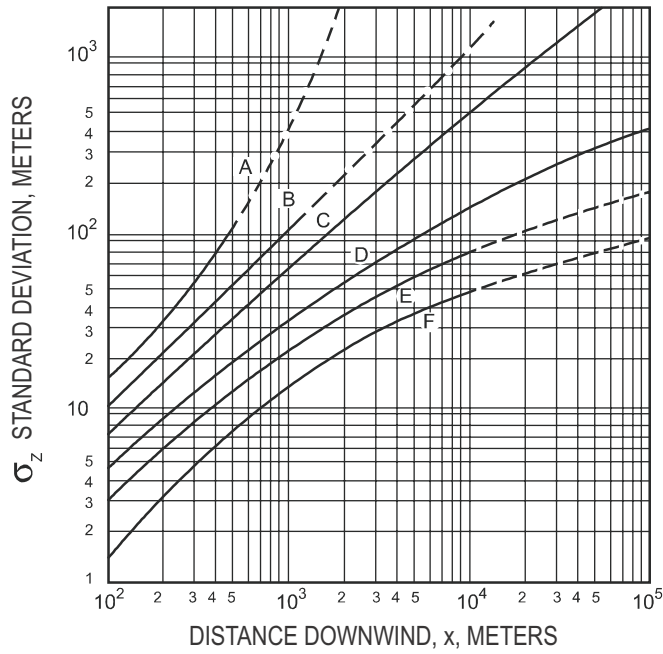
Surface Wind Speed ^a (m/s)	Day Solar Insolation			Night Cloudiness ^e	
	Strong ^b	Moderate ^c	Slight ^d	Cloudy	Clear
				(≥4/8)	(≤3/8)
<2	A	A-B ^f	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Notes:

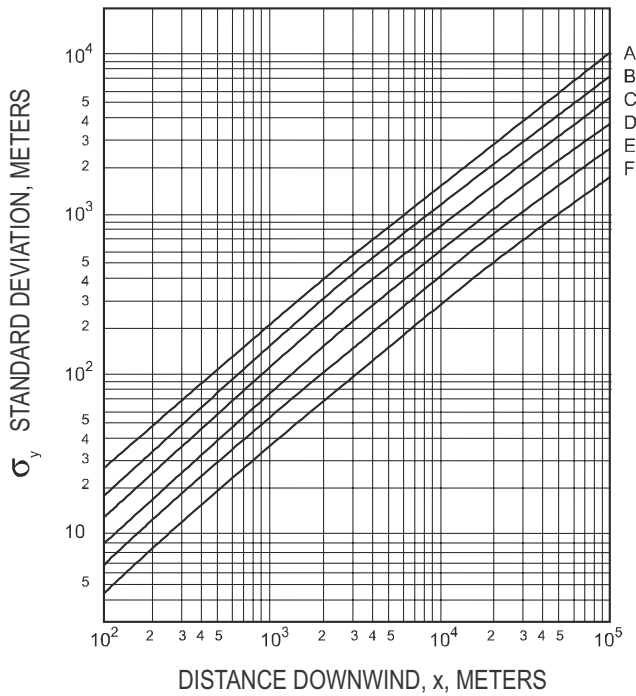
- a. Surface wind speed is measured at 10 m above the ground.
 - b. Corresponds to clear summer day with sun higher than 60° above the horizon.
 - c. Corresponds to a summer day with a few broken clouds, or a clear day with sun 35-60° above the horizon.
 - d. Corresponds to a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15-35°.
 - e. Cloudiness is defined as the fraction of sky covered by the clouds.
 - f. For A-B, B-C, or C-D conditions, average the values obtained for each.
- * A = Very unstable D = Neutral
 B = Moderately unstable E = Slightly stable
 C = Slightly unstable F = Stable

Regardless of wind speed, Class D should be assumed for overcast conditions, day or night.

Turner, D.B., "Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling," 2nd ed., Lewis Publishing/CRC Press, Florida, 1994.



VERTICAL STANDARD DEVIATIONS OF A PLUME

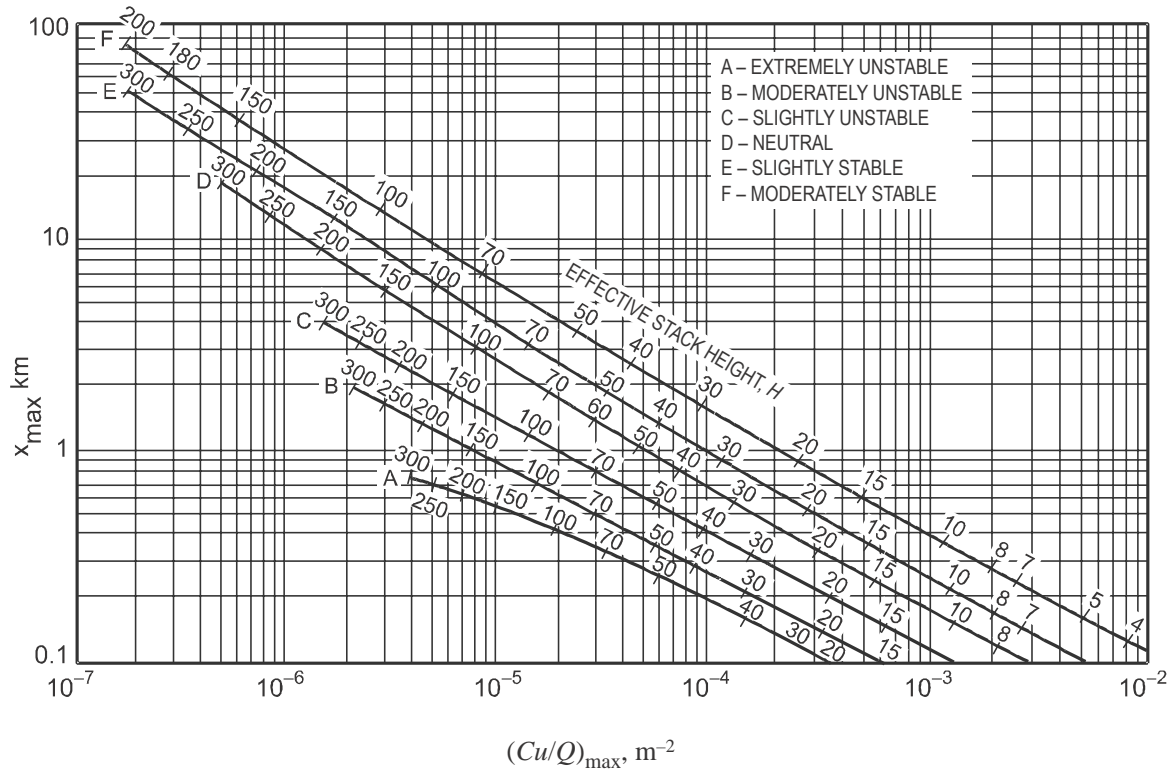


HORIZONTAL STANDARD DEVIATIONS OF A PLUME

- A – EXTREMELY UNSTABLE
- B – MODERATELY UNSTABLE
- C – SLIGHTLY UNSTABLE
- D – NEUTRAL
- E – SLIGHTLY STABLE
- F – MODERATELY STABLE

◆ Turner, D.B., "Workbook of Atmospheric Dispersion Estimates," U.S. Department of Health, Education, and Welfare, Washington, DC, 1970.

Downwind distance where the maximum concentration occurs, x_{\max} , versus $(Cu/Q)_{\max}$ as a function of stability class



NOTES: Effective stack height shown on curves numerically.

x_{\max} = distance along plume centerline to the point of maximum concentration

$$(Cu/Q)_{\max} = e^{[a + b \ln H + c (\ln H)^2 + d (\ln H)^3]}$$

H = effective stack height, stack height + plume rise, m

Values of Curve-Fit Constants for Estimating $(Cu/Q)_{\max}$ from H as a Function of Atmospheric Stability

Stability	Constants			
	a	b	c	d
A	-1.0563	-2.7153	0.1261	0
B	-1.8060	-2.1912	0.0389	0
C	-1.9748	-1.9980	0	0
D	-2.5302	-1.5610	-0.0934	0
E	-1.4496	-2.5910	0.2181	-0.0343
F	-1.0488	-3.2252	0.4977	-0.0765

Adapted from Ranchoux, R.J.P., 1976.

◆ Turner, D.B., "Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling," 2nd ed., Lewis Publishing/CRC Press, Florida, 1994.

Cyclone

Cyclone Collection (Particle Removal) Efficiency

$$\eta = \frac{1}{1 + (d_{pc}/d_p)^2}, \text{ where}$$

d_{pc} = diameter of particle collected with 50% efficiency

d_p = diameter of particle of interest

η = fractional particle collection efficiency

Cyclone 50% Collection Efficiency for Particle Diameter

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_i (\rho_p - \rho_g)} \right]^{0.5}, \text{ where}$$

d_{pc} = diameter of particle that is collected with 50% efficiency (m)

μ = dynamic viscosity of gas (kg/m•s)

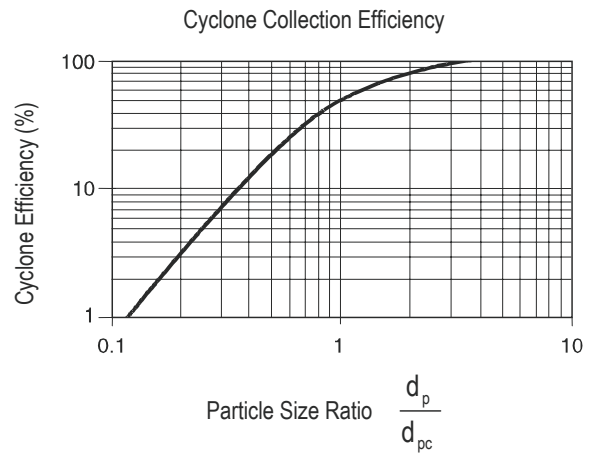
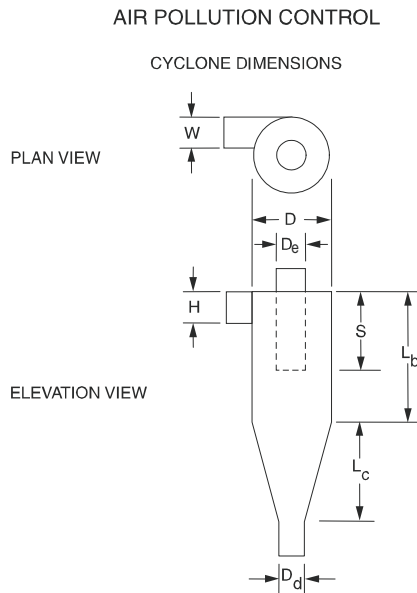
W = inlet width of cyclone (m)

N_e = number of effective turns gas makes in cyclone

V_i = inlet velocity into cyclone (m/s)

ρ_p = density of particle (kg/m³)

ρ_g = density of gas (kg/m³)



Cyclone Effective Number of Turns Approximation

$$N_e = \frac{1}{H} \left[L_b + \frac{L_c}{2} \right], \text{ where}$$

N_e = number of effective turns gas makes in cyclone

H = inlet height of cyclone (m)

L_b = length of body cyclone (m)

L_c = length of cone of cyclone (m)

Cyclone Ratio of Dimensions to Body Diameter

Dimension	High Efficiency	Conventional	High Throughput
Inlet height, H	0.44	0.50	0.80
Inlet width, W	0.21	0.25	0.35
Body length, L_b	1.40	1.75	1.70
Cone length, L_c	2.50	2.00	2.00
Vortex finder length, S	0.50	0.60	0.85
Gas exit diameter, D_e	0.40	0.50	0.75
Dust outlet diameter, D_d	0.40	0.40	0.40

♦ Adapted from Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 2nd ed., Waveland Press, Illinois, 1986.

Baghouse

Air-to-Cloth Ratio for Baghouses

Dust	Shaker/Woven	Pulse
	Reverse Air/Woven [m ³ /(min•m ²)]	Jet/Felt [m ³ /(min•m ²)]
alumina	0.8	2.4
asbestos	0.9	3.0
bauxite	0.8	2.4
carbon black	0.5	1.5
coal	0.8	2.4
cocoa	0.8	3.7
clay	0.8	2.7
cement	0.6	2.4
cosmetics	0.5	3.0
enamel frit	0.8	2.7
feeds, grain	1.1	4.3
feldspar	0.7	2.7
fertilizer	0.9	2.4
flour	0.9	3.7
fly ash	0.8	1.5
graphite	0.6	1.5
gypsum	0.6	3.0
iron ore	0.9	3.4
iron oxide	0.8	2.1
iron sulfate	0.6	1.8
lead oxide	0.6	1.8
leather dust	1.1	3.7
lime	0.8	3.0
limestone	0.8	2.4
mica	0.8	2.7
paint pigments	0.8	2.1
paper	1.1	3.0
plastics	0.8	2.1
quartz	0.9	2.7
rock dust	0.9	2.7
sand	0.8	3.0
sawdust (wood)	1.1	3.7
silica	0.8	2.1
slate	1.1	3.7
soap detergents	0.6	1.5
spices	0.8	3.0
starch	0.9	2.4
sugar	0.6	2.1
talc	0.8	3.0
tobacco	1.1	4.0

U.S. EPA OAQPS Control Cost Manual, 4th ed., EPA 450/3-90-006 (NTIS PB 90-169954), January 1990.

Electrostatic Precipitator Efficiency

Deutsch-Anderson equation:

$$\eta = 1 - e^{(-WA/Q)}$$

where

η = fractional collection efficiency

W = terminal drift velocity

A = total collection area

Q = volumetric gas flow rate

Note that any consistent set of units can be used for W , A , and Q (for example, ft/min, ft², and ft³/min).

Incineration

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

where

DRE = destruction and removal efficiency (%)

W_{in} = mass feed rate of a particular POHC (kg/h or lb/h)

W_{out} = mass emission rate of the same POHC (kg/h or lb/h)

POHC = principal organic hazardous contaminant

$$CE = \frac{CO_2}{CO_2 + CO} \times 100\%$$

CO_2 = volume concentration (dry) of CO_2
(parts per million, volume, ppm_v)

CO = volume concentration (dry) of CO (ppm_v)

CE = combustion efficiency

Kiln Formula

$$t = \frac{2.28 L/D}{SN}$$

where

t = mean residence time, min

L/D = internal length-to-diameter ratio

S = kiln rake slope, in./ft of length

N = rotational speed, rev/min

Energy Content of Waste

Typical Waste Values	Moisture, %	Energy, Btu/lb
Food Waste	70	2,000
Paper	6	7,200
Cardboard	5	7,000
Plastics	2	14,000
Wood	20	8,000
Glass	2	60
Bi-metallic Cans	3	300

FATE AND TRANSPORT

Mass Calculations

Mass balance: $\text{Mass}_{\text{in}} = \text{Mass}_{\text{out}}$

$M = CQ = CV$

Continuity equation = $Q = vA$

M = mass

C = concentration

Q = flow rate

V = volume

v = velocity

A = cross-sectional area of flow

M (lb/day) = C (mg/L) \times Q (MGD) \times 8.34 [lb-L/(mg-MG)]

where:

MGD = million gallons per day

MG = million gallons

Microbial Kinetics

BOD Exertion

$$y_t = L(1 - e^{-kt})$$

where

k = BOD decay rate constant (base e, days⁻¹)

L = ultimate BOD (mg/L)

t = time (days)

y_t = the amount of BOD exerted at time t (mg/L)

Stream Modeling

Streeter Phelps

$$D = \frac{k_1 L_0}{k_2 - k_1} [\exp(-k_1 t) - \exp(-k_2 t)] + D_0 \exp(-k_2 t)$$

$$t_c = \frac{1}{k_2 - k_1} \ln \left[\frac{k_2}{k_1} \left(1 - D_0 \frac{(k_2 - k_1)}{k_1 L_0} \right) \right]$$

$$DO = DO_{\text{sat}} - D$$

where

D = dissolved oxygen deficit (mg/L)

DO = dissolved oxygen concentration (mg/L)

D_0 = initial dissolved oxygen deficit in mixing zone (mg/L)

DO_{sat} = saturated dissolved oxygen concentration (mg/L)

k_1 = deoxygenation rate constant, base e (days⁻¹)

k_2 = reaeration rate constant, base e (days⁻¹)

L_0 = initial BOD ultimate in mixing zone (mg/L)

t = time (days)

t_c = time at which minimum dissolved oxygen occurs (days)

Monod Kinetics—Substrate Limited Growth

Continuous flow systems where growth is limited by one substrate (chemostat):

$$\mu = \frac{Yk_m S}{K_s + S} - k_d = \mu_{\text{max}} \frac{S}{K_s + S} - k_d$$

Multiple Limiting Substrates

$$\frac{\mu}{\mu_{\text{max}}} = [\mu_1(S_1)][\mu_2(S_2)][\mu_3(S_3)] \dots [\mu_n(S_n)]$$

$$\text{where } \mu_i = \frac{S_i}{K_{s_i} + S_i} \text{ for } i = 1 \text{ to } n$$

Non-steady State Continuous Flow

$$\frac{dx}{dt} = Dx_0 + (\mu - k_d - D)x$$

Steady State Continuous Flow

$$\mu = D \text{ with } k_d \ll \mu$$

Product production at steady state, single substrate limiting

$$X_1 = Y_{P/S}(S_0 - S_i)$$

k_d = microbial death rate or endogenous decay rate constant (time⁻¹)

k_m = maximum growth rate constant (time⁻¹)

K_s = saturation constant or half-velocity constant
[= concentration at $\mu_{\text{max}}/2$]

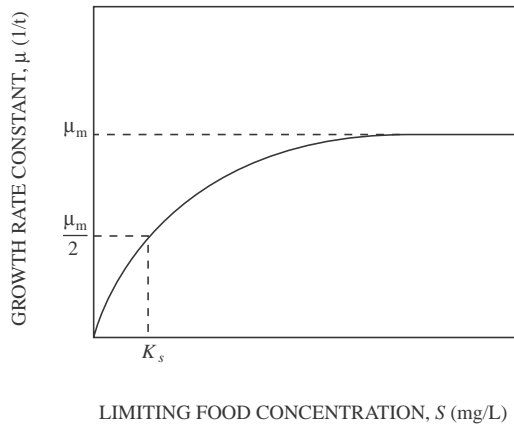
S = concentration of substrate in solution (mass/unit volume)

Y = yield coefficient [(mass/L product)/(mass/L food used)]

μ = specific growth rate (time⁻¹)

μ_{max} = maximum specific growth rate (time⁻¹) = Yk_m

- ◆ Monod growth rate constant as a function of limiting food concentration.



- X_1 = product (mg/L)
- V_r = volume (L)
- D = dilution rate (flow f /reactor volume V_r ; hr^{-1})
- f = flow rate (L/hr)
- μ_i = growth rate with one or multiple limiting substrates (hr^{-1})
- S_i = substrate i concentration (mass/unit volume)
- S_0 = initial substrate concentration (mass/unit volume)
- $Y_{P/S}$ = product yield per unit of substrate (mass/mass)
- p = product concentration (mass/unit volume)
- x = cell concentration (mass/unit volume)
- x_0 = initial cell concentration (mass/unit volume)
- t = time (time)

Kinetic Temperature Corrections

$$k_T = k_{20} (\theta)^{T-20}$$

Activated sludge: $\theta = 1.136$ ($T > 20^\circ\text{C}$)

$\theta = 1.056$ ($T < 20^\circ\text{C}$)

Reaeration $\theta = 1.024$

Biotowers $\theta = 1.035$

Trickling Filters $\theta = 1.072$

- ◆ Davis, M.L., and D. Cornwell, *Introduction to Environmental Engineering*, 3rd ed., McGraw-Hill, 1998.

Partition Coefficients

Bioconcentration Factor BCF

The amount of a chemical to accumulate in aquatic organisms.

$$BCF = C_{\text{org}}/C$$

where

C_{org} = equilibrium concentration in organism (mg/kg or ppm)

C = concentration in water (ppm)

Octanol-Water Partition Coefficient

The ratio of a chemical's concentration in the octanol phase to its concentration in the aqueous phase of a two-phase octanol-water system.

$$K_{ow} = C_o/C_w$$

where

C_o = concentration of chemical in octanol phase (mg/L or $\mu\text{g/L}$)

C_w = concentration of chemical in aqueous phase (mg/L or $\mu\text{g/L}$)

Organic Carbon Partition Coefficient K_{oc}

$$K_{oc} = C_{\text{soil}}/C_{\text{water}}$$

where

C_{soil} = concentration of chemical in organic carbon component of soil ($\mu\text{g adsorbed/kg organic C}$, or ppb)

C_{water} = concentration of chemical in water (ppb or $\mu\text{g/kg}$)

Retardation Factor R

$$R = 1 + (\rho/\eta)K_d$$

where

ρ = bulk density

η = porosity

K_d = distribution coefficient

Soil-Water Partition Coefficient $K_{sw} = K_p$

$$K_{sw} = X/C$$

where

X = concentration of chemical in soil (ppb or $\mu\text{g/kg}$)

C = concentration of chemical in water (ppb or $\mu\text{g/kg}$)

$$K_{sw} = K_{oc}f_{oc}$$

f_{oc} = fraction of organic carbon in the soil (dimensionless)

◆ **Steady-State Reactor Parameters (Constant Density Systems)**

Comparison of Steady-State Retention Times (θ) for Decay Reactions of Different Order^a

Reaction Order	r	Equations for Mean Retention Times (θ)		
		Ideal Batch	Ideal Plug Flow	Ideal CMFR
Zero ^b	$-k$	$\frac{(C_o - C_t)}{k}$	$\frac{(C_o - C_t)}{k}$	$\frac{(C_o - C_t)}{k}$
First	$-kC$	$\frac{\ln(C_o/C_t)}{k}$	$\frac{\ln(C_o/C_t)}{k}$	$\frac{(C_o/C_t) - 1}{k}$
Second	$-kC^2$	$\frac{(C_o/C_t) - 1}{kC_o}$	$\frac{(C_o/C_t) - 1}{kC_o}$	$\frac{(C_o/C_t) - 1}{kC_t}$

^a C_o = initial concentration or influent concentration; C_t = final condition or effluent concentration.

^bExpressions are valid for $k\theta \leq C_o$; otherwise $C_t = 0$.

Comparison of Steady-State Performance for Decay Reactions of Different Order^a

Reaction Order	r	Equations for C_t		
		Ideal Batch	Ideal Plug Flow	Ideal CMFR
Zero ^b	$-k$	$C_o - kt$	$C_o - k\theta$	$C_o - k\theta$
		0		
First	$-kC$	$C_o[\exp(-kt)]$	$C_o[\exp(-k\theta)]$	$\frac{C_o}{1 + k\theta}$
Second	$-kC^2$	$\frac{C_o}{1 + ktC_o}$	$\frac{C_o}{1 + k\theta C_o}$	$\frac{(4k\theta C_o + 1)^{1/2} - 1}{2k\theta}$

^a C_o = initial concentration or influent concentration; C_t = final condition or effluent concentration.

^bTime conditions are for ideal batch reactor only.

◆ Davis, M.L., and S.J. Masten, *Principles of Environmental Engineering and Science*, 2nd ed., McGraw-Hill, 2004.

LANDFILL

Break-Through Time for Leachate to Penetrate a Clay Liner

$$t = \frac{d^2 \eta}{K(d + h)}$$

where

t = breakthrough time (yr)

d = thickness of clay liner (ft)

η = porosity

K = hydraulic conductivity (ft/yr)

h = hydraulic head (ft)

Typical porosity values for clays with a coefficient of permeability in the range of 10^{-6} to 10^{-8} cm/s vary from 0.1 to 0.3.

Effect of Overburden Pressure

$$SW_p = SW_i + \frac{P}{a + bp}$$

where

SW_p = specific weight of the waste material at pressure p (lb/yd³) (typical 1,750 to 2,150)

SW_i = initial compacted specific weight of waste (lb/yd³) (typical 1,000)

p = overburden pressure (lb/in²)

a = empirical constant (yd³/in²)

b = empirical constant (yd³/lb)

Gas Flux

$$N_A = \frac{D\eta^{4/3}(C_{A_{\text{atm}}} - C_{A_{\text{fill}}})}{L}$$

where

N_A = gas flux of compound A, [g/(cm² · s)][lb · mol/(ft² · d)]

$C_{A_{\text{atm}}}$ = concentration of compound A at the surface of the landfill cover, g/cm³ (lb · mol/ft³)

$C_{A_{\text{fill}}}$ = concentration of compound A at the bottom of the landfill cover, g/cm³ (lb · mol/ft³)

L = depth of the landfill cover, cm (ft)

Typical values for the coefficient of diffusion for methane and carbon dioxide are 0.20 cm²/s (18.6 ft²/d) and 0.13 cm²/s (12.1 ft²/d), respectively.

D = diffusion coefficient, cm²/s (ft²/d)

η_{gas} = gas-filled porosity, cm³/cm³ (ft³/ft³)

η = porosity, cm³/cm³ (ft³/ft³)

Soil Landfill Cover Water Balance

$$\Delta S_{\text{LC}} = P - R - ET - \text{PER}_{\text{sw}}$$

where

ΔS_{LC} = change in the amount of water held in storage in a unit volume of landfill cover (in.)

P = amount of precipitation per unit area (in.)

R = amount of runoff per unit area (in.)

ET = amount of water lost through evapotranspiration per unit area (in.)

PER_{sw} = amount of water percolating through the unit area of landfill cover into compacted solid waste (in.)

POPULATION MODELING

Population Projection Equations

Linear Projection = Algebraic Projection

$$P_t = P_0 + k\Delta t$$

where

P_t = population at time t

P_0 = population at time zero

k = growth rate

Δt = elapsed time in years relative to time zero

Log Growth = Exponential Growth = Geometric Growth

$$P_t = P_0 e^{k\Delta t}$$

$$\ln P_t = \ln P_0 + k\Delta t$$

where

P_t = population at time t

P_0 = population at time zero

k = growth rate

Δt = elapsed time in years relative to time zero

Percent Growth

$$P_t = P_0(1 + k)^n$$

where

P_t = population at time t

P_0 = population at time zero

k = growth rate

n = number of periods

Ratio and Correlation Growth

$$\frac{P_2}{P_{2R}} = \frac{P_1}{P_{1R}} = k$$

where

P_2 = projected population

P_{2R} = projected population of a larger region

P_1 = population at last census

P_{1R} = population of larger region at last census

k = growth ratio constant

Decreasing-Rate-of-Increase Growth

$$P_t = P_0 + (S - P_0)(1 - e^{-k(t-t_0)})$$

where

P_t = population at time t

P_0 = population at time zero

k = growth rate constant

S = saturation population

t, t_0 = future time, initial time

RADIATION

Effective Half-Life

Effective half-life, τ_e , is the combined radioactive and biological half-life.

$$\frac{1}{\tau_e} = \frac{1}{\tau_r} + \frac{1}{\tau_b}$$

where

τ_r = radioactive half-life

τ_b = biological half-life

Half-Life

$$N = N_0 e^{-0.693 t/\tau}$$

where

N_0 = original number of atoms

N = final number of atoms

t = time

τ = half-life

Flux at distance 2 = (Flux at distance 1) $(r_1/r_2)^2$

where r_1 and r_2 are distances from source.

The half-life of a biologically degraded contaminant assuming a first-order rate constant is given by:

$$t_{1/2} = \frac{0.693}{k}$$

k = rate constant (time⁻¹)

$t_{1/2}$ = half-life (time)

SAMPLING AND MONITORING

Data Quality Objectives (DQO) for Sampling Soils and Solids

Investigation Type	Confidence Level (1- α) (%)	Power (1- β) (%)	Minimum Detectable Relative Difference (%)
Preliminary site investigation	70-80	90-95	10-30
Emergency clean-up	80-90	90-95	10-20
Planned removal and remedial response operations	90-95	90-95	10-20

Confidence level: 1- (Probability of a Type I error) = 1 - α = size probability of not making a Type I error.

Power = 1- (Probability of a Type II error) = 1 - β = probability of not making a Type II error.

EPA Document "EPA/600/8-89/046" *Soil Sampling Quality Assurance User's Guide*, Chapter 7.

$$CV = (100 * s)/\bar{x}$$

CV = coefficient of variation

s = standard deviation of sample

\bar{x} = sample average

Minimum Detectable Relative Difference = Relative increase over background $[100 (\mu_s - \mu_B)/\mu_B]$ to be detectable with a probability (1 - β)

μ_s = mean of pollutant concentration of the site of the contamination

μ_B = mean of pollutant concentration of the site before contamination or the noncontaminated area (background)

Daughter Product Activity

$$N_2 = \frac{\lambda_1 N_{10}}{\lambda_2 - \lambda_1} (e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

where $\lambda_{1,2}$ = decay constants (time⁻¹)

N_{10} = initial activity (curies) of parent nuclei

t = time

Daughter Product Maximum Activity Time

$$t' = \frac{\ln \lambda_2 - \ln \lambda_1}{\lambda_2 - \lambda_1}$$

Inverse Square Law

$$\frac{I_1}{I_2} = \frac{(R_2)^2}{(R_1)^2}$$

where $I_{1,2}$ = Radiation intensity at locations 1 and 2

$R_{1,2}$ = Distance from the source at locations 1 and 2

Number of Samples Required in a One-Sided One-Sample t-Test to Achieve a Minimum Detectable Relative Difference at Confidence Level (1- α) and Power (1- β)

Coefficient of Variation (%)	Power (%)	Confidence Level (%)	Minimum Detectable Relative Difference (%)				
			5	10	20	30	40
15	95	99	145	39	12	7	5
		95	99	26	8	5	3
		90	78	21	6	3	3
		80	57	15	4	2	2
	90	99	120	32	11	6	5
		95	79	21	7	4	3
		90	60	16	5	3	2
		80	41	11	3	2	1
	80	99	94	26	9	6	5
		95	58	16	5	3	3
		90	42	11	4	2	2
		80	26	7	2	2	1
25	95	99	397	102	28	14	9
		95	272	69	19	9	6
		90	216	55	15	7	5
		80	155	40	11	5	3
	90	99	329	85	24	12	8
		95	272	70	19	9	6
		90	166	42	12	6	4
		80	114	29	8	4	3
	80	99	254	66	19	10	7
		95	156	41	12	6	4
		90	114	30	8	4	3
		80	72	19	5	3	2
35	95	99	775	196	42	25	15
		95	532	134	35	17	10
		90	421	106	28	13	8
		80	304	77	20	9	6
	90	99	641	163	43	21	13
		95	421	107	28	14	8
		90	323	82	21	10	6
		80	222	56	15	7	4
	80	99	495	126	34	17	11
		95	305	78	21	10	7
		90	222	57	15	7	5
		80	140	36	10	5	3

WASTEWATER TREATMENT AND TECHNOLOGIES

Activated Sludge

$$X_A = \frac{\theta_c Y (S_0 - S_e)}{\theta (1 + k_d \theta_c)}$$

Steady State Mass Balance around Secondary Clarifier:

$$(Q_0 + Q_R)X_A = Q_e X_e + Q_R X_r + Q_w X_w$$

$$\theta_c = \text{Solids residence time} = \frac{V(X_A)}{Q_w X_w + Q_e X_e}$$

$$\text{Sludge volume/day: } Q_s = \frac{M(100)}{\rho_s (\% \text{ solids})}$$

$$\text{SVI} = \frac{\text{Sludge volume after settling (mL/L)} * 1,000}{\text{MLSS (mg/L)}}$$

k_d = microbial death ratio; kinetic constant; day⁻¹; typical range 0.1–0.01, typical domestic wastewater value = 0.05 day⁻¹

S_e = effluent BOD or COD concentration (kg/m³)

S_0 = influent BOD or COD concentration (kg/m³)

X_A = biomass concentration in aeration tank (MLSS or MLVSS kg/m³)

Y = yield coefficient (kg biomass/kg BOD or COD consumed); range 0.4–1.2

θ = hydraulic residence time = V/Q

Solids loading rate = $Q X_A$

For activated sludge secondary clarifier $Q = Q_0 + Q_R$

Organic loading rate (volumetric) = $Q_0 S_0 / \text{Vol}$

Organic loading rate (F:M) = $Q_0 S_0 / (\text{Vol } X_A)$

Organic loading rate (surface area) = $Q_0 S_0 / A_M$

ρ_s = density of solids

A = surface area of unit

A_M = surface area of media in fixed-film reactor

A_x = cross-sectional area of channel

M = sludge production rate (dry weight basis)

Q_0 = influent flow rate

Q_e = effluent flow rate

Q_w = waste sludge flow rate

ρ_s = wet sludge density

R = recycle ratio = Q_R / Q_0

Q_R = recycle flow rate = $Q_0 R$

X_e = effluent suspended solids concentration

X_w = waste sludge suspended solids concentration

V = aeration basin volume

Q = flow rate

X_r = recycled sludge suspended solids concentration

Design and Operational Parameters for Activated-Sludge Treatment of Municipal Wastewater

Type of Process	Mean cell residence time (θ_c , d)	Food-to-mass ratio [(kg BOD ₅ /day·kg MLSS)]	Volumetric loading (kg BOD ₅ /m ³)	Hydraulic residence time in aeration basin (θ , h)	Mixed liquor suspended solids (MLSS, mg/L)	Recycle ratio (Q_r / Q)	Flow regime*	BOD ₅ removal efficiency (%)	Air supplied (m ³ /kg BOD ₅)
Tapered aeration	5–15	0.2–0.4	0.3–0.6	4–8	1,500–3,000	0.25–0.5	PF	85–95	45–90
Conventional	4–15	0.2–0.4	0.3–0.6	4–8	1,500–3,000	0.25–0.5	PF	85–95	45–90
Step aeration	4–15	0.2–0.4	0.6–1.0	3–5	2,000–3,500	0.25–0.75	PF	85–95	45–90
Completely mixed	4–15	0.2–0.4	0.8–2.0	3–5	3,000–6,000	0.25–1.0	CM	85–95	45–90
Contact stabilization	4–15	0.2–0.6	1.0–1.2			0.25–1.0			45–90
Contact basin				0.5–1.0	1,000–3,000		PF	80–90	
Stabilization basin				4–6	4,000–10,000		PF		
High-rate aeration	4–15	0.4–1.5	1.6–16	0.5–2.0	4,000–10,000	1.0–5.0	CM	75–90	25–45
Pure oxygen	8–20	0.2–1.0	1.6–4	1–3	6,000–8,000	0.25–0.5	CM	85–95	
Extended aeration	20–30	0.05–0.15	0.16–0.40	18–24	3,000–6,000	0.75–1.50	CM	75–90	90–125

*PF = plug flow, CM = completely mixed.

Metcalf and Eddy, *Wastewater Engineering: Treatment, Disposal, and Reuse*, 3rd ed., McGraw-Hill, 1991.

Facultative Pond

BOD Loading Total System ≤ 35 pounds BOD₅/(acre-day)

Minimum = 3 ponds

Depth = 3–8 ft

Minimum $t = 90$ –120 days

Biotower

Fixed-Film Equation without Recycle

$$\frac{S_e}{S_0} = e^{-kD/q^n}$$

Fixed-Film Equation with Recycle

$$\frac{S_e}{S_a} = \frac{e^{-kD/q^n}}{(1 + R) - R(e^{-kD/q^n})}$$

where

S_e = effluent BOD₅ (mg/L)

S_0 = influent BOD₅ (mg/L)

R = recycle ratio = Q_R/Q_0

Q_R = recycle flow rate

$$S_a = \frac{S_0 + RS_e}{1 + R}$$

D = depth of biotower media (m)

q = hydraulic loading [$\text{m}^3/(\text{m}^2 \cdot \text{min})$]

$$= (Q_0 + RQ_0)/A_{\text{plan}} \text{ (with recycle)}$$

k = treatability constant; functions of wastewater and medium (min^{-1}); range 0.01–0.1; for municipal wastewater and modular plastic media 0.06 min^{-1} @ 20°C

$$k_T = k_{20}(1.035)^{T-20}$$

n = coefficient relating to media characteristics; modular plastic, $n = 0.5$

◆ Aerobic Digestion

Design criteria for aerobic digesters^a

Parameter	Value
Sludge retention time, d	
At 20°C	40
At 15°C	60
Solids loading, lb volatile solids/ft ³ ·d	0.1–0.3
Oxygen requirements, lb O ₂ /lb solids destroyed	
Cell tissue	~2.3
BOD ₅ in primary sludge	1.6–1.9
Energy requirements for mixing	
Mechanical aerators, hp/10 ³ ft ³	0.7–1.50
Diffused-air mixing, ft ³ /10 ³ ft ³ ·min	20–40
Dissolved-oxygen residual in liquid, mg/L	1–2
Reduction in volatile suspended solids, %	40–50

Tank Volume

$$V = \frac{Q_i(X_i + FS_i)}{X_d(k_d P_v + 1/\theta_c)}$$

where

V = volume of aerobic digester (ft³)

Q_i = influent average flowrate to digester (ft³/d)

X_i = influent suspended solids (mg/L)

F = fraction of the influent BOD₅ consisting of raw primary sludge (expressed as a decimal)

S_i = influent BOD₅ (mg/L)

X_d = digester suspended solids (mg/L); typically $X_d = (0.7)X_i$

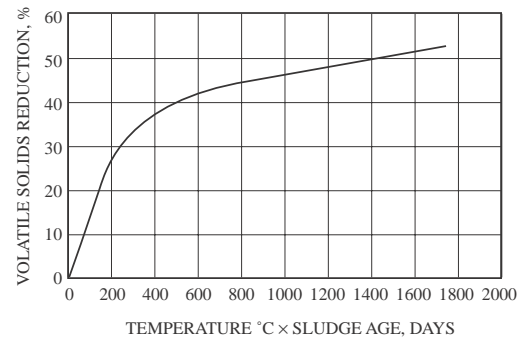
k_d = reaction-rate constant (d⁻¹)

P_v = volatile fraction of digester suspended solids (expressed as a decimal)

θ_c = solids residence time (sludge age) (d)

$F S_i$ can be neglected if primary sludge is not included on the sludge flow to the digester.

◆



VOLATILE SOLIDS REDUCTION IN AN AEROBIC DIGESTER AS A FUNCTION OF DIGESTER LIQUID TEMPERATURE AND DIGESTER SLUDGE AGE

• Anaerobic Digestion

Design parameters for anaerobic digesters

Parameter	Standard-rate	High-rate
Solids residence time, d	30–90	10–20
Volatile solids loading, kg/m ³ /d	0.5–1.6	1.6–6.4
Digested solids concentration, %	4–6	4–6
Volatile solids reduction, %	35–50	45–55
Gas production (m ³ /kg VSS added)	0.5–0.55	0.6–0.65
Methane content, %	65	65

Standard Rate

$$\text{Reactor Volume} = \frac{V_1 + V_2}{2} t_r + V_2 t_s$$

High Rate

First stage

$$\text{Reactor Volume} = V_1 t_r$$

Second Stage

$$\text{Reactor Volume} = \frac{V_1 + V_2}{2} t_r + V_2 t_s$$

where

V_1 = raw sludge input (volume/day)

V_2 = digested sludge accumulation (volume/day)

t_r = time to react in a high-rate digester = time to react and thicken in a standard-rate digester

t_i = time to thicken in a high-rate digester

t_s = storage time

◆ Tchobanoglous, G., and Metcalf and Eddy, *Wastewater Engineering: Treatment, Disposal, and Reuse*, 4th ed., McGraw-Hill, 2003.

• Peavy, HS, D.R. Rowe, and G. Tchobanoglous, *Environmental Engineering*, McGraw-Hill, 1985.

WATER TREATMENT TECHNOLOGIES

Activated Carbon Adsorption

Freundlich Isotherm

$$\frac{x}{m} = X = KC_e^{1/n}$$

where

x = mass of solute adsorbed

m = mass of adsorbent

X = mass ratio of the solid phase—that is, the mass of adsorbed solute per mass of adsorbent

C_e = equilibrium concentration of solute, mass/volume

K, n = experimental constants

Linearized Form

$$\ln \frac{x}{m} = \frac{1}{n} \ln C_e + \ln K$$

For linear isotherm, $n = 1$

Langmuir Isotherm

$$\frac{x}{m} = X = \frac{aKC_e}{1 + KC_e}$$

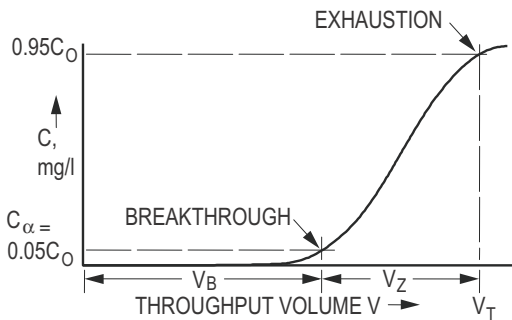
where

a = mass of adsorbed solute required to saturate completely a unit mass of adsorbent

K = experimental constant

Linearized Form

$$\frac{m}{x} = \frac{1}{a} + \frac{1}{aK} \frac{1}{C_e}$$



Depth of Sorption Zone

$$Z_s = Z \left[\frac{V_Z}{V_T - 0.5V_Z} \right]$$

where

$$V_Z = V_T - V_B$$

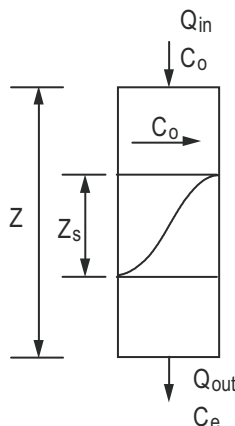
Z_s = depth of sorption zone

Z = total carbon depth

V_T = total volume treated at exhaustion ($C = 0.95 C_0$)

V_B = total volume at breakthrough ($C = C_\alpha = 0.05 C_0$)

C_0 = concentration of contaminant in influent



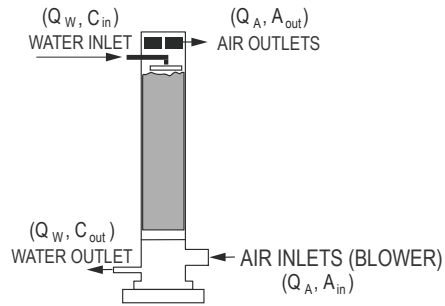
Air Stripping

$P_i = HC_i$ = Henry's Law

P_i = partial pressure of component i , atm

H = Henry's Law constant, atm·m³/kmol

C_i = concentration of component i in solvent, kmol/m³



$$A_{out} = H' C_{in}$$

$$Q_W \cdot C_{in} = Q_A H' C_{in}$$

$$Q_W = Q_A H'$$

$$H' (Q_A / Q_W) = 1$$

where

A_{out} = concentration in the effluent air (kmol/m³); in this formulation of the equation A_{in} and C_{out} are assumed to be negligible for simplicity.

Q_W = water flow rate (m³/s)

Q_A = air flow rate (m³/s)

A_{in} = concentration of contaminant in air (kmol/m³)

C_{out} = concentration of contaminants in effluent water (kmol/m³)

C_{in} = concentration of contaminants in influent water (kmol/m³)

Stripper Packing Height = Z

$$Z = HTU \times NTU$$

Assuming rapid equilibrium:

$$NTU = \left(\frac{R_S}{R_S - 1} \right) \ln \left(\frac{(C_{in}/C_{out})(R_S - 1) + 1}{R_S} \right)$$

where

NTU = number of transfer units

H = Henry's Law constant

H' = H/RT = dimensionless Henry's Law constant

T = temperature in units consistent with K

R = universal gas constant, atm·m³/(kmol·K)

R_S = stripping factor $H'(Q_A/Q_W)$

C_{in} = concentration in the influent water (kmol/m³)

C_{out} = concentration in the effluent water (kmol/m³)

HTU = Height of Transfer Units = $\frac{L}{M_W K_L a}$, where

L = liquid molar loading rate [kmol/(s·m²)]

M_W = molar density of water
(55.6 kmol/m³) = 3.47 lbmol/ft³

$K_L a$ = overall transfer rate constant (s⁻¹)

Clarifier

Overflow rate = Hydraulic loading rate = $v_o = Q/A_{\text{surface}}$

v_o = critical settling velocity
 = terminal settling velocity of smallest particle that is 100% removed

Weir loading = weir overflow rate, WOR = $Q/\text{Weir Length}$

Horizontal velocity = approach velocity = v_h
 = $Q/A_{\text{cross-section}} = Q/A_x$

Hydraulic residence time = $V/Q = \theta$

where

Q = flow rate

A_x = cross-sectional area

A = surface area, plan view

V = tank volume

Weir Loadings

1. Water Treatment—weir overflow rates should not exceed 20,000 gpd/ft
2. Wastewater Treatment
 - a. Flow \leq 1 MGD: weir overflow rates should not exceed 10,000 gpd/ft
 - b. Flow $>$ 1 MGD: weir overflow rates should not exceed 15,000 gpd/ft

Horizontal Velocities

1. Water Treatment—horizontal velocities should not exceed 0.5 fpm
2. Wastewater Treatment—no specific requirements (use the same criteria as for water)

Dimensions

1. Rectangular Tanks
 - a. Length:Width ratio = 3:1 to 5:1
 - b. Basin width is determined by the scraper width (or multiples of the scraper width)
 - c. Bottom slope is set at 1%
2. Circular Tanks
 - a. Diameters up to 200 ft
 - b. Diameters must match the dimensions of the sludge scraping mechanism
 - c. Bottom slope is less than 8%

Typical Primary Clarifier Efficiency Percent Removal

	Overflow rates			
	1,200 (gpd/ft ²) 48.9 (m/d)	1,000 (gpd/ft ²) 40.7 (m/d)	800 (gpd/ft ²) 32.6 (m/d)	600 (gpd/ft ²) 24.4 (m/d)
	Suspended Solids	54%	58%	64%
BOD ₅	30%	32%	34%	36%

Design Criteria for Sedimentation Basins

Type of Basin	Overflow Rate				Solids Loading Rate				Hydraulic Residence Time (hr)	Depth (ft)
	Average (gpd/ft ²)	Peak (m ³ /m ² ·d)	Average (gpd/ft ²)	Peak (m ³ /m ² ·d)	Average (lb/ft ² -d)	Peak (kg/m ² ·h)	Average (lb/ft ² -h)	Peak (kg/m ² ·h)		
Water Treatment										
Clarification following coagulation and flocculation:										
Alum coagulation	350-550	14-22							4-8	12-16
Ferric coagulation	550-700	22-28							4-8	12-16
Upflow clarifiers										
Groundwater	1,500-2,200	61-90							1	
Surface water	1,000-1,500	41-61							4	
Clarification following lime-soda softening										
Conventional	550-1,000	22-41							2-4	
Upflow clarifiers										
Groundwater	1,000-2,500	41-102							1	
Surface water	1,000-1,800	41-73							4	
Wastewater Treatment										
Primary clarifiers	800-1,200	32-49	1,200-2,000	50-80					2	10-12
Settling basins following fixed film reactors	400-800	16-33							2	
Settling basins following air-activated sludge reactors										
All configurations EXCEPT extended aeration	400-700	16-28							2	12-15
Extended aeration	200-400	8-16	1,000-1,200	40-64	19-29	4-6	38	8	2	12-15
Settling basins following chemical flocculation reactors	800-1,200		600-800	24-32	5-24	1-5	34	7	2	

Settling Equations

General Spherical

$$v_t = \sqrt{\frac{4g(\rho_p - \rho_f)d}{3C_D\rho_f}}$$

where

$$C_D = \text{drag coefficient}$$

$$= 24/\text{Re} \quad (\text{Laminar; } \text{Re} \leq 1.0)$$

$$= 24/\text{Re} + 3/(\text{Re}^{1/2}) + 0.34 \quad (\text{Transitional})$$

$$= 0.4 \quad (\text{Turbulent; } \text{Re} \geq 10^4)$$

$$\text{Re} = \text{Reynolds number} = \frac{v_t \rho d}{\mu}$$

$$g = \text{gravitational constant}$$

$$\rho_p \text{ and } \rho_f = \text{density of particle and fluid respectively}$$

$$d = \text{diameter of sphere}$$

$$\mu = \text{bulk viscosity of liquid} = \text{absolute viscosity}$$

$$v_t = \text{terminal settling velocity}$$

Stokes' Law

$$v_t = \frac{g(\rho_p - \rho_f)d^2}{18\mu} = \frac{g \rho_f (S.G. - 1)d^2}{18\mu}$$

$$\text{Approach velocity} = \text{horizontal velocity} = Q/A_x$$

$$\text{Hydraulic loading rate} = Q/A$$

$$\text{Hydraulic residence time} = V/Q = \theta$$

where

$$Q = \text{flow rate}$$

$$A_x = \text{cross-sectional area}$$

$$A = \text{surface area, plan view}$$

$$V = \text{tank volume}$$

$$\rho_f = \text{fluid mass density}$$

$$S.G. = \text{specific gravity}$$

Filtration Equations

$$\text{Filter bay length:width ratio} = 1.2:1 \text{ to } 1.5:1$$

$$\text{Effective size} = d_{10}$$

$$\text{Uniformity coefficient} = d_{60}/d_{10}$$

$$d_x = \text{diameter of particle class for which } x\% \text{ of sample is less than (units meters or feet)}$$

Filter equations can be used with any consistent set of units.

Head Loss Through Clean Bed

Rose Equation

Monosized Media

$$h_f = \frac{1067(v_s)^2 LC_D}{g\eta^4 d}$$

Multisized Media

$$h_f = \frac{1067(v_s)^2 L}{g\eta^4} \sum \frac{C_{Dij} x_{ij}}{d_{ij}}$$

Carmen-Kozeny Equation

Monosized Media

$$h_f = \frac{f' L (1 - \eta) v_s^2}{\eta^3 g d}$$

Multisized Media

$$h_f = \frac{L(1 - \eta) v_s^2}{\eta^3 g} \sum \frac{f'_{ij} x_{ij}}{d_{ij}}$$

$$f' = \text{friction factor} = 150 \left(\frac{1 - \eta}{\text{Re}} \right) + 1.75$$

where

$$h_f = \text{head loss through the clean bed (m of H}_2\text{O)}$$

$$L = \text{depth of filter media (m)}$$

$$\eta = \text{porosity of bed} = \text{void volume/total volume}$$

$$v_s = \text{filtration rate} = \text{empty bed approach velocity}$$

$$= Q/A_{\text{plan}} \text{ (m/s)}$$

$$g = \text{gravitational acceleration (m/s}^2\text{)}$$

$$\text{Re} = \text{Reynolds number} = \frac{v_s \rho d}{\mu}$$

$$d_{ij}, d = \text{diameter of filter media particles; arithmetic average of adjacent screen openings (m)}$$

$$i = \text{filter media (sand, anthracite, garnet)}$$

$$j = \text{filter media particle size}$$

$$x_{ij} = \text{mass fraction of media retained between adjacent sieves}$$

$$f'_{ij} = \text{friction factors for each media fraction}$$

$$C_D = \text{drag coefficient as defined in settling velocity equations}$$

Bed Expansion

Monosized

$$L_f = \frac{L_o(1 - \eta_o)}{1 - \left(\frac{v_B}{v_t} \right)^{0.22}}$$

Multisized

$$L_f = L_o(1 - \eta_o) \sum \frac{x_{ij}}{1 - \left(\frac{v_B}{v_{t,ij}} \right)^{0.22}}$$

$$\eta_f = \left(\frac{v_B}{v_t} \right)^{0.22}$$

where

$$L_f = \text{depth of fluidized filter media (m)}$$

$$v_B = \text{backwash velocity (m/s), } Q_B/A_{\text{plan}}$$

$$Q_B = \text{backwash flowrate}$$

$$v_t = \text{terminal setting velocity}$$

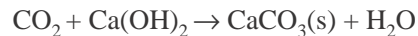
$$\eta_f = \text{porosity of fluidized bed}$$

$$L_o = \text{initial bed depth}$$

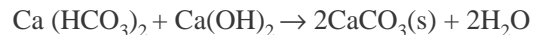
$$\eta_o = \text{initial bed porosity}$$

Lime-Soda Softening Equations

1. Carbon dioxide removal



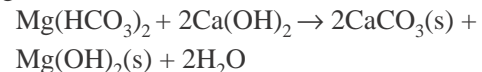
2. Calcium carbonate hardness removal



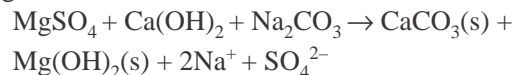
3. Calcium non-carbonate hardness removal



4. Magnesium carbonate hardness removal



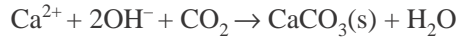
5. Magnesium non-carbonate hardness removal



6. Destruction of excess alkalinity



7. Recarbonation



Molecular Formulas	Molecular Weight	n		Equivalent Weight
		#	Equiv per mole	
CO ₃ ²⁻	60.0	2		30.0
CO ₂	44.0	2		22.0
Ca(OH) ₂	74.1	2		37.1
CaCO ₃	100.1	2		50.0
Ca(HCO ₃) ₂	162.1	2		81.1
CaSO ₄	136.1	2		68.1
Ca ²⁺	40.1	2		20.0
H ⁺	1.0	1		1.0
HCO ₃ ⁻	61.0	1		61.0
Mg(HCO ₃) ₂	146.3	2		73.2
Mg(OH) ₂	58.3	2		29.2
MgSO ₄	120.4	2		60.2
Mg ²⁺	24.3	2		12.2
Na ⁺	23.0	1		23.0
Na ₂ CO ₃	106.0	2		53.0
OH ⁻	17.0	1		17.0
SO ₄ ²⁻	96.1	2		48.0

Rapid Mix and Flocculator Design

$$G = \sqrt{\frac{P}{\mu V}} = \sqrt{\frac{\gamma H_L}{t \mu}}$$

$$Gt = 10^4 \text{ to } 10^5$$

where

G = root mean square velocity gradient (mixing intensity)
[ft/(sec-ft) or m/(s•m)]

P = power to the fluid (ft-lb/sec or N•m/s)

V = volume (ft³ or m³)

μ = dynamic viscosity [lb/(ft-sec) or Pa•s]

g = specific weight of water (lb/ft³ or N/m³)

H_L = head loss (ft or m)

t = time (sec or s)

Reel and Paddle

$$P = \frac{C_D A_p \rho_f v_r^3}{2}$$

where

C_D = drag coefficient = 1.8 for flat blade with a L:W > 20:1

A_p = area of blade (m²) perpendicular to the direction of travel through the water

ρ_f = density of H₂O (kg/m³)

v_p = velocity of paddle (m/s)

v_r = relative or effective paddle velocity

$$= v_p \cdot \text{slip coefficient}$$

slip coefficient = 0.5 to 0.75

Turbulent Flow Impeller Mixer

$$P = K_T (n)^3 (D_i)^5 \rho_f$$

where

K_T = impeller constant (see table)

n = rotational speed (rev/sec)

D_i = impeller diameter (m)

Values of the Impeller Constant K_T (Assume Turbulent Flow)

Type of Impeller	K_T
Propeller, pitch of 1, 3 blades	0.32
Propeller, pitch of 2, 3 blades	1.00
Turbine, 6 flat blades, vaned disc	6.30
Turbine, 6 curved blades	4.80
Fan turbine, 6 blades at 45°	1.65
Shrouded turbine, 6 curved blades	1.08
Shrouded turbine, with stator, no baffles	1.12

Note: Constant assumes baffled tanks having four baffles at the tank wall with a width equal to 10% of the tank diameter.

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Reverse Osmosis

Osmotic Pressure of Solutions of Electrolytes

$$\Pi = \phi v \frac{n}{V} RT$$

where

Π = osmotic pressure, Pa

ϕ = osmotic coefficient

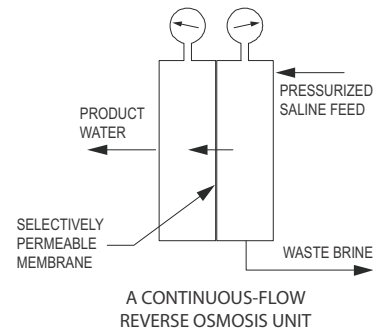
v = number of ions formed from one molecule of electrolyte

n = number of moles of electrolyte

V = specific volume of solvent, m³/kmol

R = universal gas constant, Pa • m³/(kmol • K)

T = absolute temperature, K



Salt Flux through the Membrane

$$J_s = (D_s K_s / \Delta Z)(C_{in} - C_{out})$$

where

J_s = salt flux through the membrane [kmol/(m² • s)]

D_s = diffusivity of the solute in the membrane (m²/s)

K_s = solute distribution coefficient (dimensionless)

C = concentration (kmol/m³)

ΔZ = membrane thickness (m)

$$J_s = K_p (C_{in} - C_{out})$$

K_p = membrane solute mass transfer coefficient

$$= \frac{D_s K_s}{\Delta Z} (L/t, m/s)$$

Water Flux

$$J_w = W_p (\Delta P - \Delta \pi)$$

where

J_w = water flux through the membrane [kmol/(m² • s)]

W_p = coefficient of water permeation, a characteristic of the particular membrane [kmol/(m² • s • Pa)]

ΔP = pressure differential across membrane = $P_{in} - P_{out}$ (Pa)

$\Delta \pi$ = osmotic pressure differential across membrane

$$\pi_{in} - \pi_{out} \text{ (Pa)}$$

Ultrafiltration

$$J_w = \frac{\varepsilon r^2 \int \Delta P}{8\mu \delta}$$

where

ε = membrane porosity

r = membrane pore size

ΔP = net transmembrane pressure

μ = viscosity

δ = membrane thickness

J_w = volumetric flux (m/s)

◆ Disinfection

Chlorine contact chamber length:width ratio = 20:1 to 50:1

$$T = \text{TDT} \times \text{BF}$$

T = time that the water is in contact with the disinfectant (min)

TDT = theoretical detention time (min)

$$\text{TDT (min-mg/L)} = C \times T$$

BF = baffling factor

C = residual disinfectant concentration measured during peak hourly flow (mg/L)

Baffling Factors

Baffling Condition	Baffling Factor	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles.
Average	0.5	Baffled inlet or outlet with some intra-basin baffles.
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles.

◆ *Guidance Manual LT1ESWTR Disinfection Profiling and Benchmarking*, U.S. Environmental Protection Agency, 2003.

◆ **Removal and Inactivation Requirements**

Microorganism	Required Log Reduction	Treatment
<i>Giardia</i>	3-log (99.9%)	Removal and/or inactivation
Viruses	4-log (99.99%)	Removal and/or inactivation
<i>Cryptosporidium</i>	2-log (99%)	Removal

◆ **Typical Removal Credits and Inactivation Requirements for Various Treatment Technologies**

Process	Typical Log Removal Credits		Resulting Disinfection Log Inactivation Requirements	
	<i>Giardia</i>	Viruses	<i>Giardia</i>	Viruses
Conventional Treatment	2.5	2.0	0.5	2.0
Direct Filtration	2.0	1.0	1.0	3.0
Slow Sand Filtration	2.0	2.0	1.0	2.0
Diatomaceous Earth Filtration	2.0	1.0	1.0	3.0
Unfiltered	0	0	3.0	4.0

◆ *Guidance Manual LT1ESWTR Disinfection Profiling and Benchmarking*, U.S. Environmental Protection Agency, 2003.

**CT Values* For 3-LOG Inactivation
Of *Giardia* Cysts By Free Chlorine**

Chlorine Concentration (mg/L)	Temperature <= 0.5°C								Temperature = 5°C								Temperature = 10°C							
	pH								pH								pH							
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0			
<=0.4	137	163	195	237	277	329	390	97	117	139	166	198	236	279	73	88	104	125	149	177	209			
0.6	141	168	200	239	286	342	407	100	120	143	171	204	244	291	75	90	107	128	153	183	218			
0.8	145	172	205	246	295	354	422	103	122	146	175	210	252	301	78	92	110	131	158	189	226			
1.0	148	176	210	253	304	365	437	105	125	149	179	216	260	312	79	94	112	134	162	195	234			
1.2	152	180	215	259	313	376	451	107	127	152	183	221	267	320	80	95	114	137	166	200	240			
1.4	155	184	221	266	321	387	464	109	130	155	187	227	274	329	82	98	116	140	170	206	247			
1.6	157	189	226	273	329	397	477	111	132	158	192	232	281	337	83	99	119	144	174	211	253			
1.8	162	193	231	279	338	407	489	114	135	162	196	238	287	345	86	101	122	147	179	215	259			
2.0	165	197	236	286	346	417	500	116	138	165	200	243	294	353	87	104	124	150	182	221	265			
2.2	169	201	242	297	353	426	511	118	140	169	204	248	300	361	89	105	127	153	186	225	271			
2.4	172	205	247	298	361	435	522	120	143	172	209	253	306	368	90	107	129	157	190	230	276			
2.6	175	209	252	304	368	444	533	122	146	175	213	258	312	375	92	110	131	160	194	234	281			
2.8	178	213	257	310	375	452	543	124	148	178	217	263	318	382	93	111	134	163	197	239	287			
3.0	181	217	261	316	382	460	552	126	151	182	221	268	324	389	95	113	137	166	201	243	292			
Chlorine Concentration (mg/L)	Temperature = 15°C								Temperature = 20°C								Temperature = 25°C							
	pH								pH								pH							
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0			
<=0.4	49	59	70	83	99	118	140	36	44	52	62	74	89	105	24	29	35	42	50	59	70			
0.6	50	60	72	86	102	122	146	38	45	54	64	77	92	109	25	30	36	43	51	61	73			
0.8	52	61	73	88	105	126	151	39	46	55	66	79	95	113	26	31	37	44	53	63	75			
1.0	53	63	75	90	108	130	156	39	47	56	67	81	98	117	26	31	37	45	54	65	78			
1.2	54	64	76	92	111	134	160	40	48	57	69	83	100	120	27	32	38	46	55	67	80			
1.4	55	65	78	94	114	137	165	41	49	58	70	85	103	123	27	33	39	47	57	69	82			
1.6	56	66	79	96	116	141	169	42	50	59	72	87	105	126	28	33	40	48	58	70	84			
1.8	57	68	81	98	119	144	173	43	51	61	74	89	106	129	29	34	41	49	60	72	86			
2.0	58	69	83	100	122	147	177	44	52	62	75	91	110	132	29	35	41	50	61	74	88			
2.2	59	70	85	102	124	150	181	44	53	63	77	93	113	135	30	35	42	51	62	75	90			
2.4	60	72	86	105	127	153	184	45	54	65	78	95	115	138	30	36	43	52	63	77	92			
2.6	61	73	88	107	129	156	188	46	55	66	80	97	117	141	31	37	44	53	65	78	94			
2.8	62	74	89	109	132	159	191	47	56	67	81	99	119	143	31	37	45	54	66	80	96			
3.0	63	76	91	111	134	162	195	47	57	68	83	101	122	146	32	38	46	55	67	81	97			

*Although units did not appear in the original tables, units are min-mg/L

**CT VALUES* FOR
4-LOG INACTIVATION OF VIRUSES BY FREE CHLORINE**

Temperature (°C)	pH	
	6-9	10
0.5	12	90
5	8	60
10	6	45
15	4	30
20	3	22
25	2	15

*Although units did not appear in the original tables, units are min-mg/L

◆ Guidance Manual LTIESWTR Disinfection Profiling and Benchmarking, U.S. Environmental Protection Agency, 2003.