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PE | Environmental

Reference Handbook

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PREFACE

About the *Handbook*

The Principles and Practice of Engineering (PE) Environmental exam is computer-based, and the *PE Environmental Reference Handbook* is the only resource material you can use during the exam. Reviewing it before exam day will help you become familiar with the charts, formulas, tables, and other reference information provided. You will not be allowed to bring your personal copy of the *PE Environmental Reference Handbook* into the exam room. Instead, the computer-based exam will include a PDF version of the handbook for your use. No printed copies of the handbook will be allowed in the exam room.

The PDF version of the *PE Environmental Reference Handbook* that you use on exam day will be very similar to this one. However, pages not needed to solve exam questions—such as the cover and introductory material—will not be included in the exam version. In addition, NCEES will periodically revise and update the handbook, and each PE Environmental exam will be administered using the version of the handbook in effect on the date the exam is given.

The *PE Environmental Reference Handbook* does not contain all the information required to answer every question on the exam. Theories, conversions, formulas, and definitions that examinees are expected to know have not been included. The handbook is intended solely for use on the NCEES PE Environmental exam.

Updates on Exam Content and Procedures

NCEES.org is our home on the web. Visit us there for updates on everything exam-related, including specifications, exam-day policies, scoring, and practice tests.

Errata

To report errata in this book, send your correction using our chat feature on NCEES.org. Examinees are not penalized for any errors in the *Handbook* that affect an exam question.

CONTENTS

1 WATER

Principles

Stress, Pressure, and Viscosity

Stress is defined as

$$\tau(1) = \lim_{\Delta A \to 0} \Delta F/\Delta A$$

$\tau(1)$ = surface stress vector at Point 1

ΔF = force acting on infinitesimal area ΔA

ΔA = infinitesimal area at Point 1

$$\tau_n = -P$$

$$\tau_t = \mu(dv/dy) \text{ (one-dimensional; i.e., } y\text{)}$$

τ_n and τ_t = normal and tangential stress components at Point 1, respectively

P = pressure at Point 1

μ = *absolute dynamic viscosity* of the fluid [N•s/m^2 or lbm/(ft-sec)]

dv = differential velocity

dy = differential distance, normal to boundary

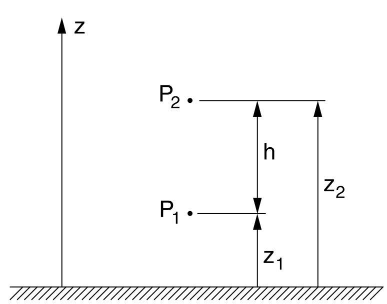
v = velocity at boundary condition

y = normal distance, measured from boundary

υ = *kinematic viscosity* (m^2/s or ft^2/sec)

where $\upsilon = \mu/\rho$

Pressure Field in a Static Liquid



Bober, W., and R.A. Kenyon, *Fluid Mechanics*, 1st ed.: Wiley, 1980 with permission of Bober and Kenyon.

The difference in pressure between two different points is

$$P_2 - P_1 = -\gamma\,(z_2 - z_1) = -\gamma h = -\rho g h$$

Absolute pressure = atmospheric pressure + gauge pressure reading

Absolute pressure = atmospheric pressure – vacuum gauge pressure reading

Energy Equation (Bernoulli)

$$H = Z_a + \frac{P_a}{\gamma} + \frac{V_a^2}{2g}$$

H = total head (ft)

$\frac{P_a}{\gamma}$ = pressure head

P_a = pressure (lb/ft^2)

γ = specific weight of fluid (lb/ft^3)

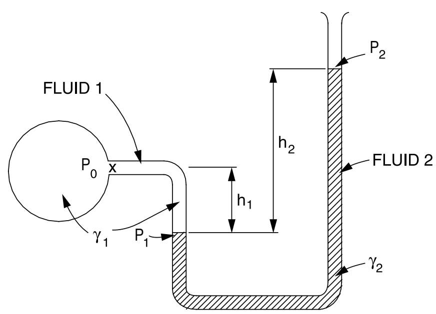
$\frac{V_a^2}{2g}$ = velocity head

V_a = velocity (ft/sec)

g = acceleration of gravity (32.2 ft/sec^2)

Z_a = elevation (ft)

Manometers



Bober, W., and R.A. Kenyon, *Fluid Mechanics*, 1st ed.: Wiley, 1980 with permission of Bober and Kenyon.

For a simple manometer,

$$P_0 = P_2 + \gamma_2 h_2 - \gamma_1 h_1 = P_2 + g\,(\rho_2\, h_2 - \rho_1\, h_1)$$

If $h_1 = h_2 = h$

$$P_0 = P_2 + (\gamma_2 - \gamma_1)h = P_2 + (\rho_2 - \rho_1)gh$$

Note that the difference between the two densities is used.

P = pressure

γ = specific weight of fluid

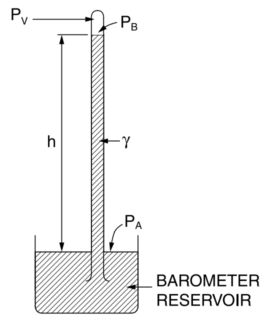
h = height

g = acceleration of gravity

ρ = fluid density

Another device that works on the same principle as the manometer is the simple barometer.

$$P_{\text{atm}} = P_A = P_v + \gamma h = P_B + \gamma h = P_B + \rho g h$$



Bober, W., and R.A. Kenyon, *Fluid Mechanics*, 1st ed.: Wiley, 1980 with permission of Bober and Kenyon.

P_v = vapor pressure of the barometer fluid

Continuity Equation

So long as the flow Q is continuous, the *continuity equation*, as applied to one-dimensional flows, states that the flow passing two points (1 and 2) in a stream is equal at each point, $A_1\text{v}_1 = A_2\text{v}_2$.

$$Q = A\text{v}$$

$$\dot{m} = \rho Q = \rho A\text{v}$$

Q = volumetric flow rate

$\dot{m}$ = mass flow rate

A = cross-sectional area of flow

v = average flow velocity

ρ = fluid density

For steady, one-dimensional flow, $\dot{m}$ is a constant. If, in addition, the density is constant, then Q is constant.

Energy Equation

The energy equation for steady incompressible flow with no shaft device is

$$\frac{P_1}{\gamma} + z_1 + \frac{\text{v}_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{\text{v}_2^2}{2g} + h_f \quad \text{or}$$

$$\frac{P_1}{\rho g} + z_1 + \frac{\text{v}_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{\text{v}_2^2}{2g} + h_f$$

h_f = head loss, considered a friction effect, and all remaining terms are defined above

If the cross-sectional area and the elevation of the pipe are the same at both sections (1 and 2), then $z_1 = z_2$ and $\text{v}_1 = \text{v}_2$.

The pressure drop $P_1 - P_2$ is given by the following:

$$P_1 - P_2 = \gamma\, h_f = \rho g h_f$$

Field Equation

The field equation is derived when the energy equation is applied to one-dimensional flows. Assuming no friction losses and that no pump or turbine exists between Sections 1 and 2 in the system,

$$\frac{P_2}{\gamma}+\frac{v_2^2}{2g}+z_2=\frac{P_1}{\gamma}+\frac{v_1^2}{2g}+z_1 \quad \text{or}$$
$$\frac{P_2}{\rho}+\frac{v_2^2}{2}+z_2 g=\frac{P_1}{\rho}+\frac{v_1^2}{2}+z_1 g$$

P_1, P_2 = pressure at Sections 1 and 2

v_1, v_2 = average velocity of the fluid at the sections

z_1, z_2 = vertical distance from a datum to the sections (potential energy)

γ = specific weight of the fluid = ρg

g = acceleration of gravity

ρ = fluid density

Reynolds Number (Newtonian Fluid)

$$\text{Re}=\frac{vD\rho}{\mu}=\frac{vD}{\upsilon}$$

where

v = average velocity

ρ = mass density

D = diameter of the pipe, dimension of the fluid streamline, or characteristic length

μ = dynamic viscosity

υ = kinematic viscosity

Re = Reynolds number (Newtonian fluid)

Flow through a pipe is generally characterized as laminar for Re < 2,100 and fully turbulent for Re > 10,000, and transitional flow for 2,100 < Re < 10,000.

Head Loss Due to Flow

The *Darcy-Weisbach equation* is

$$h_f=f\frac{L}{D}\frac{v^2}{2g}$$

h_f = head loss due to flow

f = f(Re, ε/D), the Moody, Darcy, or Stanton friction factor

D = diameter of the pipe

L = length over which the pressure drop occurs

v = average velocity

g = acceleration of gravity

ε = roughness factor for the pipe

Re = Reynolds number

A chart that gives f versus Re for various values of ε/D, known as a *Moody, Darcy,* or *Stanton diagram*, is available in this section.

Minor Losses in Pipe Fittings, Contractions, and Expansions

Head losses also occur as the fluid flows through pipe fittings (i.e., elbows, valves, couplings, etc.) and sudden pipe contractions and expansions.

$$\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + h_f + h_{f,\,\text{fitting}}$$

$$\frac{P_1}{\rho g} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{v_2^2}{2g} + h_f + h_{f,\,\text{fitting}}, \text{ where}$$

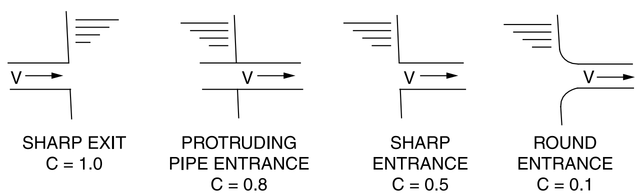
$$h_{f,\,\text{fitting}} = C\frac{v^2}{2g}, \text{ and } \frac{v^2}{2g} = 1 \text{ velocity head}$$

C = resistance coefficient

Specific fittings have characteristic values of C, which will be provided in the problem statement. A generally accepted *nominal value* for head loss in *well-streamlined gradual contractions* is

$$h_{f,\,\text{fitting}} = 0.04\ v^2/\ 2g$$

The *head loss* at either an *entrance* or *exit* of a pipe from or to a reservoir is also given by the $h_{f,\,\text{fitting}}$ equation. Values for C for various cases are shown as follows.



Bober, W., and R.A. Kenyon, *Fluid Mechanics*, 1st ed.: Wiley, 1980 with permission of Bober and Kenyon

Pressure Drop for Laminar Flow

The equation for Q in terms of the pressure drop ΔP_f is the Hagen-Poiseuille equation. This relation is valid only for flow in the laminar region.

$$Q = \frac{\pi R^4 \Delta P_f}{8\mu L} = \frac{\pi D^4 \Delta P_f}{128\mu L}$$

Flow in Noncircular Conduits

Analysis of flow in conduits having a noncircular cross section uses the *hydraulic radius* R_H, or the *hydraulic diameter* D_H, as follows:

$$R_H = \frac{\text{cross–sectional area}}{\text{wetted perimeter}} = \frac{D_H}{4}$$

Open-Channel Flow and Pipe Flow of Water

Specific Energy

$$E = \alpha\frac{V^2}{2g} + y = \frac{\alpha Q^2}{2gA^2} + y$$

E = specific energy

Q = discharge

V = velocity

y = depth of flow

A = cross-sectional area of flow

α = kinetic energy correction factor, usually 1.0

Critical Depth = that depth in a channel at minimum specific energy

$$\frac{Q^2}{g} = \frac{A^3}{T}$$

where Q and A are as defined above,

g = acceleration due to gravity

T = width of the water surface

For rectangular channels,

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$

y_c = critical depth

q = unit discharge = Q/B

B = channel width

g = acceleration due to gravity

Froude Number = ratio of inertial forces to gravity forces

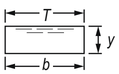
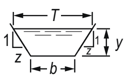
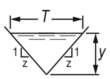
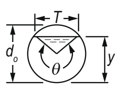
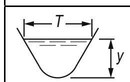
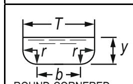
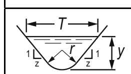
$$Fr = \frac{V}{\sqrt{gy_h}}$$

V = velocity

y_h = hydraulic depth = A/T

More channel flow details are shown in the following table.

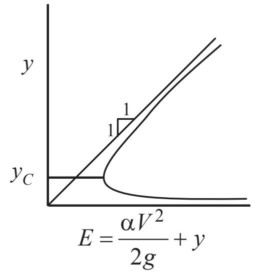
Geometric Elements of Channel Sections

Section	Area A	Wetted Perimeter P	Hydraulic Radius R	Top Width T	Hydraulic Depth D	Section Factor Z
 RECTANGLE	by	$b+2y$	$\frac{by}{b+2y}$	b	y	$by^{1.5}$
 TRAPEZOID	$(b+zy)y$	$b+2y\sqrt{1+z^2}$	$\frac{(b+zy)y}{b+2y\sqrt{1+z^2}}$	$b+2zy$	$\frac{(b+zy)y}{b+2zy}$	$\frac{[(b+zy)y]^{1.5}}{\sqrt{b+2zy}}$
 TRIANGLE	zy^2	$2y\sqrt{1+z^2}$	$\frac{zy}{2\sqrt{1+z^2}}$	$2zy$	$1/2y$	$\frac{\sqrt{2}}{2}zy^{2.5}$
 CIRCLE	$1/8(\theta-\sin\theta)d_o^2$	$1/2\theta d_o$	$1/4\left(1-\frac{\sin\theta}{\theta}\right)d_o$	$(\sin 1/2\,\theta)d_o$ or $2\sqrt{y(d_o-y)}$	$1/8\left(\frac{\theta-\sin\theta}{\sin 1/2\,\theta}\right)d_o$	$\frac{\sqrt{2}}{32}\frac{(\theta-\sin)^{1.5}}{(\sin 1/2\,\theta)^{0.5}}d_o^{2.5}$
 PARABOLA	$2/3Ty$	$T+\frac{8}{3}\frac{y^2}{T}$ *	$\frac{2T^2y}{3T^2+8y^2}$ *	$\frac{3}{2}\frac{A}{y}$	$2/3y$	$2/9\sqrt{6}\,Ty^{1.5}$
 ROUND-CORNERED RECTANGLE (y > r)	$\left(\frac{\pi}{2}-2\right)r^2+(b+2r)y$	$(\pi-2)r+b+2y$	$\frac{(\pi/2-2)r^2+(b+2r)y}{(\pi-2)r+b+2y}$	$b+2r$	$\frac{(\pi/2-2)r^2}{b+2r}+y$	$\frac{[(\pi/2-2)r^2+(b+2r)y]^{1.5}}{\sqrt{b+2r}}$
 ROUND-BOTTOMED TRIANGLE	$\frac{T^2}{4z}-\frac{r^2}{z}(1-z\cot^{-1}z)$	$\frac{T}{z}\sqrt{1+z^2}-\frac{2r}{z}(1-z\cot^{-1}z)$	$\frac{A}{P}$	$2\left[z(y-r)+r\sqrt{1+z^2}\right]$	$\frac{A}{T}$	$A\sqrt{\frac{A}{T}}$

*Satisfactory approximation for the interval $0 < x \le 1$, where $x = 4y/T$. When $x > 1$, use the exact expression $P = (T/2)\left[\sqrt{1+x^2}+1/x\ln\left(x+\sqrt{1+x^2}\right)\right]$.

Chow, Ven Te, *Open-Channel Hydraulics*, Estate of Ven Te Chow, 1959, p. 21.

Specific Energy Diagram



Alternate depths: depths with the same specific energy.

y_1 = flow depth at supercritical flow

y_2 = flow depth at subcritical flow

$$y_2 = \frac{y_1}{2}\left(\sqrt{1 + 8\,Fr_1^2} - 1\right)$$

Uniform flow: a flow condition where depth and velocity do not change along a channel.

Manning's Equation

$$v = (K/n)R_H^{2/3}S^{1/2}$$

v = velocity (m/s or ft/sec)

K = 1.0 for SI units, 1.486 for USCS units

n = roughness coefficient

R_H = hydraulic radius (m or ft)

S = slope of energy grade line (m/m or ft/ft)

Values of Manning's Roughness Coefficient, *n*

Type of Channel and Description	*n*
A. Closed conduits	
brass, smooth	0.010
steel, welded	0.012
steel, riveted	0.016
cast iron, coated	0.013
glass	0.010
concrete culvert, straight	0.011
concrete, finished	0.012
concrete, unfinished	0.014
clay	0.015
sanitary sewers coated with sewage slimes, with bends and connections	0.013
B. Excavated	
clean	0.022
gravel	0.025
grass, some weeds	0.030
cobble bottom	0.040
C. Natural streams	
clean, straight	0.030
clean, winding	0.040
sluggish	0.070
D. Flood plains	
pasture, no brush	0.035
cultivated areas	0.040
brush, light	0.050
trees	0.150

Adapted from Chow, Ven Te, *Open-Channel Hydraulics*, Estate of Ven Te Chow, 1959, pp. 110, 112, and 113.

Hazen-Williams Equation

$$V = k_1 C R_H^{0.63} S^{0.54}$$

C = roughness coefficient

k_1 = 0.849 for SI units

k_1 = 1.318 for USCS units

R_H = hydraulic radius (ft or m)

S = slope of energy grade line

= h_f/L (ft/ft or m/m)

V = velocity (ft/sec or m/s)

Values of Hazen-Williams Coefficient C

Pipe Material	C
Ductile iron	140
Concrete (regardless of age)	130
Cast iron:	
New	130
5 yr old	120
20 yr old	100
Welded steel, new	120
Wood stave (regardless of age)	120
Vitrified clay	110
Riveted steel, new	110
Brick sewers	100
Asbestos-cement	140
Plastic	150

Circular Pipe Head Loss Equation (Head Loss Expressed in Feet)

$$h_f = \frac{4.73\,L}{C^{1.852}\,D^{4.87}}\,Q^{1.852} = K'Q^{1.852}$$

h_f = head loss (ft)

L = pipe length (ft)

D = pipe diameter (ft)

Q = flow (cfs)

C = Hazen-Williams coefficient

K' = friction coefficient

Hardy Cross Method for Pipe Networks Using Hazen-Williams Equation

$$\Delta Q = \frac{-\sum h_f}{1.85\sum\left|\frac{h_f}{Q}\right|}$$

ΔQ = flow correction (gpm)

Circular Pipe Head Loss Equation (Head Loss Expressed as Pressure)

U.S. Customary Units

$$P = \frac{4.52\,Q^{1.85}}{C^{1.85}\,D^{4.87}}$$

P = pressure loss (psi per foot of pipe)

Q = flow (gpm)

D = pipe diameter (in.)

C = Hazen-Williams coefficient

SI Units

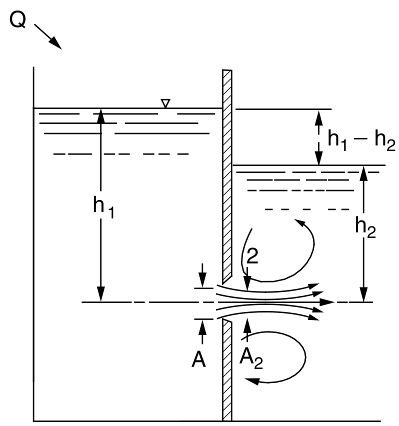
$$P = \frac{6.05\,Q^{1.85}}{C^{1.85}\,D^{4.87}} \times 10^5$$

P = pressure loss (bars per meter of pipe)

Q = flow (liters/minute)

D = pipe diameter (mm)

Submerged Orifice (Operating Under Steady-Flow Conditions)



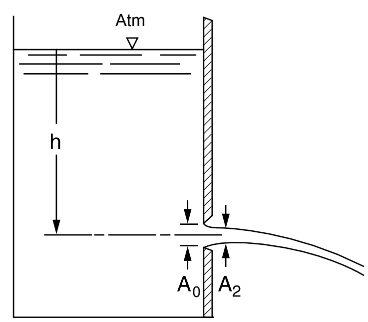
Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 534. Reproduced with permission of John Wiley & Sons, Inc.

$$Q = A_2 v_2 = C_c C_v A \sqrt{2g(h_1 - h_2)}$$
$$= CA \sqrt{2g(h_1 - h_2)}$$

in which the product of C_c and C_v is defined as the *coefficient of discharge* of the orifice.

v_2 = velocity of fluid exiting orifice

Orifice Discharging Freely into Atmosphere



Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 535. Reproduced with permission of John Wiley & Sons, Inc.

$$Q = CA_0 \sqrt{2gh}$$

in which h is measured from the liquid surface to the centroid of the orifice opening.

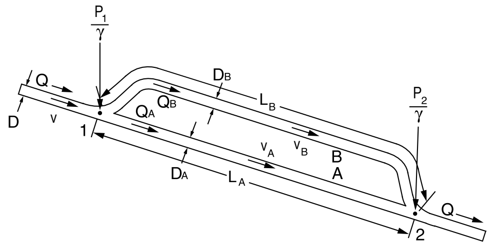
Q = volumetric flow

A_0 = cross-sectional area of flow

g = acceleration of gravity

h = height of fluid above orifice

Multipath Pipeline Problems



Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 407. Reproduced with permission of John Wiley & Sons, Inc.

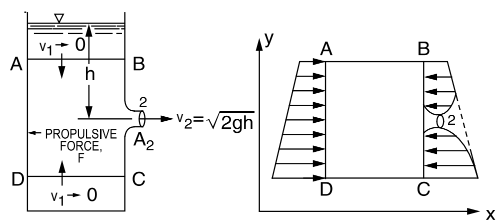
For pipes in parallel, the head loss is the same in each pipe.

$$h_L = f_A \frac{L_A}{D_A} \frac{v_A^2}{2g} = f_B \frac{L_B}{D_B} \frac{v_B^2}{2g}$$

$$\left(\pi D^2/4\right) v = \left(\pi D_A^2/4\right) v_A + \left(\pi D_B^2/4\right) v_B$$

The total flow rate Q is the sum of the flow rates in the parallel pipes.

Jet Propulsion



Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 232. Reproduced with permission of John Wiley & Sons, Inc.

$$F = Q\rho(v_2 - 0)$$

$$F = 2\gamma h A_2$$

F = propulsive force

γ = specific weight of the fluid

h = height of the fluid above the outlet

A_2 = area of the nozzle tip

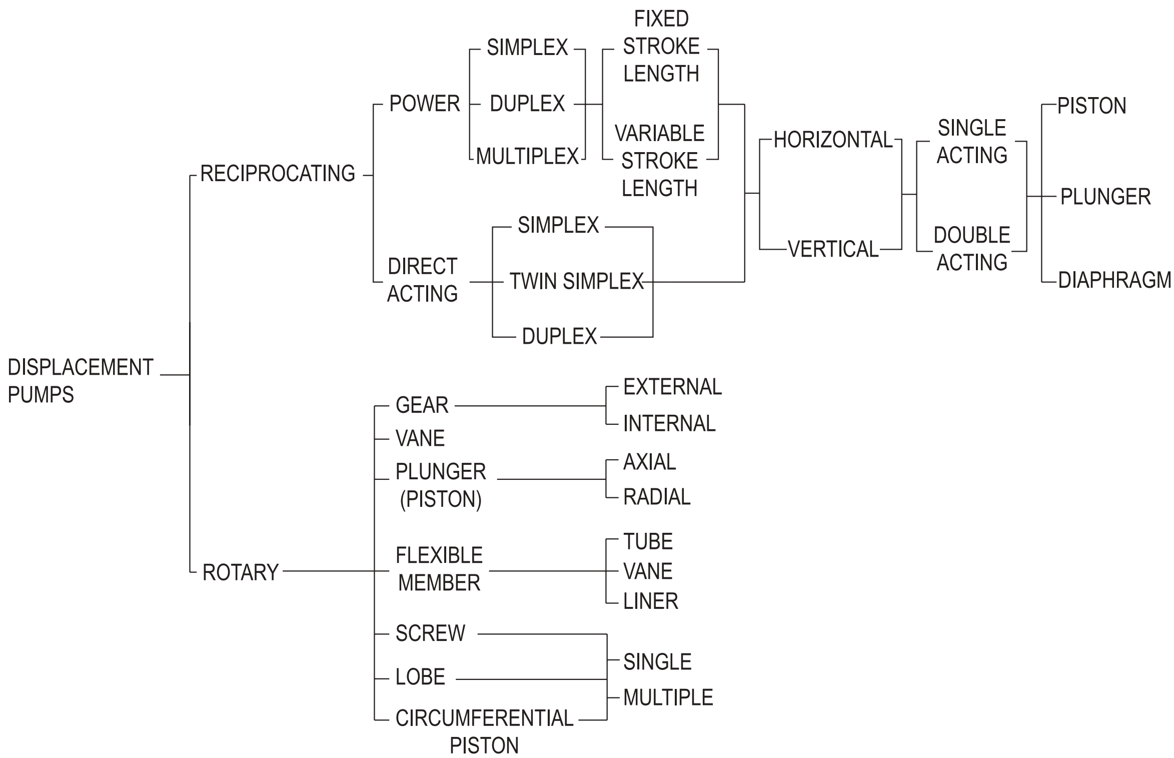
$$Q = A_2 \sqrt{2gh}$$

$$v_2 = \sqrt{2gh}$$

Fluid Flow Machinery

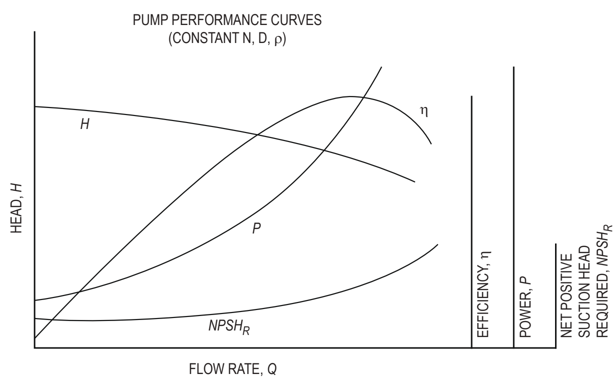
Displacement Pump Characteristics

Displacement pumps fall into two major classes: reciprocating and rotary, as shown in the figure below.



Avallone, Eugene A., Theodore Baumeister III, and Ali M. Sadegh, *Marks' Standard Handbook for Mechanical Engineers*, 11th ed. New York: McGraw-Hill, 2006, p. 14-2.

Centrifugal Pump Characteristics



Net Positive Suction Head Available ($NPSH_A$)

$$NPSH_A = \frac{P_{\text{atm}}}{\rho g} \pm H_s - H_f - \frac{V^2}{2g} - \frac{P_{\text{vapor}}}{\rho g}$$

P_{atm} = atmospheric pressure at fluid reservoir surface

H_s = elevation difference between the level of the fluid reservoir surface (zero datum) and the centerline of the pump suction inlet

H_f = friction losses from fluid source to pump inlet

V = fluid velocity at pump inlet

P_{vapor} = fluid vapor pressure at pump inlet

ρ = fluid density

g = gravitational constant

Fluid power, $\dot{W}_{\text{fluid}} = \rho gHQ$

Pump (brake) power, $\dot{W} = \dfrac{\rho gHQ}{\eta_{\text{pump}}}$

Purchased power, $\dot{W}_{\text{purchased}} = \dfrac{\dot{W}}{\eta_{\text{motor}}}$

η_{pump} = pump efficiency (0 to 1)

η_{motor} = motor efficiency (0 to 1)

H = head increase provided by pump

Pump Power Equation

$$\dot{W} = Q\gamma h/\eta = Q\rho gh/\eta_t$$

Q = volumetric flow (m^3/s or cfs)

h = head (m or ft) the fluid has to be lifted

η_t = total efficiency $(\eta_{\text{pump}} \times \eta_{\text{motor}})$

$\dot{W}$ = power ($kg{\bullet}m^2/sec^3$ or ft-lbf/sec)

Performance of Components

Fans, Pumps, and Compressors

Scaling Laws; *Affinity Laws; Fan Laws*

$$\left(\frac{Q}{ND^3}\right)_2 = \left(\frac{Q}{ND^3}\right)_1$$

$$\left(\frac{\dot{m}}{\rho ND^3}\right)_2 = \left(\frac{\dot{m}}{\rho ND^3}\right)_1$$

$$\left(\frac{H}{N^2D^2}\right)_2 = \left(\frac{H}{N^2D^2}\right)_1$$

$$\left(\frac{P}{\rho N^2D^2}\right)_2 = \left(\frac{P}{\rho N^2D^2}\right)_1$$

$$\left(\frac{\dot{W}}{\rho N^3D^5}\right)_2 = \left(\frac{\dot{W}}{\rho N^3D^5}\right)_1$$

Q = volumetric flow rate

$\dot{m}$ = mass flow rate

H = head

P = pressure rise

$\dot{W}$ = power

ρ = fluid density

N = rotational speed

D = impeller diameter

Subscripts 1 and 2 refer to different but similar machines or to different operating conditions of the same machine.

Flow Measurement

Pitot Tube

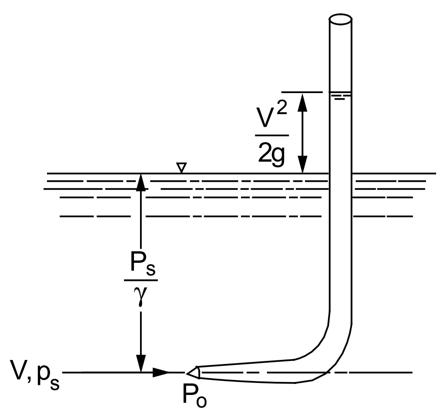
From the stagnation pressure equation for an *incompressible fluid*,

$$v = \sqrt{(2/\rho)(P_0 - P_s)} = \sqrt{2g(P_0 - P_s)/\gamma}$$

v = velocity of the fluid

P_0 = stagnation pressure

P_s = static pressure of the fluid at the elevation where the measurement is taken



Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 512. Reproduced with permission of John Wiley & Sons, Inc.

For a *compressible fluid*, use the above incompressible fluid equation if the Mach number ≤ 0.3.

Venturi Meters

$$Q = \frac{C_v A_2}{\sqrt{1 - (A_2/A_1)^2}} \sqrt{2g\left(\frac{P_1}{\gamma} + z_1 - \frac{P_2}{\gamma} - z_2\right)}$$

Q = volumetric flow rate

C_v = coefficient of velocity

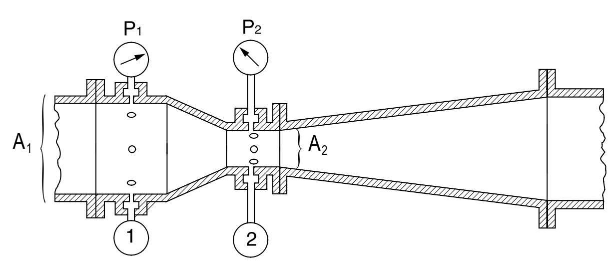
A = cross-sectional area of flow

P = pressure

$\gamma = \rho g$

z_1 = elevation of venturi entrance

z_2 = elevation of venturi throat

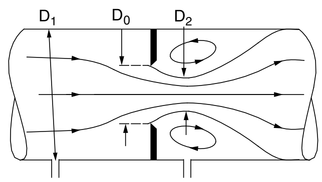


The above equation is for *incompressible fluids*.

Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 527. Reproduced with permission of John Wiley & Sons, Inc.

Orifices

The cross-sectional area at the vena contracta A_2 is characterized by a *coefficient of contraction* C_c and given by $C_c A$.

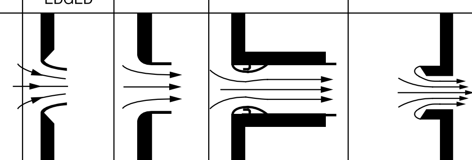


Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982, p. 532. Reproduced with permission of John Wiley & Sons, Inc.

$$Q = CA_0\sqrt{2g\left(\frac{P_1}{\gamma} + z_1 - \frac{P_2}{\gamma} - z_2\right)}$$

where C, the *coefficient of the meter* (*orifice coefficient*), is given by

$$C = \frac{C_v C_c}{\sqrt{1 - C_c^2\left(A_0/A_1\right)^2}}$$

ORIFICES AND THEIR NOMINAL COEFFICIENTS				
	SHARP EDGED	ROUNDED	SHORT TUBE	BORDA
				
C	0.61	0.98	0.80	0.51
C_c	0.62	1.00	1.00	0.52
C_v	0.98	0.98	0.80	0.98

Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed. New York: Wiley, 1982. p. 535. Reproduced with permission of John Wiley & Sons, Inc.

For incompressible flow through a horizontal orifice meter installation

$$Q = CA_0\sqrt{\frac{2}{\rho}\left(P_1 - P_2\right)}$$

Weir Formulas

Rectangular

Free discharge suppressed

$$Q = CLH^{3/2}$$

Free discharge contracted

$$Q = C(L - 0.2H)H^{3/2}$$

V-Notch

$$Q = CH^{5/2}$$

Q = discharge (cfs or m^3/s)

C = 3.33 for rectangular weir (USCS units)

C = 1.84 for rectangular weir (SI units)

C = 2.54 for 90° V-notch weir (USCS units)

C = 1.40 for 90° V-notch weir (SI units)

L = weir length (ft or m)

H = head (depth of discharge over weir) (ft or m)

Parshall (Venturi) Flume

The discharge equation for these flumes with widths of 1 ft (0.31 m) to 8 ft (2.4 m) is

$$Q = 4WH_a^{1.522W^{0.026}}$$

Q = discharge (cfs)

W = width of the flume throat

H_a = upstream head (ft)

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/Weir Length

Horizontal velocity = approach velocity = v_h

$= Q/A_{\text{cross-section}} = Q/A_x$

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

Q = flow rate

A_x = cross-sectional area

A = surface area, plan view

V = tank volume

Settling Equations

General Spherical

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

C_D = drag coefficient

= 24/Re (Laminar; Re ≤ 1.0)

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

= 0.4 (Turbulent; Re ≥ 10^4)

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

g = gravitational constant

ρ_p and ρ_f = density of particle and fluid, respectively

d = diameter of sphere

μ = bulk viscosity of liquid = absolute viscosity

v_t = terminal settling velocity

Stokes' Law

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

Approach velocity = horizontal velocity = Q/A_x

Hydraulic loading rate = Q/A

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

Q = flow rate

A_x = cross-sectional area

A = surface area, plan view

V = tank volume

ρ_f = fluid mass density

$S.G.$ = specific gravity

Lime-Soda Ash Softening Equations

1. Carbon dioxide removal

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3(s) + H_2O$$

2. Calcium carbonate hardness removal

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2\ CaCO_3(s) + 2\ H_2O$$

3. Calcium non-carbonate hardness removal

$$CaSO_4 + Na_2CO_3 \rightarrow CaCO_3(s) + 2\ Na^+ + SO_4^{2-}$$

4. Magnesium carbonate hardness removal

$$Mg(HCO_3)_2 + 2\ Ca(OH)_2 \rightarrow 2\ CaCO_3(s) + Mg(OH)_2(s) + 2\ H_2O$$

5. Magnesium non-carbonate hardness removal

$$MgSO_4 + Ca(OH)_2 + Na_2CO_3 \rightarrow CaCO_3(s) + Mg(OH)_2(s) + 2\ Na^+ + SO_4^{2-}$$

6. Destruction of excess alkalinity

$$2\ HCO_3^- + Ca(OH)_2 \rightarrow CaCO_3(s) + CO_3^{2-} + 2\ H_2O$$

7. Recarbonation

$$Ca^{2+} + 2\ OH^- + CO_2 \rightarrow CaCO_3(s) + H_2O$$

Coagulation Equations

Insoluble products are shown in italics

1. Aluminum sulfate in natural alkaline water

$$Al_2(SO_4)_3 + 3\ Ca(HCO_3)_2 \Leftrightarrow \mathit{2\ Al(OH)_3} + 3\ CaSO_4 + 6\ CO_2$$

2. Aluminum sulfate plus soda ash

$$Al_2(SO_4)_3 + 3\ NaCO_3 + 3\ H_2O \Leftrightarrow \mathit{2\ Al(OH)_3} + 3\ NaSO_4 + 3\ CO_2$$

3. Ferric sulfate

$$Fe_2(SO_4)_3 + 3\ Ca(HCO_3)_2 \Leftrightarrow \mathit{2\ Fe(OH)_3} + 3\ CaSO_4 + 6\ CO_2$$

4. Ferric chloride

$$2\ FeCl_3 + 3\ Ca(HCO_3)_2 \Leftrightarrow \mathit{2\ Fe(OH)_3} + 3\ CaCl_2 + 6\ CO_2$$

Phosphorus Removal Equations

1. Ferric chloride

$$FeCl_3 + PO_4^{3-} \rightarrow FePO_4 (\downarrow) + 3\ Cl^-$$

2. Ferrous chloride

$$3\ FeCl_2 + 2\ PO_4^{3-} \rightarrow Fe_3(PO_4)_2 (\downarrow) + 6\ Cl^-$$

3. Aluminum sulfate (alum)

$$Al_2 (SO_4)_3 \bullet 14\ H_2O + 2\ PO_4^{3-} \rightarrow 2\ AlPO_4 (\downarrow) + 3\ SO_4^{2-} + 14\ H_2O$$

Common Radicals in Water

Molecular Formulas	Molecular Weight	*n* # Equiv per mole	Equivalent Weight
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_2CO_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 to 10^5

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 (ft^3 or m^3)

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

γ = specific weight of water (lb/ft^3 or N/m^3)

H_L = head loss (ft or m)

t = time (sec or s)

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:

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

θ_c = Solids residence time = $\dfrac{V(X_A)}{Q_w X_w + Q_e X_e}$

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

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

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/m^3)

S_0 = influent BOD or COD concentration (kg/m^3)

X_A = biomass concentration in aeration tank (MLSS or MLVSS kg/m^3)

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) = $Q_0 S_0 / Vol$

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

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_0R

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

Flow Reactors, Steady State

Space-time τ is defined as the reactor volume divided by the inlet volumetric feed rate. Space-velocity SV is the reciprocal of space-time, $SV = 1/\tau$.

Plug-Flow Reactor (PFR)

$$\tau = \frac{C_{A0} V_{PFR}}{F_{A0}} = C_{A0} \int_0^{X_A} \frac{dX_A}{(-r_A)}$$

F_{A0} = moles of A fed per unit time

Continuous-Stirred Tank Reactor (CSTR)

For a constant volume, well-mixed CSTR

$$\frac{\tau}{C_{A0}} = \frac{V_{CSTR}}{F_{A0}} = \frac{X_A}{-r_A}$$

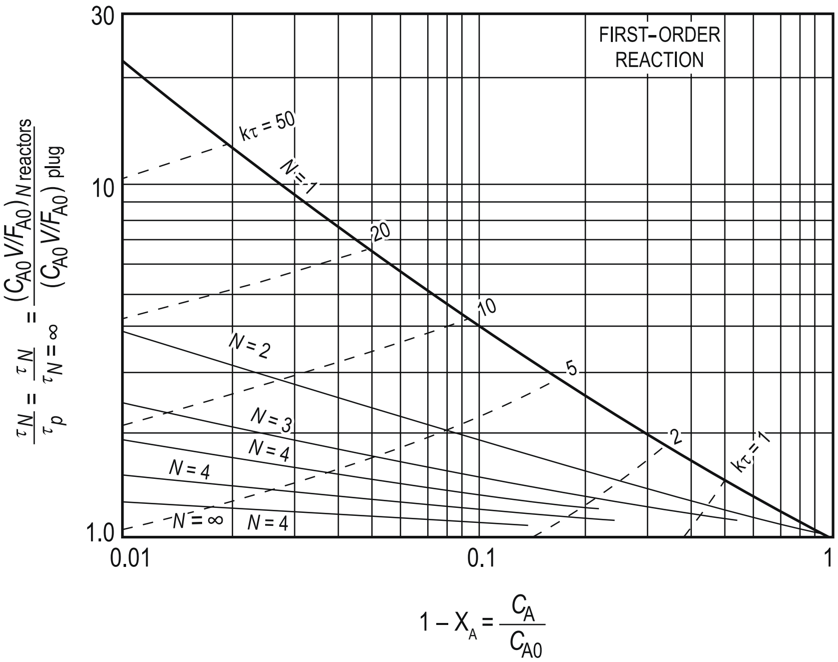
$-r_A$ is evaluated at exit stream conditions.

CSTR in Series

Now the space-time τ (or mean residence time *t*) is the same in all the equal-size reactors of volume V_i. Therefore

$$\frac{C_0}{C_N}=\frac{1}{1-X_N}=\frac{C_0}{C_1}\frac{C_1}{C_2}\cdots\frac{C_{N-1}}{C_N}=\frac{1}{\left(1+k\tau_i\right)^N}$$

Comparison of performance of a series of *N* equal-size mixed reactors with a plug flow reactor for the first-order reaction.



Levenspiel, Octove, *Chemical Reaction Engineering*, 2nd ed. New York: John Wiley and Sons, Inc., 1972.

Blowers

$$P_{\mathrm{w}}=\frac{W\ RT_1}{C\ ne}\left[\left(\frac{P_2}{P_1}\right)^{0.283}-1\right]$$

C = 29.7 (constant for SI unit conversion)

= 550 ft-lb/(sec-hp) (U.S. Customary Units)

P_W = power requirement (hp)

W = weight of flow of air (lb/sec)

R = engineering gas constant for air = 53.3 ft-lb/(lb air-°R)

T_1 = absolute inlet temperature (°R)

P_1 = absolute inlet pressure (lbf/in^2)

P_2 = absolute outlet pressure (lbf/in^2)

n = (k – 1)/k = 0.283 for air

e = efficiency (usually 0.70 < *e* < 0.90)

Specific Gravity for a Solids Slurry

$$S = \frac{W_w + W_s}{(W_w/1.00) + (W_s/S_s)}$$

S = specific gravity of wet sludge

W_w = weight of water (lb)

W_s = weight of dry solids (lb)

S_s = specific gravity of dry solids

The volume of waste sludge for a given amount of dry matter and concentration of solids is given by

$$V = \frac{W_s}{(s/100)\gamma S} = \frac{W_s}{\left[(100 - p)/100\right]\gamma S}$$

V = volume of sludge (ft^3 or gal or m^3)

W_s = weight of dry solids (lb or kg)

s = solids content (%)

γ = unit weight of water, 62.4 lb/ft^3 (8.34 lb/gal) [1,000 kg/m^3]

S = specific gravity of wet sludge

p = water content (%)

BOD_5 for Mixed Lagoons in Series

$$\frac{S}{S^0} = \frac{1}{1 + k_p \theta}$$

S^0 = Inlet total BOD_5

S = Outlet total BOD_5

θ = Fresh-feed residence time

k_p = Kinetic constant (time^{-1})

National Research Council (NRC) Trickling Filter Performance

For a single-stage or first-stage rock filter, the equation is

$$E_1 = \frac{100}{1 + 0.0561\sqrt{\frac{W}{VF}}}$$

E_1 = efficiency of BOD removal for process at 20°C, including recirculation and sedimentation, percent

W = BOD loading to filter (lb/day)

V = volume of filter media (10^3 ft^3)

F = recirculation factor

The recirculation factor is calculated using

$$F = \frac{1 + \frac{R}{I}}{\left(1 + 0.1\frac{R}{I}\right)^2}$$

R = recirculated flow

I = raw inflow

Dechlorination of Sulfite Compounds

Reaction between sodium sulfite and free chlorine residual and combined chlorine residual, as represented by monochloramine:

$$Na_2SO_3 + Cl_2 + H_2O \rightarrow Na_2SO_4 + 2\ HCl$$

Methanol Requirement for Biologically Treated Wastewater

$$C_m = 2.47N_o + 1.53N_1 + 0.87D_o$$

C_m = required methanol concentration (mg/L)

N_o = initial nitrate-nitrogen concentration (mg/L)

N_1 = initial nitrite-nitrogen concentration (mg/L)

D_o = initial dissolved-oxygen concentration (mg/L)

BOD Test Solution and Seeding Procedures

When the dilution of water is not seeded:

$$\text{BOD, mg/L} = \frac{D_1 - D_2}{P}$$

When the dilution of water is seeded:

$$\text{BOD, mg/L} = \frac{(D_1 - D_2) - (B_1 - B_2)f}{P}$$

D_1 = dissolved oxygen of diluted sample immediately after preparation (mg/L)

D_2 = dissolved oxygen of diluted sample after 5-day incubation at 20°C (mg/L)

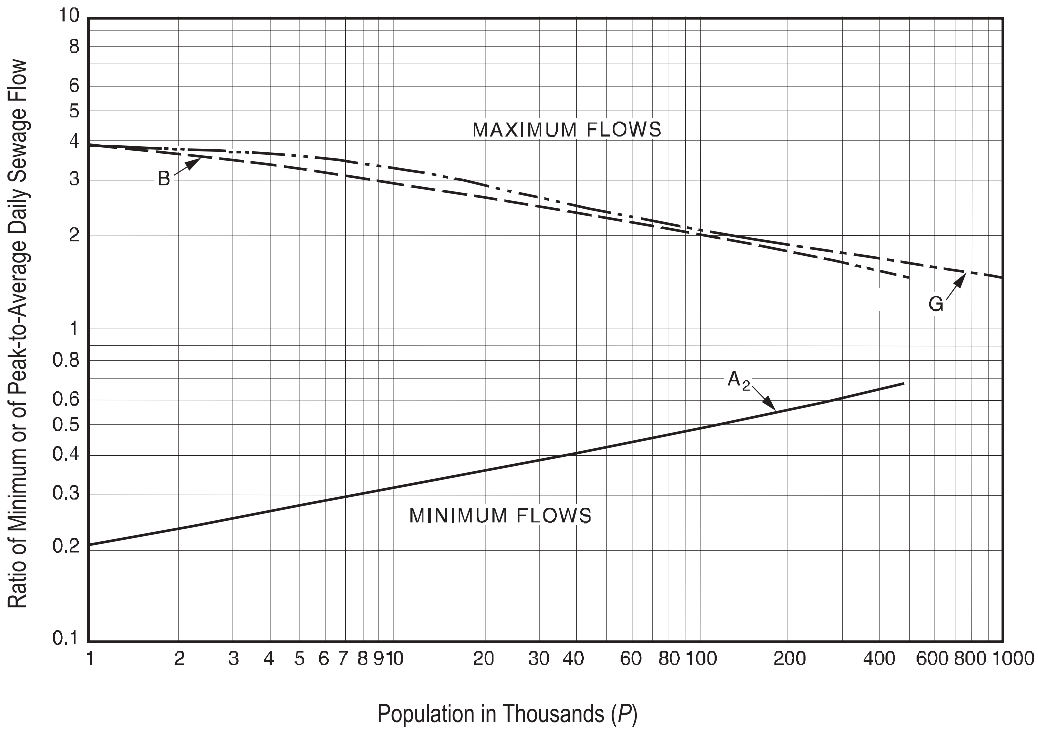
B_1 = dissolved oxygen of seed control before incubation (mg/L)

B_2 = dissolved oxygen of seed control after incubation (mg/L)

f = fraction of seeded dilution water volume in sample to volume of seeded dilution water in seed control

P = fraction of wastewater sample volume to total combined volume

Sewage Flow Ratio Curves



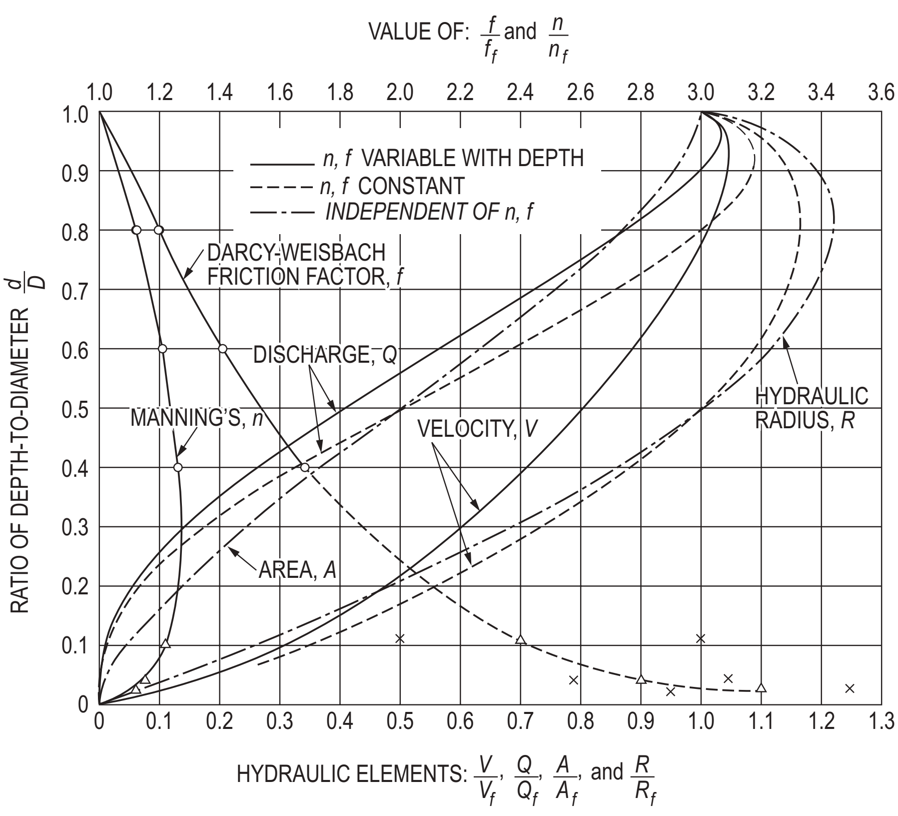
Curve A_2: $\frac{P^{0.2}}{5}$

Curve B: $\frac{14}{4+\sqrt{P}}+1$

Curve G: $\frac{18+\sqrt{P}}{4+\sqrt{P}}$

Water Pollution Control Federation and American Society of Civil Engineers, *Design and Construction of Sanitary and Storm Sewers*: American Society of Chemical Engineering, 1970. With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.

Hydraulic-Elements Graph for Circular Sewers



Water Pollution Control Federation and American Society of Civil Engineers, *Design and Construction of Sanitary and Storm Sewers*: American Society of Chemical Engineering, 1970. With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.

Common Chemicals in Water and Wastewater Processing

Name	Formula	Common Application	Molecular Weight	Equivalent Weight
Activated carbon	C	Taste and odor control	12.0	n.a.[a]
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 14.3\ H_2O$	Coagulation	600	100
Ammonia	NH_3	Chloramine disinfection	17.0	n.a.
Ammonium sulfate	$(NH_4)_2SO_4$	Coagulation	132	66.1
Calcium hydroxide	$Ca(OH)_2$	Softening	74.1	37.0
Calcium hypochlorite	$Ca(ClO)_2 \cdot 2H_2O$	Disinfection	179	n.a.
Calcium oxide	CaO	Softening	56.1	28.0
Carbon dioxide	CO_2	Recarbonation	44.0	22.0
Chlorine	Cl_2	Disinfection	71.0	n.a.
Chlorine dioxide	ClO_2	Taste and odor control	67.0	n.a.
Copper sulfate	$CuSO_4$	Algae control	160	79.8
Ferric chloride	$FeCl_3$	Coagulation	162	54.1
Ferric sulfate	$Fe_2(SO_4)_3$	Coagulation	400	66.7
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	Coagulation	278	139
Fluosilicic acid	H_2SiF_6	Fluoridation	144	n.a.
Magnesium hydroxide	$Mg(OH)_2$	Defluoridation	58.3	29.2
Oxygen	O_2	Aeration	32.0	16.0
Potassium permanganate	$KMnO_4$	Oxidation	158	n.a.
Sodium aluminate	$NaAlO_2$	Coagulation	82.0	n.a.
Sodium bicarbonate	$NaHCO_3$	pH adjustment	84.0	84.0
Sodium carbonate	Na_2CO_3	Softening	106	53.0
Sodium chloride	$NaCl$	Ion exchanger regeneration	58.4	58.4
Sodium fluoride	NaF	Fluoridation	42.0	n.a.
Sodium fluosilicate	Na_2SiF_6	Fluoridation	188	n.a.
Sodium hexameta-phosphate	$(NaPO_3)_n$	Corrosion control	n.a.	n.a.
Sodium hydroxide	$NaOH$	pH adjustment	40.0	40.0
Sodium hypochlorite	$NaClO$	Disinfection	74.4	n.a.
Sodium silicate	Na_2SiO_4	Coagulation aid	184	n.a.
Sodium thiosulfate	$Na_2S_2O_3$	Dechlorination	158	n.a.
Sulfur dioxide	SO_2	Dechlorination	64.1	n.a.
Sulfuric acid	H_2SO_4	pH adjustment	98.1	49.0

[a]Not applicable.

Viessman, W., and M.J. Hammer, *Water Supply and Pollution Control*, 4th ed., New York: Pearson, 1985, p. 353.

Data on Selected Elements, Radicals, and Compounds

Name	Symbol or Formula	Atomic or Molecular Weight	Equivalent Weight
Aluminum	Al^{3+}	27.0	9.0
Calcium	Ca^{2+}	40.1	20.0
Carbon	C	12.0	
Chloride	Cl^{-}	35.5	35.5
Hydrogen	H^{+}	1.0	1.0
Magnesium	Mg^{2+}	24.3	12.2
Manganese	Mn^{2+}	54.9	27.5
Nitrogen	N	14.0	
Oxygen	O	16.0	
Phosphorus	P	31.0	
Sodium	Na^{+}	23.0	23.0
Ammonium	NH_4^{+}	18.0	18.0
Bicarbonate	HCO_3^{-}	61.0	61.0
Carbonate	CO_3^{2-}	60.0	30.0
Hydroxyl	OH^{-}	17.0	17.0
Hypochlorite	OCl^{-}	51.5	51.5
Nitrate	NO_3^{-}	62.0	62.0
Orthophosphate	PO_4^{3-}	95.0	31.7
Sulfate	SO_4^{2-}	96.0	48.0
Aluminum hydroxide	$Al(OH)_3$	78.0	26.0
Calcium bicarbonate	$Ca(HCO_3)_2$	162	81.0
Calcium carbonate	$CaCO_3$	100	50.0
Calcium sulfate	$CaSO_4$	136	68.0
Carbon dioxide	CO_2	44.0	22.0
Ferric hydroxide	$Fe(OH)_3$	107	35.6
Hydrochloric acid	HCl	36.5	36.5
Magnesium carbonate	$MgCO_3$	84.3	42.1
Magnesium hydroxide	$Mg(OH)_2$	58.3	29.1
Magnesium sulfate	$MgSO_4$	120	60.1
Sodium sulfate	Na_2SO_4	142	71.0

Adapted from Viessman, W., and M.J. Hammer, *Water Supply and Pollution Control,* 4th ed., New York: Pearson, 1985, p. 355.

Gases Found in Wastewater at Standard Conditions (0°C, 1 atm)				
Gas	**Formula**	**Molecular weight**	**Specific weight (lb/ft^3)**	**Density (g/L)**
Air	–	28.97	0.0808	1.2928
Ammonia	NH_3	17.03	0.0482	0.7708
Carbon dioxide	CO_2	44.00	0.1235	1.9768
Carbon monoxide	CO	28.00	0.0781	1.2501
Hydrogen	H_2	2.016	0.0056	0.0898
Hydrogen sulfide	H_2S	34.08	0.0961	1.5392
Methane	CH_4	16.03	0.0448	0.7167
Nitrogen	N_2	28.02	0.0782	1.2507
Oxygen	O_2	32.00	0.0892	1.4289

Perry, R.H., D.W. Green, and J.O. Maloney, *Perry's Chemical Engineers' Handbook*, 6th ed., New York: McGraw-Hill, 1984, p. 3-78.

Water Resources/Hydrology

NRCS (SCS) Rainfall-Runoff

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

$$S = \frac{1,000}{CN} - 10$$

$$CN = \frac{1,000}{S + 10}$$

P = precipitation (in.)

S = maximum basin retention (in.)

Q = runoff (in.)

CN = curve number

Rational Formula

$$Q = CIA$$

A = watershed area (acres)

C = runoff coefficient

I = rainfall intensity (in./hr)

Q = peak discharge (cfs)

Unit Hydrographs

$$q_p = \frac{484AQ}{T_p}$$

q_p = peak discharge in cubic feet per second (ft^3/sec)

T_p = time from the beginning of the triangular hydrograph to its peak (hours)

A = drainage area in square miles (mi^2)

Q = runoff in inches (in.)

Properties of Water (SI Metric Units)

Temperature (°C)	Specific Weight γ (kN/m^3)	Density ρ (kg/m^3)	Absolute Dynamic Viscosity μ (Pa•s)	Kinematic Viscosity υ (m^2/s)	Vapor Pressure P_v (kPa)
0	9.805	999.8	0.001781	0.000001785	0.61
5	9.807	1000.0	0.001518	0.000001518	0.87
10	9.804	999.7	0.001307	0.000001306	1.23
15	9.798	999.1	0.001139	0.000001139	1.70
20	9.789	998.2	0.001002	0.000001003	2.34
25	9.777	997.0	0.000890	0.000000893	3.17
30	9.764	995.7	0.000798	0.000000800	4.24
40	9.730	992.2	0.000653	0.000000658	7.38
50	9.689	988.0	0.000547	0.000000553	12.33
60	9.642	983.2	0.000466	0.000000474	19.92
70	9.589	977.8	0.000404	0.000000413	31.16
80	9.530	971.8	0.000354	0.000000364	47.34
90	9.466	965.3	0.000315	0.000000326	70.10
100	9.399	958.4	0.000282	0.000000294	101.33

Vennard, John K., and Robert L. Street, *Elementary Fluid Mechanics*, 6th ed., New York: Wiley, 1982, p. 663. Reproduced with permission of John Wiley & Sons, Inc.

Properties of Water (English Units)

Temperature (°F)	Specific Weight γ (lbf/ft^3)	Mass Density ρ (lbf-sec^2/ft^4)	Absolute Dynamic Viscosity μ ($\times 10^{-5}$ lbf-sec/ft^2)	Kinematic Viscosity υ ($\times 10^{-5}$ ft^2/sec)	Vapor Pressure P_v (psi)
32	62.42	1.940	3.746	1.931	0.09
40	62.43	1.940	3.229	1.664	0.12
50	62.41	1.940	2.735	1.410	0.18
60	62.37	1.938	2.359	1.217	0.26
70	62.30	1.936	2.050	1.059	0.36
80	62.22	1.934	1.799	0.930	0.51
90	62.11	1.931	1.595	0.826	0.70
100	62.00	1.927	1.424	0.739	0.95
110	61.86	1.923	1.284	0.667	1.24
120	61.71	1.918	1.168	0.609	1.69
130	61.55	1.913	1.069	0.558	2.22
140	61.38	1.908	0.981	0.514	2.89
150	61.20	1.902	0.905	0.476	3.72
160	61.00	1.896	0.838	0.442	4.74
170	60.80	1.890	0.780	0.413	5.99
180	60.58	1.883	0.726	0.385	7.51
190	60.36	1.876	0.678	0.362	9.34
200	60.12	1.868	0.637	0.341	11.52
212	59.83	1.860	0.593	0.319	14.70

Vennard, John K., and Robert L. Street, *Elementary Fluid Mechanics*, 6th ed., New York: Wiley, 1982, p. 663. Reproduced with permission of John Wiley & Sons, Inc.

Time of Concentration

Time of concentration for a particular inlet to a storm sewer

$$t = t_i + t_s$$

t = time of concentration

t_s = time of sewer flow

The inlet time can be estimated by

$$t_i = C(L/S\,i^2)^{1/3}$$

t_i = time of overland flow (min)

L = distance of overland flow (ft)

S = slope of land (ft/ft)

i = rainfall intensity (in./hour)

C = coefficient

Runoff Coefficients

Land Use	*C*	Land Use	*C*
Business:		***Lawns:***	
Downtown areas	0.70–0.95	Sandy soil, flat, 2%	0.05–0.10
Neighborhood areas	0.50–0.70	Sandy soil, avg., 2–7%	0.10–0.15
		Sandy soil, steep, 7%	0.15–0.20
		Heavy soil, flat, 2%	0.13–0.17
		Heavy soil, avg., 2–7%	0.18–0.22
		Heavy soil, steep, 7%	0.25–0.35
Residential:		***Agricultural land:***	
Single-family areas	0.30–0.50	*Bare packed soil*	
Multi units, detached	0.40–0.60	*Smooth	0.30–0.60
Multi units, attached	0.60–0.75	*Rough	0.20–0.50
Suburban	0.25–0.40	*Cultivated rows*	
		*Heavy soil, no crop	0.30–0.60
		*Heavy soil, with crop	0.20–0.50
		*Sandy soil, no crop	0.20–0.40
		*Sandy soil, with crop	0.10–0.25
		Pasture	
		*Heavy soil	0.15–0.45
		*Sandy soil	0.05–0.25
		Woodlands	0.05–0.25
Industrial:		***Streets:***	
Light areas	0.50–0.80	Asphaltic	0.70–0.95
Heavy areas	0.60–0.90	Concrete	0.80–0.95
		Brick	0.70–0.85
Parks, cemeteries	0.10–0.25	Unimproved areas	0.10–0.30
Playgrounds	0.20–0.35	Drives and walks	0.75–0.85
Railroad yard areas	0.20–0.40	Roofs	0.75–0.95

Design Manual for Storm Drainage, New York: American Society of Civil Engineers, 1960, as published in Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22, Federal Highway Administration, 2009.

Storm Return Period

The probability of exceedance at least once in n years is

$$P\left(X \geq x_T \text{ at least once in } n \text{ years}\right) = 1 - \left(1 - \frac{1}{T}\right)^n$$

which is the probability that a T-year return period event will occur at least once in n years.

Microbial Kinetics

BOD Exertion

$$y_t = L\left(1 - \mathrm{e}^{-kt}\right)$$

k = BOD decay rate constant, base e (days^{-1})

L = ultimate BOD (mg/L)

t = time (days)

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

Stream Modeling

Streeter Phelps

$$D = \frac{k_1 L_0}{k_2 - k_1}\left(\mathrm{e}^{-k_1 t} - \mathrm{e}^{-k_2 t}\right) + D_0 \mathrm{e}^{-k_2 t}$$

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

$$D_c = \frac{k_1}{k_2} L_0 \mathrm{e}^{-k_1 t_c}$$

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

D = dissolved oxygen deficit (mg/L)

D_c = maximum 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)

Kinetic Temperature Corrections

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

Activated sludge:	$\theta = 1.136$	$T = 4–20°C$
	$\theta = 1.056$	$T = 21–30°C$
Reaeration	$\theta = 1.024$	
Biotowers	$\theta = 1.035$	
Trickling Filters	$\theta = 1.072$	

Determination of Required Reservoir Capacity

$$\Delta S = I - O$$

ΔS = change in storage volume during a specified time interval

I = total inflow volume during this period

O = total outflow volume during this period (evaporation, transpiration, and flood discharge)

Pan Evaporation

Pan evaporation is used widely to estimate lake evaporation in the United States. The lake evaporation E_L is usually computed for yearly time periods. Its relationship with the pan evaporation E_P can be expressed as

$$E_L = p_c E_P$$

where p_c is the pan coefficient.

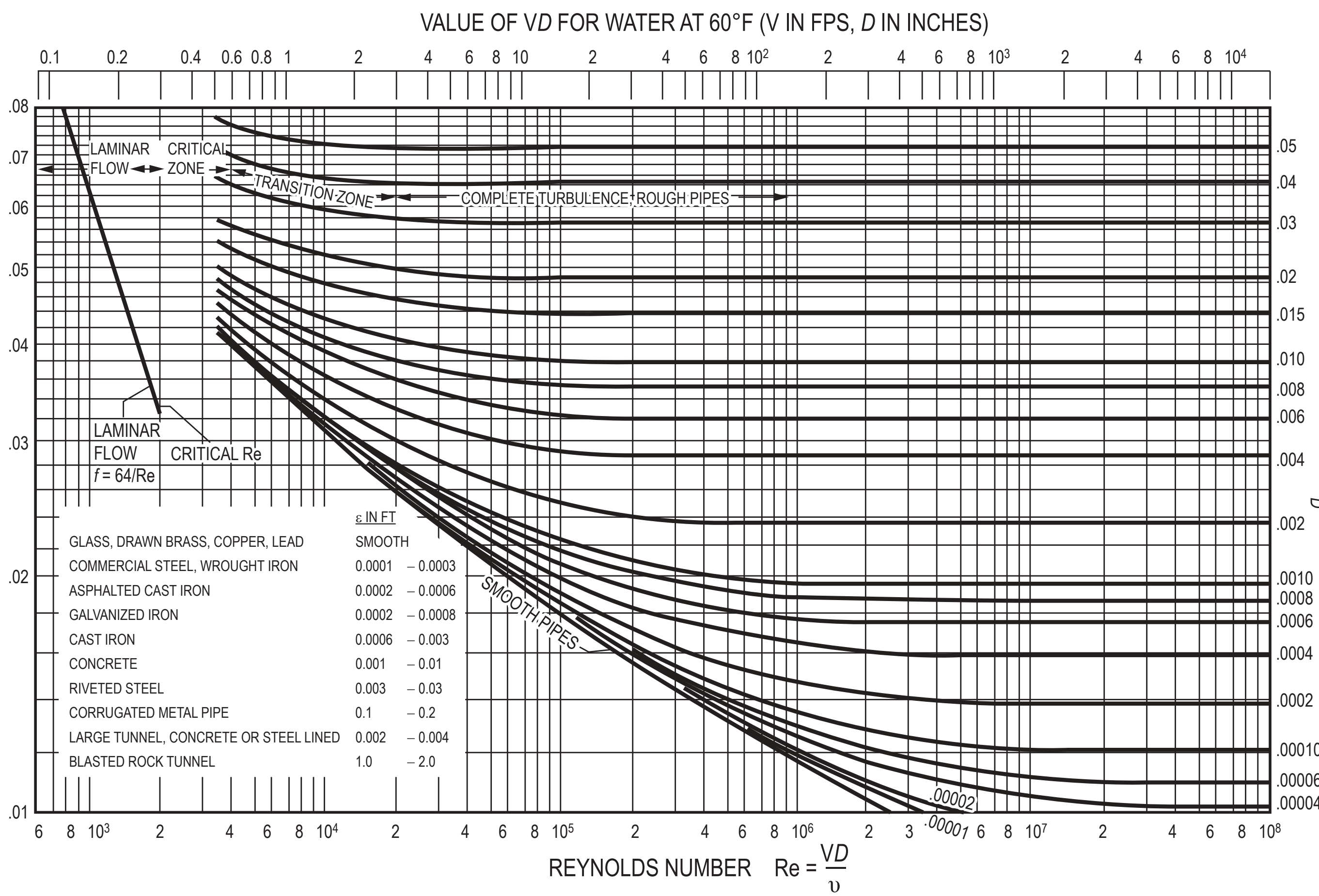
Dissolved-Oxygen Concentration in Water

Dissolved-oxygen concentration in water as a function of temperature and salinity (barometric pressure = 760 mm Hg)										
Temp, °C	Dissolved-oxygen Concentration, mg/L									
	Salinity, parts per thousand									
	0	5	10	15	20	25	30	35	40	45
0	14.60	14.11	13.64	13.18	12.74	12.31	11.90	11.50	11.11	10.74
1	14.20	13.73	13.27	12.83	12.40	11.98	11.58	11.20	10.83	10.46
2	13.81	13.36	12.91	12.49	12.07	11.67	11.29	10.91	10.55	10.20
3	13.45	13.00	12.58	12.16	11.76	11.38	11.00	10.64	10.29	9.95
4	13.09	12.67	12.25	11.85	11.47	11.09	10.73	10.38	10.04	9.71
5	12.76	12.34	11.94	11.56	11.18	10.82	10.47	10.13	9.80	9.48
6	12.44	12.04	11.65	11.27	10.91	10.56	10.22	9.89	9.57	9.27
7	12.13	11.74	11.37	11.00	10.65	10.31	9.98	9.66	9.35	9.06
8	11.83	11.46	11.09	10.74	10.40	10.07	9.75	9.44	9.14	8.85
9	11.55	11.19	10.83	10.49	10.16	9.84	9.53	9.23	8.94	8.66
10	11.28	10.92	10.58	10.25	9.93	9.62	9.32	9.03	8.75	8.47
11	11.02	10.67	10.34	10.02	9.71	9.41	9.12	8.83	8.56	8.30
12	10.77	10.43	10.11	9.80	9.50	9.21	8.92	8.65	8.38	8.12
13	10.53	10.20	9.89	9.59	9.30	9.01	8.74	8.47	8.21	7.96
14	10.29	9.98	9.68	9.38	9.10	8.82	8.55	8.30	8.04	7.80
15	10.07	9.77	9.47	9.19	8.91	8.64	8.38	8.13	7.88	7.65
16	9.86	9.56	9.28	9.00	8.73	8.47	8.21	7.97	7.73	7.50
17	9.65	9.36	9.09	8.82	8.55	8.30	8.05	7.81	7.58	7.36
18	9.45	9.17	8.90	8.64	8.39	8.14	7.90	7.66	7.44	7.22
19	9.26	8.99	8.73	8.47	8.22	7.98	7.75	7.52	7.30	7.09
20	9.08	8.81	8.56	8.31	8.07	7.83	7.60	7.38	7.17	6.96
21	8.90	8.64	8.39	8.15	7.91	7.69	7.46	7.25	7.04	6.84
22	8.73	8.48	8.23	8.00	7.77	7.54	7.33	7.12	6.91	6.72
23	8.56	8.32	8.08	7.85	7.63	7.41	7.20	6.99	6.79	6.60
24	8.40	8.16	7.93	7.71	7.49	7.28	7.07	6.87	6.68	6.49
25	8.24	8.01	7.79	7.57	7.36	7.15	6.95	6.75	6.56	6.38
26	8.09	7.87	7.65	7.44	7.23	7.03	6.83	6.64	6.46	6.28
27	7.95	7.73	7.51	7.31	7.10	6.91	6.72	6.53	6.35	6.17
28	7.81	7.59	7.38	7.18	6.98	6.79	6.61	6.42	6.25	6.08
29	7.67	7.46	7.26	7.06	6.87	6.68	6.50	6.32	6.15	5.98
30	7.54	7.33	7.14	6.94	6.75	6.57	6.39	6.22	6.05	5.89
31	7.41	7.21	7.02	6.83	6.65	6.47	6.29	6.12	5.96	5.80
32	7.29	7.09	6.90	6.72	6.54	6.36	6.19	6.03	5.87	5.71
33	7.17	6.98	6.79	6.61	6.44	6.26	6.10	5.94	5.78	5.63
34	7.05	6.86	6.68	6.51	6.33	6.17	6.01	5.85	5.69	5.54
35	6.93	6.75	6.58	6.40	6.24	6.07	5.92	5.76	5.61	5.46
36	6.82	6.65	6.47	6.31	6.14	5.98	5.83	5.68	5.53	5.39
37	6.72	6.54	6.37	6.21	6.05	5.89	5.74	5.59	5.45	5.31
38	6.61	6.44	6.28	6.12	5.96	5.81	5.66	5.51	5.37	5.24
39	6.51	6.34	6.18	6.03	5.87	5.72	5.58	5.44	5.30	5.16
40	6.41	6.25	6.09	5.94	5.79	5.64	5.50	5.36	5.22	5.09

Colt, J., *Computation of Dissolved Gas Concentration in Water as Functions of Temperature, Salinity, and Pressure*, Bethesda: American Fisheries Society, 1984.

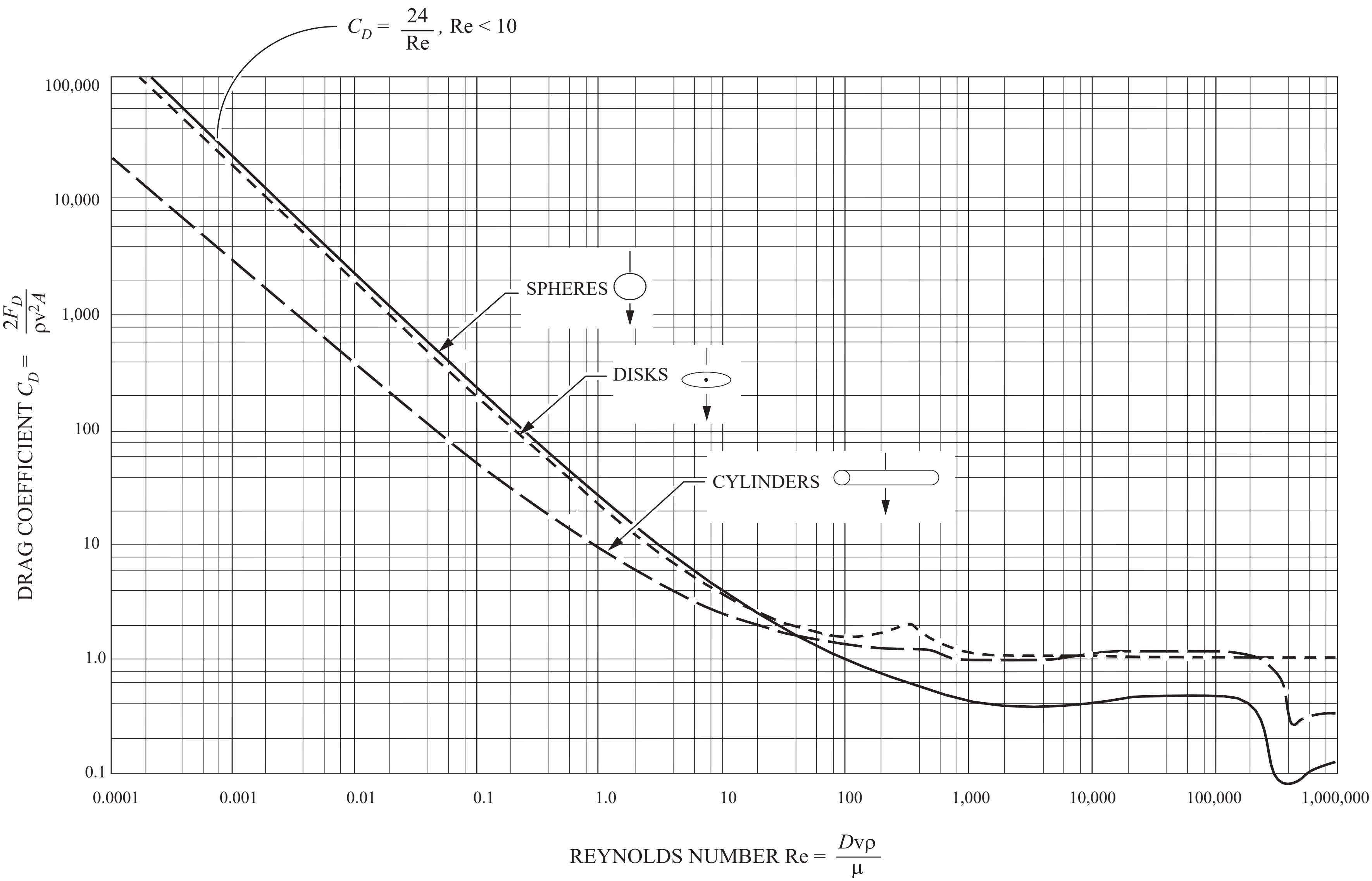
Moody, Darcy, or Stanton Diagram

FLOW IN CLOSED CONDUITS



Chow, Ven Te, *Handbook of Applied Hydrology*, New York: McGraw-Hill, 1964, p. 7-17.

Drag Coefficient for Spheres, Disks, and Cylinders



Note: Intermediate divisions are 2, 4, 6, and 8

Regulated Drinking Water Contaminants

The National Primary Drinking Water Regulations (NPDWRs or primary standards) are legally enforceable standards that apply to public water systems. Primary standards protect public health by limiting the levels of contaminants in drinking water. See the list below of regulated contaminants for details.

Microorganisms				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Cryptosporidium	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Giardia lamblia	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Heterotrophic plate count (HPC)	n/a	TT[3]	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is.	HPC measures a range of bacteria that are naturally present in the environment
Legionella	zero	TT[3]	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and *E. coli*)	zero	5.0%[4]	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present[5]	Coliforms are naturally present in the environment as well as feces; fecal coliforms an *E. coli* only come from human and animal fecal waste.
Turbidity	n/a	TT[3]	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (such as whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites, and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff
Viruses (enteric)	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste

Disinfection Byproducts				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Bromate	zero	0.010	Increased risk of cancer	Byproduct of drinking water disinfection
Chlorite	0.8	1.0	Anemia; infants and young children: nervous system effects	Byproduct of drinking water disinfection
Haloacetic acids (HAA5)	n/a[6]	0.060	Increased risk of cancer	Byproduct of drinking water disinfection
Total Trihalomethanes (TTHMs)	--> n/a[6]	========-->--> 0.080	Liver, kidney, or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection

Disinfectants				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Chloramines (as Cl_2)	MRDLG = 4[1]	MRDL = 4.0[1]	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes
Chlorine (as Cl_2)	MRDLG = 4[1]	MRDL = 4.0[1]	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO_2)	MRDLG = 0.8[1]	MRDL = 0.8[1]	Anemia; infants and young children: nervous system effects	Water additive used to control microbes

Regulated Drinking Water Contaminants (continued)

Inorganic Chemicals				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	0	0.010 as of 01/23/06	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass and electronics production wastes
Asbestos (fiber > 10 micrometers)	7 million fibers per liter (MFL)	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits
Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints
Chromium (total)	0.1	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	TT[7]; Action Level = 1.3	Short term exposure: Gastrointestinal distress Long term exposure: Liver or kidney damage People with Wilson's disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	zero	TT[7]; Action Level = 0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Mercury (inorganic)	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands
Nitrate (measured as Nitrogen)	10	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits
Nitrite (measured as Nitrogen)	1	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories

Regulated Drinking Water Contaminants (continued)

Organic Chemicals				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Acrylamide	zero	TT[8]	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	zero	0.002	Eye, liver, kidney, or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops
Benzene	zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills
Benzo(a)pyrene (PAHs)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	zero	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights-of-way
1,2-Dibromo-3-chloropropane (DBCP)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards
o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney, or spleen damage; changes in blood	Discharge from industrial chemical factories
1,2-Dichloroethane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1,1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1,2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	zero	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories
1,2-Dichloropropane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
Di(2-ethylhexyl) adipate	0.4	0.4	Weight loss, liver problems, or possible reproductive difficulties.	Discharge from chemical factories
Di(2-ethylhexyl) phthalate	zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Dioxin (2,3,7,8-TCDD)	zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Liver problems	Residue of banned insecticide
Epichlorohydrin	zero	TT[8]	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals
Ethylbenzene	0.7	0.7	Liver or kidneys problems	Discharge from petroleum refineries
Ethylene dibromide	zero	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	zero	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor
Hexachlorobenzene	zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock
Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals

Regulated Drinking Water Contaminants (continued)

Organic Chemicals				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Pentachlorophenol	zero	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Toxaphene	zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle
2,4,5-TP (Silvex)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories
1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories
Vinyl chloride	zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Radionuclides				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Alpha particles	none[7] ---------- zero	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation
Beta particles and photon emitters	none[7] ---------- zero	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation
Radium 226 and Radium 228 (combined)	none[7] ---------- zero	5 pCi/L	Increased risk of cancer	Erosion of natural deposits
Uranium	zero	30 ug/L as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

Notes

[1]Definitions

- Maximum Contaminant Level Goal (MCLG): The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.
- Maximum Contaminant Level (MCL): The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
- Maximum Residual Disinfectant Level Goal (MRDLG): The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.
- Treatment Technique (TT): A required process intended to reduce the level of a contaminant in drinking water.
- Maximum Residual Disinfectant Level (MRDL): The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.

[2]Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (PPM).

[3]EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to

a. Disinfect their water, and
b. Filter their water, or
c. Meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:
  - Cryptosporidium: Unfiltered systems are required to include Cryptosporidium in their existing watershed control provisions
  - Giardia lamblia: 99.9% removal/inactivation
  - Viruses: 99.99% removal/inactivation

- Legionella: No limit, but EPA believes that if Giardia and viruses are removed/inactivated, according to the treatment techniques in the Surface Water Treatment Rule, Legionella will also be controlled
- Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs
- Heterotrophic Plate Count (HPC): No more than 500 bacterial colonies per milliliter
- Long Term 1 Enhanced Surface Water Treatment: Surface water systems or groundwater under the direct influence (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long Term 1 Enhanced Surface Water Treatment Rule provisions (such as turbidity standards, individual filter monitoring, Cryptosporidium removal requirements, updated watershed control requirements for unfiltered systems)
- Long Term 2 Enhanced Surface Water Treatment Rule: This rule applies to all surface water systems or ground water systems under the direct influence of surface water. The rule targets additional Cryptosporidium treatment requirements for higher risk systems and includes provisions to reduce risks from uncovered finished water storage facilities and to ensure that the systems maintain microbial protection as they take steps to reduce the formation of disinfection byproducts
- Filter Backwash Recycling: This rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

[4]No more than 5.0% samples total coliform-positive (TC-positive) in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or E. coli if two consecutive TC-positive samples, and one is also positive for E.coli fecal coliforms, system has an acute MCL violation

[5]Fecal coliform and E. coli are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

[6]Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

- Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L): chloroform (0.07 mg/L).
- Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.02 mg/L); monochloroacetic acid (0.07mg/L). Bromoacetic acid and dibromoacetic acid are regulated with this group but have no MCLGs.

[7]Lead and copper are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 mg/L, and for lead is 0.015 mg/L.

Lead and copper analytical results are evaluated against an action level, not an MCL. The lead action level is exceeded if the concentration of lead in more than 10 percent of tap water samples collected during any monitoring period is greater than 0.015 mg/L (i.e., if the 90th percentile level lead level is greater than 0.015 mg/L). The copper action level is exceeded if the concentration of copper in more than 10 percent of tap water samples collected during any monitoring period conducted is greater than 1.3 mg/L (i.e., if the 90th percentile copper level is greater than 1.3 mg/L).

All samples that meet the proper site selection and sample collection procedures are used to determine the 90th percentile calculation, even if you collect samples from more sites than required.

The 90th percentile is calculated separately for lead and copper. The procedure for determining the lead 90th percentile value is as follows:

90th percentile value for more than five samples:

Step 1: Place lead results in ascending order (from lowest to highest value).

Step 2: Assign each sample a number, 1 for lowest value.

Step 3: Multiply the total number of samples by 0.9.

Step 4: Compare the 90th percentile level to the action level of 0.015 mg/L (can also be expressed as 15 parts per billion (ppb)). If the 90th percentile level calculated in Step 3 is not a whole number, either rounding or interpolation can be used to determine the 90th level.

Either rounding or interpolation can be used to determine the 90th percentile level when the sample that represents it is not a whole number.

[8]Each water system must certify, in writing, to the state (using third-party or manufacturer's certification) that when acrylamide and epichlorohydrin are used to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

- Acrylamide = 0.05% dosed at 1 mg/L (or equivalent)
- Epichlorohydrin = 0.01% dosed at 20 mg/L (or equivalent)

National Primary Drinking Water Regulations, Washington, D.C.: U.S. Environmental Protection Agency, www.epa.gov.

Secondary Drinking Water Standards

Contaminant	Secondary MCL	Noticeable Effects above the Secondary MCL
Aluminum	0.05 to 0.2 mg/L*	colored water
Chloride	250 mg/L	salty taste
Color	15 color units	visible tint
Copper	1.0 mg/L	metallic taste; blue-green staining
Corrosivity	Non-corrosive	metallic taste; corroded pipes/ fixtures staining
Fluoride	2.0 mg/L	tooth discoloration
Foaming agents	0.5 mg/L	frothy, cloudy; bitter taste; odor
Iron	0.3 mg/L	rusty color; sediment; metallic taste; reddish or orange staining
Manganese	0.05 mg/L	black to brown color; black staining; bitter metallic taste
Odor	3 TON (threshold odor number)	"rotten-egg," musty, or chemical smell
pH	6.5–8.5	low pH: bitter metallic taste; corrosion high pH: slippery feel; soda taste; deposits
Silver	0.1 mg/L	skin discoloration; graying of the white part of the eye
Sulfate	250 mg/L	salty taste
Total Dissolved Solids (TDS)	500 mg/L	hardness; deposits; colored water; staining; salty taste
Zinc	5 mg/L	metallic taste

*mg/L is milligrams of substance per liter of water.

Secondary Drinking Water Standards: Guidance for Nuisance Chemicals, "Table of Secondary Standards," Washington, D.C.: U.S. Environmental Protection Agency, www.epa.gov.

CT is the concentration of chlorine in water multiplied by the time of contact that the chlorine has with the water.

CT = concentration × time

C = mg/L free chlorine in the water where the inactivation is occurring (tanks, pipelines, etc.)

T = minutes of contact time with the disinfectant in each segment, prior to first consumer

V = volume

$$\text{Baffling Factor} = \frac{T10}{T_{\text{theoretical}}}$$

$$T\,(\text{min}) = \frac{V(\text{gal}) \times BF}{\text{peak flow (gal/min)}}$$

EPA Baffling Factors		
Baffling condition	***T*10/*T******	**Baffling Description**
Unbaffled	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities, unbaffled, inlet and outlet at the same levels.
Unbaffled	0.2	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities, unbaffled, inlet/high and outlet/low or vice versa.
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles, vertical perforated pipe for an inlet and/or outlet.
Average	0.5	Baffled inlet or outlet, vertical perforated pipe for an inlet or outlet, with some intra-basin baffles.
Superior	0.7	Perforated inlet baffle, perforated intra-basin baffles, outlet weirs or perforated launders.
Excellent	0.9	Serpentine baffling throughout
Perfect	1.0	Pipeline flow

*$T10$ = detention time at which 90% of the water passing through the unit is retained

Wyoming Association of Rural Water Systems (WARWS) Conference Handouts, Washington, D.C.: U.S. Environmental Protection Agency, www.epa.gov.

Log Removal

log removal = –log (1 – % removal/100)

Filtration Credits for Microbial Removal to Meet SWTR, IESWTR, and LTIESWTR**

(Systems consistently meeting the CFE turbidity limits in the table below, and the operational and design requirements obtained in this policy, are granted the logs removal credit in the table below.)

Filtration Treatment Technology	Combined Filter Effluent (CFE) Turbidity (95% Monthly/Max) atu	Maximum Logs of Credit for Physical Removal			Minimum Logs of Inactivation Needed by Disinfection	
		Cryptosporidium	***Giardia***	**Viruses**	***Giardia***	**Viruses**
Conventional	***0.3/1	>2	2.5	2.0	0.5	2.0
Direct	***0.3/1	>2	2.0	1.0	1.0	3.0
Slow Sand	1/5	>2	2.0	2.0	1.0	2.0
Diatomaceous Earth	1/5	>2	2.0	1.0	1.0	3.0
Reverse Osmosis	0.3/1	>2	>3.0	3.0	0	1.0
Nanofiltration	0.3/1	>2	>3.0	3.0	0	1.0
Ultrafiltration	0.3/1	>2	>3.0	0	0	4.0
Microfiltration	0.3/1	>2	>3.0	0	0	4.0
Pretreatment plus Bag or Cartridge (B/C) *	1/5	2	2.0	0	1.0	4.0
Conventional Filtration followed by (B/C)	0.5/5	2	2.5	2.0	0.5	2.0

*See policy for description of adequate pretreatment for SW and for GWUDSW using B/C Filtration

**Additional types of alternative filtration should be evaluated on a case-specific basis. 95th percentile and maximum turbidity values will be no more than 1 NTU and 5 NTU, respectively, for all alternative filtration technologies, unless different site specific values are assigned. All NTU reading shall be in accordance with EPA established policy. Also, these filtration credits do not apply to point-of-use devices.

***Conventional and direct filtration also have requirements for monitoring of individual filter effluent turbidity (IFE). See IESWTR and LTIESWTR.

Wyoming Association of Rural Water Systems (WARWS) Conference Handouts, Washington, D.C.: U.S. Environmental Protection Agency, www.epa.gov.

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

CT Values* for 4-LOG Inactivation of Viruses by Free Chlorine

	pH	
Temperature (°C)	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.

Office of Water, *LT1ESWTR Disinfection Profiling and Benchmarking: Technical Guidance Manual*, Washington, D.C.: U.S. Environmental Protection Agency, 2003, pp. 103 and 104.

Needed Fire Flow Formula

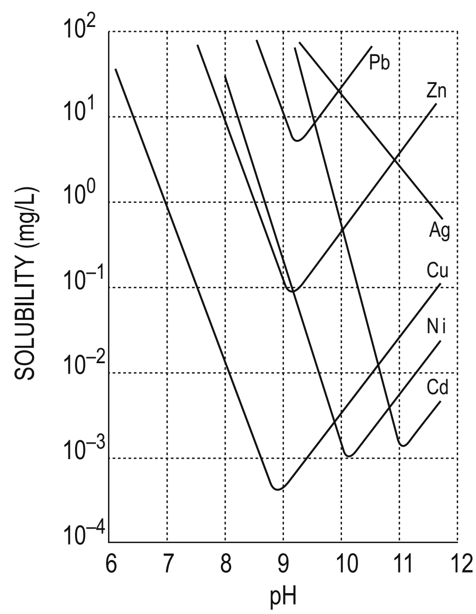
To estimate the amount of water needed to fight a fire in an individual, nonsprinklered building, ISO uses the formula:

$$NFF = (C_i)(O_i)[(1.0 + (X + P)_i]$$

NFF_i = needed fire flow in gallons per minute (gpm)
C_i = a factor related to the type of construction
$C_i = 18F\,(A_i)^{0.5}$

F = coefficient related to the class of construction
F = 1.5 for Construction Class 1 (wood frame construction)
= 1.0 for Construction Class 2 (joisted masonry construction)
= 0.8 for Construction Class 3 (noncombustible construction) and Construction Class 4 (masonry noncombustible construction)
= 0.6 for Construction Class 5 (modified fire-resistive construction) and Construction Class 6 (fire-resistive construction)
A_i = effective area
O_i = a factor related to the type of occupancy
X = a factor related to the exposure buildings
P = a factor related to the communication between buildings

Solubilities of Metal Hydroxides as Function of pH



2 AIR

Principles

Composition of Dry Ambient Air

Component	Concentration (by volume)
N_2	78.08%
O_2	20.95%
Ar	0.93%
CO_2	0.035%
Ne	18 ppmv
He	5.2 ppmv
CH_4	1.2 ppmv
NO_2	0.02 ppmv
O_3	0.02 ppmv

Normal Temperature and Pressure Air Density

$\rho_{air} = 0.075\ \text{lb/ft}^3$ at 68°F and 14.7 psia

$\rho_{air} = 1.204\ \text{kg/m}^3$ at 20°C and 101.3 kPa

Selected Properties of Air

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

Nomenclature

1. Intensive properties are independent of mass.
2. Extensive properties are proportional to mass.
3. Specific properties are lowercase (extensive/mass).

State Functions (properties)

Absolute Pressure, P	(lbf/in^2 or Pa)
Absolute Temperature, T	(°R or K)
Volume, V	(ft^3 or m^3)
Specific Volume, $v = V/m$	(ft^3/lbm or m^3/kg)
Internal Energy, U	(Btu or kJ)
Specific Internal Energy, $u = U/m$	(Btu/lbm or kJ/kg)
Enthalpy, H	(Btu or kJ)
Specific Enthalpy, $h = u + Pv = H/m$	(Btu/lbm or kJ/kg)
Entropy, S	(Btu/°R or kJ/K)
Specific Entropy, $s = S/m$	[Btu/(lbm-°R) or kJ/(kg•K)]
Gibbs Free Energy, $g = h - Ts$	(Btu/lbm or kJ/kg)
Helmholtz Free Energy, $a = u - Ts$	(Btu/lbm or kJ/kg)

For a single-phase pure component, specification of any two intensive, independent properties is sufficient to fix all the rest.

Heat Capacity at Constant Pressure,

$$c_p = \left(\frac{\partial h}{\partial T}\right)_P \qquad \text{[Btu/(lbm-°R) or kJ/(kg•K)]}$$

Heat Capacity at Constant Volume,

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v \qquad \text{[Btu/(lbm-°R) or kJ/(kg•K)]}$$

Relationship of heat capacity and temperature

$$Q = mc\Delta T$$

The steam tables in this section provide T, P, v, u, h, and s data for saturated and superheated water.

A P-h diagram for refrigerant HFC-134a providing T, P, v, h, and s data in a graphical format is included in this section.

Thermal and physical property tables for selected gases, liquids, and solids are included in this section.

Properties for Two-Phase (vapor-liquid) Systems

Quality x (for liquid-vapor systems at saturation) is defined as the mass fraction of the vapor phase:

$$x = m_g/(m_g + m_f)$$

m_g = mass of vapor

m_f = mass of liquid

Specific volume of a two-phase system can be written:

$$v = xv_g + (1 - x)v_f \text{ or } v = v_f + xv_{fg}$$

v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

v_{fg} = specific volume change upon vaporization = $v_g - v_f$

Similar expressions exist for u, h, and s:

$$u = xu_g + (1 - x)\, u_f \text{ or } u = u_f + xu_{fg}$$

$$h = xh_g + (1 - x)\, h_f \text{ or } h = h_f + xh_{fg}$$

$$s = xs_g + (1 - x)\, s_f \text{ or } s = s_f + xs_{fg}$$

Ideal gas behavior is characterized by:

- no intermolecular interactions
- molecules occupy zero volume

The properties of an ideal gas reflect those of a single molecule and are attributable entirely to the structure of the molecule and the system T.

For *ideal gases*:

$$\left(\frac{\partial h}{\partial P}\right)_T = 0 \qquad \left(\frac{\partial u}{\partial v}\right)_T = 0$$

For cold air standard, *heat capacities are assumed to be constant* at their room temperature values. In that case, the following are true:

$$\Delta u = c_v \Delta T$$

$$\Delta h = c_p \Delta T$$

$$\Delta s = c_p \ln (T_2/T_1) - R \ln (P_2/P_1)$$

$$\Delta s = c_v \ln (T_2/T_1) + R \ln (v_2/v_1)$$

Ideal Gas Mixtures

$i = 1, 2, \ldots, n$ constituents. Each constituent is an ideal gas.

Mole Fraction:

$$x_i = N_i/N;\ N = \Sigma N_i;\ \Sigma x_i = 1$$

N_i = number of moles of component i

N = total moles in the mixture

Mass Fraction: $y_i = m_i/m;\ m = \Sigma m_i;\ \Sigma y_i = 1$

Molecular Weight: $M = m/N = \Sigma x_i M_i$

To convert *mole fractions* x_i to *mass fractions* y_i:

$$y_i = \frac{x_i M_i}{\Sigma(x_i M_i)}$$

To convert *mass fractions* to *mole fractions*:

$$x_i = \frac{y_i / M_i}{\Sigma(y_i / M_i)}$$

Partial Pressures: $P_i = \frac{m_i R_i T}{V}$ and $P = \Sigma P_i$

Partial Volumes: $V_i = \frac{m_i R_i T}{P}$ and $V = \Sigma\ V_i$

P, V, T = pressure, volume, and temperature of the mixture, respectively

$R_i = R/M_i$

Combining the above generates the following additional expressions for mole fraction.

$x_i = P_i/P = V_i/V$

Other Properties:

$u = \Sigma\ (y_i u_i)$; $h = \Sigma\ (y_i h_i)$; $s = \Sigma\ (y_i s_i)$

u_i and h_i are evaluated at T

s_i is evaluated at T and P_i

The *First Law of Thermodynamics* is a statement of conservation of energy in a thermodynamic system. The net energy crossing the system boundary is equal to the change in energy inside the system.

Heat Q ($q = Q/m$) is *energy transferred* due to temperature difference and is considered positive if it is inward or added to the system.

Work W ($w = W/m$) is considered *positive if it is outward* or *work done* by the system.

Correction of Concentration and Volumetric Flows

Conversion from ppm to mg/m^3:

$$\frac{\text{mg}}{\text{m}^3} = \text{ppm} \times \frac{\text{molecular weight (g)}}{\text{molar volume (liters)}}$$

The molar volume used is typically the molar volume of a gas at 273.15 K (temperature) and 101.325 kPa (pressure), i.e., "normal" temperature and pressure.

Temperature and Pressure Correction

To convert a concentration measured at stack conditions to a concentration reference to 273.15 K (equivalent 0^{o}C), multiply by the following factor F_t:

$$F_t = \frac{T}{273.15}$$

T = measured temperature in the stack (Kelvin)

To convert a concentration measured at stack conditions to a concentration reference to 101.325 kPa, multiply by the following factor F_p:

$$F_p = \frac{101.325}{P}$$

P = measured pressure in the stack (kPa)

Moisture and Oxygen Correction

Emissions of stack gases are usually expressed on a dry gas basis so that variations in the moisture content of the stack gas do not affect the assessment of the emissions.

$$\text{Dry gas concentration}\left(\frac{\text{mg}}{\text{m}^3}\right) = \text{wet gas concentration} \times \frac{100}{100 - \%\ H_2O}$$

Pitot Tube Velocity Pressure

Standard Air

With dry air at 70°F, barometric pressure of 29.92 inches Hg., use the following formula:

$$\text{Velocity} = 4{,}004.4\sqrt{\text{Velocity Pressure}}$$

Other Than Standard Air

To determine dry air density, use the formula:

$$d = 1.325\frac{P_b}{T}$$

d = air density in pounds per cubic foot

P_b = barometric (or absolute) static pressure in inches of mercury

T = absolute temperature (indicated temperature in °F plus 460°)

$$V = 1{,}096.7\sqrt{\frac{h_v}{d}}$$

V = velocity in feet per minute

h_v = velocity pressure in inches of water

d = density of air in pounds per cubic foot

Closed Thermodynamic System

No mass crosses system boundary

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

ΔU = change in internal energy

ΔKE = change in kinetic energy

ΔPE = change in potential energy

Energy can cross the boundary only in the form of heat or work. Work can be boundary work, w_b, or other work forms (e.g., electrical work)

Reversible boundary work is given by $w_b = \int P\,dv$.

Special Cases of Closed Systems (with no change in kinetic or potential energy)

Constant System Pressure process (**Charles' Law**):

$w_b = P\Delta v$

(ideal gas) T/v = constant

Constant Volume process:

$w_b = 0$

(ideal gas) T/P = constant

Isentropic process (ideal gas):

Pv^k = constant

$w = (P_2v_2 - P_1v_1)/(1 - k)$

$= R(T_2 - T_1)/(1 - k)$

Constant Temperature process (**Boyle's Law**):

(ideal gas) Pv = constant

$w_b = RT \ln (v_2 / v_1) = RT \ln (P_1/P_2)$

Polytropic process (ideal gas):

Pv^n = constant

$w = (P_2v_2 - P_1v_1)/(1 - n),\ n \neq 1$

Open Thermodynamic System

Mass crosses the system boundary. There is flow work (Pv) done by mass entering the system.

The reversible flow work is given by:

$$w_{rev} = -\int v\, dP + \Delta KE + \Delta PE$$

First Law applies whether or not processes are reversible.

Open-System First Law (energy balance):

$$\Sigma \dot{m}_i\left[h_i + V_i^2/2 + gZ_i\right] - \Sigma \dot{m}_e\left[h_e + V_e^2/2 + gZ_e\right] + \dot{Q}_{in} - \dot{W}_{net} = d\left(m_s u_s\right)/dt$$

$\dot{W}_{net}$ = rate of net or shaft work

$\dot{m}$ = mass flow rate (subscripts i and e refer to inlet and exit states of system)

g = acceleration of gravity

Z = elevation

V = velocity

m_s = mass of fluid within the system

u_s = specific internal energy of system

$\dot{Q}_{in}$ = rate of heat transfer (neglecting kinetic and potential energy of the system)

Special Cases of Open Systems (with no change in kinetic or potential energy)

Constant Volume process:

$w_{rev} = -v\,(P_2 - P_1)$

Constant System Pressure process:

$w_{rev} = 0$

Constant Temperature process:

(ideal gas) Pv = constant

$w_{rev} = RT \ln (v_2/v_1) = RT \ln (P_1/P_2)$

Atmospheric Dispersion Modeling (Gaussian)

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

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

C = steady-state concentration at a point (x, y, z) (μg/m^3)

Q = emissions rate (μg/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) = $h + \Delta h$

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

Steady-Flow Systems

The system does not change state with time. This assumption is valid for steady operation of turbines, pumps, compressors, throttling valves, nozzles, and heat exchangers, including boilers and condensers.

$$\Sigma\dot{m}\left(h_i + V_i^2/2 + gZ_i\right) - \Sigma\dot{m}_e\left(h_e + V_e^2/2 + gZ_e\right) + \dot{Q}_{\text{in}} - \dot{W}_{\text{out}} = 0$$

and

$$\Sigma\dot{m}_i = \Sigma\dot{m}_e$$

$\dot{m}$ = mass flow rate (subscripts i and e refer to inlet and exit states of system)

g = acceleration of gravity

Z = elevation

V = velocity

$\dot{Q}$ = rate of heat transfer

$\dot{W}$ = rate of work

Special Cases of Steady-Flow Energy Equation

Nozzles, Diffusers: Velocity terms are significant. No elevation change, no heat transfer, and no work. Single mass stream.

$$h_i + V_i^2/2 = h_e + V_e^2/2$$

Isentropic Efficiency (nozzle) = $\dfrac{V_e^2 - V_i^2}{2\left(h_i - h_{es}\right)}$

where h_{es} = enthalpy at isentropic exit state.

Turbines, Pumps, Compressors: Often considered adiabatic (no heat transfer). Velocity terms usually can be ignored. There are significant work terms and a single mass stream.

$$h_i = h_e + w$$

Isentropic Efficiency (turbine) = $\dfrac{h_i - h_e}{h_i - h_{es}}$

Isentropic Efficiency (compressor, pump) = $\dfrac{h_{es} - h_i}{h_e - h_i}$

For pump only, $h_{es} - h_i = v_i(p_e - p_i)$

Throttling Valves and Throttling Processes: No work, no heat transfer, and single-mass stream. Velocity terms are often insignificant.

$$h_i = h_e$$

Boilers, Condensers, Evaporators, One Side in a Heat Exchanger: Heat transfer terms are significant. For a single-mass stream, the following applies:

$$h_i + q = h_e$$

Heat Exchangers: No heat loss to the surroundings or work. Two separate flow rates, $\dot{m}_1$ and $\dot{m}_2$:

$$\dot{m}_1\left(h_{1i} - h_{1e}\right) = \dot{m}_2\left(h_{2e} - h_{2i}\right)$$

Mixers, Separators, Open or Closed Feedwater Heaters:

$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e \quad \text{and}$$
$$\Sigma \dot{m}_i = \Sigma \dot{m}_e$$

Heat engines take in heat Q_H at a high temperature T_H, produce a net amount of work W, and reject heat Q_L at a low temperature T_L. The efficiency η of a heat engine is given by:

$$\eta = W/Q_H = (Q_H - Q_L)/Q_H$$

The most efficient engine possible is the *Carnot Cycle*. Its efficiency is given by:

$$\eta_c = (T_H - T_L)/T_H$$

T_H and T_L = absolute temperatures (Kelvin or Rankine)

The following heat-engine cycles are plotted on P-v and T-s diagrams in this section:

Carnot, Otto, Rankine

Refrigeration cycles are the reverse of heat-engine cycles. Heat is moved from low to high temperature requiring work, W. Cycles can be used either for refrigeration or as heat pumps.

Coefficient of Performance (COP) is defined as:

COP = Q_H/W for heat pumps

COP = Q_L/W for refrigerators and air conditioners

Upper limit of COP is based on reversed Carnot Cycle:

COP_c = $T_H/(T_H - T_L)$ for heat pumps

COP_c = $T_L/(T_H - T_L)$ for refrigeration

1 ton refrigeration = 12,000 Btu/hr = 3,516 W

The following refrigeration cycles are plotted on T-s diagrams in this section:

reversed Rankine, two-stage refrigeration, air refrigeration

PSYCHROMETRICS

Properties of an air-water vapor mixture at a fixed pressure are given in graphical form on a psychrometric chart as provided in this section. When the system pressure is 1 atm, an ideal-gas mixture is assumed.

The definitions that follow use subscript a for dry air and v for water vapor.

P = pressure of the air-water mixture, normally 1 atm

T = dry-bulb temp (air/water mixture temperature)

P_a = partial pressure of dry air

P_v = partial pressure of water vapor

$$P = P_a + P_v$$

Specific Humidity (absolute humidity, humidity ratio) ω:

$$\omega = m_v / m_a$$

m_v = mass of water vapor

m_a = mass of dry air

$$\omega = 0.622 P_v / P_a = 0.622 P_v / (P - P_v)$$

Relative Humidity (rh) ϕ:

$$\phi = P_v / P_g$$

P_g = saturation pressure of water at T

Enthalpy h: $h = h_a + \omega h_v$

Dew-Point Temperature T_{dp}:

$$T_{dp} = T_{sat} \text{ at } P_g = P_v$$

Wet-bulb temperature T_{wb} is the temperature indicated by a thermometer covered by a wick saturated with liquid water and in contact with moving air.

Humid volume is the volume of moist air/mass of dry air.

HEATS OF REACTION

For a chemical reaction, the associated energy can be defined in terms of heats of formation of the individual species ΔH_f° at the standard state

$$\left(\Delta H_r^\circ\right) = \sum_{\text{products}} \nu_i \left(\Delta H_f^\circ\right)_i - \sum_{\text{reactants}} \nu_i \left(\Delta H_f^\circ\right)_i$$

ν_i = stoichiometric coefficient for species "i"

The standard state is 25°C and 1 bar.

The heat of formation is defined as the enthalpy change associated with the formation of a compound from its atomic species as they normally occur in nature [i.e., O_2(g), H_2(g), C(solid), etc.]

The heat of reaction varies with the temperature as follows:

$$\Delta H_r^\circ(T) = \Delta H_r^\circ(T_{\text{ref}}) + \int_{T_{\text{ref}}}^{T} \Delta c_p dT$$

where T_{ref} is some reference temperature (typically 25°C or 298 K), and:

$$\Delta c_p = \sum_{\text{products}} \nu_i c_{p,i} - \sum_{\text{reactants}} \nu_i c_{p,i}$$

and $c_{p,i}$ is the molar heat capacity of component i.

The heat of reaction for a combustion process using oxygen is also known as the heat of combustion. The principal products are CO_2(g) and H_2O(l).

Combustion Processes

First, the combustion equation should be written and balanced. For example, for the stoichiometric combustion of methane in oxygen:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

Combustion in Air

For each mole of oxygen, there will be 3.76 moles of nitrogen. For stoichiometric combustion of methane in air:

$$CH_4 + 2\ O_2 + 2(3.76)\ N_2 \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2$$

Combustion in Excess Air

The excess oxygen appears as oxygen on the right side of the combustion equation.

Incomplete Combustion

Some carbon is burned to create carbon monoxide (CO).

$$\textit{Molar Air-Fuel Ratio, } \overline{A/F} = \frac{\text{No. of moles of air}}{\text{No. of moles of fuel}}$$

$$\textit{Air-Fuel Ratio, } A/F = \frac{\text{Mass of air}}{\text{Mass of fuel}} = \left(\overline{A/F}\right)\left(\frac{\mathrm{M_{air}}}{\mathrm{M_{fuel}}}\right)$$

Stoichiometric (theoretical) air-fuel ratio is the air-fuel ratio calculated from the stoichiometric combustion equation.

$$\text{Percent Theoretical Air} = \frac{(A/F)_{\text{actual}}}{(A/F)_{\text{stoichiometric}}} \times 100$$

$$\text{Percent Excess Air} = \frac{(A/F)_{\text{actual}} - (A/F)_{\text{stoichiometric}}}{(A/F)_{\text{stoichiometric}}} \times 100$$

Air to Fuel Ratio

$$AF = \frac{28.97 n_{\text{air}}}{MW_{\text{fuel}}\, n_{\text{fuel}}}$$

n_{air} = number of moles of air (oxygen + nitrogen)

n_{fuel} = number of moles of fuel

MW_{fuel} = molecular weight of fuel

Vapor-Liquid Equilibrium (VLE)

Henry's Law at Constant Temperature

At equilibrium, the partial pressure of a gas is proportional to its concentration in a liquid. Henry's Law is valid for low concentrations; i.e., $x \approx 0$.

$$P_i = Py_i = hx_i$$

h = Henry's Law constant

P_i = partial pressure of a gas in contact with a liquid

x_i = mol fraction of the gas in the liquid

y_i = mol fraction of the gas in the vapor

P = total pressure

Raoult's Law for Vapor-Liquid Equilibrium

Valid for concentrations near 1; i.e., $x_i \approx 1$ at low pressure (ideal gas behavior)

$$P_i = x_i P_i^*$$

P_i = partial pressure of component i

x_i = mol fraction of component i in the liquid

P_i^* = vapor pressure of pure component i at the temperature of the mixture

Chemical Reaction Equilibria

Definitions

Conversion – moles reacted/moles fed

Extent – For each species in a reaction, the mole balance may be written:

$$\text{moles}_{i,out} = \text{moles}_{i,in} + v_i \xi \text{ where}$$

ξ is the extent in moles and v_i is the stoichiometric coefficient of the ith species, the sign of which is negative for reactants and positive for products.

Limiting reactant – Reactant that would be consumed first if the reaction proceeded to completion. Other reactants are excess reactants.

Selectivity – Moles of desired product formed/moles of undesired product formed.

Yield – Moles of desired product formed/moles that would have been formed if there were no side reactions and the limiting reactant had reacted completely.

Chemical Reaction Equilibrium

For the reaction

$$aA + bB \rightleftharpoons cC + dD$$

$$\Delta G^\circ = -RT \ln K_a$$

$$K_a = \frac{\left(\hat{a}_C^c\right)\left(\hat{a}_D^d\right)}{\left(\hat{a}_A^a\right)\left(\hat{a}_B^b\right)} = \prod_i \left(\hat{a}_i\right)^{v_i}$$

$\hat{a}_i$ = activity of component $i = \dfrac{\hat{f}_i}{f_i^\circ}$

f_i° = fugacity of pure i in its standard state at the equilibrium reaction temperature T

v_i = stoichiometric coefficient of component i

ΔG° = standard Gibbs energy change of reaction

K_a = chemical equilibrium constant

For Mixtures of Ideal Gases

f_i° = unit pressure, often 1 bar

$\hat{f}_i = y_i P = p_i$

where p_i = partial pressure of component i.

Then $K_a = K_p = \frac{\left(p_C^c\right)\left(p_D^d\right)}{\left(p_A^a\right)\left(p_B^b\right)} = P^{c+d-a-b}\frac{\left(y_C^c\right)\left(y_D^d\right)}{\left(y_A^a\right)\left(y_B^b\right)}$

For Solids

$\hat{a}_i = 1$

For Liquids

$\hat{a}_i = x_i \gamma_i$

The effect of temperature on the equilibrium constant is

$$\frac{d\ln K}{dT} = \frac{\Delta H^{\circ}}{RT^2}$$

where ΔH° = standard enthalpy change of reaction.

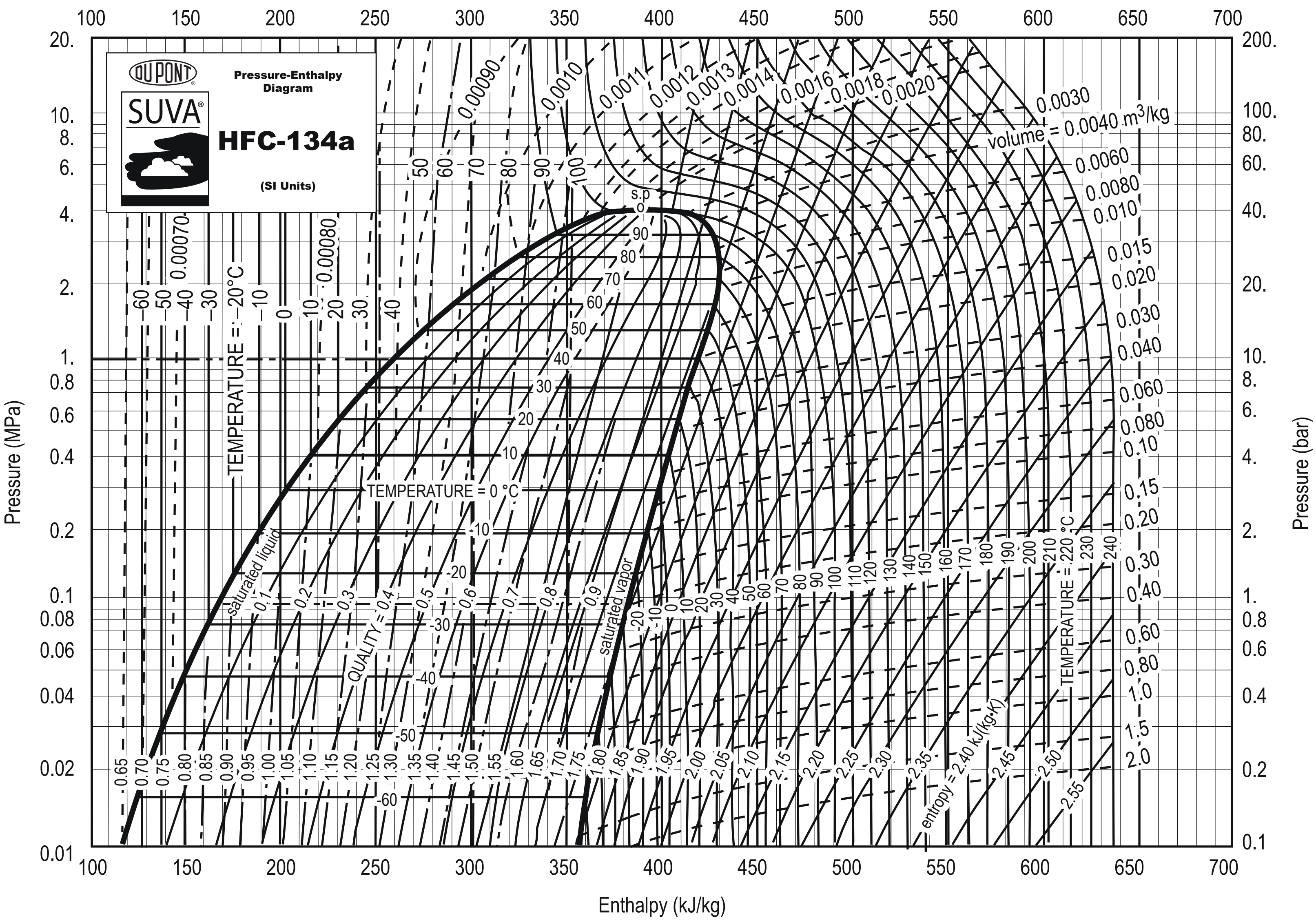
STEAM TABLES
Saturated Water - Temperature Table

Temp. °C T	Sat. Press. kPa p_{sat}	Specific Volume m³/kg		Internal Energy kJ/kg			Enthalpy kJ/kg			Entropy kJ/(kg·K)		
		Sat. liquid v_f	Sat. vapor v_g	Sat. liquid u_f	Evap. u_{fg}	Sat. vapor u_g	Sat. liquid h_f	Evap. h_{fg}	Sat. vapor h_g	Sat. liquid s_f	Evap. s_{fg}	Sat. vapor s_g
0.01	0.6113	0.001 000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
5	0.8721	0.001 000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001 000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001 001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	**2.339**	**0.001 002**	**57.79**	**83.95**	**2319.0**	**2402.9**	**83.96**	**2454.1**	**2538.1**	**0.2966**	**8.3706**	**8.6672**
25	3.169	0.001 003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001 004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001 006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	7.8478	8.3531
40	7.384	0.001 008	19.52	167.56	2262.6	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
45	**9.593**	**0.001 010**	**15.26**	**188.44**	**2248.4**	**2436.8**	**188.45**	**2394.8**	**2583.2**	**0.6387**	**7.5261**	**8.1648**
50	12.349	0.001 012	12.03	209.32	2234.2	2443.5	209.33	2382.7	2592.1	0.7038	7.3725	8.0763
55	15.758	0.001 015	9.568	230.21	2219.9	2450.1	230.23	2370.7	2600.9	0.7679	7.2234	7.9913
60	19.940	0.001 017	7.671	251.11	2205.5	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
65	25.03	0.001 020	6.197	272.02	2191.1	2463.1	272.06	2346.2	2618.3	0.8935	6.9375	7.8310
70	**31.19**	**0.001 023**	**5.042**	**292.95**	**2176.6**	**2569.6**	**292.98**	**2333.8**	**2626.8**	**0.9549**	**6.8004**	**7.7553**
75	38.58	0.001 026	4.131	313.90	2162.0	2475.9	313.93	2321.4	2635.3	1.0155	6.6669	7.6824
80	47.39	0.001 029	3.407	334.86	2147.4	2482.2	334.91	2308.8	2643.7	1.0753	6.5369	7.6122
85	57.83	0.001 033	2.828	355.84	2132.6	2488.4	355.90	2296.0	2651.9	1.1343	6.4102	7.5445
90	70.14	0.001 036	2.361	376.85	2117.7	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
95	**84.55**	**0.001 040**	**1.982**	**397.88**	**2102.7**	**2500.6**	**397.96**	**2270.2**	**2668.1**	**1.2500**	**6.1659**	**7.4159**
	MPa											
100	0.101 35	0.001 044	1.6729	418.94	2087.6	2506.5	419.04	2257.0	2676.1	1.3069	6.0480	7.3549
105	0.120 82	0.001 048	1.4194	440.02	2072.3	2512.4	440.15	2243.7	2683.8	1.3630	5.9328	7.2958
110	0.143 27	0.001 052	1.2102	461.14	2057.0	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
115	0.169 06	0.001 056	1.0366	482.30	2041.4	2523.7	482.48	2216.5	2699.0	1.4734	5.7100	7.1833
120	**0.198 53**	**0.001 060**	**0.8919**	**503.50**	**2025.8**	**2529.3**	**503.71**	**2202.6**	**2706.3**	**1.5276**	**5.6020**	**7.1296**
125	0.2321	0.001 065	0.7706	524.74	2009.9	2534.6	524.99	2188.5	2713.5	1.5813	5.4962	7.0775
130	0.2701	0.001 070	0.6685	546.02	1993.9	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269
135	0.3130	0.001 075	0.5822	567.35	1977.7	2545.0	567.69	2159.6	2727.3	1.6870	5.2907	6.9777
140	0.3613	0.001 080	0.5089	588.74	1961.3	2550.0	589.13	2144.7	2733.9	1.7391	5.1908	6.9299
145	**0.4154**	**0.001 085**	**0.4463**	**610.18**	**1944.7**	**2554.9**	**610.63**	**2129.6**	**2740.3**	**1.7907**	**5.0926**	**6.8833**
150	0.4758	0.001 091	0.3928	631.68	1927.9	2559.5	632.20	2114.3	2746.5	1.8418	4.9960	6.8379
155	0.5431	0.001 096	0.3468	653.24	1910.8	2564.1	653.84	2098.6	2752.4	1.8925	4.9010	6.7935
160	0.6178	0.001 102	0.3071	674.87	1893.5	2568.4	675.55	2082.6	2758.1	1.9427	4.8075	6.7502
165	0.7005	0.001 108	0.2727	696.56	1876.0	2572.5	697.34	2066.2	2763.5	1.9925	4.7153	6.7078
170	**0.7917**	**0.001 114**	**0.2428**	**718.33**	**1858.1**	**2576.5**	**719.21**	**2049.5**	**2768.7**	**2.0419**	**4.6244**	**6.6663**
175	0.8920	0.001 121	0.2168	740.17	1840.0	2580.2	741.17	2032.4	2773.6	2.0909	4.5347	6.6256
180	1.0021	0.001 127	0.194 05	762.09	1821.6	2583.7	763.22	2015.0	2778.2	2.1396	4.4461	6.5857
185	1.1227	0.001 134	0.174 09	784.10	1802.9	2587.0	785.37	1997.1	2782.4	2.1879	4.3586	6.5465
190	1.2544	0.001 141	0.156 54	806.19	1783.8	2590.0	807.62	1978.8	2786.4	2.2359	4.2720	6.5079
195	**1.3978**	**0.001 149**	**0.141 05**	**828.37**	**1764.4**	**2592.8**	**829.98**	**1960.0**	**2790.0**	**2.2835**	**4.1863**	**6.4698**
200	1.5538	0.001 157	0.127 36	850.65	1744.7	2595.3	852.45	1940.7	2793.2	2.3309	4.1014	6.4323
205	1.7230	0.001 164	0.115 21	873.04	1724.5	2597.5	875.04	1921.0	2796.0	2.3780	4.0172	6.3952
210	1.9062	0.001 173	0.104 41	895.53	1703.9	2599.5	897.76	1900.7	2798.5	2.4248	3.9337	6.3585
215	2.104	0.001 181	0.094 79	918.14	1682.9	2601.1	920.62	1879.9	2800.5	2.4714	3.8507	6.3221
220	**2.318**	**0.001 190**	**0.086 19**	**940.87**	**1661.5**	**2602.4**	**943.62**	**1858.5**	**2802.1**	**2.5178**	**3.7683**	**6.2861**
225	2.548	0.001 199	0.078 49	963.73	1639.6	2603.3	966.78	1836.5	2803.3	2.5639	3.6863	6.2503
230	2.795	0.001 209	0.071 58	986.74	1617.2	2603.9	990.12	1813.8	2804.0	2.6099	3.6047	6.2146
235	3.060	0.001 219	0.065 37	1009.89	1594.2	2604.1	1013.62	1790.5	2804.2	2.6558	3.5233	6.1791
240	3.344	0.001 229	0.059 76	1033.21	1570.8	2604.0	1037.32	1766.5	2803.8	2.7015	3.4422	6.1437
245	**3.648**	**0.001 240**	**0.054 71**	**1056.71**	**1546.7**	**2603.4**	**1061.23**	**1741.7**	**2803.0**	**2.7472**	**3.3612**	**6.1083**
250	3.973	0.001 251	0.050 13	1080.39	1522.0	2602.4	1085.36	1716.2	2801.5	2.7927	3.2802	6.0730
255	4.319	0.001 263	0.045 98	1104.28	1596.7	2600.9	1109.73	1689.8	2799.5	2.8383	3.1992	6.0375
260	4.688	0.001 276	0.042 21	1128.39	1470.6	2599.0	1134.37	1662.5	2796.9	2.8838	3.1181	6.0019
265	5.081	0.001 289	0.038 77	1152.74	1443.9	2596.6	1159.28	1634.4	2793.6	2.9294	3.0368	5.9662
270	**5.499**	**0.001 302**	**0.035 64**	**1177.36**	**1416.3**	**2593.7**	**1184.51**	**1605.2**	**2789.7**	**2.9751**	**2.9551**	**5.9301**
275	5.942	0.001 317	0.032 79	1202.25	1387.9	2590.2	1210.07	1574.9	2785.0	3.0208	2.8730	5.8938
280	6.412	0.001 332	0.030 17	1227.46	1358.7	2586.1	1235.99	1543.6	2779.6	3.0668	2.7903	5.8571
285	6.909	0.001 348	0.027 77	1253.00	1328.4	2581.4	1262.31	1511.0	2773.3	3.1130	2.7070	5.8199
290	7.436	0.001 366	0.025 57	1278.92	1297.1	2576.0	1289.07	1477.1	2766.2	3.1594	2.6227	5.7821
295	**7.993**	**0.001 384**	**0.023 54**	**1305.2**	**1264.7**	**2569.9**	**1316.3**	**1441.8**	**2758.1**	**3.2062**	**2.5375**	**5.7437**
300	8.581	0.001 404	0.021 67	1332.0	1231.0	2563.0	1344.0	1404.9	2749.0	3.2534	2.4511	5.7045
305	9.202	0.001 425	0.019 948	1359.3	1195.9	2555.2	1372.4	1366.4	2738.7	3.3010	2.3633	5.6643
310	9.856	0.001 447	0.018 350	1387.1	1159.4	2546.4	1401.3	1326.0	2727.3	3.3493	2.2737	5.6230
315	10.547	0.001 472	0.016 867	1415.5	1121.1	2536.6	1431.0	1283.5	2714.5	3.3982	2.1821	5.5804
320	**11.274**	**0.001 499**	**0.015 488**	**1444.6**	**1080.9**	**2525.5**	**1461.5**	**1238.6**	**2700.1**	**3.4480**	**2.0882**	**5.5362**
330	12.845	0.001 561	0.012 996	1505.3	993.7	2498.9	1525.3	1140.6	2665.9	3.5507	1.8909	5.4417
340	14.586	0.001 638	0.010 797	1570.3	894.3	2464.6	1594.2	1027.9	2622.0	3.6594	1.6763	5.3357
350	16.513	0.001 740	0.008 813	1641.9	776.6	2418.4	1670.6	893.4	2563.9	3.7777	1.4335	5.2112
360	18.651	0.001 893	0.006 945	1725.2	626.3	2351.5	1760.5	720.3	2481.0	3.9147	1.1379	5.0526
370	**21.03**	**0.002 213**	**0.004 925**	**1844.0**	**384.5**	**2228.5**	**1890.5**	**441.6**	**2332.1**	**4.1106**	**0.6865**	**4.7971**
374.14	22.09	0.003 155	0.003 155	2029.6	0	2029.6	2099.3	0	2099.3	4.4298	0	4.4298

Superheated Water Tables								
T Temp. °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg·K)	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg·K)
	***p* = 0.01 MPa (45.81°C)**				***p* = 0.05 MPa (81.33°C)**			
Sat.	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939
50	14.869	2443.9	2592.6	8.1749				
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401
200	**21.825**	**2661.3**	**2879.5**	**8.9038**	**4.356**	**2659.9**	**2877.7**	**8.1580**
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546
600	**40.295**	**3302.5**	**3705.4**	**10.1608**	**8.057**	**3302.2**	**3705.1**	**9.4178**
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964
1100	**63.372**	**4257.5**	**4891.2**	**11.2287**	**12.674**	**4257.4**	**4891.1**	**10.4859**
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382
	***p* = 0.10 MPa (99.63°C)**				***p* = 0.20 MPa (120.23°C)**			
Sat.	1.6940	2506.1	2675.5	7.3594	0.8857	2529.5	2706.7	7.1272
100	1.6958	2506.7	2676.2	7.3614				
150	1.9364	2582.8	2776.4	7.6134	0.9596	2576.9	2768.8	7.2795
200	2.172	2658.1	2875.3	7.8343	1.0803	2654.4	2870.5	7.5066
250	**2.406**	**2733.7**	**2974.3**	**8.0333**	**1.1988**	**2731.2**	**2971.0**	**7.7086**
300	2.639	2810.4	3074.3	8.2158	1.3162	2808.6	3071.8	7.8926
400	3.103	2967.9	3278.2	8.5435	1.5493	2966.7	3276.6	8.2218
500	3.565	3131.6	3488.1	8.8342	1.7814	3130.8	3487.1	8.5133
600	4.028	3301.9	3704.4	9.0976	2.013	3301.4	3704.0	8.7770
700	**4.490**	**3479.2**	**3928.2**	**9.3398**	**2.244**	**3478.8**	**3927.6**	**9.0194**
800	4.952	3663.5	4158.6	9.5652	2.475	3663.1	4158.2	9.2449
900	5.414	3854.8	4396.1	9.7767	2.705	3854.5	4395.8	9.4566
1000	5.875	4052.8	4640.3	9.9764	2.937	4052.5	4640.0	9.6563
1100	6.337	4257.3	4891.0	10.1659	3.168	4257.0	4890.7	9.8458
1200	**6.799**	**4467.7**	**5147.6**	**10.3463**	**3.399**	**4467.5**	**5147.5**	**10.0262**
1300	7.260	4683.5	5409.5	10.5183	3.630	4683.2	5409.3	10.1982
	***p* = 0.40 MPa (143.63°C)**				***p* = 0.60 MPa (158.85°C)**			
Sat.	0.4625	2553.6	2738.6	6.8959	0.3157	2567.4	2756.8	6.7600
150	0.4708	2564.5	2752.8	6.9299				
200	0.5342	2646.8	2860.5	7.1706	0.3520	2638.9	2850.1	6.9665
250	0.5951	2726.1	2964.2	7.3789	0.3938	2720.9	2957.2	7.1816
300	**0.6548**	**2804.8**	**3066.8**	**7.5662**	**0.4344**	**2801.0**	**3061.6**	**7.3724**
350	0.7137	2884.6	3170.1	7.7324	0.4742	2881.2	3165.7	7.5464
400	0.7726	2964.4	3273.4	7.8985	0.5137	2962.1	3270.3	7.7079
500	0.8893	3129.2	3484.9	8.1913	0.5920	3127.6	3482.8	8.0021
600	1.0055	3300.2	3702.4	8.4558	0.6697	3299.1	3700.9	8.2674
700	**1.1215**	**3477.9**	**3926.5**	**8.6987**	**0.7472**	**3477.0**	**3925.3**	**8.5107**
800	1.2372	3662.4	4157.3	8.9244	0.8245	3661.8	4156.5	8.7367
900	1.3529	3853.9	4395.1	9.1362	0.9017	3853.4	4394.4	8.9486
1000	1.4685	4052.0	4639.4	9.3360	0.9788	4051.5	4638.8	9.1485
1100	1.5840	4256.5	4890.2	9.5256	1.0559	4256.1	4889.6	9.3381
1200	**1.6996**	**4467.0**	**5146.8**	**9.7060**	**1.1330**	**4466.5**	**5146.3**	**9.5185**
1300	1.8151	4682.8	5408.8	9.8780	1.2101	4682.3	5408.3	9.6906
	***p* = 0.80 MPa (170.43°C)**				***p* = 1.00 MPa (179.91°C)**			
Sat.	0.2404	2576.8	2769.1	6.6628	0.194 44	2583.6	2778.1	6.5865
200	0.2608	2630.6	2839.3	6.8158	0.2060	2621.9	2827.9	6.6940
250	0.2931	2715.5	2950.0	7.0384	0.2327	2709.9	2942.6	6.9247
300	0.3241	2797.2	3056.5	7.2328	0.2579	2793.2	3051.2	7.1229
350	**0.3544**	**2878.2**	**3161.7**	**7.4089**	**0.2825**	**2875.2**	**3157.7**	**7.3011**
400	0.3843	2959.7	3267.1	7.5716	0.3066	2957.3	3263.9	7.4651
500	0.4433	3126.0	3480.6	7.8673	0.3541	3124.4	3478.5	7.7622
600	0.5018	3297.9	3699.4	8.1333	0.4011	3296.8	3697.9	8.0290
700	0.5601	3476.2	3924.2	8.3770	0.4478	3475.3	3923.1	8.2731
800	**0.6181**	**3661.1**	**4155.6**	**8.6033**	**0.4943**	**3660.4**	**4154.7**	**8.4996**
900	0.6761	3852.8	4393.7	8.8153	0.5407	3852.2	4392.9	8.7118
1000	0.7340	4051.0	4638.2	9.0153	0.5871	4050.5	4637.6	8.9119
1100	0.7919	4255.6	4889.1	9.2050	0.6335	4255.1	4888.6	9.1017
1200	0.8497	4466.1	5145.9	9.3855	0.6798	4465.6	5145.4	9.2822
1300	**0.9076**	**4681.8**	**5407.9**	**9.5575**	**0.7261**	**4681.3**	**5407.4**	**9.4543**

P-h Diagram for Refrigerant HFC-134a

(metric units)



Data provided by DuPont Refrigerants, a division of E.I. duPont de Nemours and Co., Inc.

Thermal and Physical Property Tables

(at room temperature)

Gases							
Substance	Mol wt	c_p		c_v		k	R
		kJ/(kg·K)	Btu/(lbm-°R)	kJ/(kg·K)	Btu/(lbm-°R)		kJ/(kg·K)
Gases							
Air	29	1.00	0.240	0.718	0.171	1.40	0.2870
Argon	40	0.520	0.125	0.312	0.0756	1.67	0.2081
Butane	58	1.72	0.415	1.57	0.381	1.09	0.1430
Carbon dioxide	44	0.846	0.203	0.657	0.158	1.29	0.1889
Carbon monoxide	28	1.04	0.249	0.744	0.178	1.40	0.2968
Ethane	30	1.77	0.427	1.49	0.361	1.18	0.2765
Helium	4	5.19	1.25	3.12	0.753	1.67	2.0769
Hydrogen	2	14.3	3.43	10.2	2.44	1.40	4.1240
Methane	16	2.25	0.532	1.74	0.403	1.30	0.5182
Neon	20	1.03	0.246	0.618	0.148	1.67	0.4119
Nitrogen	28	1.04	0.248	0.743	0.177	1.40	0.2968
Octane vapor	114	1.71	0.409	1.64	0.392	1.04	0.0729
Oxygen	32	0.918	0.219	0.658	0.157	1.40	0.2598
Propane	44	1.68	0.407	1.49	0.362	1.12	0.1885
Steam	18	1.87	0.445	1.41	0.335	1.33	0.4615

Selected Liquids and Solids				
Substance	c_p		Density	
	kJ/(kg·K)	Btu/(lbm-°R)	kg/m³	lbm/ft³
Liquids				
Ammonia	4.80	1.146	602	38
Mercury	0.139	0.033	13,560	847
Water	4.18	1.000	997	62.4
Solids				
Aluminum	0.900	0.215	2,700	170
Copper	0.386	0.092	8,900	555
Ice (0°C; 32°F)	2.11	0.502	917	57.2
Iron	0.450	0.107	7,840	490
Lead	0.128	0.030	11,310	705

Thermophysical Properties of Air and Water

Unit convention: $\mu = \alpha(10^{-5}$ kg/ms$) \Rightarrow \mu = \alpha \times 10^{-5}$ kg/ms

Air

T (°C)	Specific Heat c_p (kJ kg^{-1} K^{-1})	Density ρ (kg/m^3)	Dynamic Viscosity μ (10^{-5} kg m^{-1} s^{-1})	Kinematic Viscosity υ (10^{-5} m^2/s)	Thermal Conductivity k (10^{-2} W m^{-1} °C^{-1})	Prandtl no. Pr
20	1.0061	1.2042	1.817	1.509	2.564	0.713
30	1.0064	1.1644	1.865	1.601	2.638	0.712
40	1.0068	1.1273	1.911	1.696	2.710	0.710
50	1.0074	1.0924	1.957	1.792	2.781	0.709
60	1.0080	1.0596	2.003	1.890	2.852	0.708
70	1.0087	1.0287	2.047	1.990	2.922	0.707
80	1.0095	0.9996	2.092	2.092	2.991	0.706
90	1.0103	0.9721	2.135	2.196	3.059	0.705
100	1.0113	0.9460	2.178	2.302	3.127	0.704
110	1.0123	0.9213	2.220	2.410	3.194	0.704
120	1.0134	0.8979	2.262	2.519	3.261	0.703
130	1.0146	0.8756	2.303	2.631	3.328	0.702
140	1.0159	0.8544	2.344	2.744	3.394	0.702
150	1.0172	0.8342	2.384	2.858	3.459	0.701
160	1.0186	0.8150	2.424	2.975	3.525	0.701
170	1.0201	0.7966	2.463	3.093	3.589	0.700
180	1.0217	0.7790	2.503	3.213	3.654	0.700
190	1.0233	0.7622	2.541	3.334	3.718	0.699
200	1.0250	0.7461	2.579	3.457	3.781	0.699

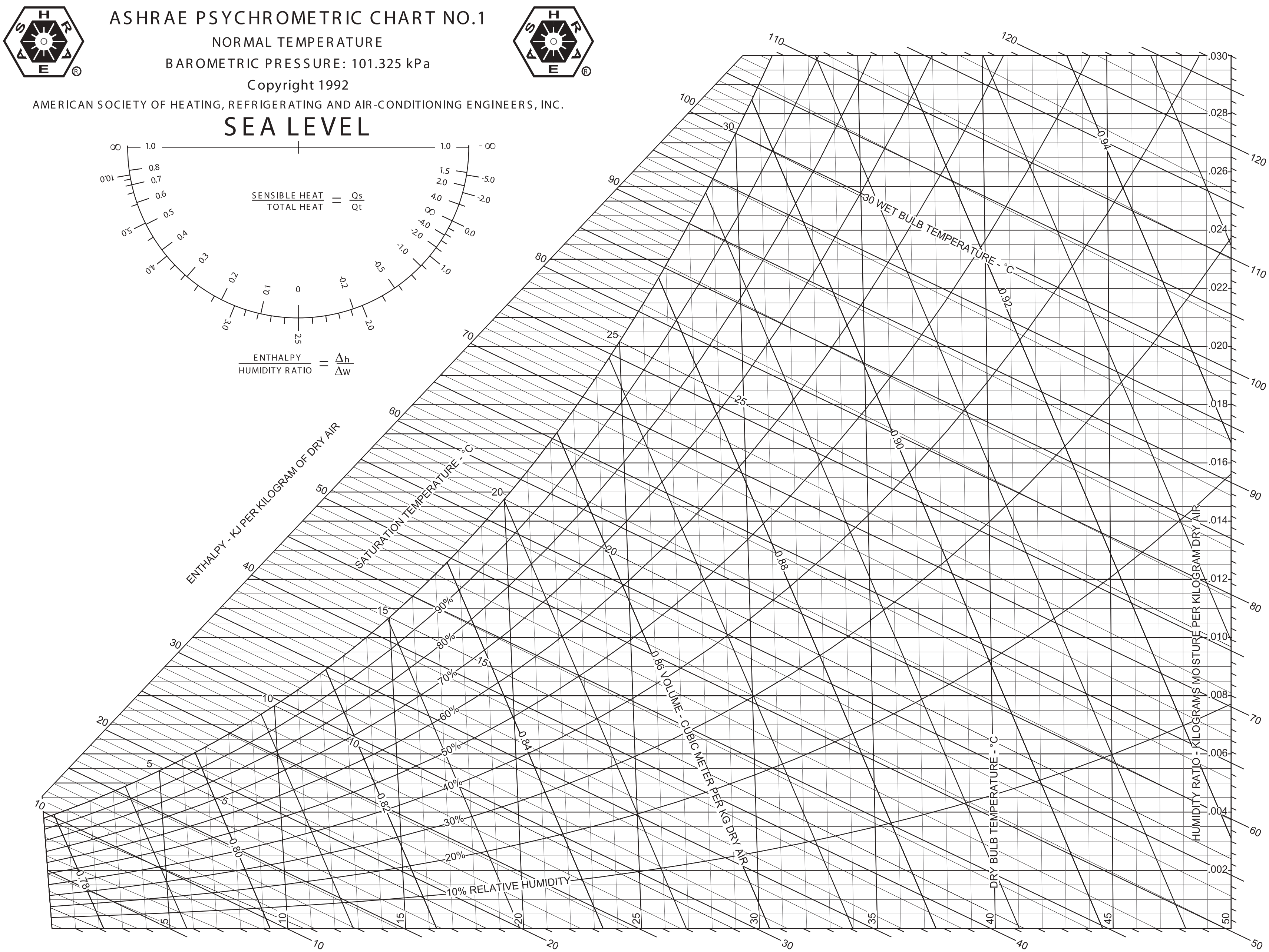
Saturated Water

T (°C)	Specific Heat c_p (kJ kg^{-1} K^{-1})	Density ρ (kg/m^3)	Dynamic Viscosity μ (10^{-3} kg m^{-1} s^{-1})	Kinematic Viscosity υ (10^{-6} m^2/s)	Thermal Conductivity k (W m^{-1} °C^{-1})	Prandtl no. Pr
20	4.182	998.3	1.003	1.004	0.5996	6.99
25	4.180	997.1	0.8908	0.8933	0.6076	6.13
30	4.180	995.7	0.7978	0.8012	0.6150	5.42
35	4.179	994.1	0.7196	0.7238	0.6221	4.83
40	4.179	992.3	0.6531	0.6582	0.6286	4.34
45	4.182	990.2	0.5962	0.6021	0.6347	3.93
50	4.182	998.0	0.5471	0.5537	0.6405	3.57
55	4.184	985.7	0.5043	0.5116	0.6458	3.27
60	4.186	983.1	0.4668	0.4748	0.6507	3.00
65	4.187	980.5	0.4338	0.4424	0.6553	2.77
70	4.191	977.7	0.4044	0.4137	0.6594	2.57
75	4.191	974.7	0.3783	0.3881	0.6633	2.39
80	4.195	971.6	0.3550	0.3653	0.6668	2.23
85	4.201	968.4	0.3339	0.3448	0.6699	2.09
90	4.203	965.1	0.3150	0.3264	0.6727	1.97

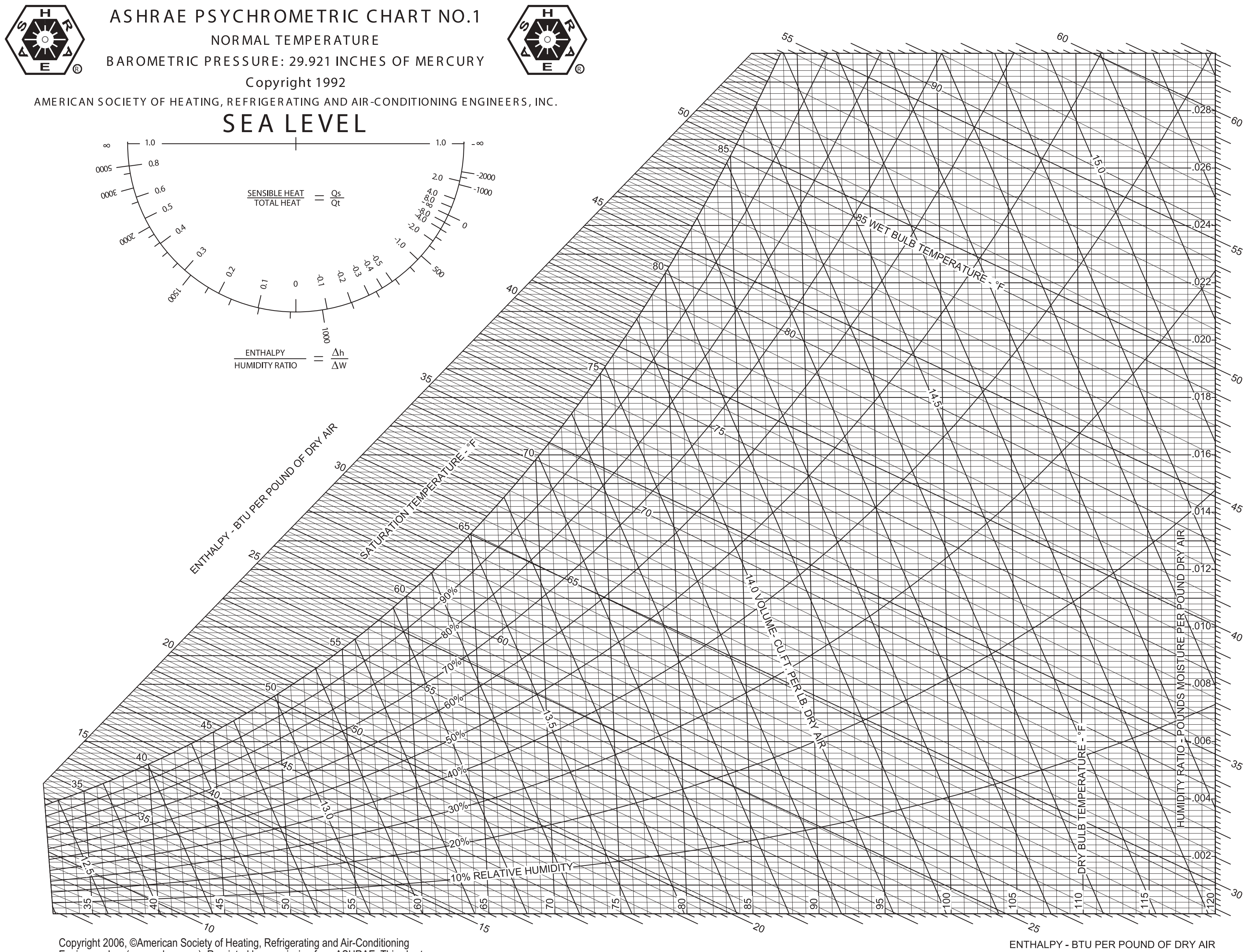
Heinsohn, Robert Jennings, and Robert Lynn Kabel, *Sources and Control of Air Pollution*: Prentice Hall, 1998, p. 668.

ASHRAE Psychrometric Chart No. 1

(metric units)



ASHRAE Psychrometric Chart No. 1
(English units)



Pollution Control

Atmospheric Stability Under Various Conditions

Surface Wind Speed[a] (m/s)	Day Solar Insolation			Night Cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy (≥4/8)	Clear (≤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*, 2nd ed., Research Triangle Park: U.S. Environmental Protection Agency, 1970, p. 6.

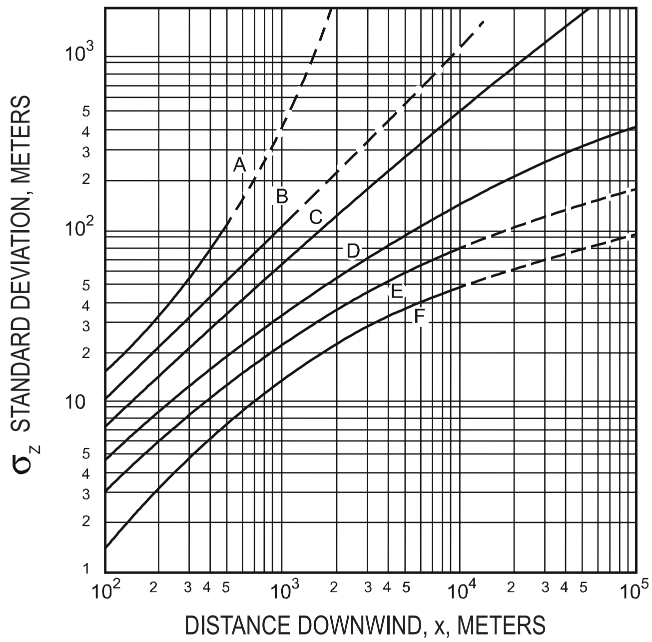
Pasquill-Gifford Curve Fit

Stability Class		**x < 1 km**			**x ≥ 1 km**		
	a	**c**	**d**	**f**	**c**	**d**	**f**
A	213	440.8	1.941	9.27	459.7	2.094	–9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
C	104	61.0	0.911	0	61.0	0.911	0
D	68	33.2	0.725	–1.7	44.5	0.516	–13.0
E	50.5	22.8	0.678	–1.3	55.4	0.305	–34.0
F	34	14.35	0.740	–0.35	62.6	0.180	–48.6

$$\sigma_y = a\,x^b$$

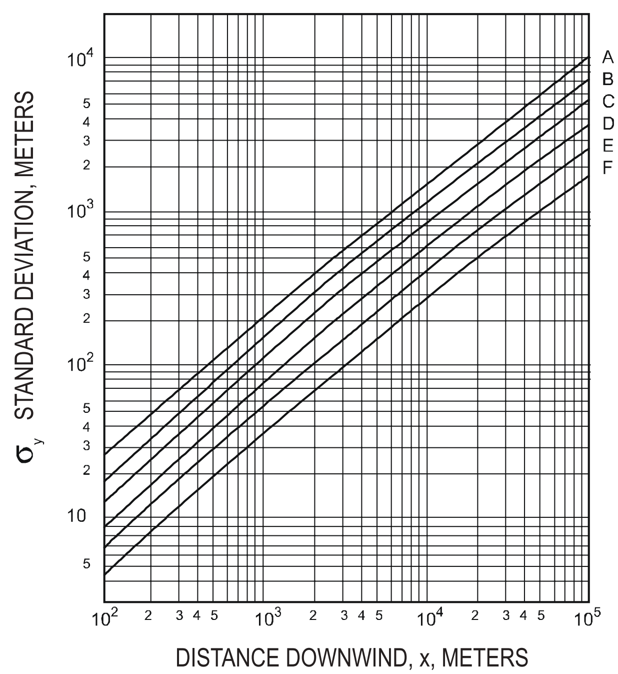
$$\sigma_z = c\,x^d + f$$

The value of b is always 0.894 and x must be expressed in kilometers.



VERTICAL STANDARD DEVIATIONS OF A PLUME

Turner, D.B., *Workbook of Atmospheric Dispersion Estimates*, 2nd ed., Research Triangle Park: U.S. Environmental Protection Agency, 1970, p. 9.

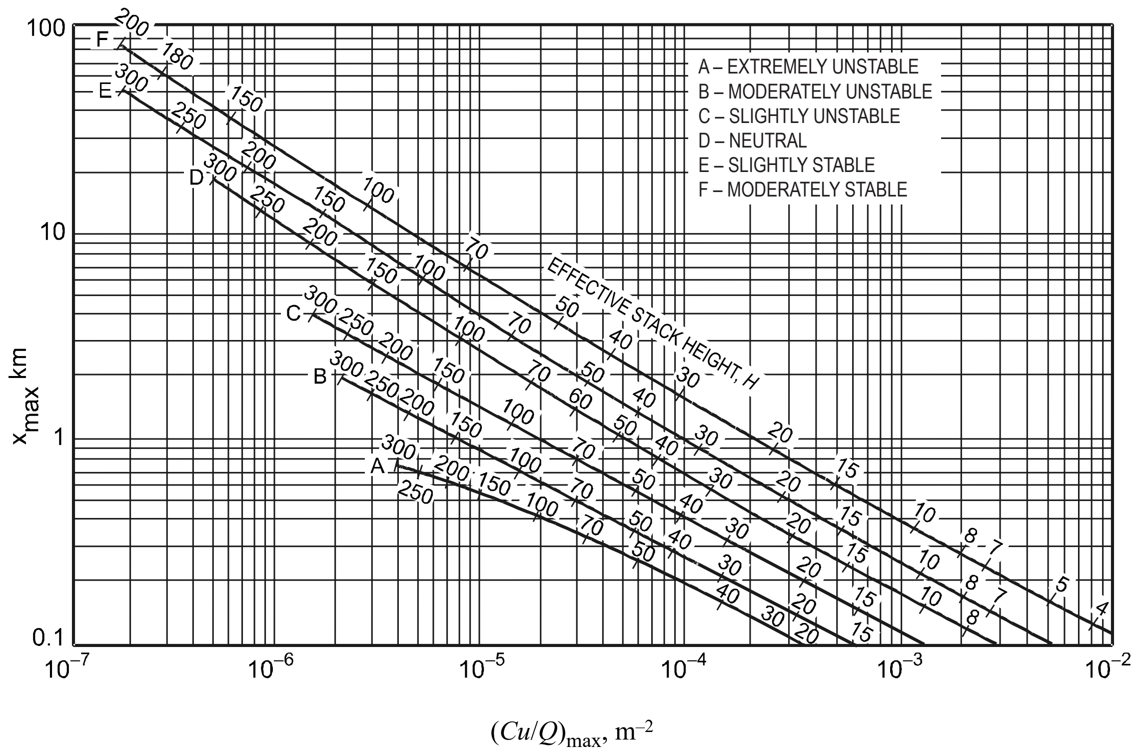


HORIZONTAL STANDARD DEVIATIONS OF A PLUME

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*, 2nd ed., Research Triangle Park: U.S. Environmental Protection Agency, 1970, p. 8.

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



Turner, D.B., *Workbook of Atmospheric Dispersion Estimates*, 2nd ed., Research Triangle Park: U.S. Environmental Protection Agency, 1970, p. 29.

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

Ranchoux, R.J.P., "Determination of Maximum Ground Level Concentration," *Journal of the Air Pollution Control Association*, vol. 26, no. 11, 1976, p. 1089, reprinted by permission of the Air & Waste Management Association, www.awma.org, and Taylor & Francis Ltd, http://www.tandfonline.com.

Fractional Control Efficiency (η)

$$\eta_T = \sum_{i=1}^{\infty} \frac{\dot{m}_{in}\left(d_{pi}\right)}{\dot{m}_{in,T}} \eta\left(d_{pi}\right)$$

$\dot{m}_{in}(d_p)$ = mass per unit time of a contaminant with a particular diameter entering first air pollution control device

$\dot{m}_{in,T}(d_p)$ = total mass feed rate of contaminant into air quality control device (mass/time)

d_{pi} = particle diameter

Cyclone

Cyclone Collection (Particle Removal) Efficiency

$$\eta = \frac{1}{1 + \left(d_{pc}/d_p\right)^2}$$

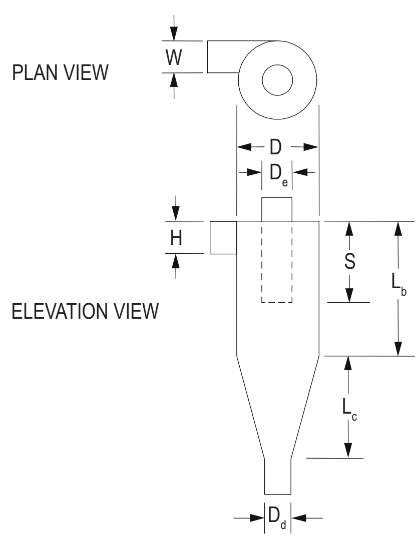
d_{pc} = diameter of particle collected with 50% efficiency

d_p = diameter of particle of interest

η = fractional particle collection efficiency

AIR POLLUTION CONTROL

CYCLONE DIMENSIONS



Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 2nd ed., Long Grove, IL: Waveland Press, 1986.

Cyclone Effective Number of Turns Approximation

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

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

Cyclone 50% Collection Efficiency for Particle Diameter

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

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

μ = dynamic viscosity of gas (kg/m•s)

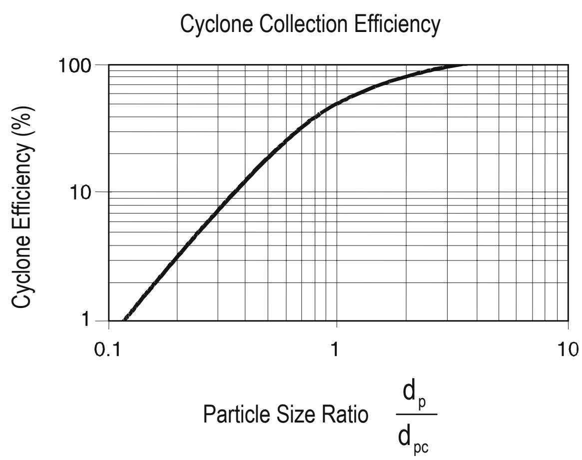
W = inlet width of cyclone (m)

N_e = number of effective turns gas makes in cyclone

V_i = inlet velocity into cyclone (m/s)

ρ_p = density of particle (kg/m^3)

ρ_g = density of gas (kg/m^3)



Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 2nd ed., Long Grove, IL: Waveland Press, 1986.

Fabric Filtration

The pressure drop through a baghouse at a given gas flow rate is given by

$$\Delta P = \Delta P_f + \Delta P_p + \Delta P_s$$

ΔP = total pressure drop

ΔP_f = pressure drop due to the fabric

ΔP_p = pressure drop due to the particular layer

ΔP_s = pressure drop due to the baghouse structure

Darcy's equation for fluid flow through porous media, fabric, and particulate layer

$$\Delta P_f = \frac{D_f \mu V}{60 K_f}$$

$$\Delta P_p = \frac{D_p \mu V}{60 K_p}$$

ΔP_f, ΔP_p = pressure drop (N/m^2)

D_f, D_p = depth (in the direction of flow) of the filter and the particulate layer, respectively (m)

μ = gas viscosity (kg/m•s)

V = superficial filtering velocity (m/min)

K_f, K_p = permeability of the filter and the particulate layer (m^2)

60 = conversion factor (s/min)

The depth of the dust layer, D_p

$$Dp = \frac{LVt}{\rho_L}$$

L = dust loading (g/m^3)

t = time of operation (min)

ρ_L = bulk density of the particulate layer (g/m^3)

The filtration time t_f

$$t_f = N(t_r + t_c) - t_c$$

t_f = filtration time (min)

t_r = run time (min)

t_c = cleaning time (min)

N = total number of compartments

Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 4th ed., Long Grove, IL: Waveland Press, 2011.

Air-to-Cloth Ratio for Baghouses

Dust	Shaker/Woven Reverse Air/Woven $[m^3/(min \cdot m^2)]$	Pulse Jet/Felt $[m^3/(min \cdot m^2)]$
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

Office of Air Quality Planning and Standards, *EPA 450/3-90-006: OAQPS Control Cost Manual*, 4th ed., Research Triangle Park: U.S. Environmental Protection Agency, 1990, p. 5-17.

Maximum Filtering Velocities for Various Dusts in Shaker or Reverse-Air Baghouses

Dusts	Maximum Filtering Velocity, cfm/ft^2 or ft/min
Activated Charcoal, Carbon Black Detergents, Metal Fumes	1.50
Aluminum Oxide, Carbon, Fertilizer Graphite, Iron Ore, Lime, Paint Pigments, Fly Ash, Dyes	2.0
Aluminum Clay, Coke, Charcoal, Cocoa, Lead Oxide, Mica, Soap, Sugar, Talc	2.25
Bauxite, Ceramics, Chrome Ore, Feldspar Flour, Flint, Glass, Gypsum, Plastics, Cement	2.50
Asbestos, Limestone, Quartz, Silica	2.75
Cork, Feeds and Grain, Marble, Oyster Salt	3.0–3.25
Leather, Paper, Tobacco, Wood	3.50

Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 3rd ed., Long Grove, IL: Waveland, 2002, p. 185.

Temperature and Chemical Resistance of Some Common Industrial Fabrics

Fabric	Recommended Maximum Temperature, °F	Chemical Resistance: Acid	Chemical Resistance: Base
Dynel	160	Good	Good
Cotton	180	Poor	Good
Wool	200	Good	Poor
Nylon	200	Poor	Good
Polypropylene	200	Excellent	Excellent
Orlon	260	Good	Fair
Dacron	275	Good	Fair
Nomex®	400	Fair	Good
Teflon®	400	Excellent	Excellent
Glass	550	Good	Good

Cooper, David C., and F.C. Alley, *Air Pollution Control: A Design Approach*, 3rd ed., Long Grove, IL: Waveland, 2002, p. 185.

Electrostatic Precipitator Design Parameters

Particulate loading, gr/actual cubic foot (acf)		0.5–9
Required efficiency, %		98–99.9
Number of fields		3–4
SCA, ft^2/1,000 acfm		400–550
Average secondary voltage, kV		35–55
Average secondary current, mA/1,000 ft^3		30–50
Gas velocity, ft/sec		3.0–3.5
	Particulate	Acid-gas control
Flue gas temperature, °F	350–450	230–300
Flue gas moisture, % vol.	8–16	12–20
Ash resistivity, ohm-cm	10^9–10^{12}	10^8–10^9

Electrostatic Precipitator

$$\eta = 1 - \exp(-Aw/Q)$$

η = fractional collection efficiency

A = area of the collection plates (m^2)

w = drift velocity of the charged particles, commonly ranging from 0.02 to 0.2 m/s, depending upon the particle diameter

Q = flow rate of the gas stream (m/s)

Mizuno, A., "Electrostatic Precipitation," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 7, no. 5,: IEEE Explore, 2000, p. 617.

Venturi Scrubber

$$\Delta P = V_t^2 L \times 10^{-6}$$

ΔP = pressure drop across venturi (cm H_2O)

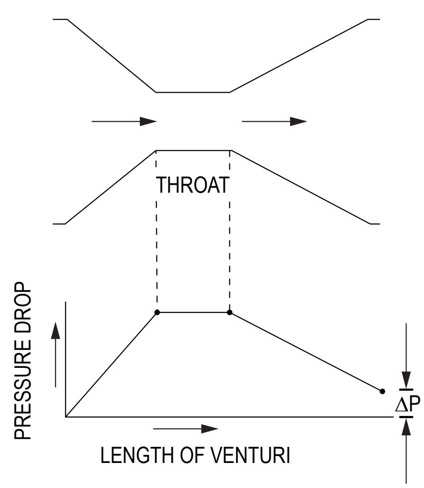
V_t = throat gas velocity (cm/s)

L = water to gas volume ratio (L/m^3)

In U.S. customary units, the equation becomes

$$\Delta P = 5 V_t^2 L \times 10^{-5}$$

where ΔP, V_t, and L are expressed in terms of inches of water, ft/sec, and gallons per 1,000 ft^3, respectively.



VENTURI SCRUBBER PRESSURE PROFILE

Corbitt, Robert A., *Standard Handbook of Environmental Engineering*, 1st ed., New York: McGraw-Hill, 1989, p. 4.33.

Incineration

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

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

$$k = Ae^{-E/RT}$$

$$\eta = 1 - \frac{[HC]_{out}}{[HC]_{in}} = 1 - e^{-k\tau_r}$$

η = HC destruction efficiency

E = activation energy (cal/mol)

A = pre-exponential factor (s^{-1})

R = ideal gas law constant = 1.987 cal/mol-K

T = absolute temperature (K)

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

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

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

Diffusion Coefficient

$$D = D_o e^{-Q/(RT)}$$

D = diffusion coefficient

D_o = proportionality constant

Q = activation energy

R = gas constant = 8.314 J/(mol•K)

T = absolute temperature

Correcting Gas Streams for Dry, Standard Conditions

$$Q_S = Q_A\left(\frac{P_A}{P_S}\right)\left(\frac{T_S}{T_A}\right)\left(\frac{1}{1-y_{H_2O(g)}}\right)$$

Q_S = gas flow rate at standard conditions

Q_A = gas flow rate at actual conditions

P_A = actual air pressure of gas

P_S = standard air pressure (e.g., 1 atm)

T_S = standard air temperature (e.g., 298 K)

T_A = actual temperature of gas

$y_{H_2O(g)}$ = mole fraction of water vapor in gas

Correcting Particle Concentrations in Gas Streams for 12% CO_2 and 7% O_2

$$C_{p,c} = \left(C_{p,d}\right)\left(\frac{12\%\ \text{CO}_2 \text{ by volume}}{\%\text{CO}_2 \text{ by volume in dry gas stream}}\right)\left(\frac{14}{21-\text{actual }\%\text{O}_2 \text{ by volume in dry gas stream}}\right)$$

$C_{p,c}$ = corrected concentration of particulate material

$C_{p,d}$ = mass of particles per unit volume of dry gas

To convert concentration (*C*) ppmv to μg/m³, use:

$$C\left[\mu\text{g/m}^3\right] = \frac{\left[C[\text{ppmv}]\right](MW)}{24.5}\left(10^3\right) \text{ at 298 K}$$

MW = molecular weight of chemical species

Standards and Regulations for Radon in Air

Source*	Focus	Level	Comments
Indoor Radon Abatement Act	Indoor air (residential)	Indoor = outdoor (~0.4 pCi/L)	National goal
National Council on Radiation Protection and Measurements (NCRP)	Indoor air (residential)	2 WLM = 8-10 pCi/L if the equilibrium ratio is 40–50%	NCRP 1993 Guideline
(EPA)	Indoor air (residential) Schools	4 pCi/L 4 pCi/L†	Current action level Guideline for action
NIOSH	Occupational (mining)	1 WLM¶/year and ALARA§	Advisory; exposure limit
OSHA	Occupational	4 WLM/year 100 pCi/L averaged over a 40-hour work week	Regulation 20CFR1910.1096
MSHA	Mining	4 WLM/year 1 WL in active, working mines	Regulation
NRC	Occupational	7,000 pCi/L 9 pCi/L 4,000 pCi/L 30 pCi/L	^{220}Rn w/o daughters ^{220}Rn w/daughters ^{222}Rn w/o daughters ^{222}Rn w/daughters
USNRC	Annual average effluent air concentration	20 pCi/L 0.03 pCi/L 10 pCi/L 0.1 pCi/L	^{220}Rn w/o daughters ^{220}Rn w/daughters ^{222}Rn w/o daughters ^{222}Rn w/daughters
WHO (2009)	Residential	2.7 pCi/L (preferred) 8.1 pCi/L (if the lower level is unreachable due to prevailing country-specific conditions).	Proposed national reference level

* NCRP = National Council for Radon Protection; EPA = U.S. Environmental Protection Agency; NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration; MSHA = Mine Safety and Health Administration; USNRC = U.S. Nuclear Regulatory Commission; WHO = World Health Organization

† EPA recommends action below 4 pCi/L in schools on a case-by-case basis

¶ WLM = working level month; a unit of measure commonly used in occupational environments (since WLM bears a complex relationship to pCi/L, physicians with responsibility for mine workers are urged to contact NIOSH or EPA for further information)

§ ALARA = As low as reasonably achievable

Agency for Toxic Substances and Disease Registry Case Studies in Environmental Medicine (CSEM): Radon Toxicity, U.S. Department of Health and Human Services, 2010, www.atsdr.cdc.gov.

National Ambient Air Quality Standards

Pollutant [links to historical tables of NAAQS reviews]		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)		primary	8 hours	9 ppm	Not to be exceeded more than once per year
			1 hour	35 ppm	
Lead (Pb)		primary and secondary	Rolling 3-month average	0.15 μg/m^3 (1)	Not to be exceeded
Nitrogen Dioxide (NO_2)		primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		primary and secondary	1 year	53 ppb (2)	Annual Mean
Ozone (O_3)		primary and secondary	8 hours	0.070 ppm (3)	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particle Pollution (PM)	$PM_{2.5}$	primary	1 year	12.0 μg/m^3	annual mean, averaged over 3 years
		secondary	1 year	15.0 μg/m^3	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 μg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24 hours	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide (SO_2)		primary	1 hour	75 ppb (4)	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

NAAQS Table: U.S. Environmental Protection Agency, 2011.

Notes:

(1) In areas designated nonattainment for the Pb standards prior to the promulgation of the current (2008) standards, and for which implementation plans to attain or maintain the current (2008) standards have not been submitted and approved, the previous standards (1.5 $\mu g/m^3$ as a calendar quarter average) also remain in effect.

(2) The level of the annual NO_2 standard is 0.053 ppm. It is shown here in terms of ppb for the purposes of clearer comparison to the 1-hour standard level.

(3) Final rule signed October 1, 2015, and effective December 28, 2015. The previous (2008) O_3 standards additionally remain in effect in some areas. Revocation of the previous (2008) O_3 standards and transitioning to the current (2015) standards will be addressed in the implementation rule for the current standards.

(4) The previous SO_2 standards (0.14 ppm 24-hour and 0.03 ppm annual) will additionally remain in effect in certain areas:
   (1) any area for which it is not yet 1 year since the effective date of designation under the current (2010) standards, and
   (2) any area for which an implementation plan providing for attainment of the current (2010) standard has not been submitted and approved and which is designated nonattainment under the previous SO_2 standards or is not meeting the requirements of a SIP call under the previous SO_2 standards (40 CFR 50.4(3)). A SIP call is an EPA action requiring a state to resubmit all or part of its State Implementation Plan to demonstrate attainment of the required NAAQS.

Gaussian Particle Size Distributions

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{d_p - d_{p,mean}}{\sigma}\right)^2\right]$$

d_p = particle diameter

σ = standard deviation

Prevention of Significant Deterioration (PSD) Increments

Pollutant	Maximum Allowable Increase [$\mu g/m^3$]			Significant Emission Rate [tons/year]
	Class I	Class II	Class III	
Particulate Material, PM-10				15
Annual arithmetic mean	4	17	34	
24-hr maximum	8	30	60	
Sulfur Dioxide, SO_2				40
Annual arithmetic mean	2	20	40	
24-hr maximum	5	91	182	
3-hr maximum	25	512	700	
Nitrogen Dioxide				40
Annual arithmetic mean	2.5	25	50	

40 CFR, Parts 51-52, *Prevention of Significant Deterioration (PSD) for Particulate Matter Less Than 2.5 Micrometers (PM2.5)—Increments, Significant Impact Levels (SILs) and Significant Monitoring Concentration (SMC), U.S. Environmental Protection Agency*, 2010, p. 64903, www.epa.gov.

Air Quality Index (AQI) (from 40 CFR Part 58)

Breakpoints for the AQI

These breakpoints							Equal these AQI's	
O_3 (ppm) 8-hour	O_3 (ppm) 1-hour[1]	$PM_{2.5}$ ($\mu g/m^3$) 24-hour	PM_{10} ($\mu g/m^3$) 24-hour	CO (ppm) 8-hour	SO_2 (ppb) 1-hour	NO_2 (ppb) 1-hour	AQI	Category
0.000–0.054	—	0.0–12.0	0–54	0.0–4.4	0–35	0–53	0–50	Good
0.055–0.070	—	12.1–35.4	55–154	4.5–9.4	36–75	54–100	51–100	Moderate
0.071–0.085	0.125–0.164	35.5–55.4	155–254	9.5–12.4	76–185	101–360	101–150	Unhealthy for Sensitive Groups
0.086–0.105	0.165–0.204	[3]55.5–150.4	255–354	12.5–15.4	[4]186–304	361–649	151–200	Unhealthy
0.106–0.200	0.205–0.404	[3]150.5–250.4	355–424	15.5–30.4	[4]305–604	650–1,249	201–300	Very Unhealthy
0.201–([2])	0.405–0.504	[3]250.5–350.4	425–504	30.5–40.4	[4]605–804	1,250–1,649	301–400	Hazardous
([2])	0.505–0.604	[3]350.5–500.4	505–604	40.5–50.4	[4]805–1,004	1,650–2,049	401–500	

1. Areas are generally required to report the AQI based on 8-hour ozone values. However, there are a small number of areas where an AQI based on 1-hour ozone values would be more precautionary. In these cases, in addition to calculating the 8-hour ozone index value, the 1-hour ozone index value may be calculated, and the maximum of the two values reported.
2. 8-hour O_3 values do not define higher AQI values (>301). AQI values > 301 are calculated with 1-hour O_3 concentrations.
3. If a different SHL for $PM_{2.5}$ is promulgated, these numbers will change accordingly.
4. 1-hr SO_2 values do not define higher AQI values (≥200). AQI values of 200 or greater are calculated with 24-hour SO_2 concentration.

Electronic Code of Federal Regulations, Title 40, Washington, D.C.: U.S. Government Publishing Office, 2016.

AQI Calculation

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo}$$

I_p = index value for pollutant p

C_p = truncated concentration of pollutant p

BP_{Hi} = breakpoint that is greater than or equal to C_p

BP_{Lo} = breakpoint that is less than or equal to C_p

I_{Hi} = AQI value corresponding to BP_{Hi}

I_{Lo} = AQI value corresponding to BP_{Lo}

Plume Opacity

$$\text{Opacity}[\%] = \left(1 - \frac{I}{I_o}\right) \times 100\%$$

I = light intensity at detector

I_o = light intensity at source

Oxidation Chemistry

Stoichiometric oxidation of a hydrocarbon in air:

$$C_xH_y + (b)O_2 + 3.76(b)N_2 \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76(b)N_2$$

C_xH_y = a generic hydrocarbon

b = $x + (y/4)$, the stoichiometric number of moles of oxygen required per mole of C_xH_y

3.76 = number of moles of nitrogen present in air for every mole of oxygen (79/21)

CATALYTIC INCINERATION

Heat Load

$$Q_h = Q\rho_g C_p\left(T - T_o\right)$$

Q_h = required heat load (Btu/hr)

Q = total gas flow rate (scfm)

ρ_g = gas density (lb/ft^3)

C_p = heat capacity [Btu/(lb-°F)]

T = temperature at catalyst bed inlet (°F)

T_o = temperature at catalyst bed outlet (°F)

Residence Time

$$C_A = C_{AO}\exp\left(-kt_r\right)$$

C_A = concentration of pollutant entering incinerator

C_{Ao} = concentration of pollutant exiting incinerator

k = rate constant (1/sec)

t_r = residence time (sec)

Greenhouse Gases

Major Long-Lived Greenhouse Gases and Their Characteristics

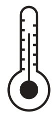
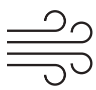
Greenhouse gas	How it's produced	Average lifetime in the atmosphere	100-year global warming potential
Carbon dioxide	Emitted primarily through the burning of fossil fuels (oil, natural gas, and coal), solid waste, and trees and wood products. Changes in land use also play a role. Deforestation and soil degradation add carbon dioxide to the atmosphere, while forest regrowth takes it out of the atmosphere.	see below *	1
Methane	Emitted during the production and transport of oil and natural gas as well as coal. Methane emissions also result from livestock and agricultural practices and from the anaerobic decay of organic waste in municipal solid waste landfills.	12.4 years	28–36
Nitrous oxide	Emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.	121 years	265–298
Fluorinated gases	A group of gases that contain fluorine, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, among other chemicals. These gases are emitted from a variety of industrial processes and commercial and household uses and do not occur naturally. Sometimes used as substitutes for ozone-depleting substances such as chlorofluorocarbons (CFCs).	A few weeks to thousands of years	Varies (the highest is sulfur hexfluoride at 23,500)

This table shows 100-year global warming potentials, which describe the effects that occur over a period of 100 years after a particular mass of a gas is emitted. Global warming potentials and lifetimes come from the Intergovernmental Panel on Climate Change's Fifth Assessment Report.

**Carbon dioxide's lifetime cannot be represented with a single value because the gas is not destroyed over time, but instead moves among different parts of the ocean–atmosphere–land system. Some of the excess carbon dioxide is absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments.*

Climate Change Indicators: Greenhouse Gases, Washington, D.C.: U.S. Environmental Protection Agency, 2017.

Climate Change Impacts

	Climate Driver	Exposure	Health Outcome	Impact
 EXTREME HEAT	More frequent, severe prolonged heat events	Elevated temperatures	Heat-related death and illness	Rising temperatures will lead to an increase in heat-related deaths and illnesses.
 OUTDOOR AIR QUALITY	Increasing temperatures and changing precipitation patterns	Worsened air quality (ozone, particulate matter, and higher pollen counts)	Premature death, acute and chronic cardiovascular and respiratory illnesses	Rising temperatures and wildfires and decreasing precipitation will lead to increases in ozone and particulate matter, elevating the risks of cardiovascular and respiratory illnesses and death
 FLOODING	Rising sea level and more frequent or intense extreme precipitation, hurricanes, and storm surge events	Contaminated water, debris, and disruptions to essential infrastructure	Drowning, injuries, mental health consequences, gastrointestinal and other illness	Increased coastal and inland flooding exposes populations to a range of negative health impacts before, during, and after events.
 VECTOR-BORNE INFECTION (LYME DISEASE)	Changes in temperature extremes and seasonal weather patterns	Earlier and geographically expanded tick activity	Lyme disease	Ticks will show earlier seasonal activity and a generally northward range expansion, increasing risk of human exposure to Lyme disease–causing bacteria.
 WATER-RELATED INFECTION (*VIBRIO VULNIFICUS*)	Rising sea surface temperature, changes in precipitation and runoff affecting coastal salinity	Recreational water or shellfish contaminated with *Vibrio vulnificus*	*Vibrio vulnificus*–induced diarrhea and intestinal illness, wound and bloodstream infections, death	Increases in water temperatures will alter timing and location of *Vibrio vulnificus* growth, increasing exposure and risk of water borne illness.
 FOOD-RELATED INFECTION (*SALMONELLA*)	Increases in temperature, humidity, and season length	Increased growth of pathogens, seasonal shifts in incidence of *Salmonella* exposure	*Salmonella* infection, gastrointestinal outbreaks	Rising temperatures increase *Salmonella* prevalence in food; longer seasons and warming winters increase risk of exposure and infection.
 MENTAL HEALTH AND WELL-BEING	Climate change impacts, especially extreme weather	Level of exposure to traumatic events, like disasters	Distress, grief, behavioral health disorders, social impacts, resilience	Changes in exposure to climate- or weather-related disasters cause or exacerbate stress and mental health consequences, with greater risk for certain populations

The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, U.S. Global Change Research Program, health2016.globalchange.gov/

Indoor Air Quality

Time Constant

$$\tau = \left(\frac{Q}{V} + k\right)^{-1}$$

τ = system time constant (hr)

Q = ventilation rate (m^3/hr)

V = volume of the room (m^3)

k = removal reaction rate constant (first order) (hr^{-1})

The quantity $(Q/V + k)^{-1}$ is the characteristic time or time constant for this system, and is given the symbol τ.

3 SOLID AND HAZARDOUS WASTE

Breakthrough Time for Leachate to Penetrate a Landfill Clay Liner

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

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

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

SW_p = specific weight of the waste material at pressure p (lb/yd^3) (typical 1,750 to 2,150)

SW_i = initial compacted specific weight of waste (lb/yd^3) (typical 1,000)

p = overburden pressure (lb/in^2)

a = empirical constant (yd^3/in^2)

b = empirical constant (yd^3/lb)

Gas Flux

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

N_A = gas flux of compound A [g/(cm^2•s) or lb-mol/(ft^2-day)]

$C_{A_{\text{atm}}}$ = concentration of compound A at the surface of the landfill cover (g/cm^3 or lb-mol/ft^3)

$C_{A_{\text{fill}}}$ = concentration of compound A at the bottom of the landfill cover (g/cm^3 or lb-mol/ft^3)

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

Typical values for the coefficient of diffusion for methane and carbon dioxide are 0.20 cm^2/s (18.6 ft^2/day) and 0.13 cm^2/s (12.1 ft^2/day), respectively.

D = diffusion coefficient (cm^2/s or ft^2/day)

η_{gas} = gas-filled porosity (cm^3/cm^3 or ft^3/ft^3)

η = porosity (cm^3/cm^3 or ft^3/ft^3)

Soil Landfill Cover Water Balance

$$\Delta S_{LC} = P - R - ET - PER_{sw}$$

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 Projection Equations

Linear Projection = Algebraic Projection

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

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

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

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

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

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

P_t = population at time t

P_0 = population at time zero

k = growth rate

n = number of periods

Ratio and Correlation Growth

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

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

$$P_t = P_0 + (S - P_0)(1 - e^{-k(t-t0)})$$

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

HAZARDOUS WASTE COMPATIBILITY CHART

Reactivity Group																																										
No.	Name																																									
1	Acid, Minerals, Non-Oxidizing	1																																								
2	Acids, Minerals, Oxidizing		2																																							
3	Acids, Organic		G H	3																																						
4	Alcohols & Glycols	H	H F	H P	4																																					
5	Aldehydes	H P	H F	H P		5																																				
6	Amides	H	H GT				6																																			
7	Amines, Aliphatic & Aromatic	H	H GT	H		H		7																																		
8	Azo Compounds, Diazo Comp, Hydrazines	H G	H GT	H G	H G	H			8																																	
9	Carbamates	H G	H GT						H G	9																																
10	Caustics	H	H	H		H				H G	10																															
11	Cyanides	GT GF	GT GF	GT GF					G			11																														
12	Dithiocarbamates	H GF F	H GF F	H GF GT		GF GT		U	H G				12																													
13	Esters	H	H F						H G		H			13																												
14	Ethers	H	H F												14																											
15	Fluorides, Inorganic	GT	GT	GT												15																										
16	Hydrocarbons, Aromatic		H F														16																									
17	Halogenated Organics	H GT	H F GT					H GT	H G		H GF	H						17																								
18	Isocyanates	H G	H F GT	H G	H P			H P	H G		H P G	H G	U						18																							
19	Ketones	H	H F						H G		H	H								19																						
20	Mercaptans & Other Organic Sulfides	GT GF	H F GT						H G									H	H	H	20																					
21	Metal, Alkali & Alkaline Earth, Elemental	GF H F	GF H F	GF H F	GF H F	GF H F	GF H	GF H	GF H	GF H	GF H	GF H	GF GT H	GF H				H E	GF H	GF H	GF H	21																				
104	Oxidizing Agents, Strong	H GT		H GT	H F	H F	H F GT	F GT H	H E	H F GT		H E GT	H F GT	H F	H F		H F	H GT	H F GT	H F	H F GT	H F GE																	104			
105	Reducing Agents, Strong	H GF	H F GT	H GF	H GF F	GF H F	GF H	H GF	H G				H GT	H F				H T	GF H	GF H	GF H																		H F E	105		
106	Water & Mixtures Containing Water	H	H						G										H G			GF H																		GF GT	106	
107	Water Reactive Substances	EXTREMELY REACTIVE! Do Not Mix With Any Chemical or Waste Material																																								107
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	101	102	103	104	105	106	107

KEY

REACTIVITY CODE	CONSEQUENCES
H	HEAT GENERATION
F	FIRE
G	INNOCUOUS & NON-FLAMMABLE GAS
GT	TOXIC GAS GENERATION
GF	FLAMMABLE GAS GENERATION
E	EXPLOSION
P	POLYMERIZATION
S	SOLUBILIZATION OF TOXIC MATERIAL
U	MAY BE HAZARDOUS BUT UNKNOWN

EXAMPLE:

H F GT	HEAT GENERATION, FIRE, AND TOXIC GAS GENERATION

Hatayama, H.K., J.J. Chen, E.R. de Vera, R.D. Stephens, and D.L. Storm, *EPA-600/2-80-076: A Method for Determining the Compatibility of Hazardous Wastes*, Cincinnati: U.S. Environmental Protection Agency, 1980, pp. 20–21.

Compaction

$$\textit{Volume reduction}\ (\%) = \left(\frac{V_i - V_f}{V_i}\right) \bullet 100$$

V_i = initial volume of wastes before compaction (yd^3)

V_f = final volume of wastes after compaction (yd^3)

$$\textit{Compaction ratio} = \left(\frac{V_i}{V_f}\right)$$

Kiln Retention Time

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

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)

Settlement

Intermediate secondary settlement:

$$S_{(t)} = H_0 C_{\alpha 1} \log\left(\frac{t}{t_{\text{initial}}}\right) t_{\text{initial}} < t < t_2$$

Long-term secondary settlement:

$$S_{(t)} = H_0 C_{\alpha 2} \log\left(\frac{t}{t_2}\right) t_2 < t < t_{\text{final}}$$

$C_{\alpha 1}$ = coefficient of intermediate secondary compression (varies from 0.015 to 0.035)

$C_{\alpha 2}$ = coefficient of long-term secondary compression (varies from 0.132 to 0.25)

t_{initial} = end of initial settlement period (16 days)

t_{final} = end of field experiment observations (1,576 days)

t_2 = time at which slope of stress-strain curve changes (day)

Typical Densities of As-Received Source-Separated Materials

Material	Typical density, lb/yd^3	Baled density,* lb/yd^3
Paper		
Newspaper	475	950
Corrugated cardboard	350	800
High grades	300–400	
Glass–whole bottles		
Clear	500	
Green or amber	550	
Glass–crushed		
Semicrushed	1,000	
1 1/2-in. mechanically crushed	1,800	
1/4-in. furnace ready	2,700	
Aluminum Cans		
Whole	50	950
Flattened	175	
Tin plated steel cans ("tin cans")		
Whole	150	1,400
Flattened	850	
Plastics		
PET, whole	34	750
PET, flattened	75	
HDPE (natural), whole	30	
HDPE (natural), flattened	65	
HDPE (colored), whole	45	
HDPE (colored), flattened	90	

*Based on bale size of 45 × 30 × 62 in.

Tchobanoglous, George, and Frank Kreith, *Handbook of Solid Waste Management*, 2nd ed., New York: McGraw-Hill, 2002, p. 8.68.

Typical Moisture Content of Municipal Solid Waste (MSW) Components

	Moisture, percent	
Component	Range	Typical
Food wastes	50–80	70
Paper	4–10	6
Cardboard	4–8	5
Plastics	1–4	2
Textiles	6–15	10
Rubber	1–4	2
Leather	8–12	10
Garden trimmings	30–80	60
Wood	15–40	20
Glass	1–4	2
Tin cans	2–4	3
Nonferrous metals	2–4	2
Ferrous metals	2–6	3
Dirt, ashes, brick, etc.	6–12	8
Municipal solid waste	15–40	20

Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, New York: McGraw-Hill, 1977, p. 57.

Typical Heating Value of MSW Components

Component	Energy, Btu/lb	
	Range	Typical
Food wastes	1,500–3,000	2,000
Paper	5,000–8,000	7,200
Cardboard	6,000–7,500	7,000
Plastics	12,000–16,000	14,000
Textiles	6,500–8,000	7,500
Rubber	9,000–12,000	10,000
Leather	6,500–8,500	7,500
Garden trimmings	1,000–8,000	2,800
Wood	7,500–8,500	8,000
Glass	50–100	60
Tin cans	100–500	300
Nonferrous metals	–	–
Ferrous metals	100–500	300
Dirt, ashes, brick, etc.	1,000–5,000	3,000
Municipal solid wastes	4,000–6,500	4,500

Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, New York: McGraw-Hill, 1977, p. 62.

Useful Relationships

Stoichiometric combustion air needed per million Btu can be calculated for typical moisture- and ash-free MSW and similar wastes as follows, using consistent values of HHV from a heat and mass balance calculation:

$$\text{lb combustion air/million Btu} = \frac{1{,}000{,}000[\text{Btu}] * 5.105\,[\text{lb}_a]}{7{,}457\,[\text{Btu/lb}_f][\text{lb}_f]} = 684.6\ \text{lb}_a\text{/MBtu}$$

Pounds of stoichiometric products per million Btu would be:

$$\text{lb products/million Btu} = \frac{1{,}000{,}000[\text{Btu}] * 6.105\,[\text{lb}_a]}{7{,}457\,[\text{Btu/lb}_f][\text{lb}_f]} = 819\ \text{lb}_p\text{/mmBtu}$$

With 50 percent excess air, we get pounds combustion air per million Btu:

$$\text{lb air/million Btu} = \frac{1{,}000{,}000[\text{Btu}][\text{lb}_f] * 7.66\,[\text{lb}_a]}{7{,}457\,[\text{Btu/lb}_f][\text{lb}_f]} = 713\ \text{lb}_a\text{/mmBtu}$$

Pounds of products at 50 percent excess air would be:

$$\text{lb products/million Btu} = \frac{1{,}000{,}000[\text{Btu}][\text{lb}_f] * 8.66\,[\text{lb}_a]}{7{,}457\,[\text{Btu/lb}_f][\text{lb}_f]} = 1{,}161\ \text{lb}_a\text{/mmBtu}$$

Weight and volume of products per million Btu at standard temperature and pressure:

Volume of 1 mol of ideal gas = 387 ft^3/lb-mol @ 70°F (20°C), 1 atmosphere.

1 lb-mol of dry products (see above) weighs 29.51 lb.

1 lb-mol of products weighs about 29.75 lb at zero excess air.

Therefore, the volume of wet products corrected to 70°F (70 + 460 = 530°R) is:

$V_{wp} = 387/29.75 = 13.0\ ft^3/lb_f$

$V_{wp} = 6.105[lb_p/lb_f] * 13\ ft^3/lb_f = 79.416\ ft^3/lb_f$

The volume of dry products is calculated when reporting emissions.

To get the volume of dry products we subtract 0.555 [H_2O] from 6.105 to get:

$V_{dp} = (6.105 – 0.555)\ [lb_{dp}/lb_f] * 13.0\ ft^3/lb_f = 72.15\ ft^3/lb_f$

Tchobanoglous, George, and Frank Kreith, *Handbook of Solid Waste Management*, 2nd ed., New York: McGraw-Hill, 2002, p. 13.173.

Typical Field Capacity (FC) and Permanent Wilting Point (PWP) Values for Various Soil Classifications

	Value, %			
	Field capacity		Permanent wilting point	
Soil classification	Range	Typical	Range	Typical
Sand	6–12	6	2–4	4
Fine sand	8–16	8	3–6	5
Sandy loam	10–18	14	4–8	6
Fine sandy loam	0	0	0	0
Loam	18–26	22	8–12	10
Silty loam	0	0	0	0
Light clay loam	0	0	0	0
Clay loam	23–31	27	11–15	12
Silty clay	27–35	31	12–17	15
Heavy clay loam	0	0	0	0
Clay	31–39	35	15–19	17

Tchobanoglous, George, and Frank Kreith, *Handbook of Solid Waste Management*, 2nd ed., New York: McGraw-Hill, 2002, p. 14.53.

Typical Compaction Factors for Various Solid Waste Components Placed in Landfills

	Compaction factors for components in landfills*		
Component	Range	Normal compaction	Well compacted
Food wastes	0.2–0.5	0.35	0.33
Paper	0.1–0.4	0.2	0.15
Cardboard	0.1–0.4	0.25	0.18
Plastics	0.1–0.2	0.15	0.10
Textiles	0.1–0.4	0.18	0.15
Rubber	0.2–0.4	0.3	0.3
Leather	0.2–0.4	0.3	0.3
Garden trimmings	0.1–0.5	0.25	0.2
Wood	0.2–0.4	0.3	0.3
Glass	0.3–0.9	0.6	0.4
Tin cans	0.1–0.3	0.18	0.15
Nonferrous metals	0.1–0.3	0.18	0.15
Ferrous metals	0.2–0.6	0.35	0.3
Dirt, ashes, brick, etc.	0.6–1.0	0.85	0.75

*Compaction factor = V_f/V_i where V_f = final volume of solid waste after compaction and V_i = initial volume of solid waste before compaction.

Tchobanoglous, George, and Frank Kreith, *Handbook of Solid Waste Management*, 2nd ed., New York: McGraw-Hill, 2002, p. 14.62.

Heating Value of Waste

$$\text{LHV} = \text{HHV} - [(\Delta H_v)(9\,H)]$$

ΔH_v = heat of vaporization of water

= 2,420 kJ/kg

H = hydrogen content of combusted material

Geotextile Permittivity

$$\Psi = K_n/t$$

Ψ = permittivity (s^{-1})

K_n = normal hydraulic conductivity (cm/s)

t = fabric (geotextile) thickness (cm)

Geotextile Transmissivity

$$\theta = K_p t$$

θ = transmissivity (cm^2/s)

K_p = in-plane hydraulic conductivity (cm/s)

t = fabric thickness

Slope Stability (Mohr-Coulomb Failure Criteria)

$$T_{ff} = c + \sigma_{ff} \times \tan \phi$$

T_{ff} = shear stress at failure on the failure plane (kPa)

c = cohesion (kPa)

σ_{ff} = applied normal stress at failure on the failure plane (kPa)

ϕ = angle of internal friction (degrees)

Factor of Safety

The factor of safety (FS) is defined as the ratio of the resisting forces F_r to the driving forces F_d, written as:

$$\text{FS} = F_r/F_d$$

The resulting equation of equilibrium for a slope at angle β measured from the horizontal line is:

$$\text{FS} = \tan \phi / \tan \beta$$

Hazardous Waste Characteristics

Ignitability (D001)

The waste

1. is a liquid, other than an aqueous solution containing less than 24% alcohol (v/v) with a flash point of less than 60°C;
2. is a nonliquid which under normal conditions can cause fire through friction, absorption of moisture, or spontaneous chemical changes, and burns so vigorously when ignited that it creates a hazard;
3. is an ignitable compressed gas defined by the DOT regulations 49 CFR 173.300, and;
4. exhibits ignitability as an oxidizer as defined by 40 CFR 173.151.

40 CFR 261.21, *Characteristic of Ignitability*, U.S. Government Printing Office.

Corrosivity (D002)

The waste

1. is aqueous and has a pH ≤2.0 or ≥12.5, and
2. is a liquid and corrodes steel at a rate greater than 6.35 mm/year.

40 CFR 261.22, *Characteristic of Corrosivity*, U.S. Government Printing Office.

Reactivity (D003)

The waste

1. is normally unstable and readily undergoes violent change without detonation,
2. violently reacts with water,
3. forms potentially explosive mixtures with water,
4. generates toxic gases or fumes in a quantity sufficient to present a danger to public health or the environment when mixed with water,
5. is a cyanide- or sulfide-bearing waste that, when exposed to pH between 2 and 12.5, can generate toxic gases,
6. is capable of detonation or explosive reaction if it is subjected to a strong initiating source or it is heated under confinement,
7. is readily capable of detonation or explosive decomposition or reaction at standard temperature and pressure, and
8. is a forbidden explosive, as defined by DOT regulations (49 CFR 173.51, 173.53, and 173.88).

40 CFR 261.23, *Characteristic of Reactivity*, U.S. Government Printing Office.

Toxicity (D004-D043)

The waste is pH adjusted to landfill conditions, and a leaching procedure is performed. This analysis, called the *Toxicity Characteristic Leaching Procedure* (TCLP), compares the leachate concentrations to a list of 31 organic chemicals and 8 inorganic chemicals. If the waste leachate concentrations are greater than the TCLP list, the waste is characterized by toxicity.

40 CFR 261.24, *Characteristic of Toxicity*, Washington, D.C.: U.S. Government Printing Office.

Maximum Concentration of Contaminants for the Toxicity Characteristic

EPA HW No. [1]	Contaminant	CAS No. [2]	Regulatory Level (mg/L)
D004	Arsenic	7440-38-2	5.0
D005	Barium	7440-39-3	100.0
D018	Benzene	71-43-2	0.5
D006	Cadmium	7440-43-9	1.0
D019	Carbon tetrachloride	56-23-5	0.5
D020	Chlordane	57-74-9	0.03
D021	Chlorobenzene	108-90-7	100.0
D022	Chloroform	67-66-3	6.0
D007	Chromium	7440-47-3	5.0
D023	o-Cresol	95-48-7	[4] 200.0
D024	m-Cresol	108-39-4	[4] 200.0
D025	p-Cresol	106-44-5	[4] 200.0
D026	Cresol		[4] 200.0
D016	2,4-D	94-75-7	10.0
D027	1,4-Dichlorobenzene	106-46-7	7.5
D028	1,2-Dichloroethane	107-06-2	0.5
D029	1,1-Dichloroethylene	75-35-4	0.7
D030	2,4-Dinitrotoluene	121-14-2	[3] 0.13
D012	Endrin	72-20-8	0.02
D031	Heptachlor (and its epoxide)	76-44-8	0.008
D032	Hexachlorobenzene	118-74-1	[3] 0.13
D033	Hexachlorobutadiene	87-68-3	0.5
D034	Hexachloroethane	67-72-1	3.0
D008	Lead	7439-92-1	5.0
D013	Lindane	58-89-9	0.4
D009	Mercury	7439-97-6	0.2
D014	Methoxychlor	72-43-5	10.0
D035	Methyl ethyl ketone	78-93-3	200.0
D036	Nitrobenzene	98-95-3	2.0
D037	Pentachlorophenol	87-86-5	100.0
D038	Pyridine	110-86-1	[3] 5.0
D010	Selenium	7782-49-2	1.0
D011	Silver	7440-22-4	5.0
D039	Tetrachloroethylene	127-18-4	0.7
D015	Toxaphene	8001-35-2	0.5
D040	Trichloroethylene	79-01-6	0.5
D041	2,4,5-Trichlorophenol	95-95-4	400.0
D042	2,4,6-Trichlorophenol	88-06-2	2.0
D017	2,4,5-TP (Silvex)	93-72-1	1.0
D043	Vinyl chloride	75-01-4	0.2

1 Hazardous waste number.
2 Chemical abstracts service number.
3 Quantitation limit is greater than the calculated regulatory level. The quantitation limit therefore becomes the regulatory level.
4 If o-, m-, and p-Cresol concentrations cannot be differentiated, the total cresol (D026) concentration is used. The regulatory level of total cresol is 200 mg/l.[55 FR 11862, Mar. 29, 1990, as amended at 55 FR 22684, June 1, 1990; 55 FR 26987, June 29, 1990; 58 FR 46049, Aug. 31, 1993; 67 FR 11254, Mar. 13, 2002; 71 FR 40259, July 14, 2006]

40 CFR 261.24, *Characteristic of Toxicity*, Washington, D.C.: U.S. Government Printing Office.

4 SITE ASSESSMENT AND REMEDIATION

Nomenclature

A chemical reaction may be expressed by the general equation

$$aA + bB \leftrightarrow cC + dD.$$

The rate of reaction of any component is defined as the moles of that component formed per unit time per unit volume.

$$-r_A = -\frac{1}{V}\frac{dN_A}{dt} \quad \text{(negative because A disappears)}$$

$$-r_A = \frac{-dC_A}{dt} \quad \text{if } V \text{ is constant}$$

The rate of reaction is frequently expressed by

$$-r_A = kf_r(C_A, C_B, ...)$$

k = reaction rate constant

C_I = concentration of component I

In the conversion of A, the fractional conversion X_A is defined as the moles of A reacted per mole of A fed.

$$X_A = (C_{A0} - C_A)/C_{A0} \quad \text{if } V \text{ is constant}$$

The Arrhenius equation gives the dependence of k on temperature

$$k = Ae^{-E_a/\overline{R}T}$$

A = pre-exponential or frequency factor

E_a = activation energy (J/mol or cal/mol)

T = temperature (K)

$\overline{R}$ = gas law constant = 8.314 J/(mol•K)

For values of rate constant k_i at two temperatures T_i,

$$E_a = \frac{RT_1T_2}{(T_1 - T_2)}\ln\left(\frac{k_1}{k_2}\right)$$

Reaction Order

$$\text{If } -r_A = kC_A^xC_B^y$$

the reaction is x order with respect to reactant A and y order with respect to reactant B. The overall order is

$$n = x + y$$

Batch Reactor, Constant Volume

For a well-mixed, constant-volume batch reactor

$$-r_A = -dC_A/dt$$

$$t = -C_{A0}\int_0^{X_A} dX_A/(-r_A)$$

Zero-Order Irreversible Reaction Kinetics

$$-r_A = kC_A^0 = k(1)$$

$$-dC_A/dt = k \quad \text{or}$$

$$C_A = C_{A0} - kt$$

$$dX_A/dt = k/C_{A0} \quad \text{or}$$

$$C_{A0}X_A = kt$$

First-Order Irreversible Reaction Kinetics

$$-r_A = kC_A$$

$$-dC_A/dt = kC_A \quad \text{or}$$

$$\ln(C_A/C_{A0}) = -kt$$

$$dX_A/dt = k(1 - X_A) \quad \text{or}$$

$$\ln(1 - X_A) = -kt$$

Second-Order Irreversible Reaction Kinetics

$$-r_A = kC_A^2$$

$$-dC_A/dt = kC_A^2 \quad \text{or}$$

$$1/C_A - 1/C_{A0} = kt$$

$$dX_A/dt = kC_{A0}(1 - X_A)^2 \quad \text{or}$$

$$X_A/[C_{A0}(1 - X_A)] = kt$$

First-Order Reversible Reaction Kinetics

$$A \underset{k_2}{\overset{k_1}{\rightleftarrows}} R$$

$$-r_A = -\frac{dC_A}{dt} = k_1C_A - k_2C_R$$

$$K_c = k_1/k_2 = \hat{C}_R/\hat{C}_A$$

$$M = C_{R_0}/C_{A_0}$$

$$\frac{d\hat{X}_A}{dt} = \frac{k_1(M + 1)}{M + \hat{X}_A}(\hat{X}_A - X_A)$$

$$-\ln\left(1 - \frac{X_A}{\hat{X}_A}\right) = -\ln\frac{C_A - \hat{C}_A}{C_{A_0} - \hat{C}_A}$$

$$= \frac{(M + 1)}{(M + \hat{X}_A)}k_1t$$

Darcy's Law

Q = –KA(dh/dx)

Q = discharge rate (ft^3/sec or m^3/s)

K = hydraulic conductivity (ft/sec or m/s)

h = hydraulic head (ft or m)

A = cross-sectional area of flow (ft^2 or m^2)

Specific Discharge

$$q = -K\left(\frac{dh}{dx}\right)$$

q = specific discharge (also called Darcy velocity)

$$v = \frac{q}{n} = \frac{-K}{n}\frac{dh}{dx}$$

v = average seepage velocity

n = effective porosity

Transmissivity

$$T = Kb$$

T = transmissivity (ft^2/day or m^2/day)

b = aquifer thickness

Hydraulic Conductivity

$$K = \rho g k/\mu$$

ρ = fluid density (kg/m^3)

k = intrinsic permeability (m^2)

μ = fluid dynamic viscosity [kg/(m•s)]

K = hydraulic conductivity (m/s)

g = acceleration due to gravity (m/s^2)

Average Horizontal Conductivity (Parallel to Layering)

$$K_h \text{ avg} = \sum_{m=1}^{n} \frac{K_{hm} b_m}{b}$$

K_h avg = average horizontal hydraulic conductivity (L/T; ft/day or m/day)

K_{hm} = horizontal hydraulic conductivity of the mth layer (L/T; ft/day or m/day)

b_m = thickness of the mth layer (L; ft or m)

b = total aquifer thickness (L; ft or m)

Overall Vertical Hydraulic Conductivity (Perpendicular to Layering)

$$K_v \text{ avg} = \frac{b}{\sum_{m=1}^{n} \frac{b_m}{K_{vm}}}$$

K_v avg = average horizontal hydraulic conductivity (L/T; ft/day or m/day)
K_{vm} = vertical hydraulic conductivity of the mth layer (L/T; ft/day or m/day)
b_m = thickness of the mth layer (L; ft or m)
b = total aquifer thickness (L; ft or m)

Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals

Chemical Name	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm•m^3/mol)	K_{oc} (mL/g)	K_{ow}
PESTICIDES					
Chlordane	5.60E–01	1.00E–05	9.63E–06	1.40E+05	2.09E+03
DDT	5.00E–03	5.50E–06	5.13E–04	2.43E+05	1.55E+06
Diazonin	4.00E+01	1.40E–04	1.40E–06	8.50E+01	1.05E+03
Malathion	1.45E+02	4.00E–05	1.20E–07	1.80E+03	7.76E+02
ALIPHATIC COMPOUNDS					
Chloroethane (Ethyl Chloride)	5.74E+03	1.00E+03	6.15E–04	1.70E+01	3.50E+01
Chloroethene (Vinyl Chloride)	2.67E+03	2.66E+03	8.19E–02	5.70E+01	2.40E+01
Chloromethane (Methyl Chloride)	6.50E+03	4.31E+03	4.40E–02	3.50E+01	9.50E–01
1,2-Dichloroethane (Ethylidine Chloride)	5.50E+03	1.82E+02	4.31E–03	3.00E+01	6.17E+01
1,2-Dichloroethane (Ethylene Dichloride)	8.52E+03	6.40E+01	9.78E–04	1.40E+01	3.02E+01
Dichloromethane (Methylene Chloride)	2.00E+04	3.62E+02	2.03E–03	8.80E+00	2.00E+01
Hexachloroethane	5.00E+01	4.00E–01	2.49E–03	2.00E+04	3.98E+04
Tetrachloroethene (PERC)	1.50E+02	1.78E+01	2.59E–02	3.64E+02	3.98E+02
Tetrachloromethane (Carbon Tetrachloride)	7.57E+02	9.00E+01	2.41E–02	4.39E+02	4.37E+02
1,1,1-Trichloroethane (Methychloroform)	1.50E+03	1.23E+01	1.44E–02	1.52E+02	3.16E+02
1,1,2-Trichloroethane (Vinyltrichloride)	4.50E+03	3.00E+01	1.17E–03	5.60E+01	2.95E+02
Trichloroethene (TCE)	1.10E+03	5.79E+01	9.10E–03	1.26E+02	2.40E+02
Trichloromethane (Chloroform)	8.20E+03	1.51E+02	2.87E–03	4.70E+01	9.33E+01
AROMATIC COMPOUNDS					
Benzene	1.75E+03	9.52E+01	5.59E–03	8.30E+01	1.32E+02
Ethylbenzene	1.52E+02	7.00E+00	6.43E–03	1.10E+03	1.41E+03
PCBs					
Polychlorinated Biphenyls (PCBs)	3.10E–02	7.70E–05	1.07E–03	5.30E+05	1.10E+06
MISCELLANEOUS ORGANIC COMPOUNDS					
Carbon Disulfide	2.94E+03	3.60E+02	1.23E–02	5.40E+01	1.00E+02

Basics of Pump-and-Treat Ground-Water Remediation Technology, Washington, D.C.: U.S. Environmental Protection Agency, 1990, pp. A-1 through A-9.

Partition Coefficients

Bioconcentration Factor BCF

The amount of a chemical to accumulate in aquatic organisms.

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

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.

$$K_{\text{ow}} = C_{\text{o}}/C_{\text{w}}$$

C_o = concentration of chemical in octanol phase (mg/L or μg/L)

C_w = concentration of chemical in aqueous phase (mg/L or μg/L)

Organic Carbon Partition Coefficient K_{oc}

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

C_{soil} = concentration of chemical in organic carbon component of soil (μg adsorbed/kg organic C, or ppb)

C_{water} = concentration of chemical in water (ppb or μg/kg)

Retardation Factor R

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

ρ = bulk density

η = porosity

K_d = distribution coefficient

Soil-Water Partition Coefficient $K_d = K\rho$

$$K_d = X/C$$

X = concentration of chemical in soil (ppb or μg/kg)

C = concentration of chemical in water (ppb or μg/L)

$$K_d = K_{oc} f_{oc}$$

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

Vadose Zone Penetration

$$D = \frac{RvV}{A}$$

D = maximum depth of penetration (m)

V = volume of infiltrating hydrocarbon (m^3)

A = area of spill (m^2)

Rv = a constant reflecting the retention capacity of the soil and the viscosity of the product (see following table)

Typical Values of *Rv*

	Rv†		
Soil	Gasoline	Kerosene	Light Fuel Oil
Coarse Gravel	400	200	100
Gravel to Coarse Sand	250	125	62
Coarse to Medium Sand	130	66	33
Medium to Fine Sand	80	40	20
Fine Sand to Silt	50	25	12

†A constant value representing capacity of soil and viscosity of product

Data from Shepherd, W. D. No date. *Practical Geohydrological Aspects of Groundwater Contamination*. Dept. of Environmental Affairs, Houston: Shell Oil, as published in *Underground Storage Tank Corrective Action Technologies*, Washington, D.C.: U.S. Environmental Protection Agency, 1987, pp. 3-8 and 3-9, epa.gov.

Steady-State Reactor Parameters (Constant Density Systems)

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

		Equations for Mean Retention Times (θ)		
Reaction Order	**r**	**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.
[b]Expressions are valid for $k\theta \le C_o$; otherwise $C_t = 0$.

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

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

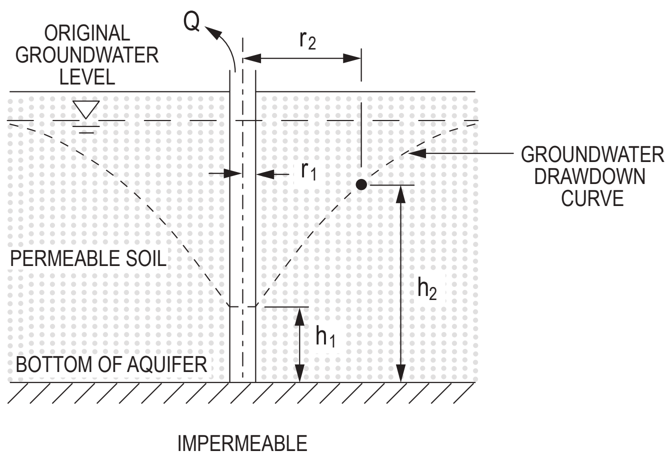
		Equations for C_t		
Reaction Order	**r**	**Ideal Batch**	**Ideal Plug Flow**	**Ideal CMFR**
Zero[b] $t \le C_o/k$	$-k$	$C_o - kt$	$C_o - k\theta$	$C_o - k\theta$
$t > C_o/k$		0		
First	$-kC$	$C_o[\exp(-kt)]$	$C_o[\exp(-k\theta)]$	$\frac{C_o}{1 + k\theta}$
Second	$-kC^2$	$\frac{C_o}{1 + ktC_o}$	$\frac{C_o}{1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

[a]C_o = initial concentration or influent concentration; C_t = final condition or effluent concentration.
[b]Time conditions are for ideal batch reactor only.

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

Well Drawdown

Unconfined Aquifer



Dupuit's Formula

$$Q = \frac{\pi k \left(h_2^2 - h_1^2\right)}{\ln\left(\frac{r_2}{r_1}\right)}$$

Q = flow rate of water drawn from well (cfs)

k = coefficient of permeability of soil (fps)

h_1 = height of water surface above bottom of aquifer at perimeter of well (ft)

h_2 = height of water surface above bottom of aquifer at distance r_2 from well centerline (ft)

r_1 = radius to water surface at perimeter of well, i.e., radius of well (ft)

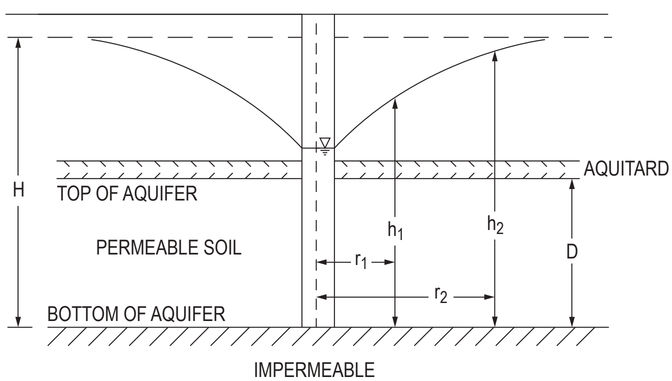
r_2 = radius to water surface whose height is h_2 above bottom of aquifer (ft)

ln = natural logarithm

Q/D_w = specific capacity

D_w = well drawdown (ft)

Confined Aquifer



Theim Equation

$$Q = \frac{2\pi T \left(h_2 - h_1\right)}{\ln\left(\frac{r_2}{r_1}\right)}$$

T = KD = transmissivity (ft^2/sec)

D = thickness of confined aquifer (ft)

h_1, h_2 = heights of piezometric surface above bottom of aquifer (ft)

r_1, r_2 = radii from pumping well (ft)

ln = natural logarithm

H = height of piezometric surface prior to pumping (ft)

Resistivity of a Medium

$$U = \rho \frac{I}{2\pi r}$$

U = potential (volts)

ρ = resistivity of the medium

r = distance from the electrode

$$\rho = 2\pi K \frac{V}{I}$$

ρ = resistivity of the medium

K = array geometric factor

Granular Activated Carbon (GAC) Isotherm

The two most common mathematical expressions used to relate the adsorption isotherm are the Freundlich equation and the Langmuir equation. The Freundlich equation is an empirical equation that accurately describes much adsorption data.

The Freundlich equation has the following form:

$$q_e = KC_e^{1/n}$$

and can be linearized as follows:

$$\log q_e = \log K + (1/\mathrm{n}) \log C_e$$

q_e = equilibrium loading on the GAC (mg chemical/g GAC)

C_e = equilibrium concentration in the water (mg chemical/L)

K = adsorption capacity at unit concentration $(\mathrm{mg/g})(\mathrm{L/mg})^{1/n}$

$1/n$ = strength of adsorption (dimensionless)

The Langmuir equation has the following form:

$$q_e = (q_{\max} bC_e)/(1 + bC_e)$$

and can be linearized as follows:

$$1/q_e = 1/(q_{\max} bC_e + 1/q_{\max})$$

$q_{\max}$ = ultimate adsorption capacity (mg chemical/g GAC)

b = relative energy of adsorption (L/mg)

5 ENVIRONMENTAL HEALTH AND SAFETY

Industrial Hygiene, Health, and Safety

Safety is the condition of protecting people from threats or failures that could harm their physical, emotional, occupational, psychological, or financial well-being. Safety is also the control of known threats to attain an acceptable level of risk.

The United States relies on public codes and standards, engineering designs, and corporate policies to ensure that a structure or place does what it should do to maintain a steady state of safety—that is, long-term stability and reliability. Some *safety/regulatory agencies* that develop codes and standards commonly used in the United States are shown in the table.

Abbreviation	Name	Jurisdiction
CSA	Canadian Standards Association	Nonprofit standards organization
FAA	Federal Aviation Administration	Federal regulatory agency
IEC	International Electrotechnical Commission	Nonprofit standards organization
ITSNA	Intertek Testing Services NA (formerly Edison Testing Labs)	Nationally recognized testing laboratory
MSHA	Mine Safety and Health Administration	Federal regulatory agency
NFPA	National Fire Protection Association	Nonprofit trade association
OSHA	Occupational Safety and Health Administration	Federal regulatory agency
UL	Underwriters Laboratories	Nationally recognized testing laboratory
USCG	United States Coast Guard	Federal regulatory agency
USDOT	United States Department of Transportation	Federal regulatory agency
USEPA	United States Environmental Protection Agency	Federal regulatory agency

Occupational Exposure Limits

OEL = Occupational exposure limit

PEL = Permissible Exposure Limit—an OEL set by and enforced by OSHA—a legal limit

REL = Recommended Exposure Limit—an OEL recommended by NIOSH

TLV = Threshold Limit Value—an OEL set by a professional organization, the ACGIH

OELs may be set as an 8-hour TWA; a short-turn exposure limit (STEL), which is a 15-min TWA; or a ceiling limit (C), which is a limit value never to be exceeded.

Safety and Prevention

A traditional preventive approach to both accidents and occupational illness involves recognizing, evaluating, and controlling hazards and work conditions that may cause physical or other injuries.

Hazard is the capacity to cause harm. It is an inherent quality of a material or a condition. For example, a rotating saw blade or an uncontrolled high-pressure jet of water has the capability (hazard) to slice through flesh. A toxic chemical or a pathogen has the capability (hazard) to cause illness.

Risk is the chance or probability that a person will experience harm and is not the same as a hazard. Risk always involves both probability and severity elements. The hazard associated with a rotating saw blade or the water jet continues to exist, but the probability of causing harm, and thus the risk, can be reduced by installing a guard or by controlling the jet's path. Risk is expressed by the equation:

$$\text{Risk} = \text{Hazard} \times \text{Probability}$$

When people discuss the hazards of disease-causing agents, the term *exposure* is typically used more than *probability*.

If a certain type of chemical has a toxicity hazard, the risk of illness rises with the degree to which that chemical contacts your body or enters your lungs. In that case, the equation becomes:

$$Risk = Hazard \times Exposure$$

Organizations evaluate hazards using multiple techniques and data sources.

Job Safety Analysis

Job safety analysis (JSA) is known by many names, including activity hazard analysis (AHA) or job hazard analysis (JHA). Hazard analysis helps integrate accepted safety and health principles and practices into a specific task. In a JSA, each basic step of the job is reviewed, potential hazards identified, and recommendations documented as to the safest way to do the job. JSA techniques work well when used on a task that the analysts understand well. JSA analysts look for specific types of potential accidents and ask basic questions about each step, such as these:

Can the employee strike against or otherwise make injurious contact with the object?

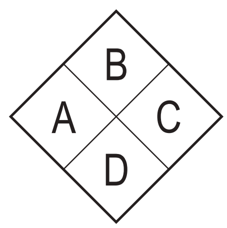
Can the employee be caught in, on, or between objects?

Can the employee strain muscles by pushing, pulling, or lifting?

Is exposure to toxic gases, vapors, dust, heat, electrical currents, or radiation possible?

Hazard Assessment

The fire/hazard diamond below summarizes common hazard data available on the SDS and is frequently shown on chemical labels.



Position A – Health Hazard (Blue)

0 = normal material

1 = slightly hazardous

2 = hazardous

3 = extreme danger

4 = deadly

Position B – Flammability (Red)

0 = will not burn

1 = will ignite if preheated

2 = will ignite if moderately heated

3 = will ignite at most ambient temperature

4 = burns readily at ambient conditions

Position C – Reactivity (Yellow)

0 = stable and not reactive with water

1 = unstable if heated

2 = violent chemical change

3 = shock short may detonate

4 = may detonate

Position D – (White)

ALKALI = alkali

OXY = oxidizer

ACID = acid

Cor = corrosive

~~W~~ = use no water

☢ = radiation hazard

GHS

The *Globally Harmonized System of Classification and Labeling of Chemicals*, or GHS, is a system for standardizing and harmonizing the classification and labeling of chemicals. GHS is a comprehensive approach to:

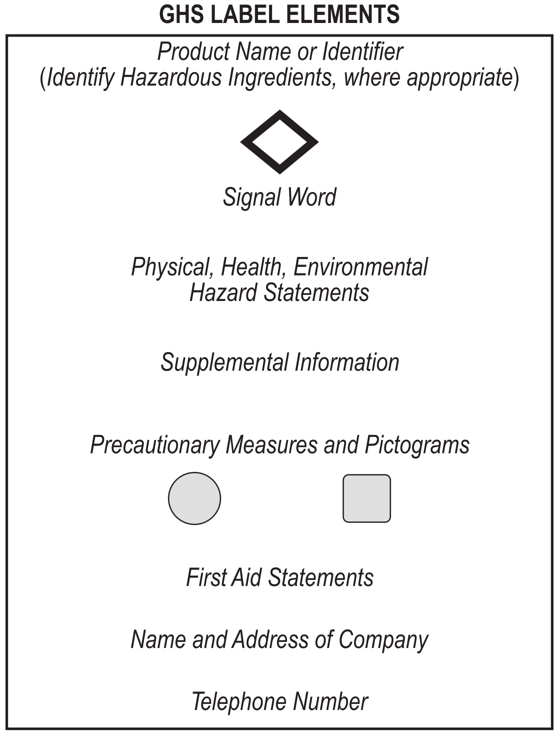
- Defining health, physical, and environmental hazards of chemicals
- Creating classification processes that use available data on chemicals for comparison with the defined hazard criteria
- Communicating hazard information, as well as protective measures, on labels and Safety Data Sheets (SDSs), formerly called Material Safety Data Sheets (MSDSs).

GHS label elements include:

- Precautionary statements and pictograms: measures to minimize or prevent adverse effects
- Product identifier (ingredient disclosure): name or number used for a hazardous product on a label or in the SDS
- Supplier identification: the name, address, and telephone number of the supplier
- Supplemental information: nonharmonized information

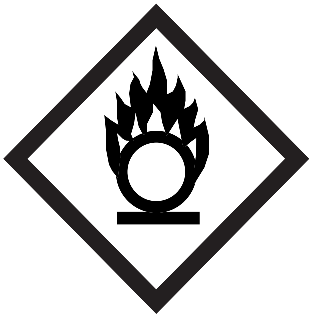
Other label elements include symbols, signal words, and hazard statements.

GHS LABEL ELEMENTS



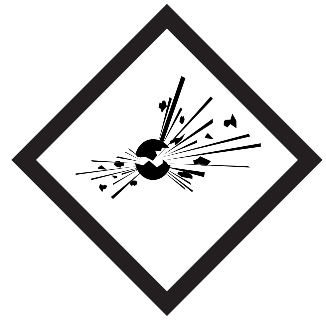
A Guide to the Globally Harmonized System of Classification and Labelling of Chemicals (*GHS*), Washington, D.C.: U.S. Department of Labor, Occupational Health and Safety Administration, p. 38.

GHS PICTOGRAMS AND HAZARD CLASSES



- OXIDIZERS

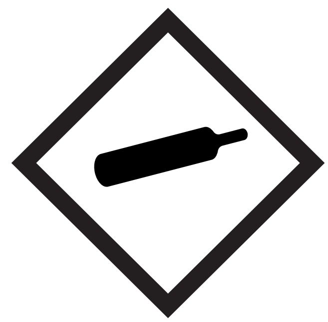
- FLAMMABLES
- SELF-REACTIVES
- PYROPHORICS
- SELF-HEATING
- EMITS FLAMMABLE GAS
- ORGANIC PEROXIDES



- EXPLOSIVES
- SELF-REACTIVES
- ORGANIC PEROXIDES

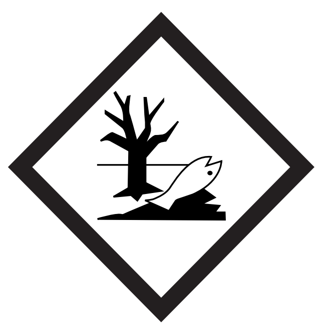
- ACUTE TOXICITY (SEVERE)

- CORROSIVES



- GASES UNDER PRESSURE

- CARCINOGEN
- RESPIRATORY SENSITIZER
- REPRODUCTIVE TOXICITY
- TARGET ORGAN TOXICITY
- MUTAGENICITY
- ASPIRATION TOXICITY



- ENVIRONMENTAL TOXICITY

- IRRITANT
- DERMAL SENSITIZER
- ACUTE TOXICITY (HARMFUL)
- NARCOTIC EFFECTS
- RESPIRATORY TRACT IRRITATION

A Guide to the Globally Harmonized System of Classification and Labelling of Chemicals (*GHS*), Washington, D.C.: U.S. Department of Labor, Occupational Health and Safety Administration, p. 40.

TRANSPORT PICTOGRAMS

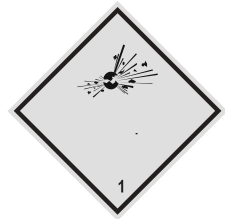
FLAMMABLE LIQUID
FLAMMABLE GAS
FLAMMABLE AEROSOL

FLAMMABLE SOLID
SELF-REACTIVE
SUBSTANCES

PYROPHORICS (SPONTANEOUSLY COMBUSTIBLE)
SELF-HEATING SUBSTANCES

SUBSTANCES WHICH, IN CONTACT WITH WATER, EMIT FLAMMABLE GASES (DANGEROUS WHEN WET)

OXIDIZING GASES
OXIDIZING LIQUIDS
OXIDIZING SOLIDS

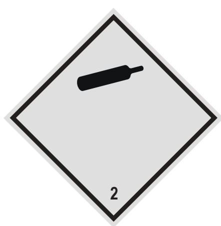


EXPLOSIVE DIVISIONS 1.1, 1.2, 1.3

EXPLOSIVE DIVISION 1.4

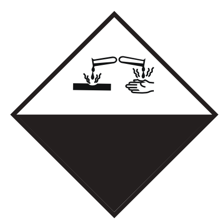
EXPLOSIVE DIVISION 1.5

EXPLOSIVE DIVISION 1.6



COMPRESSED GASES

ACUTE TOXICITY (POISON): ORAL, DERMAL, INHALATION



CORROSIVE

MARINE POLLUTANT

ORGANIC PEROXIDES

A Guide to the Globally Harmonized System of Classification and Labelling of Chemicals (*GHS*), Washington, D.C.: U.S. Department of Labor, Occupational Health and Safety Administration, p. 41.

ACUTE ORAL TOXICITY

	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5
LD_{50}	≤ 5 mg/kg	> 5 < 50 mg/kg	≥ 50 < 300 mg/kg	≥ 300 < 2,000 mg/kg	≥ 2,000 < 5,000 mg/kg
PICTOGRAM					NO SYMBOL
SIGNAL WORD	DANGER	DANGER	DANGER	WARNING	WARNING
HAZARD STATEMENT	FATAL IF SWALLOWED	FATAL IF SWALLOWED	TOXIC IF SWALLOWED	HARMFUL IF SWALLOWED	MAY BE HARMFUL IF SWALLOWED

A Guide to the Globally Harmonized System of Classification and Labelling of Chemicals (*GHS*), Washington, D.C.: U.S. Department of Labor, Occupational Health and Safety Administration, p. 42.

Safety Data Sheet (SDS)

The SDS provides comprehensive information for use in workplace chemical management. Employers and workers use the SDS as a source of information about hazards and to obtain advice on safety precautions. The SDS is product related and, usually, is not able to provide information that is specific for any given workplace where the product may be used. However, the SDS information enables the employer to develop an active program of worker protection measures, including training, which is specific to the individual workplace, and to consider any measures that may be necessary to protect the environment. Information in an SDS also provides a source of information for those involved with the transport of dangerous goods, emergency responders, poison centers, those involved with the professional use of pesticides, and consumers.

The GHS and SDSs have 16 sections in a set order, and minimum information is prescribed.

The Hazard Communication Standard (HCS) requires chemical manufacturers, distributors, or importers to provide SDSs to communicate the hazards of hazardous chemical products. As of June 1, 2015, the HCS requires new SDSs to be in a uniform format, and include the section numbers, the headings, and associated information under the headings below:

Section 1, Identification: Includes product identifier; manufacturer or distributor name, address, phone number; emergency phone number; recommended use; restrictions on use

Section 2, Hazard(s) identification: Includes all hazards regarding the chemical; required label elements

Section 3, Composition/information on ingredients: Includes information on chemical ingredients; trade secret claims

Section 4, First-aid measures: Includes important symptoms/effects, acute, delayed; required treatment

Section 5, Fire-fighting measures: Lists suitable extinguishing techniques, equipment; chemical hazards from fire

Section 6, Accidental release measures: Lists emergency procedures; protective equipment; proper methods of containment and cleanup

Section 7, Handling and storage: Lists precautions for safe handling and storage, including incompatibilities

Section 8, Exposure controls/personal protection: Lists OSHA's Permissible Exposure Limits (PELs); Threshold Limit Values (TLVs); appropriate engineering controls; personal protective equipment (PPE)

Section 9, Physical and chemical properties: Lists the chemical's characteristics

Section 10, Stability and reactivity: Lists chemical stability and possibility of hazardous reactions

Section 11, Toxicological information: Includes routes of exposure; related symptoms, acute and chronic effects; numerical measures of toxicity

Section 12, Ecological information*

Section 13, Disposal considerations*

Section 14, Transport information*

Section 15, Regulatory information*

Section 16, Other information: Includes the date of preparation or last revision

*Note: Since other Agencies regulate this information, OSHA will not be enforcing Sections 12 through 15 (29 CFR 1910.1200(g)(2)).

A Guide to the Globally Harmonized System of Classification and Labelling of Chemicals (*GHS*), Washington, D.C.: U.S. Department of Labor, Occupational Health and Safety Administration, pp. 46–49.

Signal Words

The signal word found on every product's label is based on test results from various oral, dermal, and inhalation toxicity tests, as well as skin and eye corrosion assays in some cases. Signal words are placed on labels to convey a level of care that should be taken (especially personal protection) when handling and using a product, from purchase to disposal of the empty container, as demonstrated by the Pesticide Toxicity Table.

Pesticide Toxicity Categories

Signal Word on Label	Toxicity Category	Acute-Oral LD_{50} for Rats	Amount Needed to Kill an Average Size Adult	Notes
Danger–Poison	Highly Toxic	50 or less	Taste to a teaspoon	Skull and crossbones; Keep Out of Reach of Children
Warning	Moderately Toxic	50 to 500	One to six teaspoons	Keep Out of Reach of Children
Caution	Slightly Toxic	500 to 5,000	One ounce to a pint	Keep Out of Reach of Children
Caution	Relatively Nontoxic	>5,000	More than a pint	Keep Out of Reach of Children

Regulating Pesticides, Washington, D.C.: U.S. Environmental Protection Agency.

Flammability

Flammable describes any solid, liquid, vapor, or gas that will ignite easily and burn rapidly. A flammable liquid is defined by NFPA and USDOT as a liquid with a flash point below 100°F (38°C). Flammability is further defined with lower and upper limits:

LFL = lower flammability limit (volume % in air)

UFL = upper flammability limit (volume % in air)

A vapor-air mixture will only ignite and burn over the range of concentrations between LFL and UFL. Examples are:

Compound	LFL	UFL
Ethyl alcohol	3.3	19
Ethyl ether	1.9	36
Ethylene	2.7	36
Methane	5	15
Propane	2.1	9.5

Predicting Lower Flammable Limits of Mixtures of Flammable Gases (Le Chatelier's Rule)

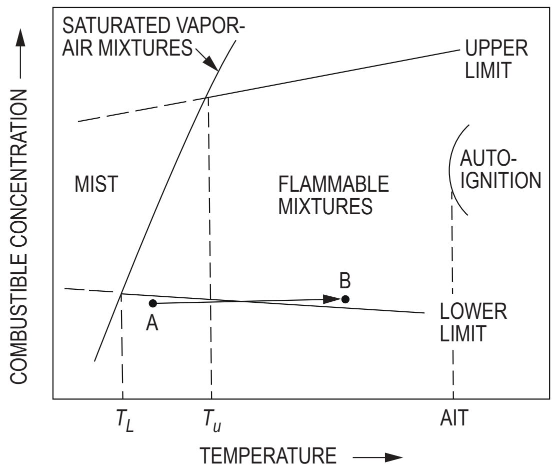
Based on an empirical rule developed by Le Chatelier, the lower flammable limit of mixtures of multiple flammable gases in air can be determined. A generalization of Le Chatelier's rule is

$$\sum_{i=1}^{n} \left(C_i/\mathrm{LFL}_i\right) \geq 1$$

where C_i is the volume percent of fuel gas, i, in the fuel/air mixture, and LFL_i is the volume percent of fuel gas, i, at its lower flammable limit in air alone. If the indicated sum is greater than unity, the mixture is above the lower flammable limit. This can be restated in terms of the lower flammable limit concentration of the fuel mixture, LFL_m, as follows:

$$\mathrm{LFL}_m = \frac{100}{\sum_{i=1}^{n} \left(C_{fi}/\mathrm{LFL}_i\right)}$$

where C_{fi} is the volume percent of fuel gas i in the fuel gas mixture.



DiNenno, Philip J., *The SFPE Handbook of Fire Protection Engineering,* 1st ed., Gaithersburg: Society of Fire Protection Engineers, 1988, p. 1-288.

Granular Storage and Process Safety

Some materials that are not inherently hazardous can become hazardous during storage or processing. An example is the handling of grain in grain bins. Grain bins should not be entered when the grain is being removed since grains flow to the center of the emptying bin and create suffocation hazards. Bridging may occur at the top surface due to condensation and resulting spoilage creating a crust.

Organic vapors and dusts associated with grain handling often contain toxic yeasts or molds and have low oxygen contents. These organic vapors and dusts may also be explosive.

Confined Space Safety

Many workplaces contain spaces that are considered "confined" because their configurations hinder the activities of employees who must enter, work in, and exit them. A confined space has limited or restricted means for entry or exit and is not designed for continuous employee occupancy. Confined spaces include, but are not limited to, underground vaults, tanks, storage bins, manholes, pits, silos, process vessels, and pipelines. OSHA uses the term "permit-required confined spaces" (permit space) to describe a confined space that has one or more of the following characteristics: contains or has the potential to contain a hazardous atmosphere; contains a material that has the potential to engulf an entrant; has walls that converge inward or floors that slope downward and taper into a smaller area that could trap or asphyxiate an entrant; or contains any other recognized safety or health hazard such as unguarded machinery, exposed live wires, or heat stress.

OSHA has developed standards, directives (instructions for compliance officers), standard interpretations (official letters of interpretation of the standards), and national consensus standards related to confined spaces. The following gases are often present in confined spaces:

Ammonia – irritating at 50 ppm and deadly above 1,000 ppm; sharp, cutting odor

Hydrogen sulfide – irritating at 10 ppm and deadly at 500 ppm; accumulates at lower levels and in corners where circulation is minimal; rotten egg odor

Methane – explosive at levels above 50,000 ppm, lighter than air, odorless

Carbon dioxide – heavier than air, accumulates at lower levels and in corners where circulation is minimal, displaces air, leading to asphyxiation

Electrical Safety

Current Level (Milliamperes)	Probable Effect on Human Body
1 mA	Perception level. Slight tingling sensation. Still dangerous under certain conditions.
5 mA	Slight shock felt; not painful but disturbing. Average individual can let go. However, strong involuntary reactions to shocks in this range may lead to injuries.
6 mA–16 mA	Painful shock, begin to lose muscular control. Commonly referred to as the freezing current or "let-go" range.
17 mA–99 mA	Extreme pain, respiratory arrest, severe muscular contractions. Individual cannot let go. Death is possible.
100 mA–2,000 mA	Ventricular fibrillation (uneven, uncoordinated pumping of the heart.) Muscular contraction and nerve damage begins to occur. Death is likely.
> 2,000 mA	Cardiac arrest, internal organ damage, and severe burns. Death is probable.

Greenwald, E.K., *Electrical Hazards and Accidents - Their Causes and Prevention*, New York: Wiley, 1991.

NIOSH Formula

Recommended Weight Limit (RWL)

$$\text{RWL} = 51(10/H)(1 - 0.0075|V - 30|)(0.82 + 1.8/D)(1 - 0.0032A)(FM)(CM)$$

RWL = recommended weight limit, in pounds

H = horizontal distance of the hand from the midpoint of the line joining the inner ankle bones to a point projected on the floor directly below the load center, in inches

V = vertical distance of the hands from the floor, in inches

D = vertical travel distance of the hands between the origin and destination of the lift, in inches

A = asymmetry angle, in degrees

FM = frequency multiplier (see table)

CM = coupling multiplier (see table)

Frequency Multiplier Table

<table>
<tr><th></th><th colspan="2">≤ 8 hr/day</th><th colspan="2">≤ 2 hr/day</th><th colspan="2">≤ 1 hr/day</th></tr>
<tr><th>F, min^{-1}</th><th>V< 30 in.</th><th>V ≥ 30 in.</th><th>V < 30 in.</th><th>V ≥ 30 in.</th><th>V < 30 in.</th><th>V ≥ 30 in.</th></tr>
<tr><td>0.2</td><td colspan="2">0.85</td><td colspan="2">0.95</td><td colspan="2">1.00</td></tr>
<tr><td>0.5</td><td colspan="2">0.81</td><td colspan="2">0.92</td><td colspan="2">0.97</td></tr>
<tr><td>1</td><td colspan="2">0.75</td><td colspan="2">0.88</td><td colspan="2">0.94</td></tr>
<tr><td>2</td><td colspan="2">0.65</td><td colspan="2">0.84</td><td colspan="2">0.91</td></tr>
<tr><td>3</td><td colspan="2">0.55</td><td colspan="2">0.79</td><td colspan="2">0.88</td></tr>
<tr><td>4</td><td colspan="2">0.45</td><td colspan="2">0.72</td><td colspan="2">0.84</td></tr>
<tr><td>5</td><td colspan="2">0.35</td><td colspan="2">0.60</td><td colspan="2">0.80</td></tr>
<tr><td>6</td><td colspan="2">0.27</td><td colspan="2">0.50</td><td colspan="2">0.75</td></tr>
<tr><td>7</td><td colspan="2">0.22</td><td colspan="2">0.42</td><td colspan="2">0.70</td></tr>
<tr><td>8</td><td colspan="2">0.18</td><td colspan="2">0.35</td><td colspan="2">0.60</td></tr>
<tr><td>9</td><td></td><td>0.15</td><td colspan="2">0.30</td><td colspan="2">0.52</td></tr>
<tr><td>10</td><td></td><td>0.13</td><td colspan="2">0.26</td><td colspan="2">0.45</td></tr>
<tr><td>11</td><td></td><td></td><td></td><td>0.23</td><td colspan="2">0.41</td></tr>
<tr><td>12</td><td></td><td></td><td></td><td>0.21</td><td colspan="2">0.37</td></tr>
<tr><td>13</td><td colspan="5">0.00</td><td>0.34</td></tr>
<tr><td>14</td><td colspan="5"></td><td>0.31</td></tr>
<tr><td>15</td><td colspan="5"></td><td>0.28</td></tr>
</table>

Waters, Thomas R., Vern Putz-Anderson, and Arun Garg, *Applications Manual for the Revised NIOSH Lifting Equation*, Cincinnati: U.S. Department of Health and Human Services, 1994, p. 26.

Coupling Multiplier (CM) Table
(Function of Coupling of Hands to Load)

<table>
<tr><td colspan="3">Container</td><td colspan="2">Loose Part / Irreg. Object</td></tr>
<tr><td colspan="2">Optimal Design</td><td>Not</td><td>Comfort Grip</td><td>Not</td></tr>
<tr><td>Opt. Handles
or Cut-outs</td><td>Not</td><td>POOR</td><td>GOOD</td><td></td></tr>
<tr><td rowspan="2">GOOD</td><td colspan="2">Flex Fingers 90 Degrees</td><td colspan="2">Not</td></tr>
<tr><td colspan="2">FAIR</td><td colspan="2">POOR</td></tr>
</table>

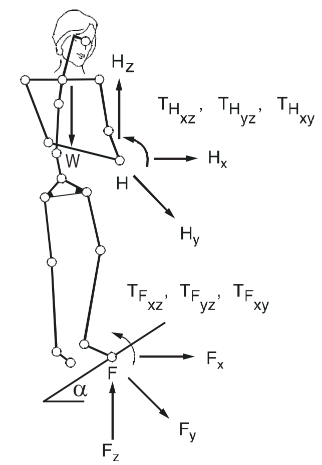
<table>
<tr><th>Coupling</th><th>V < 30 in. or 75 cm</th><th>V ≥ 30 in. or 75 cm</th></tr>
<tr><td>GOOD</td><td colspan="2">1.00</td></tr>
<tr><td>FAIR</td><td>0.95</td><td></td></tr>
<tr><td>POOR</td><td colspan="2">0.90</td></tr>
</table>

Waters, Thomas R., Vern Putz-Anderson, and Arun Garg, *Applications Manual for the Revised NIOSH Lifting Equation*, Cincinnati: U.S. Department of Health and Human Services, 1994, p. 31.

Biomechanics of the Human Body

Basic Equations

$H_x + F_x = 0$
$H_y + F_y = 0$
$H_z + W + F_z = 0$
$T_{Hxz} + T_{Wxz} + T_{Fxz} = 0$
$T_{Hyz} + T_{Wyz} + T_{Fyz} = 0$
$T_{Hxy} + T_{Fxy} = 0$



The coefficient of friction μ and the angle α at which the floor is inclined determine the equations at the foot.

$$F_x = \mu F_z$$

With the slope angle α,

$$F_x = \mu F_z \cos \alpha$$

Of course, when motion must be considered, dynamic conditions come into play according to Newton's Second Law. Force transmitted with the hands is counteracted at the foot. Further, the body must also react with internal forces at all points between the hand and the foot.

Incidence Rates

Two concepts can be important when completing OSHA forms. These concepts are *incidence rates* and *severity rates*.
On occasion it is necessary to calculate the total injury/illness incident rate of an organization in order to complete OSHA forms. This calculation must include fatalities and all injuries requiring medical treatment beyond mere first aid. The formula for determining the total injury/illness incident rate is as follows:

$$IR = N \times 200{,}000 \div T$$

IR = Total injury/illness incidence rate

N = Number of injuries, illnesses, and fatalities

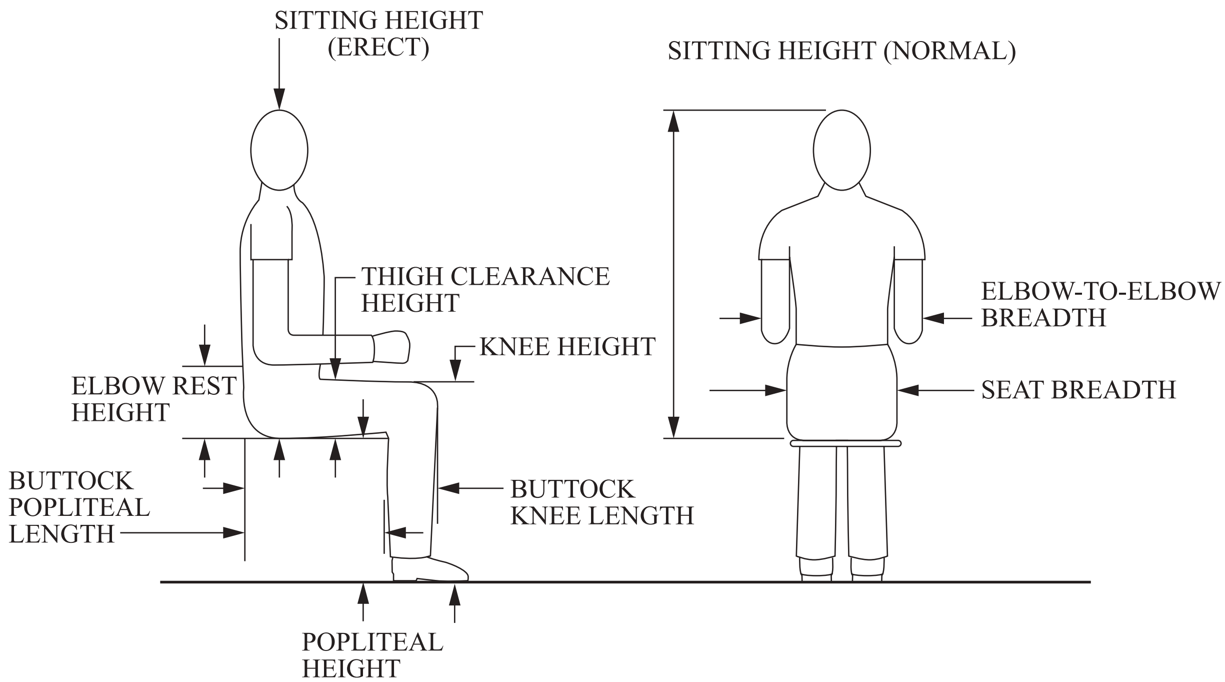
T = Total hours worked by all employees during the period in question

The number 200,000 in the formula represents the number of hours 100 employees work in a year (40 hours per week × 50 weeks = 2,000 hours per year per employee). Using the same basic formula with only minor substitutions, safety managers can calculate the following types of incidence rates:

1. Injury rate
2. Illness rate
3. Fatality rate

4. Lost workday cases rate
5. Number of lost workdays rate
6. Specific hazard rate
7. Lost workday injuries rate

Anthropometric Measurements



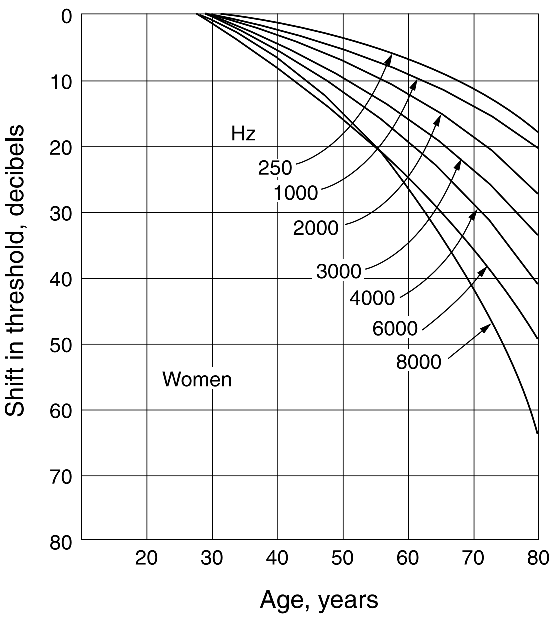
After Sanders, Mark S., and Ernest J. McCormick, *Human Factors In Engineering and Design*, New York: McGraw-Hill, 1993.

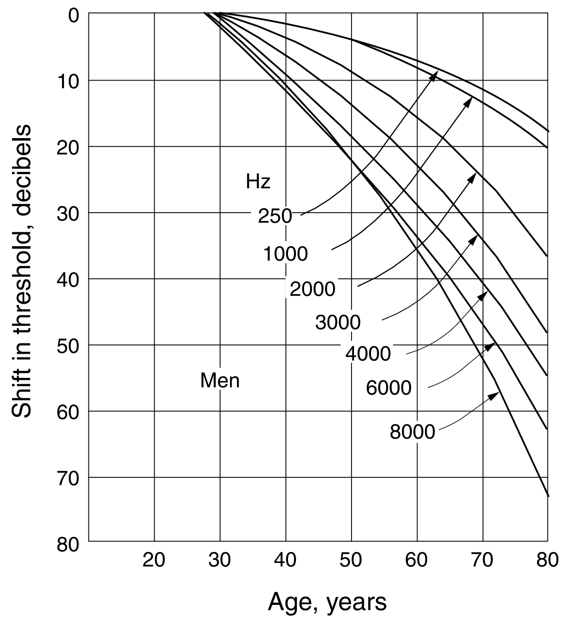
U.S. Civilian Body Dimensions, Female/Male, for Ages 20 to 60 Years (Centimeters)				
(See Anthropometric Measurements Figure)	Percentiles			
	5th	50th	95th	Std. Dev.
HEIGHTS				
Stature (height)	149.5 / 161.8	160.5 / 173.6	171.3 / 184.4	6.6 / 6.9
Eye height	138.3 / 151.1	148.9 / 162.4	159.3 / 172.7	6.4 / 6.6
Shoulder (acromion) height	121.1 / 132.3	131.1 / 142.8	141.9 / 152.4	6.1 / 6.1
Elbow height	93.6 / 100.0	101.2 / 109.9	108.8 / 119.0	4.6 / 5.8
Knuckle height	**64.3 / 69.8**	**70.2 / 75.4**	**75.9 / 80.4**	**3.5 / 3.2**
Height, sitting (erect)	78.6 / 84.2	85.0 / 90.6	90.7 / 96.7	3.5 / 3.7
Eye height, sitting	67.5 / 72.6	73.3 / 78.6	78.5 / 84.4	3.3 / 3.6
Shoulder height, sitting	49.2 / 52.7	55.7 / 59.4	61.7 / 65.8	3.8 / 4.0
Elbow rest height, sitting	18.1 / 19.0	23.3 / 24.3	28.1 / 29.4	2.9 / 3.0
Knee height, sitting	**45.2 / 49.3**	**49.8 / 54.3**	**54.5 / 59.3**	**2.7 / 2.9**
Popliteal height, sitting	35.5 / 39.2	39.8 / 44.2	44.3 / 48.8	2.6 / 2.8
Thigh clearance height	10.6 / 11.4	13.7 / 14.4	17.5 / 17.7	1.8 / 1.7
DEPTHS				
Chest depth	21.4 / 21.4	24.2 / 24.2	29.7 / 27.6	2.5 / 1.9
Elbow-fingertip distance	38.5 / 44.1	42.1 / 47.9	46.0 / 51.4	2.2 / 2.2
Buttock-knee length, sitting	51.8 / 54.0	56.9 / 59.4	62.5 / 64.2	3.1 / 3.0
Buttock-popliteal length, sitting	43.0 / 44.2	48.1 / 49.5	53.5 / 54.8	3.1 / 3.0
Forward reach, functional	64.0 / 76.3	71.0 / 82.5	79.0 / 88.3	4.5 / 5.0
BREADTHS				
Elbow-to-elbow breadth	31.5 / 35.0	38.4 / 41.7	49.1 / 50.6	5.4 / 4.6
Seat (hip) breadth, sitting	31.2 / 30.8	36.4 / 35.4	43.7 / 40.6	3.7 / 2.8
HEAD DIMENSIONS				
Head breadth	13.6 / 14.4	14.54 / 15.42	15.5 / 16.4	0.57 / 0.59
Head circumference	52.3 / 53.8	54.9 / 56.8	57.7 / 59.3	1.63 / 1.68
Interpupillary distance	5.1 / 5.5	5.83 / 6.20	6.5 / 6.8	0.4 / 0.39
HAND DIMENSIONS				
Hand length	16.4 / 17.6	17.95 / 19.05	19.8 / 20.6	1.04 / 0.93
Breadth, metacarpal	7.0 / 8.2	7.66 / 8.88	8.4 / 9.8	0.41 / 0.47
Circumference, metacarpal	16.9 / 19.9	18.36 / 21.55	19.9 / 23.5	0.89 / 1.09
Thickness, metacarpal III	2.5 / 2.4	2.77 / 2.76	3.1 / 3.1	0.18 / 0.21
Digit 1				
Breadth, interphalangeal	1.7 / 2.1	1.98 / 2.29	2.1 / 2.5	0.12 / 0.13
Crotch-tip length	4.7 / 5.1	5.36 / 5.88	6.1 / 6.6	0.44 / 0.45
Digit 2				
Breadth, distal joint	1.4 / 1.7	1.55 / 1.85	1.7 / 2.0	0.10 / 0.12
Crotch-tip length	6.1 / 6.8	6.88 / 7.52	7.8 / 8.2	0.52 / 0.46
Digit 3				
Breadth, distal joint	1.4 / 1.7	1.53 / 1.85	1.7 / 2.0	0.09 / 0.12
Crotch-tip length	7.0 / 7.8	7.77 / 8.53	8.7 / 9.5	0.51 / 0.51
Digit 4				
Breadth, distal joint	1.3 / 1.6	1.42 / 1.70	1.6 / 1.9	0.09 / 0.11
Crotch-tip length	6.5 / 7.4	7.29 / 7.99	8.2 / 8.9	0.53 / 0.47
Digit 5				
Breadth, distal joint	1.2 / 1.4	1.32 / 1.57	1.5 / 1.8	0.09/0.12
Crotch-tip length	4.8 / 5.4	5.44 / 6.08	6.2 / 6.99	0.44/0.47
FOOT DIMENSIONS				
Foot length	22.3 / 24.8	24.1 / 26.9	26.2 / 29.0	1.19 / 1.28
Foot breadth	8.1 / 9.0	8.84 / 9.79	9.7 / 10.7	0.50 / 0.53
Lateral malleolus height	5.8 / 6.2	6.78 / 7.03	7.8 / 8.0	0.59 / 0.54
Weight (kg)	46.2 / 56.2	61.1 / 74.0	89.9 / 97.1	13.8 / 12.6

Kroemer, Karl H. E., "Engineering Anthropometry," *Ergonomics*, Vol. 32, No. 7, pp. 779–780, 1989, Taylor and Francis, Ltd.

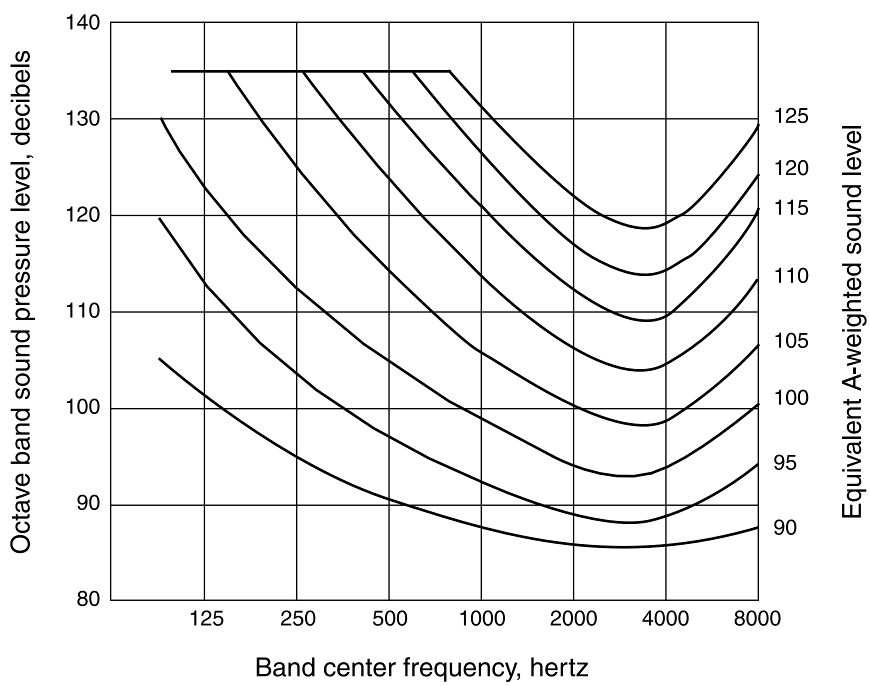
Hearing

The average shifts with age of the threshold of hearing for pure tones of persons with "normal" hearing, using a 25-year-old group as a reference group.

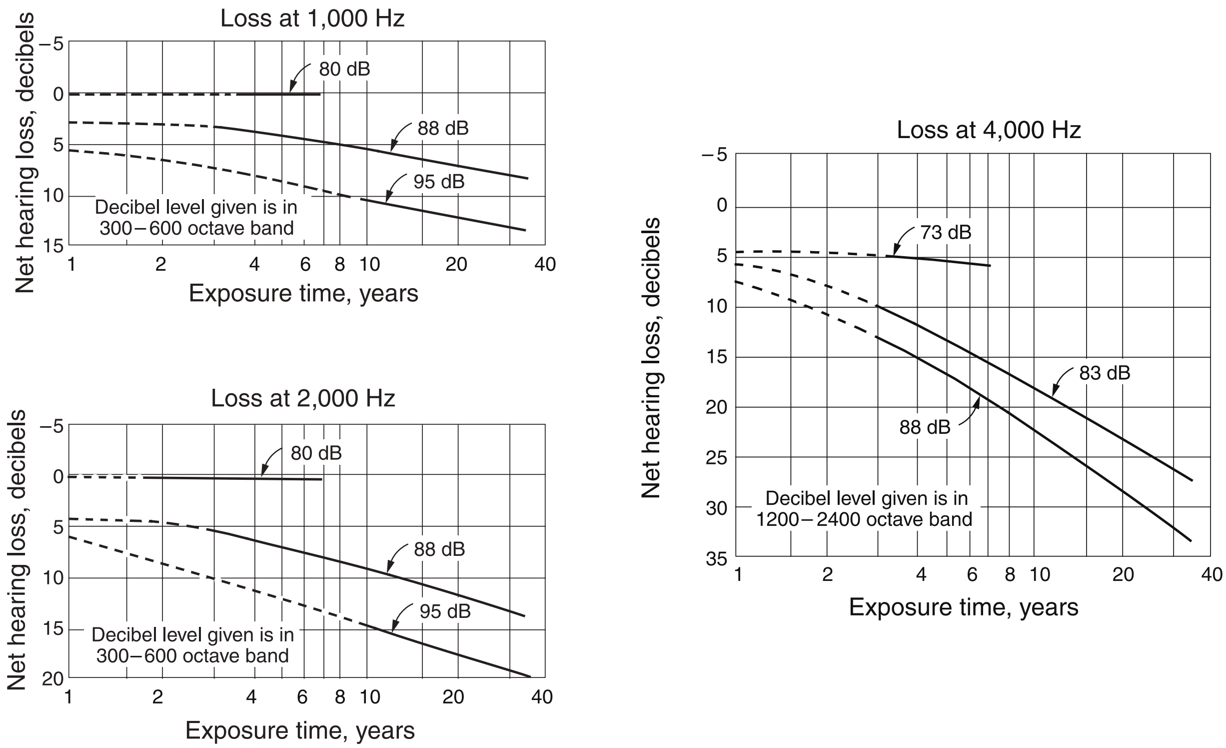




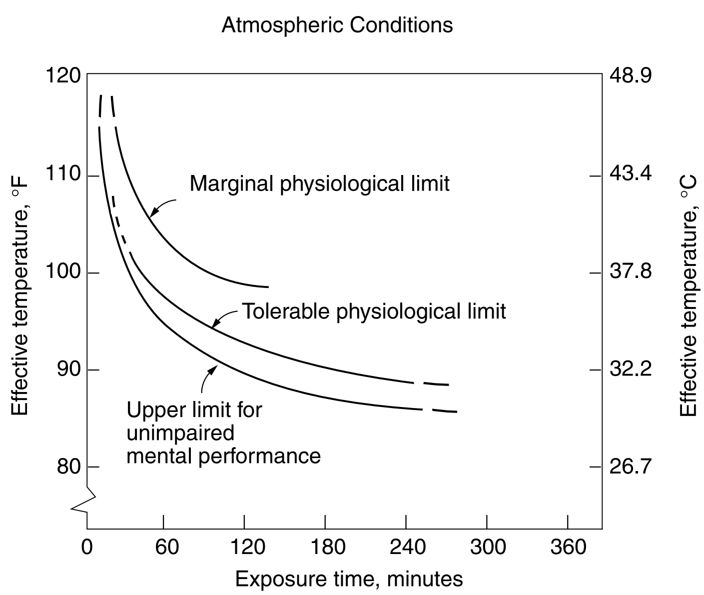
Equivalent sound-level contours used in determining the A-weighted sound level on the basis of an octave-band analysis are shown. The curve at the point of the highest penetration of the noise spectrum reflects the A-weighted sound level.



Estimated average trend curves for net hearing loss at 1,000, 2,000, and 4,000 Hz after continuous exposure to steady noise are shown. Data are corrected for age, but not for temporary threshold shift. Dotted portions of curves represent extrapolation from available data.



Tentative upper limit of effective temperature (ET) for unimpaired mental performance as related to exposure time are shown; data are based on an analysis of 15 studies. Comparative curves of tolerable and marginal physiological limits are also given.



Effective temperature (ET) is the dry bulb temperature at 50% relative humidity, which results in the same physiological effect as the present conditions.

Security

Security at chemical facilities is covered by the U.S. Department of Homeland Security, which has established risk-based performance standards. A performance standard specifies the outcome required, but leaves the specific measures to achieve that outcome up to the discretion of the regulated entity.

Risk-based performance standards include restrict area perimeter; secure site assets; screen and control access; deter, detect, and delay; shipping, receipt, and storage; theft and diversion; sabotage; cyber; response; monitoring; training; personnel safety; elevated threats; specific threats, vulnerabilities, or risks; reporting of significant security incidents; significant security incidents and suspicious activities; officials and organization; and records.

The goal is to protect critical assets, which are defined as assets whose theft, loss, damage, disruption, or degradation would result in significant adverse impacts to human life or health, national security, or critical economic assets.

High-risk facilities are those that possess, in specified quantities, these types of chemicals:

- Chemicals with the potential to create a toxic cloud or vapor cloud explosion that would affect populations within and beyond the facility if intentionally released
- Chemicals with the potential to affect populations within or beyond the facility if intentionally detonated
- Chemicals that could be stolen or diverted and used in explosives or improvised explosive devices
- Chemicals that could be stolen or diverted and used directly as chemical weapons or weapons of mass effect or could be easily converted to chemical weapons
- Possession of chemicals that, if mixed with other readily available materials, have potential to create significant adverse consequences for human life or health

Risk-Based Performance Standards Guidance: Chemical Facility Anti-Terrorism Standards, Washington, D.C.: U.S. Department of Homeland Security, 2009, pp. 17–18.

Incident Response Procedures

The purpose of the incident command system is to provide a common, flexible but standardized, approach for managing incidents.

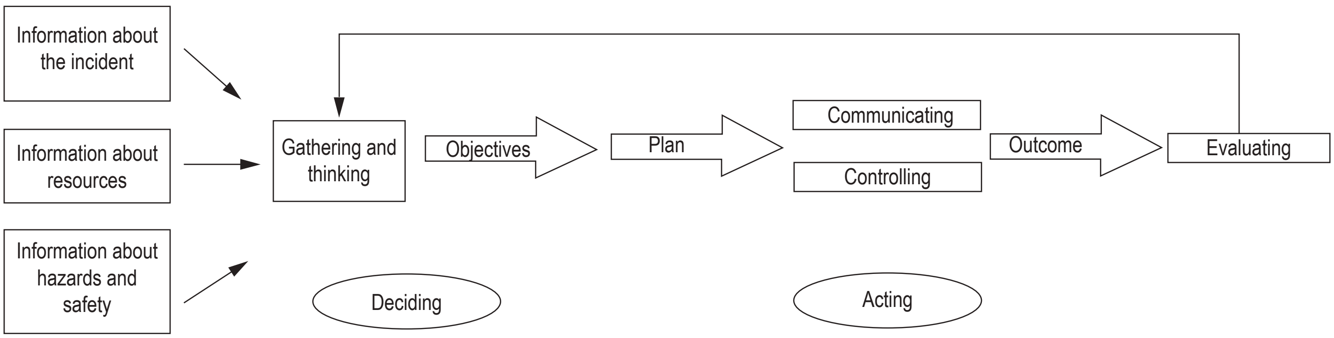
Incidents typically begin and end locally, and they are managed daily at the lowest possible geographical, organizational, and jurisdictional levels. A comprehensive national approach improves the effectiveness of emergency management and response personnel across the full spectrum of potential threats and hazards (including natural hazards, terrorist activities, and other human-caused disasters) regardless of size or complexity.

Steps to a Safe Response

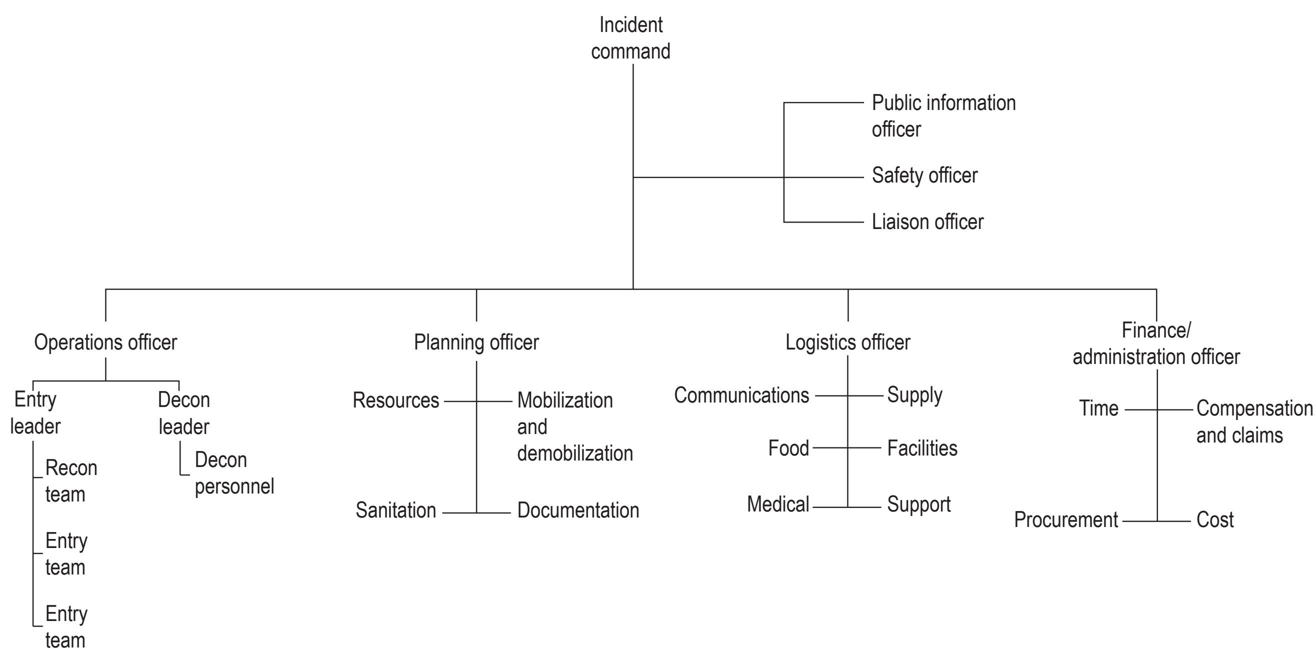
1. Clear area and check for injuries.
2. Report the incident/request help.
3. Secure the area.
4. Indentify the material/threat.
5. Identify the hazards.
6. Select the proper equipment.
7. Develop a response plan.
8. Contain and control the release.
9. Clean up the release.
10. Decontaminate personnel and equipment.

National Incident Management System, Washington, D.C.: Federal Emergency Management Agency.

Incident Command Model



Incident Command Structure

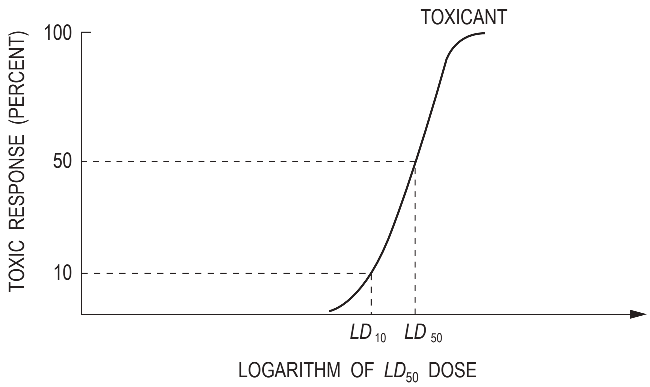


Span of control: A supervisor should be responsible for between three and seven subordinates.

Exposure Assessments

Dose-Response Curves

The dose-response curve relates toxic response (i.e., percentage of test population exhibiting a specified symptom or dying) to the logarithm of the dosage [i.e., mg/(kg•day) ingested]. A typical dose-response curve is shown below.



LC_{50}
Median lethal concentration in air that, based on laboratory tests, is expected to kill 50% of a group of test animals when administered as a single exposure over one or four hours.

LD_{50}
Median lethal single dose, based on laboratory tests, expected to kill 50% of a group of test animals, usually by oral or skin exposure.

Similar definitions exist for LC_{10} and LD_{10}, where the corresponding percentages are 10%.

The following table lists the probable effect on the human body of different current levels.

Comparative Acutely Lethal Doses

Actual Ranking No.	LD_{50} (mg/kg)	Toxic Chemical
1	15,000	PCBs
2	10,000	Alcohol (ethanol)
3	4,000	Table salt—sodium chloride
4	1,500	Ferrous sulfate—an iron supplement
5	1,375	Malathion—pesticide
6	900	Morphine
7	150	Phenobarbital—a sedative
8	142	Tylenol (acetaminophen)
9	2	Strychnine—a rat poison
10	1	Nicotine
11	0.5	Curare—an arrow poison
12	0.001	2,3,7,8-TCDD (dioxin)
13	0.00001	Botulinum toxin (food poison)

Loomis, T.A., and A.W. Hayes, *Loomis's Essentials of Toxicology*, 4th ed., San Diego: Academic Press, 1996.

Selected Chemical Interaction Effects

Effect	Relative toxicity (hypothetical)	Example
Additive	2 + 3 = 5	Organophosphate pesticides
Synergistic	2 + 3 = 20	Cigarette smoking + asbestos
Antagonistic	6 + 6 = 8	Toluene + benzene or caffeine + alcohol

EPA/630/R-00/002: Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures, Washington, D.C.: U.S. Environmental Protection Agency, 2000, pp. B-3–B-4.

Exposure Limits for Selected Compounds

N	Allowable Workplace Exposure Level (mg/m^3)	Chemical (use)
1	0.1	Iodine
2	5	Aspirin
3	10	Vegetable oil mists (cooking oil)
4	55	1,1,2-Trichloroethane (solvent/degreaser)
5	188	Perchloroethylene (dry-cleaning fluid)
6	170	Toluene (organic solvent)
7	269	Trichloroethylene (solvent/degreaser)
8	590	Tetrahydrofuran (organic solvent)
9	890	Gasoline (fuel)
10	1,590	Naphtha (rubber solvent)
11	1,910	1,1,1-Trichloroethane (solvent/degreaser)

American Conference of Government Industrial Hygienists (ACGIH), 1996.

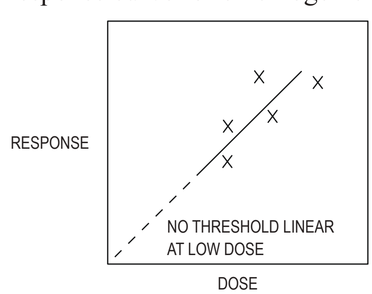
Carcinogens

For carcinogens, EPA considers an acceptable risk to be within the range of 10^{-4} to 10^{-6}. The added risk of cancer is calculated as follows:

$$\text{Risk} = \text{dose} \times \text{toxicity} = \text{CDI} \times \text{CSF}$$

CDI = Chronic Daily Intake

CSF = Cancer Slope Factor. Slope of the dose-response curve for carcinogenic materials.



CARCINOGENIC DOSE RESPONSE CURVE

Threshold Value

TLV is the highest dose (ppm by volume in the atmosphere) the body is able to detoxify without any detectable effects.

Examples are the ACGIH Threshold Limit Values (TLV):

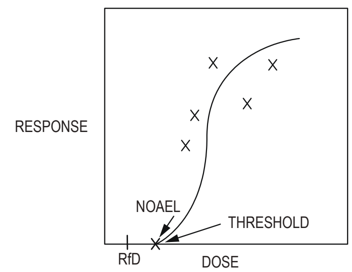
Compound	TLV
Ammonia	25
Chlorine	0.5
Ethyl Chloride	1,000
Ethyl Ether	400

Noncarcinogens

For noncarcinogens, a hazard index (*HI*) is used to characterize risk from all pathways and exposure routes. EPA considers an $HI > 1.0$ as representing the possibility of an adverse effect occurring.

$HI = CDI_{\text{noncarcinogen}}/RfD$

$CDI_{\text{noncarcinogen}}$ = chronic daily intake of noncarcinogenic compound



NONCARCINOGENIC DOSE RESPONSE CURVE

Dose is expressed

$$\left(\frac{\text{mass of chemical}}{\text{body weight} \cdot \text{exposure time}}\right)$$

NOAEL = No Observable Adverse Effect Level. The dose below which there are no harmful effects

LOAEL = Lowest Observed Adverse Effect Level

Reference Dose

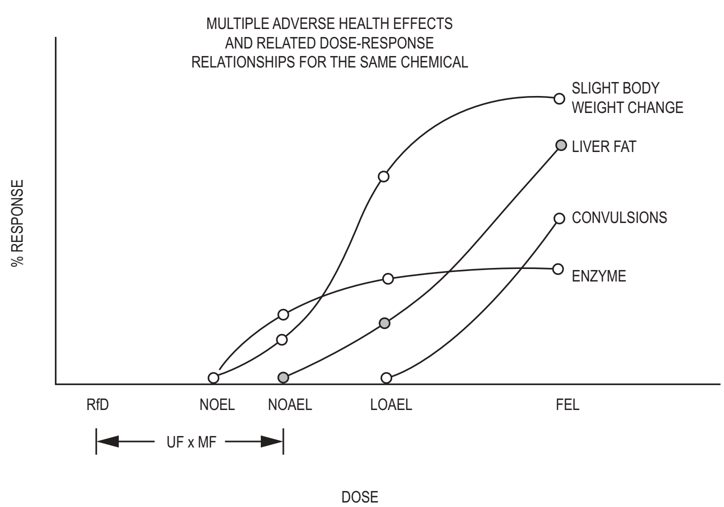
Reference dose (*RfD*) is determined from the Noncarcinogenic Dose-Response Curve using *NOAEL*.

RfD = lifetime (i.e., chronic) dose that a healthy person could be exposed to daily without adverse effects

$$RfD = \frac{NOAEL}{MF \times UF} \qquad RfD = \frac{LOAEL}{UF \times MF}$$

and

$$SHD = RfD \times W = \frac{NOAEL \times W}{UF}$$



SHD = safe human dose (mg/day)

NOAEL = threshold dose per kg of test animal [mg/(kg•day)] from the dose-response curve

UF = total uncertainty factor, depending on nature and reliability of the animal test data

W = bodyweight of an adult male (kg)

MF = total modifying factor for NOAEL or LOAEL

DWEL = drinking water equivalent level

Q = daily water consumption (L/day)

$$DWEL = \frac{RfD \cdot W}{Q}$$

Saxena, Jitendra, ed., *Hazard Assessment of Chemicals*, Washington, D.C.: Taylor and Francis, 1993, p. 83.

Exposure

Residential Exposure Equations for Various Pathways

Ingestion in drinking water

$$CDI = \frac{(CW)(IR)(EF)(ED)}{(BW)(AT)}$$

Ingestion while swimming

$$CDI = \frac{(CW)(CR)(ET)(EF)(ED)}{(BW)(AT)}$$

Dermal contact with water

$$AD = \frac{(CW)(SA)(PC)(ET)(EF)(ED)(CF)}{(BW)(AT)}$$

Ingestion of chemicals in soil

$$CDI = \frac{(CS)(IR)(CF)(FI)(EF)(ED)}{(BW)(AT)}$$

Dermal contact with soil

$$AD = \frac{(CS)(CF)(SA)(AF)(ABS)(EF)(ED)}{(BW)(AT)}$$

Inhalation of airborne (vapor phase) chemicals

$$CDI = \frac{(CA)(IR)(ET)(EF)(ED)}{(BW)(AT)}$$

Ingestion of contaminated fruits, vegetables, fish and shellfish

$$CDI = \frac{(CF)(IR)(FI)(EF)(ED)}{(BW)(AT)}$$

$$CW = \frac{BW \times LRF}{CSF(IR + FI \times BCF)}$$

where ABS = absorption factor for soil contaminant (unitless)

AD = absorbed dose (mg/[kg•day])

AF = soil-to-skin adherence factor (mg/cm^2)

AT = averaging time (days)

BW = body weight (kg)

CA = contaminant concentration in air (mg/m^3)

CDI = chronic daily intake (mg/[kg•day])

CF = volumetric conversion factor for water = 1 L/1,000 cm^3

= conversion factor for soil = 10^{-6} kg/mg

CR = contact rate (L/hr)

CS = chemical concentration in soil (mg/kg)

CW = chemical concentration in water (mg/L)

ED = exposure duration (years)

EF = exposure frequency (days/yr or events/year)

ET = exposure time (hr/day or hr/event)

FI = fraction ingested (unitless)

IR = ingestion rate (L/day or mg soil/day or kg/meal)

= inhalation rate (m^3/hr)

PC = chemical-specific dermal permeability constant (cm/hr)

SA = skin surface area available for contact (cm^2)

LRF = excess risk factor (unitless)

CSF = cancer slope factor $[mg/(kg•day)]^{-1}$

BCF = bioconcentration factor (L/kg)

Office of Emergency and Remedial Response, *EPA/540/1-89/002: Risk Assessment Guidance for Superfund,* vol. 1, Washington, D.C.: U.S. Environmental Protection Agency, 1989.

Time-Weighted Average (TWA)

$$TWA = \frac{\sum_{i=1}^{n} c_i t_i}{\sum_{i=1}^{n} t_i}$$

c_i = concentration during *ith* interval

t_i = duration of *ith* interval

Intake Rates

EPA Recommended Values for Estimating Intake

Parameter	Standard Value
Average body weight, female adult	65.4 kg
Average body weight, male adult	78 kg
Average body weight, child[a]	
6-11 months	9 kg
1-5 years	16 kg
6-12 years	33 kg
Amount of water ingested, adult	2.3 L/day
Amount of water ingested, child	1.5 L/day
Amount of air breathed, female adult	11.3 m^3/day
Amount of air breathed, male adult	15.2 m^3/day
Amount of air breathed, child (3-5 years)	8.3 m^3/day
Amount of fish consumed, adult	6 g/day
Water swallowing rate, while swimming	50 mL/hr
Inhalation rates	
adult (6-hr day)	0.98 m^3/hr
adult (2-hr day)	1.47 m^3/hr
child	0.46 m^3/hr
Skin surface available, adult male	1.94 m^2
Skin surface available, adult female	1.69 m^2
Skin surface available, child	
3–6 years (average for male and female)	0.720 m^2
6–9 years (average for male and female)	0.925 m^2
9–12 years (average for male and female)	1.16 m^2
12–15 years (average for male and female)	1.49 m^2
15–18 years (female)	1.60 m^2
15–18 years (male)	1.75 m^2
Soil ingestion rate, child 1–6 years	>100 mg/day
Soil ingestion rate, persons > 6 years	50 mg/day
Skin adherence factor, gardener's hands	0.07 mg/cm^2
Skin adherence factor, wet soil	0.2 mg/cm^2
Exposure duration	
Lifetime (carcinogens, for noncarcinogens use actual exposure duration)	75 years
At one residence, 90th percentile	30 years
National median	5 years
Averaging time	(ED)(365 days/year)
Exposure frequency (EF)	
Swimming	7 days/year
Eating fish and shellfish	48 days/year
Oral ingestion	350 days/year
Exposure time (ET)	
Shower, 90th percentile	12 min
Shower, 50th percentile	7 min

[a] Data in this category taken from: Copeland, T., A. M. Holbrow, J. M. Otan, et al., "Use of probabilistic methods to understand the conservatism in California's approach to assessing health risks posed by air contaminants," *Journal of the Air and Waste Management Association,* vol. 44, pp. 1399–1413, 1994.

Office of Emergency and Remedial Response, *EPA/540/1-89/002: Risk Assessment Guidance for Superfund,* vol. 1, Washington, D.C.: U.S. Environmental Protection Agency, 1989.

Concentrations of Vaporized Liquids

Vaporization Rate (Q_m, mass/time) from a Liquid Surface

$$Q_m = [MKA_S P^{sat}/(R_g T_L)]$$

M = molecular weight of volatile substance

K = mass-transfer coefficient

A_S = area of liquid surface

P^{sat} = saturation vapor pressure of the pure liquid at T_L

R_g = ideal gas constant

T_L = absolute temperature of the liquid

Mass Flow Rate of Liquid from a Hole in the Wall of a Process Unit

$$Q_m = A_H C_0 (2\rho g_c P_g)^{1/2}$$

A_H = area of hole

C_0 = discharge coefficient

ρ = density of the liquid

g_c = gravitational constant

P_g = gauge pressure within the process unit

Concentration (C_{ppm}) of Vaporized Liquid in Ventilated Space

$$C_{ppm} = [Q_m R_g T \times 10^6/(kQ_V PM)]$$

T = absolute ambient temperature

k = non-ideal mixing factor

Q_V = ventilation rate

P = absolute ambient pressure

Sweep-Through Concentration Change in a Vessel

$$Q_V t = V \ln[(C_1 - C_0)/(C_2 - C_0)]$$

Q_V = volumetric flow rate

t = time

V = vessel volume

C_0 = inlet concentration

C_1 = initial concentration

C_2 = final concentration

Radiation Protection/Health Physics

Effective Half-Life

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

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

τ_r = radioactive half-life

τ_b = biological half-life

Shielding

$$I = I_0 e^{-\mu X}$$

$$I = I_0 B e^{-\mu X}$$

I = resulting intensity

I_0 = initial intensity

μ = attenuation coefficient

X = thickness

B = buildup

Half-Life (Radioactive Decay)

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

$$N = N_0\,(0.5)^{t/\tau}$$

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 assuming a first-order rate constant is given by:

$$\tau = \frac{0.693}{\lambda}$$

λ = rate constant (time^{-1})

τ = half-life (time)

Daughter Product Activity

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

$\lambda_{1,\,2}$ = 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

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

$I_{1,\,2}$ = radiation intensity at Locations l and 2

$R_{1,\,2}$ = distance from the source at Locations l and 2

Activity

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/s}$$
$$1 \text{ Bq} = 1 \text{ decay/s}$$

Ci = curie

Bq = becquerel

Number of nuclei in a sample N

$$N = \frac{mL}{M}$$

m = mass of source

M = molar mass

L = Avogadro's number = 6.02×10^{23} particles

Since N is directly proportional to the activity A and mass M:

Activity can be expressed: $A = A_0 e^{-\lambda t}$

Mass can be expressed: $m = m_0 e^{-\lambda t}$

Noise Pollution

$$\text{SPL (dB)} = 10 \log_{10}\left(P^2 / P_0^2\right)$$

$$\text{SPL}_{\text{total}} = 10 \log_{10} \Sigma 10^{\text{SPL}/10}$$

Point Source Attenuation

$$\Delta \text{ SPL (dB)} = 10 \log_{10} (r_1/r_2)^2$$

Line Source Attenuation

$$\Delta \text{ SPL (dB)} = 10 \log_{10} (r_1/r_2)$$

SPL (dB) = sound pressure level, measured in decibels

P = sound pressure (Pa)

P_0 = reference sound pressure (2×10^{-5} Pa)

$\text{SPL}_{\text{total}}$ = sum of multiple sources

Δ SPL (dB) = change in sound pressure level with distance, measured in decibels

r_1 = distance from source to receptor at Point 1

r_2 = distance from source to receptor at Point 2

Noise dose D should not exceed 100%.

$$D = 100\% \times \Sigma \frac{C_i}{T_i}$$

C_i = time spent at specified SPL (hours)

T_i = time permitted at SPL (hours)

$\sum C_i$ = 8 (hours)

Noise Level (dBA)	Permissible Time (hr)
80	32
85	16
90	8
95	4
100	2
105	1
110	0.5
115	0.25
120	0.125
125	0.063
130	0.031

If $D > 100\%$, noise abatement required.

If $50\% \le D \le 100\%$, hearing conservation program required.

Note: $D = 100\%$ is equivalent to 90 dBA time-weighted average (TWA). $D = 50\%$ equivalent to TWA of 85 dBA.

Hearing conservation program requires: (1) testing employee hearing, (2) providing hearing protection at employee's request, and (3) monitoring noise exposure.

Exposure to impulsive or impact noise should not exceed 140 dB sound pressure level (SPL).

TWA Noise Level

$$\text{TWA} \cong 90 + 16.61\left(\log_{10}\frac{D}{100}\right)$$

TWA in dBA

D = percentage dose

E_m = mixed exposure

$$E_m = \sum_{i=1}^{n} \frac{c_i}{t_i}$$

Heat Stress

Wet-Bulb Globe Temperature (WBGT)

$$\text{Average WBGT} = (\text{WBGT}_1)(t_1) + (\text{WBGT}_2)(t_2) + ... + (\text{WBGT}_n)(t_n) / [(t_1) + (t_2) + ...(t_n)]$$

For indoor and outdoor conditions with no solar load, WBGT is calculated as:

$$\text{WBGT} = 0.7\text{NWB} + 0.3\text{GT}$$

For outdoors with a solar load, WBGT is calculated as

$$\text{WBGT} = 0.7\text{NWB} + 0.2\text{GT} + 0.1\text{DB}$$

WBGT = Wet-Bulb Globe Temperature Index

NWB = Natural Wet-Bulb Temperature

DB = Dry-Bulb Temperature

GT = Globe Temperature

OSHA-Permissible Heat Exposure Threshold Limit Value

	------------ Work Load* ------------		
Work/rest regimen	**Light**	**Moderate**	**Heavy**
Continuous work	30.0°C (86°F)	26.7°C (80°F)	25.0°C (77°F)
75% Work, 25% rest, each hour	30.6°C (87°F)	28.0°C (82°F)	25.9°C (78°F)
50% Work, 50% rest, each hour	31.4°C (89°F)	29.4°C (85°F)	27.9°C (82°F)
25% Work, 75% rest, each hour	32.2°C (90°F)	31.1°C (88°F)	30.0°C (86°F)

These TLV's are based on the assumption that nearly all acclimatized, fully clothed workers with adequate water and salt intake should be able to function effectively under the given working conditions without exceeding a deep body temperature of 38°C (100.4°F). They are also based on the assumption that the WBGT of the resting place is the same or very close to that of the workplace. Where the WBGT of the work area is different from that of the rest area, a time-weighted average should be used (consult the ACGIH *1992–1993 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*, 1992).

These TLVs apply to physically fit and acclimatized individuals wearing light summer clothing. If heavier clothing that impedes sweat or has a higher insulation value is required, the permissible heat exposure TLVs must be reduced by the clothing corrections shown below.

OSHA WBGT Correction Factors in °C

Clothing type	Clo* value	WBGT correction
Summer lightweight working clothing	0.6	0
Cotton coveralls	1.0	–2
Winter work clothing	1.4	–4
Water barrier, permeable	1.2	–6

* Clo: insulation value of clothing. One clo = 5.55 kcal/m^2/hr of heat exchange by radiation and convention for each degree C difference in temp between the skin and the adjusted dry bulb temp.

1992–1993 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices, Cincinnati: American Conference of Governmental Industrial Hygienists, 1992, as published in *OSHA Technical Manual*: Section III, Chapter 4, osha.gov/dts/osta/otm.

$$WBGT_{eff} = \text{WBGT measured} + \text{Clothing Adjustment Factor (CAF)}$$

Heat Stress Index

$$HSI = E_{req}/E_{max} * 100$$

E_{req} = Metabolic ± Convective + Radiant required BTUs heat loss/hour, if > 0

E_{max} = evaporation rate < 2,400 BTU /hr sweat rate equivalent to 1 liter water/hr

Metabolic

Work-load category is determined by averaging metabolic rates for the tasks and then ranking them:

1. Light work: up to 200 kcal/hour
2. Medium work: 200–350 kcal/hour
3. Heavy work: 350–500 kcal/hour

Convective

$$C = 0.65\, V_{air}^{0.6}\, (t_{air} - 95°)$$

C = convective heat load (BTU/hour)

V = air velocity (ft/minute)

t_{air} = dry bulb temperature (°F)

Radiant

$$R = 15\,(t_w - 95°)$$

R = radiant heat load (BTU/hour)

t_w = mean radiant temperature (°F)

HSI Values

10–30 moderate

40–60 severe

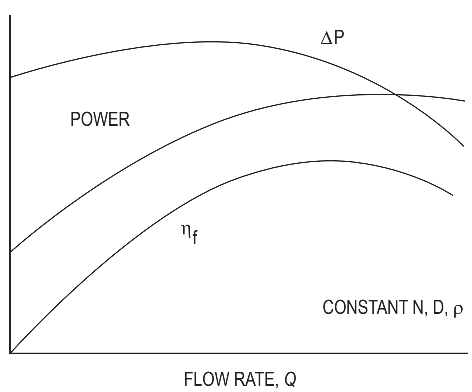
70–90 very severe

Body Heat Storage, S

$$S = E_{req} - E_{max} \text{ (BTU/hr)}$$

Ventilation

Fan Characteristics



Typical Backward Curved Fans

$$\dot{W} = \frac{\Delta P Q}{\eta_f}$$

$\dot{W}$ = fan power

ΔP = pressure rise

η_f = fan efficiency

Air Horsepower (ahp)

Assuming 100% efficiency, air horsepower (ahp) is the power required to move a given air volume against a given pressure. AHP can be expressed as

$$P_{ahp} = q\, dp_{inWG} SG/6{,}356 \qquad (1)$$

P_{ahp} = air horsepower (hp)
q = air flow (cfm)
SG = specific gravity air = 1.0
dp_{inWG} = total pressure (in. W.G.)

Brake Horsepower (bhp)

Brake horsepower (bhp) is the actual power a fan requires because no fan is 100% efficient. BHP can be expressed as

$$P_{bhp} = q\ dp_{inWG} / \mu\ 6{,}356 \quad (2)$$

P_{bhp} = brake horsepower (hp)

μ = fan efficiency

Types of Pressure Measurements

$$TP = VP + SP$$

TP = total pressure

VP = velocity pressure

SP = static pressure

Conservation of Energy

$$SP_1 + VP_1 = SP_2 + VP_2 + h_L$$

h_L = head loss

Velocity Pressure

$$V = 1{,}096\left(\frac{VP}{\rho}\right)^{0.5}$$

$$V = 4{,}005(VP)^{0.5}$$

V = velocity (ft/min)

VP = velocity pressure (water column inches)

ρ = density of air at STP

Overall Fan Efficiency

$$\eta_{overall} = \eta_f \times \eta_t \times \eta_m \times \eta_c$$

$\eta_{overall}$ = overall fan efficiency

η_f = fan, $\eta_f = \eta_{se} \times \eta_{catalog}$

η_{se} = system effect, zero system effect means $\eta = 1.0$

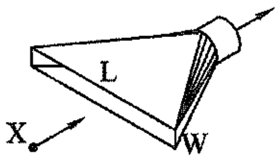
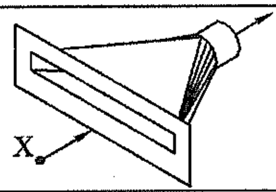
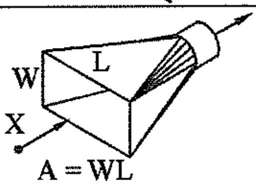
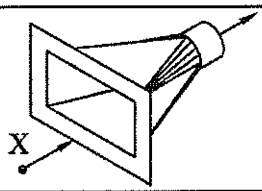
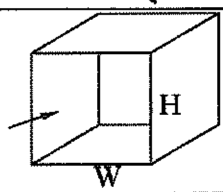
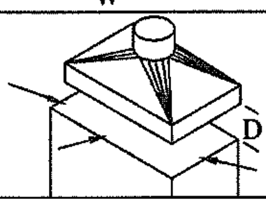
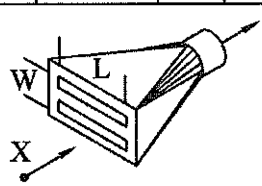
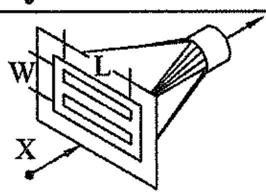
$\eta_{catalog}$ = catalog fan efficiency

η_t = transmission

η_m = motor

η_c = control system

Summary of Hood Airflow Equations

HOOD TYPE	DESCRIPTION	ASPECT RATIO, W/L	AIRFLOW
	Slot	0.2 or less	$Q = 3.7\ LV_xX$
	Flanged slot	0.2 or less	$Q = 2.6\ LV_xX$
	Plain opening	0.2 or greater and round	$Q = V_x(10X^2 + A)$
	Flanged opening	0.2 or greater and round	$Q = 0.75V_x(10X^2 + A)$
	Booth	To suit work	$Q = VA = VWH$
	Canopy	To suit work	$Q = 1.4\ PVD$ P = Perimeter D = Height above work
	Plain multiple slot opening 2 or more slots	0.2 or greater	$Q = V_x(10X^2 + A)$
	Flanged multiple slot opening 2 or more slots	0.2 or greater	$Q = 0.75V_x(10X^2 + A)$

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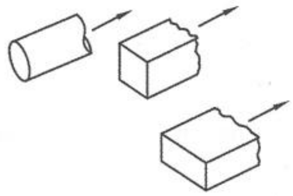
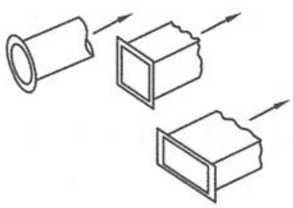
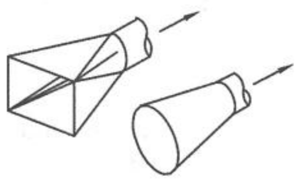
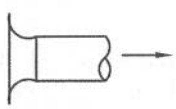
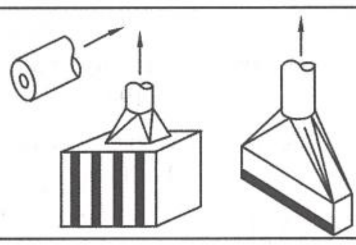
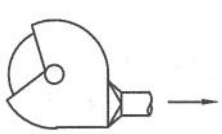
Hood Loss Coefficients

FIGURE 6-43

HOOD TYPE	DESCRIPTION	HOOD ENTRY LOSS (F_h) COEFFICIENT
	Plain opening	0.93
	Flanged opening	0.49
	Taper or Cone hood	See Hood Entry Loss Coefficients Table
	Bell mouth inlet	0.04
	Orifice	See Expansions and Contractions Table
	Typical grinding hood	(Straight takeoff) 0.65 (Tapered takeoff) 0.40

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TITLE: HOOD LOSS COEFFICIENTS

FIGURE: 6-43

DATE: 1-12

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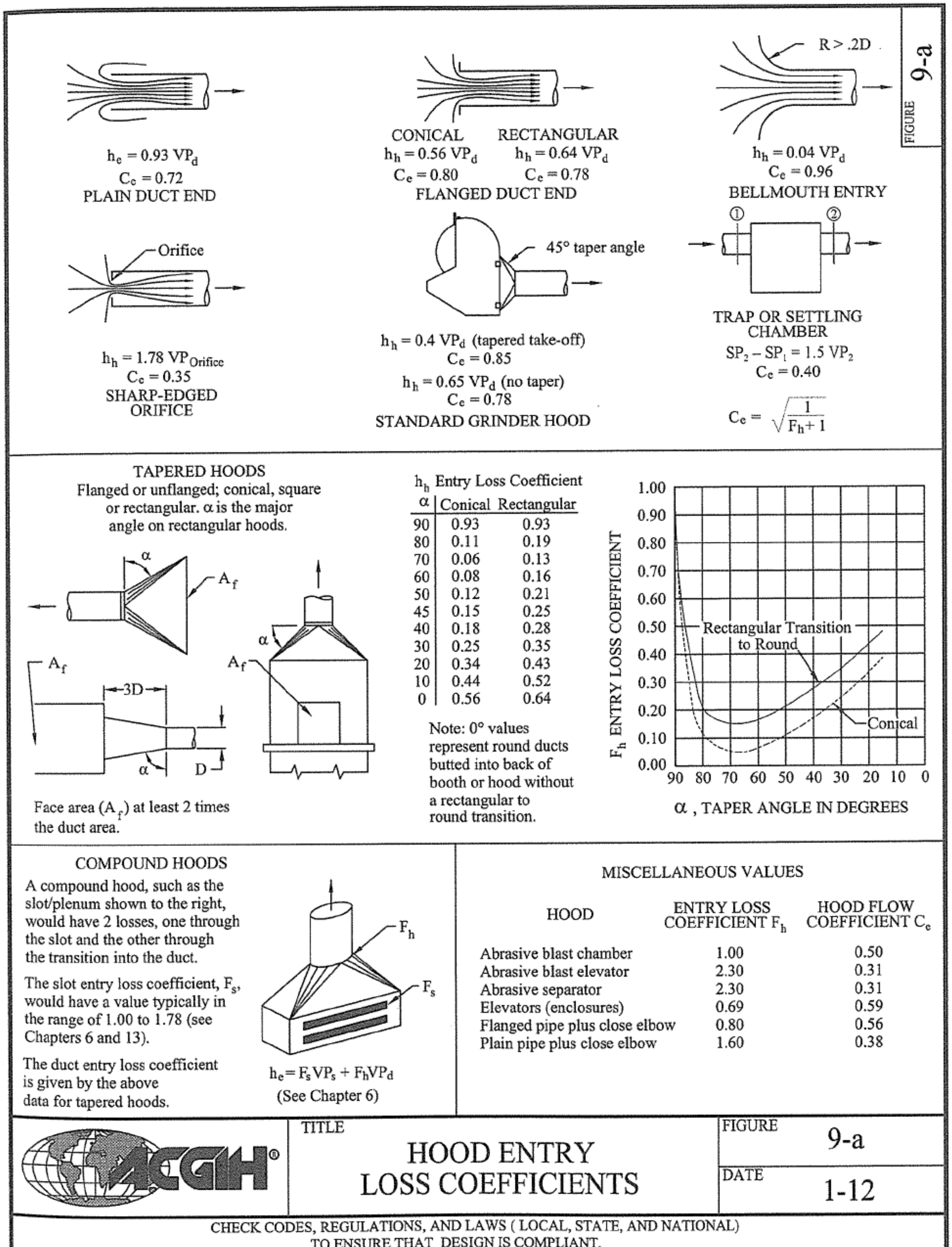
Hood Entry Loss Coefficients



h_h Entry Loss Coefficient

α	Conical	Rectangular
90	0.93	0.93
80	0.11	0.19
70	0.06	0.13
60	0.08	0.16
50	0.12	0.21
45	0.15	0.25
40	0.18	0.28
30	0.25	0.35
20	0.34	0.43
10	0.44	0.52
0	0.56	0.64

Note: 0° values represent round ducts butted into back of booth or hood without a rectangular to round transition.

MISCELLANEOUS VALUES

HOOD	ENTRY LOSS COEFFICIENT F_h	HOOD FLOW COEFFICIENT C_e
Abrasive blast chamber	1.00	0.50
Abrasive blast elevator	2.30	0.31
Abrasive separator	2.30	0.31
Elevators (enclosures)	0.69	0.59
Flanged pipe plus close elbow	0.80	0.56
Plain pipe plus close elbow	1.60	0.38

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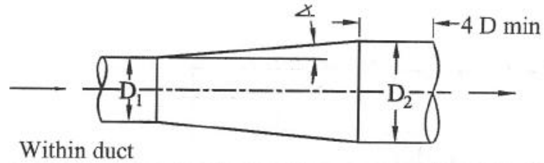
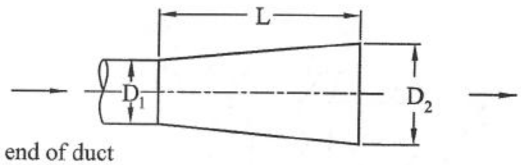
Expansions and Contractions

STATIC PRESSURE REGAINS FOR EXPANSIONS

FIGURE 9-d



Within duct



At end of duct

Regain (R), fraction of VP difference					
Taper angle degrees	Diameter ratios D_2/D_1				
	1.25:1	1.5:1	1.75:1	2:1	2.5:1
3 1/2	0.92	0.88	0.84	0.81	0.75
5	0.88	0.84	0.80	0.76	0.68
10	0.85	0.76	0.70	0.63	0.53
15	0.83	0.70	0.62	0.55	0.43
20	0.81	0.67	0.57	0.48	0.43
25	0.80	0.65	0.53	0.44	0.28
30	0.79	0.63	0.51	0.41	0.25
Abrupt 90	0.77	0.62	0.50	0.40	0.25

Where: $SP_2 = SP_1 + R(VP_1 - VP_2)$

Regain (R), fraction of inlet VP						
Taper length to inlet diam L / D	Diameter ratios D_2/D_1					
	1.2:1	1.3:1	1.4:1	1.5:1	1.6:1	1.7:1
1.0:1	0.37	0.39	0.38	0.35	0.31	0.27
1.5:1	0.39	0.46	0.47	0.46	0.44	0.41
2.0:1	0.42	0.49	0.52	0.52	0.51	0.49
3.0:1	0.44	0.52	0.57	0.59	0.60	0.59
4.0:1	0.45	0.55	0.60	0.63	0.63	0.64
5.0:1	0.47	0.56	0.62	0.65	0.66	0.68
7.5:1	0.48	0.58	0.64	0.68	0.70	0.72

Where: $SP_1 = SP_2 - R(VP_1)^*$

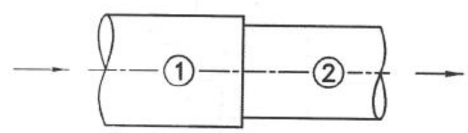
* When $SP_2 = 0$ (atmosphere) SP_1 will be (-)

The regain (R) will only be 70% of value shown above when expansion follows a disturbance or elbow (including a fan) by less than 5 duct diameters.

STATIC PRESSURE LOSSES FOR CONTRACTIONS

Tapered contraction

$SP_2 = SP_1 - (VP_2 - VP_1) - L(VP_2 - VP_1)$



Abrupt contraction

$SP_2 = SP_1 - (VP_2 - VP_1) - K(VP_2)$

Taper angle degrees	L(loss)
5	0.05
10	0.06
15	0.08
20	0.10
25	0.11
30	0.13
45	0.20
60	0.30
over 60	Abrupt contraction

Ratio A_2/A_1	K
0.1	0.48
0.2	0.46
0.3	0.42
0.4	0.37
0.4	0.32
0.6	0.26
0.7	0.20

Note:

In calculating SP for expansion or contraction use algebraic signs: VP is (+), and usually SP is (+) in discharge duct from fan, and SP is (-) in inlet duct to fan.

ACGIH®	TITLE: EXPANSIONS AND CONTRACTIONS	FIGURE: 9-d
		DATE: 1-12

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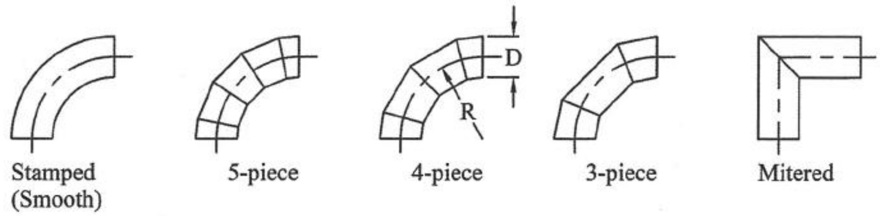
Duct Design Data Elbow Losses

FIGURE 9-e



	R / D				
	0.75	1.00	1.50	2.00	2.50
Stamped	0.33	0.22	0.15	0.13	0.12
5-piece	0.46	0.33	0.24	0.19	0.17*
4-piece	0.50	0.37	0.27	0.24	0.23*
3-piece	0.54	0.42	0.34	0.33	0.33*

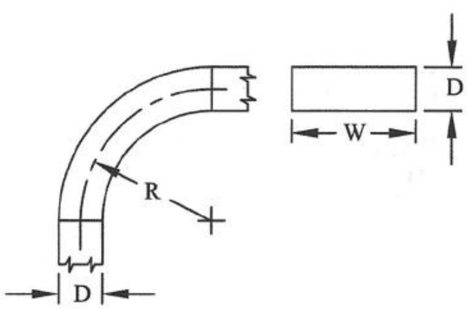
* extrapolated from published data

OTHER ELBOW LOSS COEFFICIENTS

Mitered, no vanes	1.2
Mitered, turning vanes	0.6
Flatback (R/D = 2.5)	0.05 (see Chapter 5, Figure 5-16)

NOTE: Loss factors are assumed to be for elbows of "zero length." Friction losses should be included to the intersection of centerlines.

ROUND ELBOW LOSS COEFFICIENTS



R/D	Aspect Ratio, W/D					
	0.25	0.5	1.0	2.0	3.0	4.0
0.0 (Mitered)	1.50	1.32	1.15	1.04	0.92	0.86
0.5	1.36	1.21	1.05	0.95	0.84	0.79
1.0	0.45	0.28	0.21	0.21	0.20	0.19
1.5	0.28	0.18	0.13	0.13	0.12	0.12
2.0	0.24	0.15	0.11	0.11	0.10	0.10
3.0	0.24	0.15	0.11	0.11	0.10	0.10

SQUARE & RECTANGULAR ELBOW LOSS COEFFICIENTS

ACGIH®	TITLE DUCT DESIGN DATA ELBOW LOSSES	FIGURE 9-e DATE 1-12

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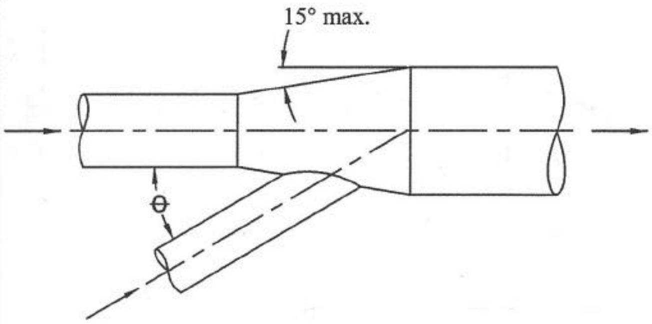
Branch Entry and Weather Cap Losses

FIGURE 9-f

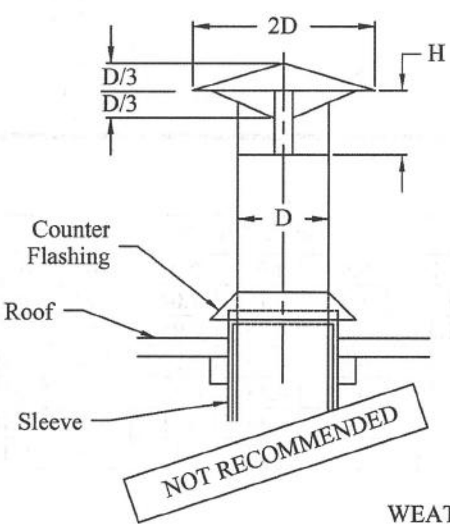


Angle θ Degrees	Loss Fraction of VP in Branch
10	0.06
15	0.09
20	0.12
25	0.15
30	0.18
35	0.21
40	0.25
45	0.28
50	0.32
60	0.44
90	1.00

Note: Branch entry loss assumed to occur in branch and is so calculated.

Do not include a regain calculation for branch entry enlargements.

BRANCH ENTRY LOSSES



H, No. of Diameters	Loss Fraction of VP
1.0 D	0.10
0.75 D	0.18
0.70 D	0.22
0.65 D	0.30
0.60 D	0.41
0.55 D	0.56
0.50 D	0.73
0.45 D	1.0

WEATHER CAP LOSSES

See Chapter 5, Figure 5-14

ACGIH®

TITLE: BRANCH ENTRY AND WEATHER CAP LOSSES

FIGURE: 9-f

DATE: 1-12

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6 ASSOCIATED ENGINEERING PRINCIPLES

Quadratic Equation

$$ax^2 + bx + c = 0$$

$$x = \text{Roots} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Quadric Surface (Sphere)

The standard form of the equation is

$$(x - h)^2 + (y - k)^2 + (z - m)^2 = r^2$$

with center at (h, k, m).

In a three-dimensional space, the distance between two points is

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Exponentials

$$a^x a^y = a^{x+y}$$

$$(a^x)^y = a^{xy}$$

$$a^x / a^y = a^{x-y}$$

Logarithms

The logarithm of x to the Base b is defined by

$$\log_b (x) = c, \text{ where } b^c = x$$

Special definitions for $b = e$ or $b = 10$ are:

$$\ln x, \text{ Base} = e$$

$$\log x, \text{ Base} = 10$$

To change from one Base to another:

$$\log_b x = (\log_a x)/(\log_a b)$$

e.g., $\ln x = (\log_{10} x)/(\log_{10} e) = 2.302585 (\log_{10} x)$

Identities

$$\log_b b^n = n$$

$$\log x^c = c \log x; \; x^c = \text{antilog } (c \log x)$$

$$\log xy = \log x + \log y$$

$$\log_b b = 1; \; \log 1 = 0$$

$$\log x/y = \log x - \log y$$

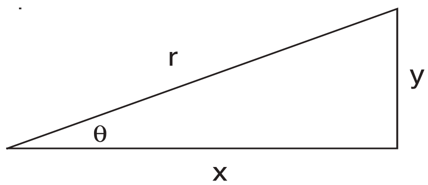
Trigonometry

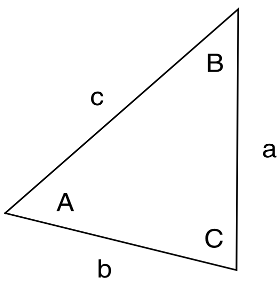
Trigonometric functions are defined using a right triangle.

$\sin \theta = y/r$, $\cos \theta = x/r$

$\tan \theta = y/x$, $\cot \theta = x/y$

$\csc \theta = r/y$, $\sec \theta = r/x$





Law of Sines $\dfrac{a}{\sin A} = \dfrac{b}{\sin B} = \dfrac{c}{\sin C}$

Law of Cosines

$a^2 = b^2 + c^2 - 2bc \cos A$

$b^2 = a^2 + c^2 - 2ac \cos B$

$c^2 = a^2 + b^2 - 2ab \cos C$

Mensuration of Areas and Volumes

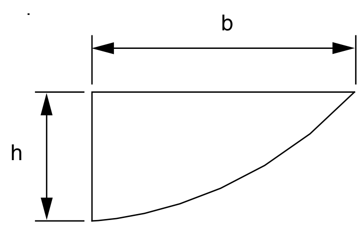
Nomenclature

A = total surface area

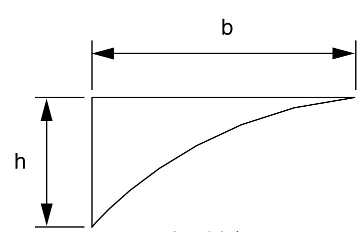
P = perimeter

V = volume

Parabola

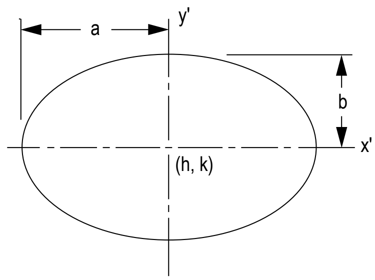


A = 2bh/3



A = bh/3

Ellipse



$A = \pi ab$

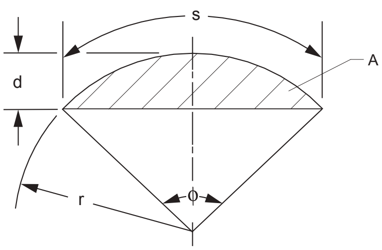
$$P_{approx} = 2\pi\sqrt{\left(a^2 + b^2\right)/2}$$

$$P = \pi\left(a+b\right)\begin{bmatrix} 1 + \left(1/2\right)^2\lambda^2 + \left(1/2 \times 1/4\right)^2\lambda^4 \\ +\left(1/2 \times 1/4 \times 3/6\right)^2\lambda^6 + \left(1/2 \times 1/4 \times 3/6 \times 5/8\right)^2\lambda^8 \\ +\left(1/2 \times 1/4 \times 3/6 \times 5/8 \times 7/10\right)^2\lambda^{10} + \ldots \end{bmatrix},$$

where

$$\lambda = \left(a-b\right)/\left(a+b\right)$$

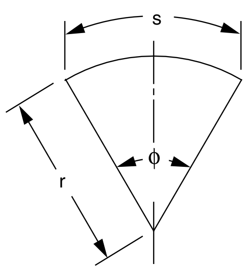
Circular Segment



$$A = \left[r^2\left(\phi - \sin\phi\right)\right]/2$$

$$\phi = s/r = 2\left\{\arccos\left[\left(r-d\right)/r\right]\right\}$$

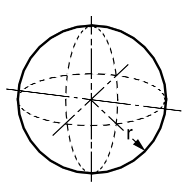
Circular Sector



$$A = \phi r^2/2 = sr/2$$

$$\phi = s/r$$

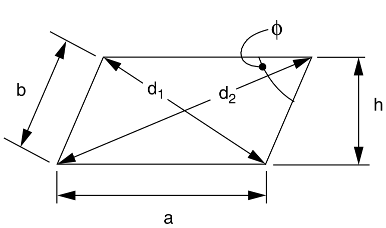
Sphere



$$V = 4\pi r^3/3 = \pi d^3/6$$

$$A = 4\pi r^2 = \pi d^2$$

Parallelogram



$$P = 2\left(a+b\right)$$

$$d_1 = \sqrt{a^2 + b^2 - 2ab\left(\cos\phi\right)}$$

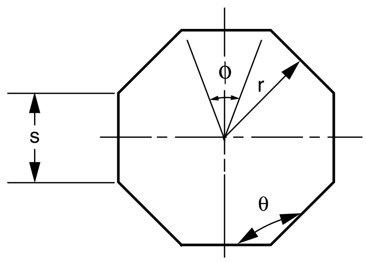
$$d_2 = \sqrt{a^2 + b^2 + 2ab\left(\cos\phi\right)}$$

$$d_1^2 + d_2^2 = 2\left(a^2 + b^2\right)$$

$$A = ah = ab\left(\sin\phi\right)$$

If $a = b$, the parallelogram is a rhombus.

Regular Polygon (*n* equal sides)



$\phi = 2\pi/n$

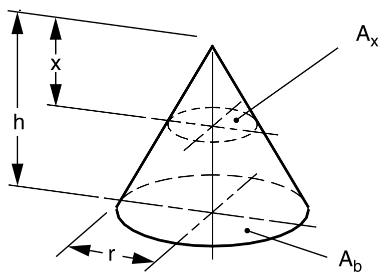
$\theta = \left[\frac{\pi(n - 2)}{n}\right] = \pi\left(1 - \frac{2}{n}\right)$

$P = ns$

$s = 2r\left[\tan(\phi/2)\right]$

$A = (nsr)/2$

Right Circular Cone



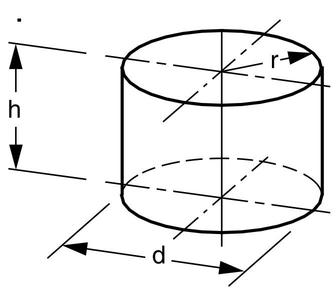
$V = (\pi r^2 h)/3$

$A =$ side area + base area

$= \pi r\left(r + \sqrt{r^2 + h^2}\right)$

$A_x : A_b = x^2 : h^2$

Right Circular Cylinder



$V = \pi r^2 h = \frac{\pi d^2 h}{4}$

$A =$ side area + end areas $= 2\pi r(h + r)$

Centroids and Moments of Inertia

The *location of the centroid of an area*, bounded by the axes and the function $y = f(x)$, can be found by integration.

$$x_c = \frac{\int x dA}{A}$$

$$y_c = \frac{\int y dA}{A}$$

$$A = \int f(x) dx$$

$$dA = f(x) dx = g(y) dy$$

The *first moment of area* with respect to the *y*-axis and the *x*-axis, respectively, are:

$$M_y = \int x \, dA = x_c A$$

$$M_x = \int y \, dA = y_c A$$

The *moment of inertia* (*second moment of area*) with respect to the *y*-axis and the *x*-axis, respectively, are:

$$I_y = \int x^2 \, dA$$

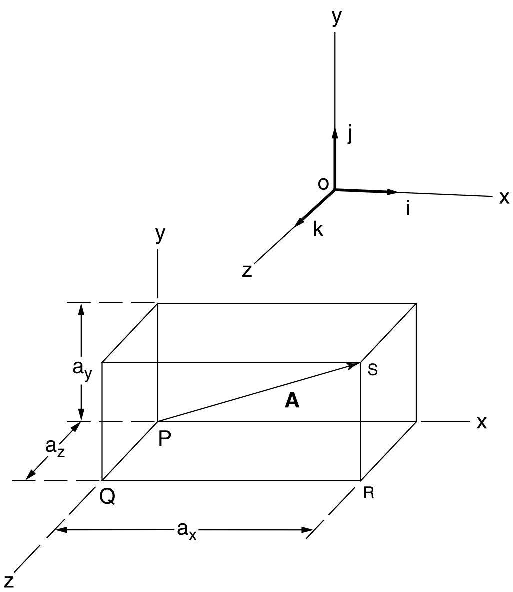
$$I_x = \int y^2 \, dA$$

The moment of inertia taken with respect to an axis passing through the area's centroid is the *centroidal moment of inertia*. The *parallel axis theorem* for the moment of inertia with respect to another axis parallel with and located *d* units from the centroidal axis is expressed by

$$I_{\text{parallel axis}} = I_c + Ad^2$$

In a plane, $J = \int r^2 dA = I_x + I_y$

Vectors



$$\mathbf{A} = a_x\mathbf{i} + a_y\mathbf{j} + a_z\mathbf{k}$$

Addition and *subtraction:*

$$\mathbf{A} + \mathbf{B} = (a_x + b_x)\mathbf{i} + (a_y + b_y)\mathbf{j} + (a_z + b_z)\mathbf{k}$$

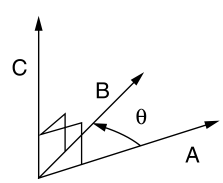
$$\mathbf{A} - \mathbf{B} = (a_x - b_x)\mathbf{i} + (a_y - b_y)\mathbf{j} + (a_z - b_z)\mathbf{k}$$

The *dot product* is a *scalar product* and represents the projection of **B** onto **A** times |**A**|. It is given by

$$\begin{aligned} A \bullet B &= axbx + ayby + azbz \\ &= |A||B|\cos\theta = B \bullet A \end{aligned}$$

The *cross product* is a *vector product* of magnitude |**B**| |**A**| sin θ which is perpendicular to the plane containing **A** and **B**. The product is

$$\mathbf{A} \times \mathbf{B} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix} = -\,\mathbf{B} \times \mathbf{A}$$



The sense of **A** × **B** is determined by the right-hand rule.

$$\mathbf{A} \times \mathbf{B} = |\mathbf{A}||\mathbf{B}|\mathbf{n}\sin\theta\text{, where}$$

n = unit vector perpendicular to the plane of **A** and **B**.

Gradient, Divergence, and Curl

$$\nabla\phi = \left(\frac{\partial}{\partial x}\mathbf{i} + \frac{\partial}{\partial y}\mathbf{j} + \frac{\partial}{\partial z}\mathbf{k}\right)\phi$$

$$\nabla \bullet \mathbf{V} = \left(\frac{\partial}{\partial x}\mathbf{i} + \frac{\partial}{\partial y}\mathbf{j} + \frac{\partial}{\partial z}\mathbf{k}\right) \bullet \left(V_1\mathbf{i} + V_2\mathbf{j} + V_3\mathbf{k}\right)$$

$$\nabla \times \mathbf{V} = \left(\frac{\partial}{\partial x}\mathbf{i} + \frac{\partial}{\partial y}\mathbf{j} + \frac{\partial}{\partial z}\mathbf{k}\right) \times \left(V_1\mathbf{i} + V_2\mathbf{j} + V_3\mathbf{k}\right)$$

The Laplacian of a scalar function ϕ is

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2}$$

Identities

$\mathbf{A} \bullet \mathbf{B} = \mathbf{B} \bullet \mathbf{A}$; $\mathbf{A} \bullet (\mathbf{B} + \mathbf{C}) = \mathbf{A} \bullet \mathbf{B} + \mathbf{A} \bullet \mathbf{C}$

$\mathbf{A} \bullet \mathbf{A} = |\mathbf{A}|^2$

$\mathbf{i} \bullet \mathbf{i} = \mathbf{j} \bullet \mathbf{j} = \mathbf{k} \bullet \mathbf{k} = 1$

$\mathbf{i} \bullet \mathbf{j} = \mathbf{j} \bullet \mathbf{k} = \mathbf{k} \bullet \mathbf{i} = 0$

If $\mathbf{A} \bullet \mathbf{B} = 0$, then either $\mathbf{A} = 0$, $\mathbf{B} = 0$, or $\mathbf{A}$ is perpendicular to $\mathbf{B}$.

$\mathbf{A} \times \mathbf{B} = -\mathbf{B} \times \mathbf{A}$

$\mathbf{A} \times (\mathbf{B} + \mathbf{C}) = (\mathbf{A} \times \mathbf{B}) + (\mathbf{A} \times \mathbf{C})$

$(\mathbf{B} + \mathbf{C}) \times \mathbf{A} = (\mathbf{B} \times \mathbf{A}) + (\mathbf{C} \times \mathbf{A})$

$\mathbf{i} \times \mathbf{i} = \mathbf{j} \times \mathbf{j} = \mathbf{k} \times \mathbf{k} = \mathbf{0}$

$\mathbf{i} \times \mathbf{j} = \mathbf{k} = -\mathbf{j} \times \mathbf{i}$; $\mathbf{j} \times \mathbf{k} = \mathbf{i} = -\mathbf{k} \times \mathbf{j}$

$\mathbf{k} \times \mathbf{i} = \mathbf{j} = -\mathbf{i} \times \mathbf{k}$

If $\mathbf{A} \times \mathbf{B} = \mathbf{0}$, then either $\mathbf{A} = \mathbf{0}$, $\mathbf{B} = \mathbf{0}$, or $\mathbf{A}$ is parallel to $\mathbf{B}$.

$\nabla^2\phi = \nabla \bullet (\nabla\phi) = (\nabla \bullet \nabla)\phi$

$\nabla \times \nabla\phi = \mathbf{0}$

$\nabla \bullet (\nabla \times \mathbf{A}) = \mathbf{0}$

$\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \bullet \mathbf{A}) - \nabla^2\mathbf{A}$

Dispersion, Mean, Median, and Mode Values

If $X_1, X_2, \ldots, X_n$ represent the values of a random sample of n items or observations, the *arithmetic mean* of these items or observations, denoted $\bar{X}$, is defined as

$$\bar{X} = (1/n)(X_1 + X_2 + \ldots + X_n) = (1/n)\sum_{i=1}^{n} X_i$$

$\bar{X} \rightarrow \mu$ for sufficiently large values of n.

The *weighted arithmetic mean* is

$$\bar{X}_w = \frac{\sum w_i X_i}{\sum w_i}$$

X_i = value of the ith observation

w_i = weight applied to X_i

The *variance* of the population is the *arithmetic mean* of the *squared deviations from the population mean*. If μ is the arithmetic mean of a discrete population of size *N*, the *population variance* is defined by

$$\sigma^2 = (1/N)\left[(X_1 - \mu)^2 + (X_2 - \mu)^2 + \ldots + (X_N - \mu)^2\right]$$
$$= (1/N)\sum_{i=1}^{N}(X_i - \mu)^2$$

Standard deviation formulas are

$$\sigma_{\text{population}} = \sqrt{(1/N)\sum(X_i - \mu)^2}$$
$$\sigma_{\text{sum}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2}$$
$$\sigma_{\text{series}} = \sigma\sqrt{n}$$
$$\sigma_{\text{mean}} = \frac{\sigma}{\sqrt{n}}$$
$$\sigma_{\text{product}} = \sqrt{A^2\sigma_b^2 + B^2\sigma_a^2}$$

The sample variance is

$$s^2 = [1/(n-1)]\sum_{i=1}^{n}(X_i - \overline{X})^2$$

The *sample standard deviation* is

$$s = \sqrt{[1/(n-1)]\sum_{i=1}^{n}(X_i - \overline{X})^2}$$

The *sample coefficient of variation* = $CV = s/\overline{X}$

The *sample geometric mean* = $\sqrt[n]{X_1 X_2 X_3 \ldots X_n}$

The *sample root-mean-square value* = $\sqrt{(1/n)\sum X_i^2}$

When the discrete data are rearranged in increasing order and *n* is odd, the median is the value of the $\left(\frac{n+1}{2}\right)^{\text{th}}$ item

When *n* is even, the median is the average of the $\left(\frac{n}{2}\right)^{\text{th}}$ and $\left(\frac{n}{2}+1\right)^{\text{th}}$ items.

The *mode* of a set of data is the value that occurs with greatest frequency.

The *sample range R* is the largest sample value minus the smallest sample value.

Permutations and Combinations

A *permutation* is a particular sequence of a given set of objects. A *combination* is the set itself without reference to order.

1. The number of different *permutations* of *n* distinct objects *taken r at a time* is

$$P(n,r) = \frac{n!}{(n-r)!}$$

   nPr is an alternative notation for P(n,r)

2. The number of different *combinations* of *n* distinct objects *taken r at a time* is

$$C(n,r) = \frac{P(n,r)}{r!} = \frac{n!}{[r!(n-r)!]}$$

   nCr and $\binom{n}{r}$ are alternative notations for C(n,r)

3. The number of different *permutations* of n objects *taken n at a time*, given that n_i are of type i, where $i = 1, 2, \ldots, k$ and $\sum n_i = n$, is

$$P(n; n_1, n_2, \ldots, n_k) = \frac{n!}{n_1! n_2! \ldots n_k!}$$

Laws of Probability

Property 1. General Character of Probability

The probability $P(E)$ of an event E is a real number in the range of 0 to 1. The probability of an impossible event is 0 and that of an event certain to occur is 1.

Property 2. Law of Total Probability

$$P(A + B) = P(A) + P(B) - P(A, B)$$

$P(A + B)$ = probability that either A or B occur alone or that both occur together

$P(A)$ = probability that A occurs

$P(B)$ = probability that B occurs

$P(A, B)$ = probability that both A and B occur simultaneously

Property 3. Law of Compound or Joint Probability

If neither $P(A)$ nor $P(B)$ is zero,

$$P(A, B) = P(A)P(B \mid A) = P(B)P(A \mid B)$$

$P(B \mid A)$ = probability that B occurs given the fact that A has occurred

$P(A \mid B)$ = probability that A occurs given the fact that B has occurred

If either $P(A)$ or $P(B)$ is zero, then $P(A, B) = 0$.

Bayes' Theorem

$$P(B_j|A) = \frac{P(B_j)P(A|B_j)}{\sum_{i=1}^{n} P(A|B_i)P(B_i)}$$

$P(A_j)$ = probabilityof event A_j within the population of A
$P(B_j)$ = probabilityof event B_j within the population of B

Probability Functions, Distributions, and Expected Values

A random variable X has a probability associated with each of its possible values. The probability is termed a discrete probability if X can assume only discrete values, or

$$X = x_1, x_2, x_3, \ldots, x_n$$

The *discrete probability* of any single event, $X = x_i$, occurring is defined as $P(x_i)$ while the *probability mass function* of the random variable X is defined by

$$f(x_k) = P(X = x_k),\ k = 1, 2, \ldots, n$$

Probability Density Function

If X is continuous, the *probability density function, f,* is defined such that

$$P(a \le X \le b) = \int_a^b f(x)dx$$

Cumulative Distribution Functions

The *cumulative distribution function, F,* of a discrete random variable X that has a probability distribution described by $P(x_i)$ is defined as

$$F(x_m) = \sum_{k=1}^{m} P(x_k) = P(X \le x_m), m = 1, 2, \ldots, n$$

If X is continuous, the *cumulative distribution function, F,* is defined by

$$F(x) = \int_{-\infty}^{x} f(t)\,dt$$

which implies that $F(a)$ is the probability that $X \le a$.

Expected Values

Let X be a discrete random variable having a probability mass function

$$f(x_k), k = 1, 2, \ldots, n$$

The expected value of X is defined as

$$\mu = E[X] = \sum_{k=1}^{n} x_k f(x_k)$$

The variance of X is defined as

$$\sigma^2 = V[X] = \sum_{k=1}^{n} (x_k - \mu)^2 f(x_k)$$

Let X be a continuous random variable having a density function $f(X)$ and let $Y = g(X)$ be some general function.

The expected value of Y is:

$$E[Y] = E[g(X)] = \int_{-\infty}^{\infty} g(x) f(x)\,dx$$

The mean or expected value of the random variable X is now defined as

$$\mu = E[X] = \int_{-\infty}^{\infty} x f(x)\,dx$$

while the variance is given by

$$\sigma^2 = V[X] = E\left[(X - \mu)^2\right] = \int_{-\infty}^{\infty} (x - \mu)^2 f(x)\,dx$$

The standard deviation is given by

$$\sigma = \sqrt{V[X]}$$

The coefficient of variation is defined as σ/μ.

Combinations of Random Variables

$$Y = a_1 X_1 + a_2 X_2 + \ldots + a_n X_n$$

The expected value of Y is:

$$\mu_y = E(Y) = a_1 E(X_1) + a_2 E(X_2) + \ldots + a_n E(X_n)$$

If the random variables are statistically *independent*, then the variance of Y is:

$$\sigma_y^2 = V(Y) = a_1^2 V(X_1) + a_2^2 V(X_2) + \ldots + a_n^2 V(X_n)$$
$$= a_1^2 \sigma_1^2 + a_2^2 \sigma_2^2 + \ldots + a_n^2 \sigma_n^2$$

Also, the standard deviation of Y is:

$$\sigma_y = \sqrt{\sigma_y^2}$$

When $Y = f(X_1, X_2, .., X_n)$ and X_i are independent, the standard deviation of Y is expressed as:

$$\sigma_y = \sqrt{\left(\frac{\partial f}{\partial X_1}\sigma_{X_1}\right)^2 + \left(\frac{\partial f}{\partial X_2}\sigma_{X_2}\right)^2 + \ldots + \left(\frac{\partial f}{\partial X_n}\sigma_{X_n}\right)^2}$$

Binomial Distribution

$P(x)$ is the probability that x successes will occur in n trials. If p = probability of success and q = probability of failure = $1 - p$, then

$$P_n(x) = C(n,x) p^x q^{n-x} = \frac{n!}{x!(n-x)!} p^x q^{n-x},$$

x = 0, 1, 2, …, n

C(n, x) = number of combinations

n, p = parameters

The variance is given by the form

$$\sigma^2 = npq$$

Normal Distribution (Gaussian Distribution)

This is a unimodal distribution, the mode being $x = \mu$, with two points of inflection (each located at a distance σ to either side of the mode). The averages of n observations tend to become normally distributed as n increases. The variate x is said to be normally distributed if its density function $f(x)$ is given by an expression of the form

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

μ = population mean

σ = standard deviation of the population $-\infty \le x \le \infty$

When $\mu = 0$ and $\sigma^2 = \sigma = 1$, the distribution is called a *standardized* or *unit normal* distribution. Then

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$$

where $-\infty \le x \le \infty$

It is noted that $Z = \dfrac{x - \mu}{\sigma}$ follows a standardized normal distribution function.

A unit normal distribution table is included at the end of this section. In the table, the following notations are utilized:

$F(x)$ = area under the curve from $-\infty$ to x

$R(x)$ = area under the curve from x to ∞

$W(x)$ = area under the curve between $-x$ and x

$$F(-x) = 1 - F(x)$$

The Central Limit Theorem

Let $X_1, X_2, ..., X_n$ be a sequence of independent and identically distributed random variables each having mean μ and variance σ^2. Then for large n, the Central Limit Theorem asserts that the sum

$\mathrm{Y} = \mathrm{X}_1 + \mathrm{X}_2 + ... \mathrm{X}_n$ is approximately normal.

$$\mu_{\bar{y}} = \mu$$

and the standard deviation

$$\sigma_{\bar{y}} = \frac{\sigma}{\sqrt{n}}$$

Confidence Limits

For a normally distributed data set: $x_1, x_2,..., x_n$ (e.g., collected after excavation), $UCL95$ and $LCL95$ are given as follows:

$$UCL95 = \overline{x} + t_{n-1,0.05}(sd/\sqrt{n}), \text{ and}$$
$$LCL95 = \overline{x} - t_{n-1,0.05}(sd/\sqrt{n})$$

sd = standard deviation

n = number of observations/measurements in a sample

$\overline{x}$ = arithmetic average

$UCL95$ = 95% upper confidence limit

$LCL95$ = 95% lower confidence limit

t = Student's t-statistic

t-Distribution

Student's t-distribution has the probability density function given by:

$$f(t) = \frac{\Gamma\left(\frac{v+1}{2}\right)}{\sqrt{v\pi}\,\Gamma\left(\frac{v}{2}\right)}\left(1 + \frac{t^2}{v}\right)^{-\frac{v+1}{2}}$$

v = number of *degrees of freedom*

n = sample size

$v = n - 1$

Γ = gamma function

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

$-\infty \le t \le \infty$

A table later in this section gives the values of $t_{\alpha, v}$ for values of α and v. Note that, in view of the symmetry of the t-distribution, $t_{1-\alpha,v} = -t_{\alpha,v}$

The function for α follows:

$$\alpha = \int_{t_{\alpha,v}}^{\infty} f(t)\,dt$$

χ^2 - Distribution

If $Z_1, Z_2, \ldots, Z_n$ are independent unit normal random

variables, then

$$\chi^2 = Z_1^2 + Z_2^2 + \ldots + Z_n^2$$

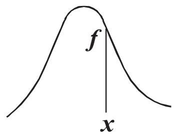
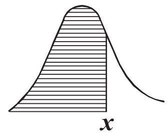
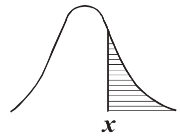
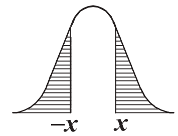
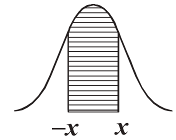
is said to have a chi-square distribution with n degrees of freedom.

A table at the end of this section gives values of $\chi^2_{\alpha,n}$ for selected values of α and n.

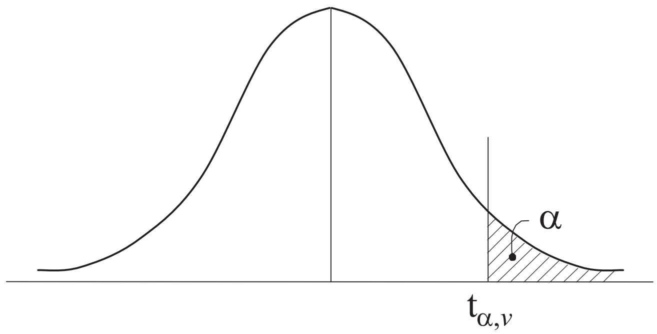
Gamma Function

$$\Gamma(n) = \int_0^{\infty} t^{n-1} e^{-t} dt, \; n > 0$$

Unit Normal Distribution

					
x	$f(x)$	$F(x)$	$R(x)$	$2R(x)$	$W(x)$
0.0	0.3989	0.5000	0.5000	1.0000	0.0000
0.1	0.3970	0.5398	0.4602	0.9203	0.0797
0.2	0.3910	0.5793	0.4207	0.8415	0.1585
0.3	0.3814	0.6179	0.3821	0.7642	0.2358
0.4	0.3683	0.6554	0.3446	0.6892	0.3108
0.5	0.3521	0.6915	0.3085	0.6171	0.3829
0.6	0.3332	0.7257	0.2743	0.5485	0.4515
0.7	0.3123	0.7580	0.2420	0.4839	0.5161
0.8	0.2897	0.7881	0.2119	0.4237	0.5763
0.9	0.2661	0.8159	0.1841	0.3681	0.6319
1.0	0.2420	0.8413	0.1587	0.3173	0.6827
1.1	0.2179	0.8643	0.1357	0.2713	0.7287
1.2	0.1942	0.8849	0.1151	0.2301	0.7699
1.3	0.1714	0.9032	0.0968	0.1936	0.8064
1.4	0.1497	0.9192	0.0808	0.1615	0.8385
1.5	0.1295	0.9332	0.0668	0.1336	0.8664
1.6	0.1109	0.9452	0.0548	0.1096	0.8904
1.7	0.0940	0.9554	0.0446	0.0891	0.9109
1.8	0.0790	0.9641	0.0359	0.0719	0.9281
1.9	0.0656	0.9713	0.0287	0.0574	0.9426
2.0	0.0540	0.9772	0.0228	0.0455	0.9545
2.1	0.0440	0.9821	0.0179	0.0357	0.9643
2.2	0.0355	0.9861	0.0139	0.0278	0.9722
2.3	0.0283	0.9893	0.0107	0.0214	0.9786
2.4	0.0224	0.9918	0.0082	0.0164	0.9836
2.5	0.0175	0.9938	0.0062	0.0124	0.9876
2.6	0.0136	0.9953	0.0047	0.0093	0.9907
2.7	0.0104	0.9965	0.0035	0.0069	0.9931
2.8	0.0079	0.9974	0.0026	0.0051	0.9949
2.9	0.0060	0.9981	0.0019	0.0037	0.9963
3.0	0.0044	0.9987	0.0013	0.0027	0.9973
Fractiles					
1.2816	0.1755	0.9000	0.1000	0.2000	0.8000
1.6449	0.1031	0.9500	0.0500	0.1000	0.9000
1.9600	0.0584	0.9750	0.0250	0.0500	0.9500
2.0537	0.0484	0.9800	0.0200	0.0400	0.9600
2.3263	0.0267	0.9900	0.0100	0.0200	0.9800
2.5758	0.0145	0.9950	0.0050	0.0100	0.9900

Student's *t*-Distribution



VALUES OF $t_{\alpha,v}$

v	α								v
	0.25	**0.20**	**0.15**	**0.10**	**0.05**	**0.025**	**0.01**	**0.005**	
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	1
2	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	2
3	0.765	0.978	1.350	1.638	2.353	3.182	4.541	5.841	3
4	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	4
5	**0.727**	**0.920**	**1.156**	**1.476**	**2.015**	**2.571**	**3.365**	**4.032**	**5**
6	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	6
7	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	7
8	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	8
9	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	9
10	**0.700**	**0.879**	**1.093**	**1.372**	**1.812**	**2.228**	**2.764**	**3.169**	**10**
11	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	11
12	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	12
13	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	13
14	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	14
15	**0.691**	**0.866**	**1.074**	**1.341**	**1.753**	**2.131**	**2.602**	**2.947**	**15**
16	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	16
17	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	17
18	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	18
19	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	19
20	**0.687**	**0.860**	**1.064**	**1.325**	**1.725**	**2.086**	**2.528**	**2.845**	**20**
21	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	21
22	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	22
23	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	23
24	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	24
25	**0.684**	**0.856**	**1.058**	**1.316**	**1.708**	**2.060**	**2.485**	**2.787**	**25**
26	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	26
27	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	27
28	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	28
29	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	29
30	**0.683**	**0.854**	**1.055**	**1.310**	**1.697**	**2.042**	**2.457**	**2.750**	**30**
∞	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	∞

Economics

Factor Name	Converts	Symbol	Formula
Single Payment Compound Amount	to F given P	$(F/P, i\%, n)$	$(1+i)^n$
Single Payment Present Worth	to P given F	$(P/F, i\%, n)$	$(1+i)^{-n}$
Uniform Series Sinking Fund	to A given F	$(A/F, i\%, n)$	$\frac{i}{(1+i)^n-1}$
Capital Recovery	to A given P	$(A/P, i\%, n)$	$\frac{i(1+i)^n}{(1+i)^n-1}$
Uniform Series Compound Amount	to F given A	$(F/A, i\%, n)$	$\frac{(1+i)^n-1}{i}$
Uniform Series Present Worth	to P given A	$(P/A, i\%, n)$	$\frac{(1+i)^n-1}{i(1+i)^n}$
Uniform Gradient Present Worth	to P given G	$(P/G, i\%, n)$	$\frac{(1+i)^n-1}{i^2(1+i)^n}-\frac{n}{i(1+i)^n}$
Uniform Gradient † Future Worth	to F given G	$(F/G, i\%, n)$	$\frac{(1+i)^n-1}{i^2}-\frac{n}{i}$
Uniform Gradient Uniform Series	to A given G	$(A/G, i\%, n)$	$\frac{1}{i}-\frac{n}{(1+i)^n-1}$

Nomenclature and Definitions

A.......... Uniform amount per interest period

B.......... Benefit

BV........ Book value

C.......... Cost

d........... Inflation-adjusted interest rate per interest period

D_j......... Depreciation in year j

F.......... Future worth, value, or amount

f........... General inflation rate per interest period

G.......... Uniform gradient amount per interest period

i........... Interest rate per interest period

i_e.......... Annual effective interest rate

m.......... Number of compounding periods per year

n........... Number of compounding periods; or the expected life of an asset

P.......... Present worth, value, or amount

r........... Nominal annual interest rate

S_n......... Expected salvage value in year n

Subscripts

j .... at time j

n........... at time n

†........... $F/G = (F/A - n)/i = (F/A) \times (A/G)$

Risk

Risk is the chance of an outcome other than what is planned to occur or expected in the analysis.

Non-Annual Compounding

$$i_e = \left(1 + \frac{r}{m}\right)^m - 1$$

Break-Even Analysis

By altering the value of any one of the variables in a situation, holding all of the other values constant, it is possible to find a value for that variable that makes the two alternatives equally economical. This value is the break-even point.

Break-even analysis is used to describe the percentage of capacity of operation for a manufacturing plant at which income will just cover expenses.

The payback period is the period of time required for the profit or other benefits of an investment to equal the cost of the investment.

Inflation

To account for inflation, the dollars are deflated by the general inflation rate per interest period f, and then they are shifted over the time scale using the interest rate per interest period i. Use an inflation-adjusted interest rate per interest period d for computing present worth values P.

The formula for d is

$$d = i + f + (i \times f)$$

Depreciation

Straight Line

$$D_j = \frac{C - S_n}{n}$$

Modified Accelerated Cost Recovery System (MACRS)

$$D_j = (\text{factor})\ C$$

A table of MACRS factors is provided below.

Book Value

$$BV = \text{initial cost} - \Sigma\ D_j$$

Taxation

Income taxes are paid at a specific rate on taxable income. Taxable income is total income less depreciation and ordinary expenses. Expenses do not include capital items, which should be depreciated.

MACRS FACTORS				
Year	Recovery Period (Years)			
	3	5	7	10
	Recovery Rate (Percent)			
1	33.33	20.00	14.29	10.00
2	44.45	32.00	24.49	18.00
3	14.81	19.20	17.49	14.40
4	7.41	11.52	12.49	11.52
5		11.52	8.93	9.22
6		5.76	8.92	7.37
7			8.93	6.55
8			4.46	6.55
9				6.56
10				6.55
11				3.28

Capitalized Costs

Capitalized costs are present worth values using an assumed perpetual period of time.

$$\text{Capitalized Costs} = P = \frac{A}{i}$$

Bonds

Bond value equals the present worth of the payments the purchaser (or holder of the bond) receives during the life of the bond at some interest rate i.

Bond yield equals the computed interest rate of the bond value when compared with the bond cost.

Rate-of-Return

The minimum acceptable rate-of-return (MARR) is that interest rate that one is willing to accept, or the rate one desires to earn on investments. The rate-of-return on an investment is the interest rate that makes the benefits and costs equal.

Benefit-Cost Analysis

In a benefit-cost analysis, the benefits B of a project should exceed the estimated costs C.

$$B - C \geq 0, \text{ or } B/C \geq 1$$

Factor Table - *i* = 0.50%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9950	0.9950	0.0000	1.0050	1.0000	1.0050	1.0000	0.0000
2	0.9901	1.9851	0.9901	1.0100	2.0050	0.5038	0.4988	0.4988
3	0.9851	2.9702	2.9604	1.0151	3.0150	0.3367	0.3317	0.9967
4	0.9802	3.9505	5.9011	1.0202	4.0301	0.2531	0.2481	1.4938
5	**0.9754**	**4.9259**	**9.8026**	**1.0253**	**5.0503**	**0.2030**	**0.1980**	**1.9900**
6	0.9705	5.8964	14.6552	1.0304	6.0755	0.1696	0.1646	2.4855
7	0.9657	6.8621	20.4493	1.0355	7.1059	0.1457	0.1407	2.9801
8	0.9609	7.8230	27.1755	1.0407	8.1414	0.1278	0.1228	3.4738
9	0.9561	8.7791	34.8244	1.0459	9.1821	0.1139	0.1089	3.9668
10	**0.9513**	**9.7304**	**43.3865**	**1.0511**	**10.2280**	**0.1028**	**0.0978**	**4.4589**
11	0.9466	10.6770	52.8526	1.0564	11.2792	0.0937	0.0887	4.9501
12	0.9419	11.6189	63.2136	1.0617	12.3356	0.0861	0.0811	5.4406
13	0.9372	12.5562	74.4602	1.0670	13.3972	0.0796	0.0746	5.9302
14	0.9326	13.4887	86.5835	1.0723	14.4642	0.0741	0.0691	6.4190
15	**0.9279**	**14.4166**	**99.5743**	**1.0777**	**15.5365**	**0.0694**	**0.0644**	**6.9069**
16	0.9233	15.3399	113.4238	1.0831	16.6142	0.0652	0.0602	7.3940
17	0.9187	16.2586	128.1231	1.0885	17.6973	0.0615	0.0565	7.8803
18	0.9141	17.1728	143.6634	1.0939	18.7858	0.0582	0.0532	8.3658
19	0.9096	18.0824	160.0360	1.0994	19.8797	0.0553	0.0503	8.8504
20	**0.9051**	**18.9874**	**177.2322**	**1.1049**	**20.9791**	**0.0527**	**0.0477**	**9.3342**
21	0.9006	19.8880	195.2434	1.1104	22.0840	0.0503	0.0453	9.8172
22	0.8961	20.7841	214.0611	1.1160	23.1944	0.0481	0.0431	10.2993
23	0.8916	21.6757	233.6768	1.1216	24.3104	0.0461	0.0411	10.7806
24	0.8872	22.5629	254.0820	1.1272	25.4320	0.0443	0.0393	11.2611
25	**0.8828**	**23.4456**	**275.2686**	**1.1328**	**26.5591**	**0.0427**	**0.0377**	**11.7407**
30	0.8610	27.7941	392.6324	1.1614	32.2800	0.0360	0.0310	14.1265
40	0.8191	36.1722	681.3347	1.2208	44.1588	0.0276	0.0226	18.8359
50	0.7793	44.1428	1,035.6966	1.2832	56.6452	0.0227	0.0177	23.4624
60	0.7414	51.7256	1,448.6458	1.3489	69.7700	0.0193	0.0143	28.0064
100	**0.6073**	**78.5426**	**3,562.7934**	**1.6467**	**129.3337**	**0.0127**	**0.0077**	**45.3613**

Factor Table - *i* = 1.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9901	0.9901	0.0000	1.0100	1.0000	1.0100	1.0000	0.0000
2	0.9803	1.9704	0.9803	1.0201	2.0100	0.5075	0.4975	0.4975
3	0.9706	2.9410	2.9215	1.0303	3.0301	0.3400	0.3300	0.9934
4	0.9610	3.9020	5.8044	1.0406	4.0604	0.2563	0.2463	1.4876
5	**0.9515**	**4.8534**	**9.6103**	**1.0510**	**5.1010**	**0.2060**	**0.1960**	**1.9801**
6	0.9420	5.7955	14.3205	1.0615	6.1520	0.1725	0.1625	2.4710
7	0.9327	6.7282	19.9168	1.0721	7.2135	0.1486	0.1386	2.9602
8	0.9235	7.6517	26.3812	1.0829	8.2857	0.1307	0.1207	3.4478
9	0.9143	8.5650	33.6959	1.0937	9.3685	0.1167	0.1067	3.9337
10	**0.9053**	**9.4713**	**41.8435**	**1.1046**	**10.4622**	**0.1056**	**0.0956**	**4.4179**
11	0.8963	10.3676	50.8067	1.1157	11.5668	0.0965	0.0865	4.9005
12	0.8874	11.2551	60.5687	1.1268	12.6825	0.0888	0.0788	5.3815
13	0.8787	12.1337	71.1126	1.1381	13.8093	0.0824	0.0724	5.8607
14	0.8700	13.0037	82.4221	1.1495	14.9474	0.0769	0.0669	6.3384
15	**0.8613**	**13.8651**	**94.4810**	**1.1610**	**16.0969**	**0.0721**	**0.0621**	**6.8143**
16	0.8528	14.7179	107.2734	1.1726	17.2579	0.0679	0.0579	7.2886
17	0.8444	15.5623	120.7834	1.1843	18.4304	0.0643	0.0543	7.7613
18	0.8360	16.3983	134.9957	1.1961	19.6147	0.0610	0.0510	8.2323
19	0.8277	17.2260	149.8950	1.2081	20.8109	0.0581	0.0481	8.7017
20	**0.8195**	**18.0456**	**165.4664**	**1.2202**	**22.0190**	**0.0554**	**0.0454**	**9.1694**
21	0.8114	18.8570	181.6950	1.2324	23.2392	0.0530	0.0430	9.6354
22	0.8034	19.6604	198.5663	1.2447	24.4716	0.0509	0.0409	10.0998
23	0.7954	20.4558	216.0660	1.2572	25.7163	0.0489	0.0389	10.5626
24	0.7876	21.2434	234.1800	1.2697	26.9735	0.0471	0.0371	11.0237
25	**0.7798**	**22.0232**	**252.8945**	**1.2824**	**28.2432**	**0.0454**	**0.0354**	**11.4831**
30	0.7419	25.8077	355.0021	1.3478	34.7849	0.0387	0.0277	13.7557
40	0.6717	32.8347	596.8561	1.4889	48.8864	0.0305	0.0205	18.1776
50	0.6080	39.1961	879.4176	1.6446	64.4632	0.0255	0.0155	22.4363
60	0.5504	44.9550	1,192.8061	1.8167	81.6697	0.0222	0.0122	26.5333
100	**0.3697**	**63.0289**	**2,605.7758**	**2.7048**	**170.4814**	**0.0159**	**0.0059**	**41.3426**

Factor Table - *i* = 1.50%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9852	0.9852	0.0000	1.0150	1.0000	1.0150	1.0000	0.0000
2	0.9707	1.9559	0.9707	1.0302	2.0150	0.5113	0.4963	0.4963
3	0.9563	2.9122	2.8833	1.0457	3.0452	0.3434	0.3284	0.9901
4	0.9422	3.8544	5.7098	1.0614	4.0909	0.2594	0.2444	1.4814
5	**0.9283**	**4.7826**	**9.4229**	**1.0773**	**5.1523**	**0.2091**	**0.1941**	**1.9702**
6	0.9145	5.6972	13.9956	1.0934	6.2296	0.1755	0.1605	2.4566
7	0.9010	6.5982	19.4018	1.1098	7.3230	0.1516	0.1366	2.9405
8	0.8877	7.4859	26.6157	1.1265	8.4328	0.1336	0.1186	3.4219
9	0.8746	8.3605	32.6125	1.1434	9.5593	0.1196	0.1046	3.9008
10	**0.8617**	**9.2222**	**40.3675**	**1.1605**	**10.7027**	**0.1084**	**0.0934**	**4.3772**
11	0.8489	10.0711	48.8568	1.1779	11.8633	0.0993	0.0843	4.8512
12	0.8364	10.9075	58.0571	1.1956	13.0412	0.0917	0.0767	5.3227
13	0.8240	11.7315	67.9454	1.2136	14.2368	0.0852	0.0702	5.7917
14	0.8118	12.5434	78.4994	1.2318	15.4504	0.0797	0.0647	6.2582
15	**0.7999**	**13.3432**	**89.6974**	**1.2502**	**16.6821**	**0.0749**	**0.0599**	**6.7223**
16	0.7880	14.1313	101.5178	1.2690	17.9324	0.0708	0.0558	7.1839
17	0.7764	14.9076	113.9400	1.2880	19.2014	0.0671	0.0521	7.6431
18	0.7649	15.6726	126.9435	1.3073	20.4894	0.0638	0.0488	8.0997
19	0.7536	16.4262	140.5084	1.3270	21.7967	0.0609	0.0459	8.5539
20	**0.7425**	**17.1686**	**154.6154**	**1.3469**	**23.1237**	**0.0582**	**0.0432**	**9.0057**
21	0.7315	17.9001	169.2453	1.3671	24.4705	0.0559	0.0409	9.4550
22	0.7207	18.6208	184.3798	1.3876	25.8376	0.0537	0.0387	9.9018
23	0.7100	19.3309	200.0006	1.4084	27.2251	0.0517	0.0367	10.3462
24	0.6995	20.0304	216.0901	1.4295	28.6335	0.0499	0.0349	10.7881
25	**0.6892**	**20.7196**	**232.6310**	**1.4509**	**30.0630**	**0.0483**	**0.0333**	**11.2276**
30	0.6398	24.0158	321.5310	1.5631	37.5387	0.0416	0.0266	13.3883
40	0.5513	29.9158	524.3568	1.8140	54.2679	0.0334	0.0184	17.5277
50	0.4750	34.9997	749.9636	2.1052	73.6828	0.0286	0.0136	21.4277
60	0.4093	39.3803	988.1674	2.4432	96.2147	0.0254	0.0104	25.0930
100	**0.2256**	**51.6247**	**1,937.4506**	**4.4320**	**228.8030**	**0.0194**	**0.0044**	**37.5295**

Factor Table - *i* = 2.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9804	0.9804	0.0000	1.0200	1.0000	1.0200	1.0000	0.0000
2	0.9612	1.9416	0.9612	1.0404	2.0200	0.5150	0.4950	0.4950
3	0.9423	2.8839	2.8458	1.0612	3.0604	0.3468	0.3268	0.9868
4	0.9238	3.8077	5.6173	1.0824	4.1216	0.2626	0.2426	1.4752
5	**0.9057**	**4.7135**	**9.2403**	**1.1041**	**5.2040**	**0.2122**	**0.1922**	**1.9604**
6	0.8880	5.6014	13.6801	1.1262	6.3081	0.1785	0.1585	2.4423
7	0.8706	6.4720	18.9035	1.1487	7.4343	0.1545	0.1345	2.9208
8	0.8535	7.3255	24.8779	1.1717	8.5830	0.1365	0.1165	3.3961
9	0.8368	8.1622	31.5720	1.1951	9.7546	0.1225	0.1025	3.8681
10	**0.8203**	**8.9826**	**38.9551**	**1.2190**	**10.9497**	**0.1113**	**0.0913**	**4.3367**
11	0.8043	9.7868	46.9977	1.2434	12.1687	0.1022	0.0822	4.8021
12	0.7885	10.5753	55.6712	1.2682	13.4121	0.0946	0.0746	5.2642
13	0.7730	11.3484	64.9475	1.2936	14.6803	0.0881	0.0681	5.7231
14	0.7579	12.1062	74.7999	1.3195	15.9739	0.0826	0.0626	6.1786
15	**0.7430**	**12.8493**	**85.2021**	**1.3459**	**17.2934**	**0.0778**	**0.0578**	**6.6309**
16	0.7284	13.5777	96.1288	1.3728	18.6393	0.0737	0.0537	7.0799
17	0.7142	14.2919	107.5554	1.4002	20.0121	0.0700	0.0500	7.5256
18	0.7002	14.9920	119.4581	1.4282	21.4123	0.0667	0.0467	7.9681
19	0.6864	15.6785	131.8139	1.4568	22.8406	0.0638	0.0438	8.4073
20	**0.6730**	**16.3514**	**144.6003**	**1.4859**	**24.2974**	**0.0612**	**0.0412**	**8.8433**
21	0.6598	17.0112	157.7959	1.5157	25.7833	0.0588	0.0388	9.2760
22	0.6468	17.6580	171.3795	1.5460	27.2990	0.0566	0.0366	9.7055
23	0.6342	18.2922	185.3309	1.5769	28.8450	0.0547	0.0347	10.1317
24	0.6217	18.9139	199.6305	1.6084	30.4219	0.0529	0.0329	10.5547
25	**0.6095**	**19.5235**	**214.2592**	**1.6406**	**32.0303**	**0.0512**	**0.0312**	**10.9745**
30	0.5521	22.3965	291.7164	1.8114	40.5681	0.0446	0.0246	13.0251
40	0.4529	27.3555	461.9931	2.2080	60.4020	0.0366	0.0166	16.8885
50	0.3715	31.4236	642.3606	2.6916	84.5794	0.0318	0.0118	20.4420
60	0.3048	34.7609	823.6975	3.2810	114.0515	0.0288	0.0088	23.6961
100	**0.1380**	**43.0984**	**1,464.7527**	**7.2446**	**312.2323**	**0.0232**	**0.0032**	**33.9863**

Factor Table - *i* = 4.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9615	0.9615	0.0000	1.0400	1.0000	1.0400	1.0000	0.0000
2	0.9246	1.8861	0.9246	1.0816	2.0400	0.5302	0.4902	0.4902
3	0.8890	2.7751	2.7025	1.1249	3.1216	0.3603	0.3203	0.9739
4	0.8548	3.6299	5.2670	1.1699	4.2465	0.2755	0.2355	1.4510
5	0.8219	4.4518	8.5547	1.2167	5.4163	0.2246	0.1846	1.9216
6	0.7903	5.2421	12.5062	1.2653	6.6330	0.1908	0.1508	2.3857
7	0.7599	6.0021	17.0657	1.3159	7.8983	0.1666	0.1266	2.8433
8	0.7307	6.7327	22.1806	1.3686	9.2142	0.1485	0.1085	3.2944
9	0.7026	7.4353	27.8013	1.4233	10.5828	0.1345	0.0945	3.7391
10	0.6756	8.1109	33.8814	1.4802	12.0061	0.1233	0.0833	4.1773
11	0.6496	8.7605	40.3772	1.5395	13.4864	0.1141	0.0741	4.6090
12	0.6246	9.3851	47.2477	1.6010	15.0258	0.1066	0.0666	5.0343
13	0.6006	9.9856	54.4546	1.6651	16.6268	0.1001	0.0601	5.4533
14	0.5775	10.5631	61.9618	1.7317	18.2919	0.0947	0.0547	5.8659
15	0.5553	11.1184	69.7355	1.8009	20.0236	0.0899	0.0499	6.2721
16	0.5339	11.6523	77.7441	1.8730	21.8245	0.0858	0.0458	6.6720
17	0.5134	12.1657	85.9581	1.9479	23.6975	0.0822	0.0422	7.0656
18	0.4936	12.6593	94.3498	2.0258	25.6454	0.0790	0.0390	7.4530
19	0.4746	13.1339	102.8933	2.1068	27.6712	0.0761	0.0361	7.8342
20	0.4564	13.5903	111.5647	2.1911	29.7781	0.0736	0.0336	8.2091
21	0.4388	14.0292	120.3414	2.2788	31.9692	0.0713	0.0313	8.5779
22	0.4220	14.4511	129.2024	2.3699	34.2480	0.0692	0.0292	8.9407
23	0.4057	14.8568	138.1284	2.4647	36.6179	0.0673	0.0273	9.2973
24	0.3901	15.2470	147.1012	2.5633	39.0826	0.0656	0.0256	9.6479
25	0.3751	15.6221	156.1040	2.6658	41.6459	0.0640	0.0240	9.9925
30	0.3083	17.2920	201.0618	3.2434	56.0849	0.0578	0.0178	11.6274
40	0.2083	19.7928	286.5303	4.8010	95.0255	0.0505	0.0105	14.4765
50	0.1407	21.4822	361.1638	7.1067	152.6671	0.0466	0.0066	16.8122
60	0.0951	22.6235	422.9966	10.5196	237.9907	0.0442	0.0042	18.6972
100	0.0198	24.5050	563.1249	50.5049	1,237.6237	0.0408	0.0008	22.9800

Factor Table - *i* = 6.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9434	0.9434	0.0000	1.0600	1.0000	1.0600	1.0000	0.0000
2	0.8900	1.8334	0.8900	1.1236	2.0600	0.5454	0.4854	0.4854
3	0.8396	2.6730	2.5692	1.1910	3.1836	0.3741	0.3141	0.9612
4	0.7921	3.4651	4.9455	1.2625	4.3746	0.2886	0.2286	1.4272
5	0.7473	4.2124	7.9345	1.3382	5.6371	0.2374	0.1774	1.8836
6	0.7050	4.9173	11.4594	1.4185	6.9753	0.2034	0.1434	2.3304
7	0.6651	5.5824	15.4497	1.5036	8.3938	0.1791	0.1191	2.7676
8	0.6274	6.2098	19.8416	1.5938	9.8975	0.1610	0.1010	3.1952
9	0.5919	6.8017	24.5768	1.6895	11.4913	0.1470	0.0870	3.6133
10	0.5584	7.3601	29.6023	1.7908	13.1808	0.1359	0.0759	4.0220
11	0.5268	7.8869	34.8702	1.8983	14.9716	0.1268	0.0668	4.4213
12	0.4970	8.3838	40.3369	2.0122	16.8699	0.1193	0.0593	4.8113
13	0.4688	8.8527	45.9629	2.1329	18.8821	0.1130	0.0530	5.1920
14	0.4423	9.2950	51.7128	2.2609	21.0151	0.1076	0.0476	5.5635
15	0.4173	9.7122	57.5546	2.3966	23.2760	0.1030	0.0430	5.9260
16	0.3936	10.1059	63.4592	2.5404	25.6725	0.0990	0.0390	6.2794
17	0.3714	10.4773	69.4011	2.6928	28.2129	0.0954	0.0354	6.6240
18	0.3505	10.8276	75.3569	2.8543	30.9057	0.0924	0.0324	6.9597
19	0.3305	11.1581	81.3062	3.0256	33.7600	0.0896	0.0296	7.2867
20	0.3118	11.4699	87.2304	3.2071	36.7856	0.0872	0.0272	7.6051
21	0.2942	11.7641	93.1136	3.3996	39.9927	0.0850	0.0250	7.9151
22	0.2775	12.0416	98.9412	3.6035	43.3923	0.0830	0.0230	8.2166
23	0.2618	12.3034	104.7007	3.8197	46.9958	0.0813	0.0213	8.5099
24	0.2470	12.5504	110.3812	4.0489	50.8156	0.0797	0.0197	8.7951
25	0.2330	12.7834	115.9732	4.2919	54.8645	0.0782	0.0182	9.0722
30	0.1741	13.7648	142.3588	5.7435	79.0582	0.0726	0.0126	10.3422
40	0.0972	15.0463	185.9568	10.2857	154.7620	0.0665	0.0065	12.3590
50	0.0543	15.7619	217.4574	18.4202	290.3359	0.0634	0.0034	13.7964
60	0.0303	16.1614	239.0428	32.9877	533.1282	0.0619	0.0019	14.7909
100	0.0029	16.6175	272.0471	339.3021	5,638.3681	0.0602	0.0002	16.3711

Factor Table - *i* = 8.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9259	0.9259	0.0000	1.0800	1.0000	1.0800	1.0000	0.0000
2	0.8573	1.7833	0.8573	1.1664	2.0800	0.5608	0.4808	0.4808
3	0.7938	2.5771	2.4450	1.2597	3.2464	0.3880	0.3080	0.9487
4	0.7350	3.3121	4.6501	1.3605	4.5061	0.3019	0.2219	1.4040
5	0.6806	3.9927	7.3724	1.4693	5.8666	0.2505	0.1705	1.8465
6	0.6302	4.6229	10.5233	1.5869	7.3359	0.2163	0.1363	2.2763
7	0.5835	5.2064	14.0242	1.7138	8.9228	0.1921	0.1121	2.6937
8	0.5403	5.7466	17.8061	1.8509	10.6366	0.1740	0.0940	3.0985
9	0.5002	6.2469	21.8081	1.9990	12.4876	0.1601	0.0801	3.4910
10	0.4632	6.7101	25.9768	2.1589	14.4866	0.1490	0.0690	3.8713
11	0.4289	7.1390	30.2657	2.3316	16.6455	0.1401	0.0601	4.2395
12	0.3971	7.5361	34.6339	2.5182	18.9771	0.1327	0.0527	4.5957
13	0.3677	7.9038	39.0463	2.7196	21.4953	0.1265	0.0465	4.9402
14	0.3405	8.2442	43.4723	2.9372	24.2149	0.1213	0.0413	5.2731
15	0.3152	8.5595	47.8857	3.1722	27.1521	0.1168	0.0368	5.5945
16	0.2919	8.8514	52.2640	3.4259	30.3243	0.1130	0.0330	5.9046
17	0.2703	9.1216	56.5883	3.7000	33.7502	0.1096	0.0296	6.2037
18	0.2502	9.3719	60.8426	3.9960	37.4502	0.1067	0.0267	6.4920
19	0.2317	9.6036	65.0134	4.3157	41.4463	0.1041	0.0241	6.7697
20	0.2145	9.8181	69.0898	4.6610	45.7620	0.1019	0.0219	7.0369
21	0.1987	10.0168	73.0629	5.0338	50.4229	0.0998	0.0198	7.2940
22	0.1839	10.2007	76.9257	5.4365	55.4568	0.0980	0.0180	7.5412
23	0.1703	10.3711	80.6726	5.8715	60.8933	0.0964	0.0164	7.7786
24	0.1577	10.5288	84.2997	6.3412	66.7648	0.0950	0.0150	8.0066
25	0.1460	10.6748	87.8041	6.8485	73.1059	0.0937	0.0137	8.2254
30	0.0994	11.2578	103.4558	10.0627	113.2832	0.0888	0.0088	9.1897
40	0.0460	11.9246	126.0422	21.7245	259.0565	0.0839	0.0039	10.5699
50	0.0213	12.2335	139.5928	46.9016	573.7702	0.0817	0.0017	11.4107
60	0.0099	12.3766	147.3000	101.2571	1,253.2133	0.0808	0.0008	11.9015
100	0.0005	12.4943	155.6107	2,199.7613	27,484.5157	0.0800		12.4545

Factor Table - *i* = 10.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9091	0.9091	0.0000	1.1000	1.0000	1.1000	1.0000	0.0000
2	0.8264	1.7355	0.8264	1.2100	2.1000	0.5762	0.4762	0.4762
3	0.7513	2.4869	2.3291	1.3310	3.3100	0.4021	0.3021	0.9366
4	0.6830	3.1699	4.3781	1.4641	4.6410	0.3155	0.2155	1.3812
5	0.6209	3.7908	6.8618	1.6105	6.1051	0.2638	0.1638	1.8101
6	0.5645	4.3553	9.6842	1.7716	7.7156	0.2296	0.1296	2.2236
7	0.5132	4.8684	12.7631	1.9487	9.4872	0.2054	0.1054	2.6216
8	0.4665	5.3349	16.0287	2.1436	11.4359	0.1874	0.0874	3.0045
9	0.4241	5.7590	19.4215	2.3579	13.5735	0.1736	0.0736	3.3724
10	0.3855	6.1446	22.8913	2.5937	15.9374	0.1627	0.0627	3.7255
11	0.3505	6.4951	26.3962	2.8531	18.5312	0.1540	0.0540	4.0641
12	0.3186	6.8137	29.9012	3.1384	21.3843	0.1468	0.0468	4.3884
13	0.2897	7.1034	33.3772	3.4523	24.5227	0.1408	0.0408	4.6988
14	0.2633	7.3667	36.8005	3.7975	27.9750	0.1357	0.0357	4.9955
15	0.2394	7.6061	40.1520	4.1772	31.7725	0.1315	0.0315	5.2789
16	0.2176	7.8237	43.4164	4.5950	35.9497	0.1278	0.0278	5.5493
17	0.1978	8.0216	46.5819	5.0545	40.5447	0.1247	0.0247	5.8071
18	0.1799	8.2014	49.6395	5.5599	45.5992	0.1219	0.0219	6.0526
19	0.1635	8.3649	52.5827	6.1159	51.1591	0.1195	0.0195	6.2861
20	0.1486	8.5136	55.4069	6.7275	57.2750	0.1175	0.0175	6.5081
21	0.1351	8.6487	58.1095	7.4002	64.0025	0.1156	0.0156	6.7189
22	0.1228	8.7715	60.6893	8.1403	71.4027	0.1140	0.0140	6.9189
23	0.1117	8.8832	63.1462	8.9543	79.5430	0.1126	0.0126	7.1085
24	0.1015	8.9847	65.4813	9.8497	88.4973	0.1113	0.0113	7.2881
25	0.0923	9.0770	67.6964	10.8347	98.3471	0.1102	0.0102	7.4580
30	0.0573	9.4269	77.0766	17.4494	164.4940	0.1061	0.0061	8.1762
40	0.0221	9.7791	88.9525	45.2593	442.5926	0.1023	0.0023	9.0962
50	0.0085	9.9148	94.8889	117.3909	1,163.9085	0.1009	0.0009	9.5704
60	0.0033	9.9672	97.7010	304.4816	3,034.8164	0.1003	0.0003	9.8023
100	0.0001	9.9993	99.9202	13,780.6123	137,796.1234	0.1000		9.9927

Factor Table - *i* = 12.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.8929	0.8929	0.0000	1.1200	1.0000	1.1200	1.0000	0.0000
2	0.7972	1.6901	0.7972	1.2544	2.1200	0.5917	0.4717	0.4717
3	0.7118	2.4018	2.2208	1.4049	3.3744	0.4163	0.2963	0.9246
4	0.6355	3.0373	4.1273	1.5735	4.7793	0.3292	0.2092	1.3589
5	**0.5674**	**3.6048**	**6.3970**	**1.7623**	**6.3528**	**0.2774**	**0.1574**	**1.7746**
6	0.5066	4.1114	8.9302	1.9738	8.1152	0.2432	0.1232	2.1720
7	0.4523	4.5638	11.6443	2.2107	10.0890	0.2191	0.0991	2.5515
8	0.4039	4.9676	14.4714	2.4760	12.2997	0.2013	0.0813	2.9131
9	0.3606	5.3282	17.3563	2.7731	14.7757	0.1877	0.0677	3.2574
10	**0.3220**	**5.6502**	**20.2541**	**3.1058**	**17.5487**	**0.1770**	**0.0570**	**3.5847**
11	0.2875	5.9377	23.1288	3.4785	20.6546	0.1684	0.0484	3.8953
12	0.2567	6.1944	25.9523	3.8960	24.1331	0.1614	0.0414	4.1897
13	0.2292	6.4235	28.7024	4.3635	28.0291	0.1557	0.0357	4.4683
14	0.2046	6.6282	31.3624	4.8871	32.3926	0.1509	0.0309	4.7317
15	**0.1827**	**6.8109**	**33.9202**	**5.4736**	**37.2797**	**0.1468**	**0.0268**	**4.9803**
16	0.1631	6.9740	36.3670	6.1304	42.7533	0.1434	0.0234	5.2147
17	0.1456	7.1196	38.6973	6.8660	48.8837	0.1405	0.0205	5.4353
18	0.1300	7.2497	40.9080	7.6900	55.7497	0.1379	0.0179	5.6427
19	0.1161	7.3658	42.9979	8.6128	63.4397	0.1358	0.0158	5.8375
20	**0.1037**	**7.4694**	**44.9676**	**9.6463**	**72.0524**	**0.1339**	**0.0139**	**6.0202**
21	0.0926	7.5620	46.8188	10.8038	81.6987	0.1322	0.0122	6.1913
22	0.0826	7.6446	48.5543	12.1003	92.5026	0.1308	0.0108	6.3514
23	0.0738	7.7184	50.1776	13.5523	104.6029	0.1296	0.0096	6.5010
24	0.0659	7.7843	51.6929	15.1786	118.1552	0.1285	0.0085	6.6406
25	**0.0588**	**7.8431**	**53.1046**	**17.0001**	**133.3339**	**0.1275**	**0.0075**	**6.7708**
30	0.0334	8.0552	58.7821	29.9599	241.3327	0.1241	0.0041	7.2974
40	0.0107	8.2438	65.1159	93.0510	767.0914	0.1213	0.0013	7.8988
50	0.0035	8.3045	67.7624	289.0022	2,400.0182	0.1204	0.0004	8.1597
60	0.0011	8.3240	68.8100	897.5969	7,471.6411	0.1201	0.0001	8.2664
100		**8.3332**	**69.4336**	**83,522.2657**	**696,010.5477**	**0.1200**		**8.3321**

Factor Table - *i* = 18.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.8475	0.8475	0.0000	1.1800	1.0000	1.1800	1.0000	0.0000
2	0.7182	1.5656	0.7182	1.3924	2.1800	0.6387	0.4587	0.4587
3	0.6086	2.1743	1.9354	1.6430	3.5724	0.4599	0.2799	0.8902
4	0.5158	2.6901	3.4828	1.9388	5.2154	0.3717	0.1917	1.2947
5	**0.4371**	**3.1272**	**5.2312**	**2.2878**	**7.1542**	**0.3198**	**0.1398**	**1.6728**
6	0.3704	3.4976	7.0834	2.6996	9.4423	0.2859	0.1059	2.0252
7	0.3139	3.8115	8.9670	3.1855	12.1415	0.2624	0.0824	2.3526
8	0.2660	4.0776	10.8292	3.7589	15.3270	0.2452	0.0652	2.6558
9	0.2255	4.3030	12.6329	4.4355	19.0859	0.2324	0.0524	2.9358
10	**0.1911**	**4.4941**	**14.3525**	**5.2338**	**23.5213**	**0.2225**	**0.0425**	**3.1936**
11	0.1619	4.6560	15.9716	6.1759	28.7551	0.2148	0.0348	3.4303
12	0.1372	4.7932	17.4811	7.2876	34.9311	0.2086	0.0286	3.6470
13	0.1163	4.9095	18.8765	8.5994	42.2187	0.2037	0.0237	3.8449
14	0.0985	5.0081	20.1576	10.1472	50.8180	0.1997	0.0197	4.0250
15	**0.0835**	**5.0916**	**21.3269**	**11.9737**	**60.9653**	**0.1964**	**0.0164**	**4.1887**
16	0.0708	5.1624	22.3885	14.1290	72.9390	0.1937	0.0137	4.3369
17	0.0600	5.2223	23.3482	16.6722	87.0680	0.1915	0.0115	4.4708
18	0.0508	5.2732	24.2123	19.6731	103.7403	0.1896	0.0096	4.5916
19	0.0431	5.3162	24.9877	23.2144	123.4135	0.1881	0.0081	4.7003
20	**0.0365**	**5.3527**	**25.6813**	**27.3930**	**146.6280**	**0.1868**	**0.0068**	**4.7978**
21	0.0309	5.3837	26.3000	32.3238	174.0210	0.1857	0.0057	4.8851
22	0.0262	5.4099	26.8506	38.1421	206.3448	0.1848	0.0048	4.9632
23	0.0222	5.4321	27.3394	45.0076	244.4868	0.1841	0.0041	5.0329
24	0.0188	5.4509	27.7725	53.1090	289.4944	0.1835	0.0035	5.0950
25	**0.0159**	**5.4669**	**28.1555**	**62.6686**	**342.6035**	**0.1829**	**0.0029**	**5.1502**
30	0.0070	5.5168	29.4864	143.3706	790.9480	0.1813	0.0013	5.3448
40	0.0013	5.5482	30.5269	750.3783	4,163.2130	0.1802	0.0002	5.5022
50	0.0003	5.5541	30.7856	3,927.3569	21,813.0937	0.1800		5.5428
60	0.0001	5.5553	30.8465	20,555.1400	114,189.6665	0.1800		5.5526
100		**5.5556**	**30.8642**	**15,424,131.91**	**85,689,616.17**	**0.1800**		**5.5555**

Critical Path Method (CPM)

d_{ij} = duration of activity (i, j)

CP = critical path (longest path)

T = duration of project

$$T = \sum_{(i,j) \in CP} d_{ij}$$

PERT

(a_{ij}, b_{ij}, c_{ij}) = (optimistic, most likely, pessimistic) durations for activity (i, j)

μ_{ij} = mean duration of activity (i, j)

σ_{ij} = standard deviation of the duration of activity (i, j)

μ = project mean duration

σ = standard deviation of project duration

$$\mu_{ij} = \frac{a_{ij} + 4b_{ij} + c_{ij}}{6}$$

$$\sigma_{ij} = \frac{c_{ij} - a_{ij}}{6}$$

$$\mu = \sum_{(i,j) \in CP} \mu_{ij}$$

$$\sigma^2 = \sum_{(i,j) \in CP} \sigma_{ij}^2$$

Cost Estimation

Cost Indexes

Cost indexes are used to update historical cost data to the present. If a purchase cost is available for an item of equipment in year M, the equivalent current cost would be found by:

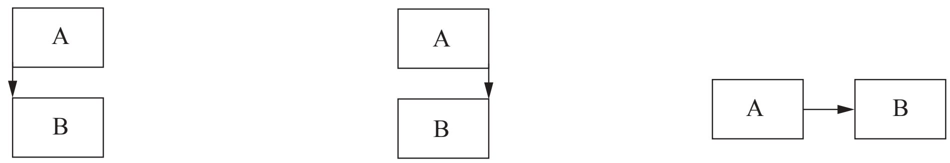
$$\text{Current \$} = (\text{Cost in year } M)\left(\frac{\text{Current Index}}{\text{Index in year } M}\right)$$

Construction

Construction project scheduling and analysis questions may be based on either the activity-on-node method or the activity-on-arrow method.

CPM Precedence Relationships

ACTIVITY-ON-NODE



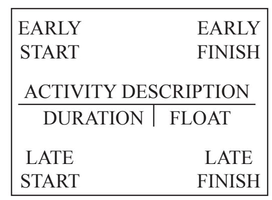
START-TO-START: START OF B DEPENDS ON THE START OF A

FINISH-TO-FINISH: FINISH OF B DEPENDS ON THE FINISH OF A

FINISH-TO-START: START OF B DEPENDS ON THE FINISH OF A

ACTIVITY-ON-ARROW ANNOTATION

ACTIVITY-ON-NODE ANNOTATION



Nomenclature

ES = Early start = Latest EF of predecessors

EF = Early finish = ES + duration

LS = Late start = LF – duration

LF = Late finish = Earliest LS of successors

D = Duration

Float = LS – ES or LF – EF

Earned-Value Analysis

BCWS = Budgeted cost of work scheduled (Planned)

ACWP = Actual cost of work performed (Actual)

BCWP = Budgeted cost of work performed (Earned)

Variances

CV = BCWP – ACWP (Cost variance = Earned – Actual)

SV = BCWP – BCWS (Schedule variance = Earned – Planned)

Indexes

$$CPI = \frac{BCWP}{ACWP} \quad \left(\text{Cost Performance Index} = \frac{\text{Earned}}{\text{Actual}}\right)$$

$$SPI = \frac{BCWP}{BCWS} \quad \left(\text{Schedule Performance Index} = \frac{\text{Earned}}{\text{Planned}}\right)$$

Forecasting

BAC = Original project estimate (Budget at completion)

$$\text{ETC} = \frac{\text{BAC} - \text{BCWP}}{\text{CPI}} \qquad (\text{Estimate to complete})$$

$$\text{EAC} = (\text{ACWP} + \text{ETC}) \qquad (\text{Estimate to complete})$$

Transport Phenomena—Momentum, Heat, and Mass-Transfer Analogy

For the equations that apply to *turbulent flow in circular tubes*, the following definitions apply:

Nu = Nusselt Number = $\frac{hD}{k}$

Pr = Prandtl Number = $\frac{c_p \mu}{k}$

Re = Reynolds Number = $\frac{DV\rho}{\mu}$

Sc = Schmidt Number = $\frac{\mu}{\rho D_m}$

Sh = Sherwood Number = $\frac{k_m D}{D_m}$

St = Stanton Number = $\frac{h}{c_p G}$

c_m = concentration (mol/m^3)

c_p = heat capacity of fluid [J/(kg•K)]

D = tube inside diameter (m)

D_m = diffusion coefficient (m^2/s)

$\left(\frac{dc_m}{dy}\right)_w$ = concentration gradient at the wall (mol/m^4)

$\left(\frac{dT}{dy}\right)_w$ = temperature gradient at the wall (K/m)

$\left(\frac{dv}{dy}\right)_w$ = velocity gradient at the wall (s^{-1})

f = Moody friction factor

G = mass velocity [kg/(m^2•s)]

h = heat-transfer coefficient at the wall [W/(m^2•K)]

k = thermal conductivity of fluid [W/(m•K)]

k_m = mass-transfer coefficient (m/s)

L = length over which pressure drop occurs (m)

$\left(\frac{N}{A}\right)_w$ = inward mass-transfer flux at the wall [mol/(m^2•s)]

$\left(\frac{\dot{Q}}{A}\right)_w$ = inward heat-transfer flux at the wall (W/m^2)

y = distance measured from inner wall toward centerline (m)

Δc_m = concentration difference between wall and bulk fluid (mol/m^3)

ΔT = temperature difference between wall and bulk fluid (K)

μ = absolute dynamic viscosity (N•s/m^2)

τ_w = shear stress (momentum flux) at the tube wall (N/m^2)

Definitions already introduced also apply.

Rate of Transfer as a Function of Gradients at the Wall

Momentum Transfer

$$\tau_w = -\mu\left(\frac{dv}{dy}\right)_w = -\frac{f\rho V^2}{8} = \left(\frac{D}{4}\right)\left(-\frac{\Delta p}{L}\right)_f$$

Heat Transfer

$$\left(\frac{\dot{Q}}{A}\right)_w = -k\left(\frac{dT}{dy}\right)_w$$

Mass Transfer in Dilute Solutions

$$\left(\frac{N}{A}\right)_w = -D_m\left(\frac{dc_m}{dy}\right)_w$$

Rate of Transfer in Terms of Coefficients

Momentum Transfer

$$\tau_w = \frac{f\rho V^2}{8}$$

Heat Transfer

$$\left(\frac{\dot{Q}}{A}\right)_w = h\Delta T$$

Mass Transfer

$$\left(\frac{N}{A}\right)_w = k_m \Delta c_m$$

Use of Friction Factor (f) to Predict Heat-Transfer and Mass-Transfer Coefficients (Turbulent Flow)

Heat Transfer

$$j_H = \left(\frac{\mathrm{Nu}}{\mathrm{RePr}}\right)\mathrm{Pr}^{2/3} = \frac{f}{8}$$

Mass Transfer

$$j_M = \left(\frac{\mathrm{Sh}}{\mathrm{ReSc}}\right)\mathrm{Sc}^{2/3} = \frac{f}{8}$$

Chemistry Definitions

Solubility Product of a slightly soluble substance *AB:*

$$A_mB_n \rightarrow mA^{n+} + nB^{m-}$$

Solubility Product Constant = $K_{SP} = [A^+]^m \, [B^-]^n$

Faraday's Law – One gram equivalent weight of matter is chemically altered at each electrode for 96,485 coulombs, or 1 Faraday, of electricity passed through the electrolyte.

Acids, Bases, and pH

For aqueous solutions:

$$\text{pH} = \log_{10}\left(\frac{1}{[H^+]}\right), \text{ where}$$

$[H^+]$ = molar concentration of hydrogen ion, in gram moles per liter. *Acids* have pH < 7. *Bases* have pH > 7.

Periodic Table of Elements

Key: Atomic Number / **Symbol** / Atomic Weight

I	II											III	IV	V	VI	VII	VIII
1 **H** 1.0079																	2 **He** 4.0026
3 **Li** 6.941	4 **Be** 9.0122											5 **B** 10.811	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.179
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.981	14 **Si** 28.086	15 **P** 30.974	16 **S** 32.066	17 **Cl** 35.453	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.88	23 **V** 50.941	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.847	27 **Co** 58.933	28 **Ni** 58.69	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.61	33 **As** 74.921	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57–71	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.85	75 **Re** 186.21	76 **Os** 190.2	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.02	89–103	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (269)	111 **Rg** (272)	112 **Cn** (277)	113 **Uut** unknown	114 **Fl** (289)	115 **Uup** unknown	116 **Lv** (298)	117 **Uus** unknown	118 **Uuo** unknown

Lanthanide Series	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.92	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
Actinide Series	89 **Ac** 227.03	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** 237.05	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)

Important Families of Organic Compounds

	FAMILY											
	Alkane	**Alkene**	**Alkyne**	**Arene**	**Haloalkane**	**Alcohol**	**Ether**	**Amine**	**Aldehyde**	**Ketone**	**Carboxylic Acid**	**Ester**
Specific Example	CH_3CH_3	$H_2C = CH_2$	$HC \equiv CH$		CH_3CH_2Cl	CH_3CH_2OH	CH_3OCH_3	CH_3NH_2	$CH_3\overset{O}{\overset{\Vert}{C}}H$	$CH_3\overset{O}{\overset{\Vert}{C}}CH_3$	$CH_3\overset{O}{\overset{\Vert}{C}}OH$	$CH_3\overset{O}{\overset{\Vert}{C}}OCH_3$
IUPAC Name	Ethane	Ethene or Ethylene	Ethyne or Acetylene	Benzene	Chloroethane	Ethanol	Methoxy-methane	Methan-amine	Ethanal	Acetone	Ethanoic Acid	Methyl ethanoate
Common Name	Ethane	Ethylene	Acetylene	Benzene	Ethyl chloride	Ethyl alcohol	Dimethyl ether	Methyl-amine	Acetal-dehyde	Dimethyl ketone	Acetic Acid	Methyl acetate
General Formula	RH	$RCH = CH_2$ $RCH = CHR$ $R_2C = CHR$ $R_2C = CR_2$	$RC \equiv CH$ $RC \equiv CR$	ArH	RX	ROH	ROR	RNH_2 R_2NH R_3N	$R\overset{O}{\overset{\Vert}{C}}H$	$R_1\overset{O}{\overset{\Vert}{C}}R_2$	$R\overset{O}{\overset{\Vert}{C}}OH$	$R\overset{O}{\overset{\Vert}{C}}OR$
Functional Group	C–H and C–C bonds	$\diagdown C = C \diagup$ $\diagup \quad \diagdown$	$- C \equiv C -$	Aromatic Ring	$-\overset{\vert}{\underset{\vert}{C}}- X$	$-\overset{\vert}{\underset{\vert}{C}}- OH$	$-\overset{\vert}{\underset{\vert}{C}}-O-\overset{\vert}{\underset{\vert}{C}}-$	$-\overset{\vert}{\underset{\vert}{C}}-\underset{\vert}{N}-$	$-\overset{O}{\overset{\Vert}{C}}- H$	$-\overset{O}{\overset{\Vert}{C}}-$	$-\overset{O}{\overset{\Vert}{C}}- OH$	$-\overset{O}{\overset{\Vert}{C}}-O-\overset{\vert}{\underset{\vert}{C}}-$

Common Names and Molecular Formulas of Some Industrial (Inorganic and Organic) Chemicals

Common Name	Chemical Name	Molecular Formula
Muriatic acid	Hydrochloric acid	HCl
Cumene	Isopropyl benzene	$C_6H_5CH(CH_3)_2$
Styrene	Vinyl benzene	$C_6H_5CH{=}CH_2$
—	Hypochlorite ion	OCl^{-1}
—	Chlorite ion	ClO_2^{-1}
—	Chlorate ion	ClO_3^{-1}
—	Perchlorate ion	ClO_4^{-1}
Gypsum	Calcium sulfate	$CaSO_4$
Limestone	Calcium carbonate	$CaCO_3$
Dolomite	Magnesium carbonate	$MgCO_3$
Bauxite	Aluminum oxide	Al_2O_3
Anatase	Titanium dioxide	TiO_2
Rutile	Titanium dioxide	TiO_2
—	Vinyl chloride	$CH_2{=}CHCl$
—	Ethylene oxide	C_2H_4O
Pyrite	Ferrous sulfide	FeS
Epsom salt	Magnesium sulfate	$MgSO_4$
Hydroquinone	p-Dihydroxy benzene	$C_6H_4(OH)_2$
Soda ash	Sodium carbonate	Na_2CO_3
Salt	Sodium chloride	$NaCl$
Potash	Potassium carbonate	K_2CO_3
Baking soda	Sodium bicarbonate	$NaHCO_3$
Lye	Sodium hydroxide	$NaOH$
Caustic soda	Sodium hydroxide	$NaOH$
—	Vinyl alcohol	$CH_2{=}CHOH$
Carbolic acid	Phenol	C_6H_5OH
Aniline	Aminobenzene	$C_6H_5NH_2$
—	Urea	$(NH_2)_2CO$
Toluene	Methyl benzene	$C_6H_5CH_3$
Xylene	Dimethyl benzene	$C_6H_4(CH_3)_2$
—	Silane	SiH_4
—	Ozone	O_3
Neopentane	2,2-Dimethylpropane	$CH_3C(CH_3)_2CH_3$
Magnetite	Ferrous/ferric oxide	Fe_3O_4
Quicksilver	Mercury	Hg
Heavy water	Deuterium oxide	$(H^2)_2O$
—	Borane	BH_3
Eyewash	Boric acid (solution)	H_3BO_3
—	Deuterium	H^2
—	Tritium	H^3
Laughing gas	Nitrous oxide	N_2O
—	Phosgene	$COCl_2$
Wolfram	Tungsten	W
—	Permanganate ion	MnO_4^{-1}
—	Dichromate ion	$Cr_2O_7^{-2}$
—	Hydronium ion	H_3O^{+1}
Brine	Sodium chloride (solution)	$NaCl$
Battery acid	Sulfuric acid	H_2SO_4

Properties of Metals

Metal	Symbol	Atomic Weight	Density ρ (kg/m^3) Water = 1000	Melting Point (°C)	Melting Point (°F)	Specific Heat [J/(kg·K)]	Electrical Resistivity (10^{-8} Ω·m) at 0°C (273.2 K)	Heat Conductivity λ[W/(m·K)] at 0°C (273.2 K)
Aluminum	Al	26.98	2,698	660	1,220	895.9	2.5	236
Antimony	Sb	121.75	6,692	630	1,166	209.3	39	25.5
Arsenic	As	74.92	5,776	subl. 613	subl. 1,135	347.5	26	–
Barium	Ba	137.33	3,594	710	1,310	284.7	36	–
Beryllium	Be	9.012	1,846	1,285	2,345	2,051.5	2.8	218
Bismuth	Bi	208.98	9,803	271	519	125.6	107	8.2
Cadmium	Cd	112.41	8,647	321	609	234.5	6.8	97
Caesium	Cs	132.91	1,900	29	84	217.7	18.8	36
Calcium	Ca	40.08	1,530	840	1,544	636.4	3.2	–
Cerium	Ce	140.12	6,711	800	1,472	188.4	7.3	11
Chromium	Cr	52	7,194	1,860	3,380	406.5	12.7	96.5
Cobalt	Co	58.93	8,800	1,494	2,721	431.2	5.6	105
Copper	Cu	63.54	8,933	1,084	1,983	389.4	1.55	403
Gallium	Ga	69.72	5,905	30	86	330.7	13.6	41
Gold	Au	196.97	19,281	1,064	1,947	129.8	2.05	319
Indium	In	114.82	7,290	156	312	238.6	8	84
Iridium	Ir	192.22	22,550	2,447	4,436	138.2	4.7	147
Iron	Fe	55.85	7,873	1,540	2,804	456.4	8.9	83.5
Lead	Pb	207.2	11,343	327	620	129.8	19.2	36
Lithium	Li	6.94	533	180	356	4,576.2	8.55	86
Magnesium	Mg	24.31	1,738	650	1,202	1,046.7	3.94	157
Manganese	Mn	54.94	7,473	1,250	2,282	502.4	138	8
Mercury	Hg	200.59	13,547	–39	–38	142.3	94.1	7.8
Molybendum	Mo	95.94	10,222	2,620	4,748	272.1	5	139
Nickel	Ni	58.69	8,907	1,455	2,651	439.6	6.2	94
Niobium	Nb	92.91	8,578	2,425	4,397	267.9	15.2	53
Osmium	Os	190.2	22,580	3,030	5,486	129.8	8.1	88
Palladium	Pd	106.4	11,995	1,554	2,829	230.3	10	72
Platinum	Pt	195.08	21,450	1,772	3,221	134	9.81	72
Potassium	K	39.09	862	63	145	753.6	6.1	104
Rhodium	Rh	102.91	12,420	1,963	3,565	242.8	4.3	151
Rubidium	Rb	85.47	1,533	38.8	102	330.7	11	58
Ruthenium	Ru	101.07	12,360	2,310	4,190	255.4	7.1	117
Silver	Ag	107.87	10,500	961	1,760	234.5	1.47	428
Sodium	Na	22.989	966	97.8	208	1,235.1	4.2	142
Strontium	Sr	87.62	2,583	770	1,418	–	20	–
Tantalum	Ta	180.95	16,670	3,000	5,432	150.7	12.3	57
Thallium	Tl	204.38	11,871	304	579	138.2	10	10
Thorium	Th	232.04	11,725	1,700	3,092	117.2	14.7	54
Tin	Sn	118.69	7,285	232	449	230.3	11.5	68
Titanium	Ti	47.88	4,508	1,670	3,038	527.5	39	22
Tungsten	W	183.85	19,254	3,387	6,128	142.8	4.9	177
Uranium	U	238.03	19,050	1,135	2,075	117.2	28	27
Vanadium	V	50.94	6,090	1,920	3,488	481.5	18.2	31
Zinc	Zn	65.38	7,135	419	786	393.5	5.5	117
Zirconium	Zr	91.22	6,507	1,850	3,362	284.7	40	23

Heat Transfer

Energy and Heat

$$Q_t = Q_s + Q_l = mc\Delta T + mh$$

Q_t = total energy (heat)

Q_s = energy to change temperature (sensible heat)

Q_l = energy to change phase (latent heat)

m = mass

c = specific heat (heat capacity)

ΔT = change in temperature

h_{sl} = latent heat of fusion (143.4 Btu/lb for water at 1 atm)

h_{fg} = latent heat of vaporization (970.3 Btu/lb for water at 1 atm)

Conduction

Fourier's Law of Conduction

$$\dot{Q} = -kA\frac{dT}{dx}$$

$\dot{Q}$ = rate of heat transfer (W)

k = thermal conductivity [W/(m•K)]

A = surface area perpendicular to direction of heat transfer (m^2)

Convection

Newton's Law of Cooling

$$\dot{Q} = hA\left(T_w - T_\infty\right)$$

h = convection heat-transfer coefficient of the fluid [W/(m^2•K)]

A = convection surface area (m^2)

T_w = wall surface temperature (K)

T_∞ = bulk fluid temperature (K)

Radiation

The radiation emitted by a body is given by

$$\dot{Q} = \varepsilon\sigma A T^4$$

ε = emissivity of the body

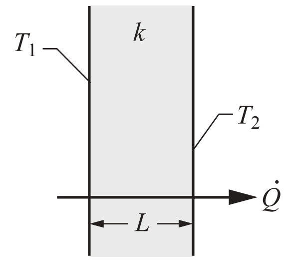
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/(m^2•K^4)

A = body surface area (m^2)

T = absolute temperature (K)

Conduction Through a Plane Wall

$$\dot{Q} = \frac{-kA(T_2 - T_1)}{L}$$



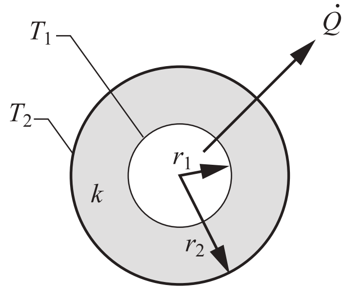
A = wall surface area normal to heat flow (m^2)

L = wall thickness (m)

T_1 = temperature of one surface of the wall (K)

T_2 = temperature of the other surface of the wall (K)

Conduction Through a Cylindrical Wall

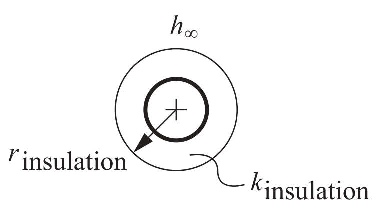


Cylinder (Length = L)

$$\dot{Q} = \frac{2\pi kL(T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)}$$

Critical Insulation Radius

$$r_{cr} = \frac{k_{\text{insulation}}}{h_\infty}$$



Thermal Resistance (R)

$$\dot{Q} = \frac{\Delta T}{R_{\text{total}}}$$

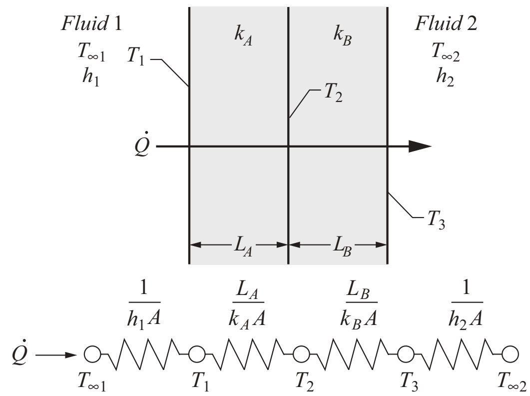
Resistances in series are added: $R_{\text{total}} = \Sigma R$, where

Plane Wall Conduction Resistance (K/W): $R = \frac{L}{kA}$, where L = wall thickness

Cylindrical Wall Conduction Resistance (K/W): $R = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi kL}$, where L = cylinder length

Convection Resistance (K/W): $R = \frac{1}{hA}$

Composite Plane Wall



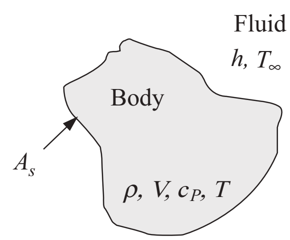
To evaluate surface or intermediate temperatures:

$$\dot{Q} = \frac{T_1 - T_2}{R_A} = \frac{T_2 - T_3}{R_B}$$

Transient Conduction Using the Lumped Capacitance Model

The lumped capacitance model is valid if

Biot number, $\text{Bi} = \dfrac{hV}{kA_s} \ll 1$



h = convection heat-transfer coefficient of the fluid [W/(m^2•K)]

V = volume of the body (m^3)

k = thermal conductivity of the body [W/(m•K)]

A_s = surface area of the body (m^2)

Constant Fluid Temperature

If the temperature may be considered uniform within the body at any time, the heat-transfer rate at the body surface is given by

$$\dot{Q} = hA_s(T - T_\infty) = -\rho V(c_P)\left(\frac{dT}{dt}\right)$$

T = body temperature (K)

T_∞ = fluid temperature (K)

ρ = density of the body (kg/m^3)

c_P = heat capacity of the body [J/(kg•K)]

t = time (s)

The temperature variation of the body with time is

$$T - T_\infty = (T_i - T_\infty)e^{-\beta t}, \text{ where}$$

$$\beta = \frac{hA_s}{\rho V c_P} \qquad \text{where } \beta = \frac{1}{\tau} \text{ and}$$

τ = time constant (s)

The total heat transferred (Q_{total}) up to time t is

$$Q_{total} = \rho V c_P (T_i - T), \text{ where}$$

T_i = initial body temperature (K)

Fins

For a straight fin with uniform cross section (assuming negligible heat transfer from tip),

$$\dot{Q} = \sqrt{hPkA_c}\left(T_b - T_\infty\right)\tanh\left(mL_c\right)$$

h = convection heat-transfer coefficient of the fluid [W/(m^2•K)]

P = perimeter of exposed fin cross section (m)

k = fin thermal conductivity [W/(m•K)]

A_c = fin cross-sectional area (m^2)

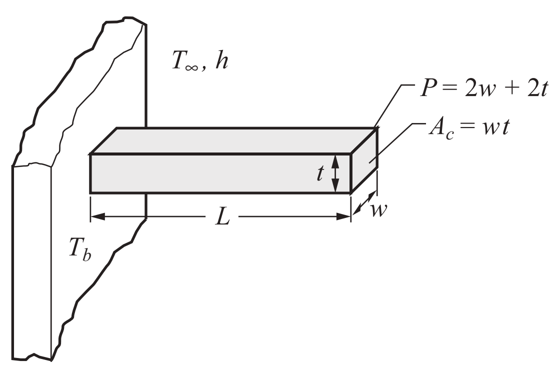
T_b = temperature at base of fin (K)

T_∞ = fluid temperature (K)

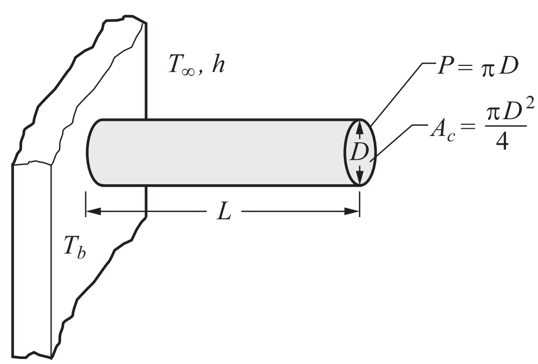
$$m = \sqrt{\frac{hP}{kA_c}}$$

$$L_c = L + \frac{A_c}{P}, \text{ corrected length of fin (m)}$$

Rectangular Fin



Pin Fin



Convection

Terms

D = diameter (m)

$\bar{h}$ = average convection heat-transfer coefficient of the fluid [W/(m^2•K)]

L = length (m)

$\overline{Nu}$ = average Nusselt number

Pr = Prandtl number = $\frac{c_P \mu}{k}$

u_m = mean velocity of fluid (m/s)

u_∞ = free stream velocity of fluid (m/s)

μ = dynamic viscosity of fluid [kg/(s•m)]

ρ = density of fluid (kg/m^3)

External Flow

In all cases, evaluate fluid properties at average temperature between that of the body and that of the flowing fluid.

Flat Plate of Length L in Parallel Flow

$$\mathrm{Re}_L = \frac{\rho u_\infty L}{\mu}$$

$$\overline{Nu}_L = \frac{\bar{h}L}{k} = 0.6640\,\mathrm{Re}_L^{1/2}\,\mathrm{Pr}^{1/3} \qquad \left(\mathrm{Re}_L < 10^5\right)$$

$$\overline{Nu}_L = \frac{\bar{h}L}{k} = 0.0366\,\mathrm{Re}_L^{0.8}\,\mathrm{Pr}^{1/3} \qquad \left(\mathrm{Re}_L > 10^5\right)$$

Cylinder of Diameter D in Cross Flow

$$\mathrm{Re}_D = \frac{\rho u_\infty D}{\mu}$$

$$\overline{Nu}_D = \frac{\bar{h}D}{k} = C\,\mathrm{Re}_D^n\,\mathrm{Pr}^{1/3}, \text{ where}$$

Re_D	C	n
1 – 4	0.989	0.330
4 – 40	0.911	0.385
40 – 4,000	0.683	0.466
4,000 – 40,000	0.193	0.618
40,000 – 250,000	0.0266	0.805

Flow Over a Sphere of Diameter D

$$\overline{Nu}_D = \frac{\bar{h}D}{k} = 2.0 + 0.60\,\mathrm{Re}_D^{1/2}\,\mathrm{Pr}^{1/3},$$

$$\left(1 < \mathrm{Re}_D < 70,000;\, 0.6 < \mathrm{Pr} < 400\right)$$

Internal Flow

$$\text{Re}_D = \frac{\rho u_m D}{\mu}$$

Laminar Flow in Circular Tubes

For laminar flow ($\text{Re}_D < 2{,}300$), fully developed conditions

$Nu_D = 4.36$ (uniform heat flux)

$Nu_D = 3.66$ (constant surface temperature)

For laminar flow ($\text{Re}_D < 2{,}300$), combined entry length with constant surface temperature

$$Nu_D = 1.86\left(\frac{\text{Re}_D \text{Pr}}{\frac{L}{D}}\right)^{1/3}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$$

L = length of tube (m)

D = tube diameter (m)

μ_b = dynamic viscosity of fluid [kg/(s•m)] at bulk temperature of fluid, T_b

μ_s = dynamic viscosity of fluid [kg/(s•m)] at inside surface temperature of the tube, T_s

Turbulent Flow in Circular Tubes

For turbulent flow ($\text{Re}_D > 10^4$, $\text{Pr} > 0.7$) for either uniform surface temperature or uniform heat flux condition, the Sieder-Tate equation offers a good approximation:

$$Nu_D = 0.023\,\text{Re}_D^{0.8}\text{Pr}^{1/3}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$$

Noncircular Ducts

In place of the diameter, D, use the equivalent (hydraulic) diameter (D_H) defined as

$$D_H = \frac{4 \times \text{cross-sectional area}}{\text{wetted perimeter}}$$

Circular Annulus ($D_o > D_i$)

In place of the diameter, D, use the equivalent (hydraulic) diameter (D_H) defined as

$$D_H = D_o - D_i$$

Liquid Metals (0.003 < Pr < 0.05)

$Nu_D = 6.3 + 0.0167\,\text{Re}_D^{0.85}\text{Pr}^{0.93}$ (uniform heat flux)

$Nu_D = 7.0 + 0.025\,\text{Re}_D^{0.8}\text{Pr}^{0.8}$ (constant wall temperature)

Boiling

Evaporation occurring at a solid-liquid interface when $T_{solid} > T_{sat, liquid}$

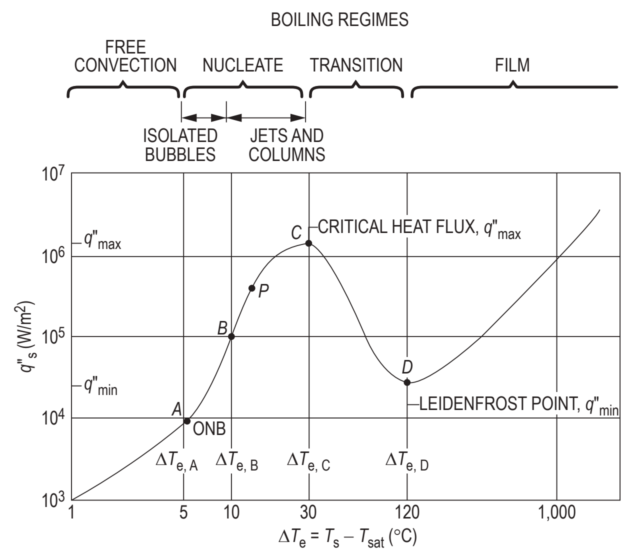
$$q'' = h(T_s - T_{sat}) = h\Delta T_e \text{ , where } \Delta T_e = \text{excess temperature}$$

Pool Boiling – Liquid is quiescent; motion near solid surface is due to free convection and mixing induced by bubble growth and detachment.

Forced Convection Boiling – Fluid motion is induced by external means in addition to free convection and bubble-induced mixing.

Sub-Cooled Boiling – Temperature of liquid is below saturation temperature; bubbles forming at surface may condense in the liquid.

Saturated Boiling – Liquid temperature slightly exceeds the saturation temperature; bubbles forming at the surface are propelled through liquid by buoyancy forces.



Typical boiling curve for water at one atmosphere: surface heat flux q''_s as a function of excess temperature, $\Delta T_e = T_s - T_{sat}$

Incropera, Frank P., and David P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 4th ed., New York: Wiley, 1996. Reproduced with permission of John Wiley & Sons, Inc.

Free Convection Boiling – Insufficient vapor is in contact with the liquid phase to cause boiling at the saturation temperature.

Nucleate Boiling – Isolated bubbles form at nucleation sites and separate from surface; vapor escapes as jets or columns.

For nucleate boiling, a widely used correlation was proposed in 1952 by Rohsenow:

$$\dot{q}_{\text{nucleate}} = \mu_l \, h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{c_{pl}(T_s - T_{\text{sat}})}{C_{sf} \, h_{fg} \, \text{Pr}_l^n} \right]^3$$

$\dot{q}_{\text{nucleate}}$ = nucleate boiling heat flux (W/m^2)

μ_l = viscosity of the liquid [kg/(m•s)]

h_{fg} = enthalpy of vaporization (J/kg)

g = gravitational acceleration (m/s^2)

ρ_l = density of the liquid (kg/m^3)

ρ_v = density of the vapor (kg/m^3)

σ = surface tension of liquid–vapor interface (N/m)

c_{pl} = specific heat of the liquid [J/(kg•°C)]

T_s = surface temperature of the heater (°C)

T_{sat} = saturation temperature of the fluid (°C)

C_{sf} = experimental constant that depends on surface–fluid combination

Pr_l = Prandtl number of the liquid

n = experimental constant that depends on the fluid

Rohsenow, Warren M., Technical Report No. 5: *A Method of Correlating Heat Transfer Data for Surface Boiling of Liquids,* Cambridge: The Office of Naval Research, 1951.

Peak Heat Flux

The maximum (or critical) heat flux (CHF) in nucleate pool boiling:

$$\dot{q}_{\max} = C_{cr} \, h_{fg} \left[\sigma g \rho^2{}_v (\rho_l - \rho_v) \right]^{1/4}$$

C_{cr} is a constant whose value depends on the heater geometry, but generally is about 0.15.

The CHF is independent of the fluid–heating surface combination, as well as the viscosity, thermal conductivity, and specific heat of the liquid.

The CHF increases with pressure up to about one-third of the critical pressure, and then starts to decrease and becomes zero at the critical pressure.

The CHF is proportional to h_{fg}, and large maximum heat fluxes can be obtained using fluids with a large enthalpy of vaporization, such as water.

Zuber, Novak, and Myron Tribus, *Further Remarks on the Stability of Boiling Heat Transfer*, Los Angeles: U.S. Atomic Energy Commission, 1958.

Values of the coefficient C_{cr} for maximum heat flux
(dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9\ K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cyclinder	0.12	Radius	$L^* > 1.2$
Small horizontal cyclinder	$0.12\ L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227\ L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

Minimum Heat Flux

Minimum heat flux, which occurs at the Leidenfrost point, represents the lower limit for the heat flux in the film boiling regime.

The following expression is for the minimum heat flux for a large horizontal plate:

$$\dot{q}_{\min} = 0.09\ \rho_v\ h_{fg}\left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4}$$

The relation above can be in error by 50% or more.

Zuber, Novak, and Myron Tribus, *Further Remarks on the Stability of Boiling Heat Transfer*, Los Angeles: U.S. Atomic Energy Commission, 1958.

Transition Boiling – Rapid bubble formation results in vapor film on surface and oscillation between film and nucleate boiling.

Film Boiling – Surface completely covered by vapor blanket; includes significant radiation through vapor film.

Film Boiling

The heat flux for film boiling on a horizontal cylinder or sphere of diameter D is given by

$$\dot{q}_{\text{film}} = C_{\text{film}}\left[\frac{gk_v^3\ \rho_v(\rho_l - \rho_v)\left[h_{fg} + 0.4c_{pv}(T_s - T_{\text{sat}})\right]}{\mu_v D(T_s - T_{\text{sat}})}\right]^{1/4}(T_s - T_{\text{sat}})$$

$$C_{\text{film}} = \begin{Bmatrix} 0.62 \text{ for horizontal cylinders} \\ 0.67 \text{ for spheres} \end{Bmatrix}$$

Film Condensation of a Pure Vapor

On a Vertical Surface

$$\overline{Nu}_L = \frac{\bar{h}L}{k_l} = 0.943\left[\frac{\rho_l^2 g h_{fg} L^3}{\mu_l k_l(T_{\text{sat}} - T_s)}\right]^{0.25}$$

ρ_l = density of liquid phase of fluid (kg/m^3)

g = gravitational acceleration (9.81 m/s^2)

h_{fg} = latent heat of vaporization (J/kg)

L = length of surface (m)

μ_l = dynamic viscosity of liquid phase of fluid [kg/(s•m)]

k_l = thermal conductivity of liquid phase of fluid [W/(m•K)]

T_{sat} = saturation temperature of fluid (K)

T_s = temperature of vertical surface (K)

Note: Evaluate all liquid properties at the average temperature between the saturated temperature T_{sat} and the surface temperature T_s.

Outside Horizontal Tubes

$$\overline{Nu}_D = \frac{\bar{h}D}{k} = 0.729\left[\frac{\rho_l^2 g h_{fg} D^3}{\mu_l k_l \left(T_{sat} - T_s\right)}\right]^{0.25}$$

D = tube outside diameter (m)

Note: Evaluate all liquid properties at the average temperature between the saturated temperature T_{sat} and the surface temperature T_s.

Natural (Free) Convection

Vertical Flat Plate in Large Body of Stationary Fluid

This equation can also apply to a vertical cylinder of sufficiently large diameter in a large body of stationary fluid.

$$\bar{h} = C\left(\frac{k}{L}\right)Ra_L^n$$

L = length of the plate (cylinder) in the vertical direction

Ra_L = Rayleigh Number = $\dfrac{g\beta\left(T_s - T_\infty\right)L^3}{\upsilon^2}\Pr$

T_s = surface temperature (K)

T_∞ = fluid temperature (K)

β = coefficient of thermal expansion (1/K)

(For an ideal gas: $\beta = \dfrac{2}{T_s + T_\infty}$ with T in absolute temperature)

υ = kinematic viscosity (m^2/s)

Range of Ra_L	C	n
10^4–10^9	0.59	1/4
10^9–10^{13}	0.10	1/3

Long Horizontal Cylinder in Large Body of Stationary Fluid

$$\overline{h} = C\left(\frac{k}{D}\right)\text{Ra}_D^n$$

where

$$\text{Ra}_D = \frac{g\beta\left(T_s - T_\infty\right)D^3}{\upsilon^2}\text{Pr}$$

Ra_D	C	n
10^{-3}–10^{2}	1.02	0.148
10^{2}–10^{4}	0.850	0.188
10^{4}–10^{7}	0.480	0.250
10^{7}–10^{12}	0.125	0.333

Heat Exchangers

The rate of heat transfer in a heat exchanger is

$$\dot{Q} = UAF\Delta T_{lm}$$

A = any convenient reference area (m^2)

F = correction factor for log mean temperature difference for more complex heat exchangers (shell and tube arrangements with several tube or shell passes or cross-flow exchangers with mixed and unmixed flow); otherwise $F = 1$.

U = overall heat-transfer coefficient based on area A and the log mean temperature difference [W/(m^2•K)]

ΔT_{lm} = log mean temperature difference (K)

Overall Heat-Transfer Coefficient for Concentric Tube and Shell-and-Tube Heat Exchangers

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{R_{fi}}{A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi kL} + \frac{R_{fo}}{A_o} + \frac{1}{h_o A_o}$$

A_i = inside area of tubes (m^2)

A_o = outside area of tubes (m^2)

D_i = inside diameter of tubes (m)

D_o = outside diameter of tubes (m)

h_i = convection heat-transfer coefficient for inside of tubes [W/(m^2•K)]

h_o = convection heat-transfer coefficient for outside of tubes [W/(m^2•K)]

k = thermal conductivity of tube material [W/(m•K)]

R_{fi} = fouling factor for inside of tube [(m^2•K)/W]

R_{fo} = fouling factor for outside of tube [(m^2•K)/W]

Log Mean Temperature Difference (LMTD)

For *counterflow* in tubular heat exchangers,

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Ci}) - (T_{Hi} - T_{Co})}{\ln\left(\frac{T_{Ho} - T_{Ci}}{T_{Hi} - T_{Co}}\right)}$$

For *parallel flow* in tubular heat exchangers,

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Co}) - (T_{Hi} - T_{Ci})}{\ln\left(\frac{T_{Ho} - T_{Co}}{T_{Hi} - T_{Ci}}\right)}$$

ΔT_{lm} = log mean temperature difference (K)

T_{Hi} = inlet temperature of the hot fluid (K)

T_{Ho} = outlet temperature of the hot fluid (K)

T_{Ci} = inlet temperature of the cold fluid (K)

T_{Co} = outlet temperature of the cold fluid (K)

Heat Exchanger Effectiveness, ε

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\text{actual heat-transfer rate}}{\text{maximum possible heat-transfer rate}}$$

$$\varepsilon = \frac{C_H(T_{Hi} - T_{Ho})}{C_{\min}(T_{Hi} - T_{Ci})} \quad \text{or} \quad \varepsilon = \frac{C_C(T_{Co} - T_{Ci})}{C_{\min}(T_{Hi} - T_{Ci})}$$

$C = \dot{m}c_P =$ heat capacity rate (W/K)

$C_{\min}$ = smaller of C_C or C_H

Number of Transfer Units (NTU)

$$NTU = \frac{UA}{C_{\min}}$$

Effectiveness-NTU Relations

$$C_r = \frac{C_{\min}}{C_{\max}} = \text{heat capacity ratio}$$

For *parallel flow concentric tube* heat exchanger,

$$\varepsilon = \frac{1 - \exp[-NTU(1 + C_r)]}{1 + C_r}$$

$$NTU = -\frac{\ln[1 - \varepsilon(1 + C_r)]}{1 + C_r}$$

For *counterflow concentric tube* heat exchanger,

$$\varepsilon = \frac{1 - \exp\left[-NTU(1 - C_r)\right]}{1 - C_r\exp\left[-NTU(1 - C_r)\right]} \qquad (C_r < 1)$$

$$\varepsilon = \frac{NTU}{1 + NTU} \qquad (C_r = 1)$$

$$NTU = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right) \qquad (C_r < 1)$$

$$NTU = \frac{\varepsilon}{1 - \varepsilon} \qquad (C_r = 1)$$

Radiation

Types of Bodies

Any Body

For any body: $\alpha + \rho + \tau = 1$

α = absorptivity (ratio of energy absorbed to incident energy)

ρ = reflectivity (ratio of energy reflected to incident energy)

τ = transmissivity (ratio of energy transmitted to incident energy)

Opaque Body

For an opaque body: $\alpha + \rho = 1$

Gray Body

A gray body is one for which

$\alpha = \varepsilon$, $(0 < \alpha < 1; 0 < \varepsilon < 1)$

ε = emissivity of the body

For a gray body: $\varepsilon + \rho = 1$

Real bodies are frequently approximated as gray bodies.

Black Body

A black body is defined as one that absorbs all energy incident upon it. It also emits radiation at the maximum rate for a body of a particular size at a particular temperature. For such a body,

$\alpha = \varepsilon = 1$

Shape Factor (View Factor, Configuration Factor) Relations

Reciprocity Relations

$$A_iF_{ij} = A_jF_{ji}$$

A_i = surface area (m^2) of surface i

F_{ij} = shape factor (view factor, configuration factor); fraction of the radiation leaving surface i that is intercepted by surface j; $0 \le F_{ij} \le 1$

Summation Rule for N Surfaces

$$\sum_{j=1}^{N} F_{ij} = 1$$

Net Energy Exchange by Radiation between Two Bodies

Body Small Compared to its Surroundings

$$\dot{Q}_{12} = \varepsilon\sigma A\left(T_1^4 - T_2^4\right)$$

$\dot{Q}_{12}$ = net heat-transfer rate from the body (W)

ε = emissivity of the body

σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/(m^2•K^4)

A = body surface area (m^2)

T_1 = absolute temperature (K) of the body surface

T_2 = absolute temperature (K) of the surroundings

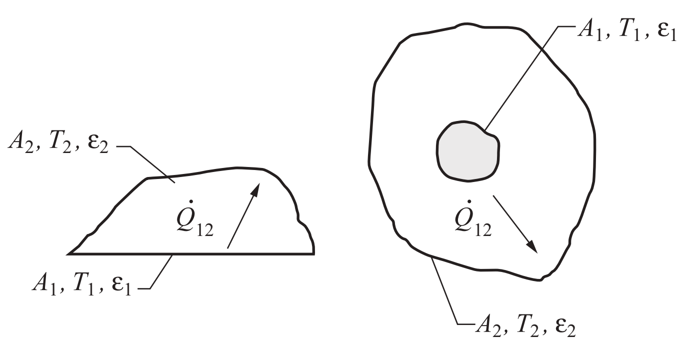
Net Energy Exchange by Radiation between Two Black Bodies

The net energy exchange by radiation between two black bodies that see each other is given by

$$\dot{Q}_{12} = A_1F_{12}\sigma\left(T_1^4 - T_2^4\right)$$

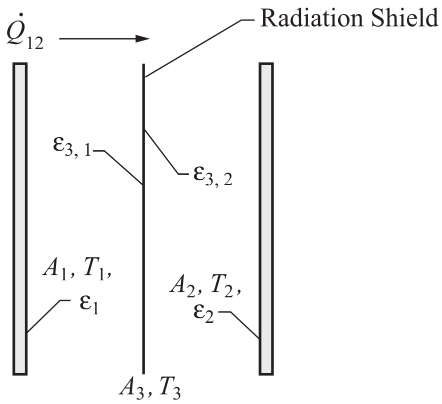
Net Energy Exchange by Radiation between Two Diffuse-Gray Surfaces that Form an Enclosure

Generalized Cases



$$\dot{Q}_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\dfrac{1-\varepsilon_1}{\varepsilon_1A_1} + \dfrac{1}{A_1F_{12}} + \dfrac{1-\varepsilon_2}{\varepsilon_2A_2}}$$

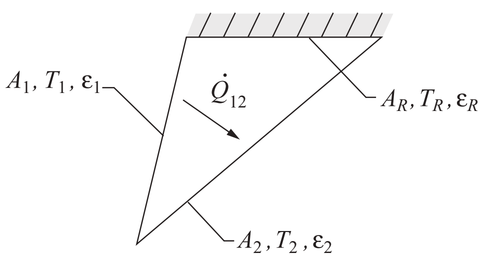
One-Dimensional Geometry with Thin Low-Emissivity Shield Inserted between Two Parallel Plates



$$\dot{Q}_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{13}} + \frac{1-\varepsilon_{3,1}}{\varepsilon_{3,1} A_3} + \frac{1-\varepsilon_{3,2}}{\varepsilon_{3,2} A_3} + \frac{1}{A_3 F_{32}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

Reradiating Surface

Reradiating surfaces are considered to be insulated or adiabatic $\left(\dot{Q}_R = 0\right)$.



$$\dot{Q}_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12} + \left[\left(\frac{1}{A_1 F_{1R}}\right) + \left(\frac{1}{A_2 F_{2R}}\right)\right]^{-1}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

Mass Transfer

Diffusion

Molecular Diffusion

Gas: $N_A = \frac{p_A}{P}\left(N_A + N_B\right) - \frac{D_m}{\overline{R}T}\frac{\partial p_A}{\partial z}$

Liquid: $N_A = x_A\left(N_A + N_B\right) - CD_m\frac{\partial x_A}{\partial z}$

N_i = molar flux of component i

P = pressure

p_i = partial pressure of component i

D_m = mass diffusivity

$\overline{R}$ = universal gas constant

T = temperature

z = length

Unidirectional Diffusion of a Gas A Through a Second Stagnant Gas B (N_b= 0)

$$N_A = \frac{D_m P}{\overline{R}T\left(p_B\right)_{lm}} \times \frac{\left(p_{A2} - p_{A1}\right)}{z_2 - z_1}$$

in which $(p_B)_{lm}$ is the log mean of p_{B2} and p_{B1}

$$\left(p_{BM}\right)_{lm} = \frac{p_{B2} - p_{B1}}{\ln\left(\frac{p_{B2}}{p_{B1}}\right)}$$

N_i = diffusive flux [mole/(time × area)] of component i through area A, in z direction

D_m = mass diffusivity

p_I = partial pressure of species I

C = concentration (mole/volume)

$(z_2 - z_1)$ = diffusion flow path length

Equimolar Counter-Diffusion (Gases)

$(N_B = -N_A)$

$$N_A = D_m/(RT) \times \left[(p_{A1} - p_{A2})/(\Delta z)\right]$$

$$N_A = D_m(C_{A1} - C_{A2})/\Delta z$$

Convection

Two-Film Theory (for Equimolar Counter-Diffusion)

$$\begin{aligned} N_A &= k'_G(p_{AG} - p_{Ai}) \\ &= k'_L(C_{Ai} - C_{AL}) \\ &= K'_G(p_{AG} - p_A^*) \\ &= K'_L(C_A^* - C_{AL}) \end{aligned}$$

N_A = molar flux of component A

k'_G = gas phase mass-transfer coefficient

k'_L = liquid phase mass-transfer coefficient

K'_G = overall gas phase mass-transfer coefficient

K'_L = overall liquid phase mass-transfer coefficient

p_{AG} = partial pressure in component A in the bulk gas phase

p_{Ai} = partial pressure at component A at the gas-liquid interface

C_{Ai} = concentration (mole/volume) of component A in the liquid phase at the gas-liquid interface

C_{AL} = concentration of component A in the bulk liquid phase

p_A^* = partial pressure of component A in equilibrium with C_{AL}

C_A^* = concentration of component A in equilibrium with the bulk gas vapor composition of A

Overall Coefficients

$$1/K'_G = 1/k'_G + H/k'_L$$

$$1/K'_L = 1/Hk'_G + 1/k'_L$$

H = Henry's Law constant where $p_A^* = H\,C_{AL}$ and $C_A^* = p_{AG}/H$

Dimensionless Group Equation (Sherwood)

For the turbulent flow inside a tube, the Sherwood number is:

$$\mathrm{Sh} = \left(\frac{k_m D}{D_m}\right) = 0.023\left(\frac{DV\rho}{\mu}\right)^{0.8}\left(\frac{\mu}{\rho D_m}\right)^{1/3}$$

D = inside diameter

D_m = diffusion coefficient

V = average velocity in the tube

ρ = fluid density

μ = fluid viscosity

k_m = mass-transfer coefficient

Unit and Conversion Factors

This handbook uses both the metric system of units and the U.S. Customary System (USCS). In the USCS system of units, both force and mass are called pounds. Therefore, one must distinguish the pound-force (lbf) from the pound-mass (lbm).

The pound-force is that force which accelerates one pound-mass at 32.174 ft/sec^2. Thus, 1 lbf = 32.174 lbm-ft/sec^2. The expression 32.174 lbm-ft/(lbf-sec^2) is designated as g_c and is used to resolve expressions involving both mass and force expressed as pounds. For instance, in writing Newton's second law, the equation would be written as $F = ma/g_c$, where F is in lbf, m in lbm, and a is in ft/sec^2.

Similar expressions exist for other quantities: Kinetic Energy, $KE = mv^2/2g_c$, with KE in (ft-lbf); Potential Energy, $PE = mgh/g_c$, with PE in (ft-lbf); Fluid Pressure, $p = \rho gh/g_c$, with p in (lbf/ft^2); Specific Weight, $SW = \rho g/g_c$, in (lbf/ft^3); Shear Stress, $\tau = (\mu/g_c)(dv/dy)$, with shear stress in (lbf/ft^2). In all these examples, g_c should be regarded as a unit conversion factor. It is frequently not written explicitly in engineering equations. However, its use is required to produce a consistent set of units.

Note that the conversion factor g_c [lbm-ft/(lbf-sec^2)] should not be confused with the local acceleration of gravity g, which has different units (m/s^2 or ft/sec^2) and may be either its standard value (9.807 m/s^2 or 32.174 ft/sec^2) or some other local value.

If the problem is presented in USCS units, it may be necessary to use the constant g_c in the equation to have a consistent set of units.

METRIC PREFIXES		
Multiple	Prefix	Symbol
10^{-18}	atto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	µ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{1}	deka	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E

COMMONLY USED EQUIVALENTS	
1 gallon of water weighs	8.34 lbf
1 cubic foot of water weighs	62.4 lbf
1 cubic inch of mercury weighs	0.491 lbf
The mass of 1 cubic meter of water is	1,000 kilograms
1 mg/L is	8.34 lbf/MG

TEMPERATURE CONVERSIONS
ºF = 1.8 (ºC) + 32
ºC = (ºF – 32)/1.8
ºR = ºF + 459.69
K = ºC + 273.15

Ideal Gas Constants

Values of the Gas Constant in Different Unit Systems

In SI units the value of the gas constant, R, is:

R = 8.314510 Pa m^3 K^{-1} mol^{-1}
= 9314.510 Pa L K^{-1} mol^{-1}
= 0.08314510 bar L K^{-1} mol^{-1}

This table gives the appropriate value of R for use in the ideal gas equation, $PV = nRT$, when the variables are expressed in other units.

Units of *V, T, n*			**Units of *P***						
V	***T***	***n***	**atm**	**psi**	**mm Hg**	**cm Hg**	**in. Hg**	**in. H_2O**	**ft H_2O**
ft^3	K	mol	0.00290	0.0426	2.20	0.220	0.0867	1.18	0.0982
		lb-mol	1.31	19.31	999	99.9	39.3	535	44.6
	°R	mol	0.00161	0.02366	1.22	0.122	0.0482	0.655	0.0546
		lb-mol	0.730	10.73	555	55.5	21.8	297	24.8
cm^3	K	mol	82.05	1,206	62,400	6,240	2,450	33,400	2,780
		lb-mol	37,200	547,000	2.83×10^7	2.83×10^6	1.11×10^6	1.51×10^7	1.26×10^6
	°R	mol	45.6	670	34,600	3,460	1,360	18,500	1,550
		lb-mol	20,700	304,000	1.57×10^7	1.57×10^6	619,000	8.41×10^6	701,000
L	K	mol	0.08205	1.206	62.4	6.24	2.45	33.4	2.78
		lb-mol	37.2	547	28,300	2,830	1,113	15,140	1,262
	°R	mol	0.0456	0.670	34.6	3.46	1.36	18.5	1.55
		lb-mol	20.7	304	15,700	1,570	619	8,410	701

Adapted from *Fundamental Physical Constants*: U.S. National Institute of Standards and Technology (NIST).

Fundamental Constants

Quantity		Symbol	Value	Units
electron charge		e	1.6022×10^{-19}	C (coulombs)
Faraday constant		F	96,485	coulombs/mol
gravitation–Newtonian constant		G	6.673×10^{-11}	$m^3/(kg \cdot s^2)$
gravitation–Newtonian constant		G	6.673×10^{-11}	$(N \cdot m^2)/kg^2$
gravity acceleration (standard)	metric	g	9.807	m/s^2
gravity acceleration (standard)	USCS	g	32.174	ft/sec^2
heat of vaporization of water		H_v	970	Btu/lb
molar volume (ideal gas), T = 273.15K, p = 101.3 kPa	metric	V_m	22.414	L/mol
molar volume (ideal gas), T = 273.15K, p = 101.3 kPa	USCS	V_m	359	ft^3/mol
speed of light in vacuum		c	299,792,000	m/s
Stefan-Boltzmann constant		σ	5.67×10^{-8}	$W/(m^2 \cdot K^4)$

Conversion Factors

Multiply	By	To Obtain
acre	43,560	square feet (ft^2)
ampere-hr (A-hr)	3,600	coulomb (C)
ångström (Å)	1×10^{-10}	meter (m)
atmosphere (atm)	76.0	cm, mercury (Hg)
atm, std	29.92	in., mercury (Hg)
atm, std	14.70	lbf/in^2 abs (psia)
atm, std	33.90	ft, water
atm, std	1.013×10^5	pascal (Pa)
bar	1×10^5	Pa
bar	0.987	atm
barrels–oil	42	gallons–oil
Btu	1,055	joule (J)
Btu	2.928×10^{-4}	kilowatt-hr (kWh)
Btu	778	ft-lbf
Btu/hr	3.930×10^{-4}	horsepower (hp)
Btu/hr	0.293	watt (W)
Btu/hr	0.216	ft-lbf/sec
calorie (g-cal)	3.968×10^{-3}	Btu
cal	1.560×10^{-6}	hp-hr
cal	4.186	joule (J)
cal/sec	4.184	watt (W)
centimeter (cm)	3.281×10^{-2}	foot (ft)
cm	0.394	inch (in)
centipoise (cP)	0.001	pascal•sec (Pa•s)
centipoise (cP)	1	g/(m•s)
centipoise (cP)	2.419	lbm/hr-ft
centistoke (cSt)	1×10^{-6}	m^2/sec (m^2/s)
cubic feet/second (cfs)	0.646317	million gallons/day (MGD)
cubic foot (ft^3)	7.481	gallon
cubic foot	28.32	liters
cubic meters (m^3)	1,000	liters
degree (angular)	1/0.9	grad
degree (angular)	$2\pi/360$	radian
degree (angular)	17.778	mil
electronvolt (eV)	1.602×10^{-19}	joule (J)
foot (ft)	30.48	cm
ft	0.3048	meter (m)
ft-pound (ft-lbf)	1.285×10^{-3}	Btu
ft-lbf	3.766×10^{-7}	kilowatt-hr (kWh)
ft-lbf	0.324	calorie (g-cal)
ft-lbf	1.356	joule (J)
ft-lbf/sec	1.818×10^{-3}	horsepower (hp)
ft^3	7.4805	gal
ft^3	28.32	L
gal	1/325,851	ac-ft
gal	3,785.4	cm^3
gal	0.13368	ft^3
gal (Imperial)	1.2	gal (U.S)
gal (U.S)	0.8327	gal (Imperial)
gal	3.7854	L
gal	3.7854×10^{-3}	m^3
gal	1.0×10^{-6}	MG
gal	0.00495	yd^3
gal (of water)	8.34	lbm (of water)

Multiply	By	To Obtain
gamma (γ, Γ)	1×10^{-9}	tesla (T)
gauss	1×10^{-4}	T
grains	1.54×10^{-2}	milligram
grains	1.43×10^{-4}	pound (lbm)
gram (g)	2.205×10^{-3}	pound (lbm)
hectare	1×10^4	square meters (m^2)
hectare	2.47104	acres
horsepower (hp)	42.4	Btu/min
hp	745.7	watt (W)
hp	33,000	(ft-lbf)/min
hp	550	(ft-lbf)/sec
hp-hr	2,545	Btu
hp-hr	1.98×10^6	ft-lbf
hp-hr	2.68×10^6	joule (J)
hp-hr	0.746	kWh
inch (in.)	2.540	centimeter (cm)
in. of Hg	0.0334	atm
in. of Hg	13.60	in. of H_2O
in. of H_2O	0.0361	lbf/in^2 (psi)
in. of H_2O	0.002458	atm
joule (J)	9.478×10^{-4}	Btu
J	0.7376	ft-lbf
J	1	newton•m (N•m)
J/s	1	watt (W)
kilogram (kg)	2.205	pound (lbm)
kgf	9.8066	newton (N)
kilometer (km)	3,281	feet (ft)
km/hr	0.621	mph
kilopascal (kPa)	0.145	lbf/in^2 (psi)
kilowatt (kW)	1.341	horsepower (hp)
kW	3,413	Btu/hr
kW	737.6	(ft-lbf)/sec
kW-hour (kWh)	3,413	Btu
kWh	1.341	hp-hr
kWh	3.6×10^6	joule (J)
kip (K)	1,000	lbf
K	4,448	newton (N)
lbm	7000.0	grains
lbm	453.59	g
lbm	0.45359	kg
lbm	4.5359×10^5	mg
lbm	5.0×10^{-4}	tons (mass)
lbm (of water)	0.12	gal (of water)
lbm/ac-ft-day	0.02296	lbm/1,000 ft^3-day
lbm/ft^3	0.016018	g/cm^3
lbm/ft^3	16.018	kg/m^3
lbm/1,000 ft^3-day	43.560	lbm/ac-ft-day
lbm/1,000 ft^3-day	133.68	lbm/MG-day
lbm/MG	0.0070	grains/gal
lbm/MG	0.12	mg/L
lbm/MG-day	0.00748	lbm/1,000 ft^3-day

Conversion Factors (continued)

Multiply	By	To Obtain
liter (L)	61.02	in^3
L	0.0353	ft^3
L	0.264	gal (U.S. liq)
L	10^{-3}	m^3
L/second (L/s)	2.119	ft^3/min (cfm)
L/s	15.85	gal (U.S.)/min (gpm)
meter (m)	3.281	feet (ft)
m	1.094	yard
m/second (m/s)	196.8	feet/min (ft/min)
mg	2.2046×10^{-6}	lbm
mg/L	1.0	ppm
mg/L	0.05842	grains/gal
mg/L	8.3454	lbm/MG
MG	1.0×10^6	gal
MG/ac-day	22.968	gal/ft^2-day
MGD	1.5472	ft^3/sec
MGD	1×10^6	gal/day
MGD/ac (mgad)	22.957	gal/day-ft^2
mile (statute)	5,280	feet (ft)
mile (statute)	1.609	kilometer (km)
mile/hour (mph)	88.0	ft/min (fpm)
mph	1.609	km/h
mm of Hg	1.316×10^{-3}	atm
mm of H_2O	9.678×10^{-5}	atm
newton (N)	0.225	lbf
newton (N)	1	kg•m/s^2
N•m	0.7376	ft-lbf
N•m	1	joule (J)
oz	28.353	g
pascal (Pa)	9.869×10^{-6}	atmosphere (atm)
Pa	1	newton/m^2 (N/m^2)
Pa•sec (Pa•s)	10	poise (P)
pound (lbm, avdp)	0.454	kilogram (kg)
lbf	4.448	N
lbf-ft	1.356	N•m
lbf/in^2 (psi)	0.068	atm
psi	2.307	ft of H_2O
psi	2.036	in. of Hg
psi	6,895	Pa
radian	$180/\pi$	degree
stokes	1×10^{-4}	m^2/s
therm	1×10^5	Btu
ton (metric)	1,000	kilogram (kg)
ton (short)	2,000	pound (lb)
watt (W)	3.413	Btu/hr
W	1.341×10^{-3}	horsepower (hp)
W	1	joule/s (J/s)
weber/m^2 (Wb/m^2)	10,000	gauss