Lecture 11 Air stripping

Used to remove volatile organic compounds (VOCs), ammonia, H_2S

Basic principle: mass exchange between gas and water phases

Henry's Law: $\frac{C_G}{C_W} = H'$

H' = dimensionless Henry's Law coeff.
C_G = conc. in gas (moles/m³)
C_W = conc. in water (moles/m³)

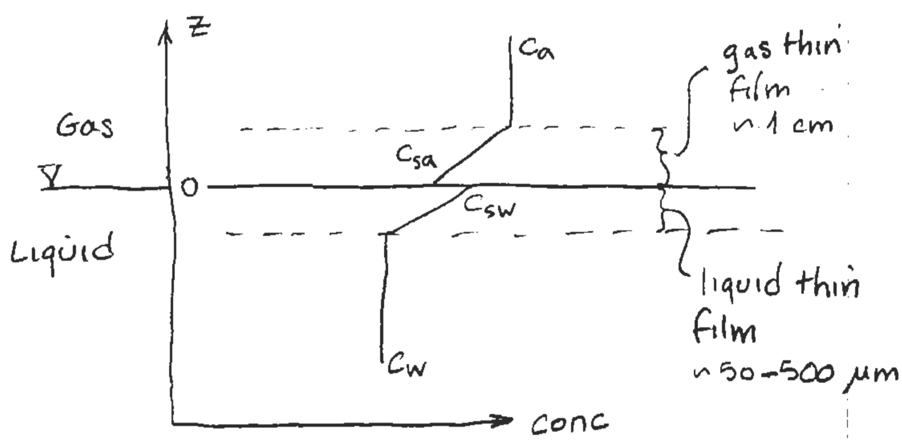
or: $\frac{P}{C_W} = H$

H = dimensional Henry's Law coeff. (atm m³/mol)
P = partial pressure of gas (atm)

$H' = H/RT$

R = gas const = 8.206×10^{-5} atm m³/(mol °K)
T = absolute temp. (°K)

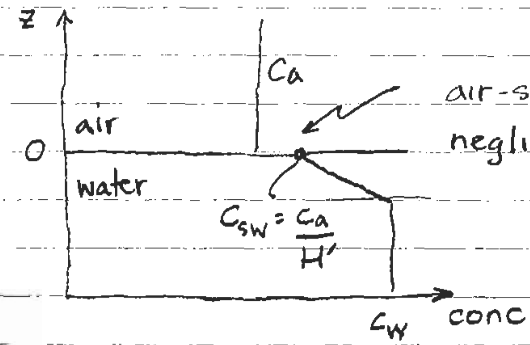
Two-film theory: Mass transfer between liquid and gas is limited by diffusion through thin films at water-gas interface



In this example, $\frac{C_{sa}}{C_{sw}} = H' < 1$

For VOCs $\quad H' >> 0.01$

Only water-side film controls



air-side film has negligible effect

$$\text{Rate of mass transfer} = \frac{dm}{dt} = -D_w A \left[\frac{C_a/H' - c_w}{\delta_w} \right]$$

m = mass
δ_w = thickness of water-side film
D_w = molecular diffusion coeff for water
A = interface area between air & water

Examples of H'

TCE (trichloroethylene) - common industrial solvent - 0.53
Carbon tetrachloride - 0.98
O_2 - 26
Benzene - 0.24
Ammonia gas - 0.73 (Note: pH must be raised to convert ionic NH_4^+ (ammonium) to gaseous NH_3 (ammonia): $NH_3 \text{ (percent)} = 100/(1 - 1.75\times10^{9}[H^+])$

Note: convert conc in moles/liter to conc in g/liter by multiplying by molecular weight (g/mole)

Vapor pressure defines the "saturation" concentration of chemical in a gas

V.P. = partial pressure of a chemical in a gas phase in equilibrium with the pure chemical

Example: head space in closed bottle of liquid TCE will be at V.P.

If VP > 1.3×10^{-3} atm, compound is defined as volatile

Goal of treatment process design is to maximize

$$\frac{dm}{dt} = -D_w A \left[\frac{C_a/H' - C_w}{\delta_w}\right]$$

C_w is fixed (influent conc.)

D_w, H' are essentially fixed (could change temp.)

A is increased by splashing water to form smaller droplets

δ_w is decreased by increasing turbulence

$(C_a/H' - C_w)$ is increased by decreasing C_a

Accomplished via counter-current air stripping tower - pg 4

Water with compounds to be stripping splashes down through tower film (maximizing A), clean air is drafted upward (minimizing C_A)

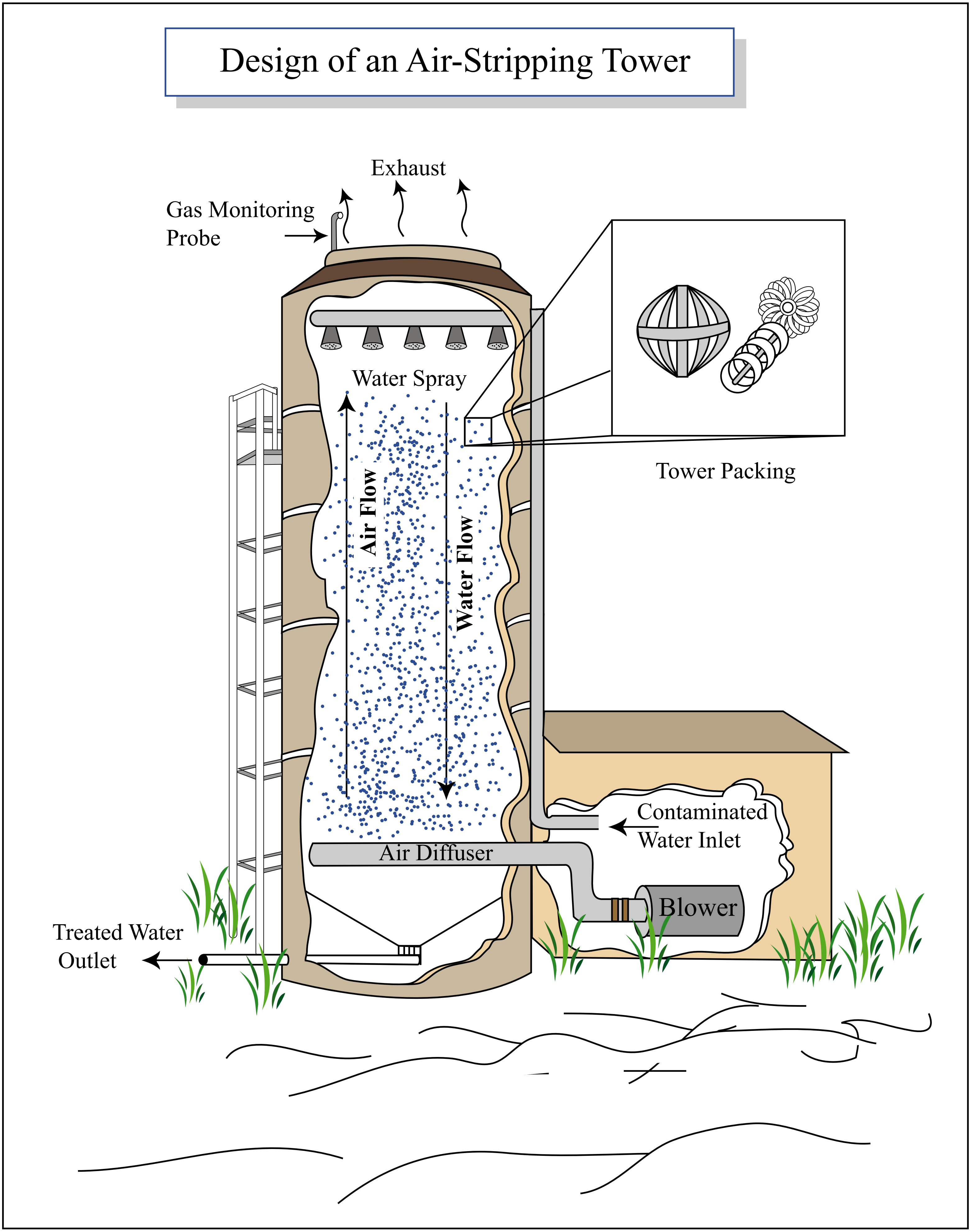
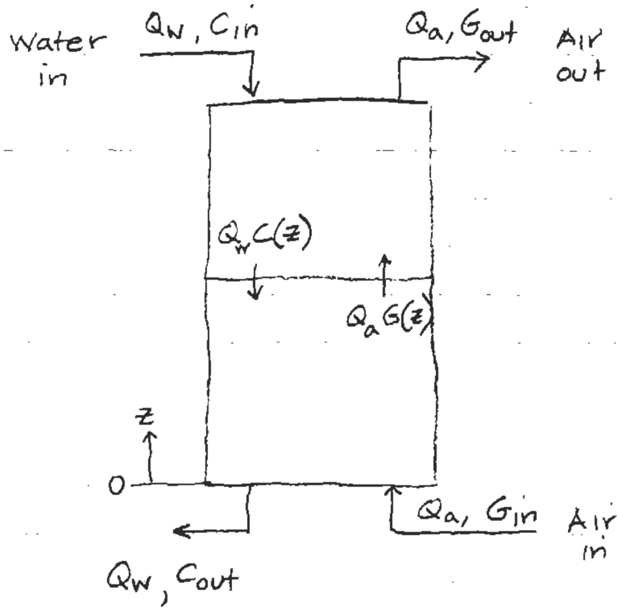


Figure by MIT OCW.

Adapted from: Fetter, C. W. *Contaminant Hydrogeology*. New York, NY: Macmillan Publishing Company, 1993, p. 418.

Mass balance for air stripper:



Q_W = water flow rate $[L^3/T]$
Q_a = air flow rate $[L^3/T]$
C_{in} = influent water conc. $[M/L^3]$
C_{out} = effluent water conc.
G_{in} = influent air conc $[M/L^3]$
G_{out} = effluent air conc (set by env'l regulations)
z = height above bottom of air stipper $[L]$
$C(z)$ = water conc at z
$G(z)$ = air conc at z

Mass balance between 0 and z:

$$\underbrace{Q_W C(z) + Q_a G_{in}}_{\text{Mass in}} = \underbrace{Q_W C_{out} + Q_a G(z)}_{\text{Mass out}} \qquad (1)$$

Assume $G_{in} = 0$

$$G(z) = \frac{Q_W}{Q_a}\left(C(z) - C_{out}\right) \qquad (2)$$

For overall air stipper

$$G_{out} = (Q_W/Q_a)\left(C_{in} - C_{out}\right) \qquad (3)$$

With equilibrium per Henry's Law

$$G_{out} = H' C_{in} = \frac{Q_W}{Q_a}\left(C_{in} - C_{out}\right) \qquad (4)$$

Defines minimum air to water flow rate ratio

$$\left(\frac{Q_a}{Q_W}\right)_{min} = \frac{C_{in} - C_{out}}{H' C_{in}} \approx \frac{1}{H'} \qquad (5)$$

Stripping factor, $S \equiv \frac{Q_a}{Q_w} H'$ (6)

= number of minimum air-to-water ratios needed for high efficiency stripping

In ideal case, $S = 1$

Practically, $S = 2$ to 10, 3.5 is optimal

If $S < 1$, air stripper cannot achieve desired removal

Required air stipper height is function of mass transfer kinetics:

Mass balance for differential element of length Δz at height z inside tower:

$$\underbrace{QC(z+\Delta z)}_{\substack{\text{contaminant}\\ \text{mass in water}\\ \text{inflow}}} - \underbrace{QC(z)}_{\substack{\text{mass in}\\ \text{water}\\ \text{outflow}}} = \frac{dm'}{dt}\, a\, \Delta V \qquad (7)$$

$\frac{dm'}{dt}$ = mass flux per unit area across air-water interface $\left[\frac{M}{L^2T}\right]$

a = interface area per unit volume of tower $[L^2/L^3]$

ΔV = volume in differential element $[L^3]$
= $A_T \Delta z$

A_T = cross-section area of tower $[L^2]$

check units:
$$\frac{L^3}{T}\cdot\frac{M}{L^3} - \frac{L^3}{T}\cdot\frac{M}{L^3} = \frac{M}{L^2T}\,\frac{L^2}{L^3}\,L^3$$
$$\frac{M}{T} = \frac{M}{T} \checkmark$$

From thin-film theory with water-side control:

$$\frac{dm'}{dt} = -D_W \frac{G(z)/H' - C(z)}{\delta_W} \quad (8)$$

$$= \frac{D_W}{\delta_W}\left(C(z) - C_{eq}(z)\right) \quad (9)$$

$$= K_L\left(C(z) - C_{eq}(z)\right) \quad (10)$$

K_L = liquid-phase mass transfer coeff (piston velocity) $[L/T]$

C_{eq} = water conc in equilibrium with gas conc. = G/H'

Back to mass balance:

$$Q_W C(z+\Delta z) - Q_W C(z) = K_L\left(C(z) - C_{eq}(z)\right) a A_T \Delta z \quad (11)$$

$$\frac{Q_W}{A_T K_L a} \frac{C(z+\Delta z) - C(z)}{\Delta z} = C(z) - C_{eq}(z) \quad (12)$$

In limit as $\Delta z \to 0$ $\qquad \frac{Q_W}{A_T K_L a}\frac{dc}{dz} = C(z) - C_{eq}(z) \quad (13)$

$$\frac{Q_W}{A_T K_L a} \frac{dc}{C(z) - C_{eq}(z)} = dz \quad (14)$$

$$\frac{Q_W}{A_T K_L a} \int_{C_{out}}^{C_{in}} \frac{dc}{C - C_{eq}} = \int_0^L dz = L \quad (15)$$

req'd tower height

To solve, need C_{eq} as function of C

From Eq (2):

$$G(z) = \frac{Q_w}{Q_a}\left(C(z) - C_{out}\right) \qquad (2)$$

$$C_{eq}(z) = \frac{G(z)}{H'} = \frac{(Q_w/Q_a)(C(z) - C_{out})}{H'} \qquad (16)$$

$$\therefore \quad L = \frac{Q_w}{A_T K_L a} \int_{C_{out}}^{C_{in}} \frac{dc}{c - (Q_w/Q_a)\,(c - C_{out})/H'} \qquad (17)$$

skip in class

$$= \frac{Q_w}{A_T K_L a} \int_{C_{out}}^{C_{in}} \frac{dc}{c\left[1 - (Q_w/Q_a)/H'\right] + C_{out}(Q_w/Q_a)/H'}$$

$$= \frac{Q_w}{A_T K_L a} \left[\frac{1}{1 - (Q_w/Q_a)/H'}\right] \ln\left[c\left(1 - \frac{Q_w/Q_a}{H'}\right) + C_{out}\frac{Q_w}{Q_a}\frac{1}{H'}\right]_{C_{out}}^{C_{in}}$$

$$L = \frac{Q_w}{A_T K_L a}\left[\frac{1}{1 - (Q_w/Q_a)/H'}\right] \ln\left[\frac{C_{in} + (C_{out} - C_{in})(Q_w/Q_a)/H'}{C_{out}}\right] \qquad (18)$$

since $S = (Q_a/Q_w)H'$ = stripping factor

$$L = \frac{Q_w}{A_T K_L a}\left(\frac{S}{S-1}\right) \ln\left[\frac{1 + (C_{in}/C_{out})(S-1)}{S}\right] \qquad (19)$$

For design, stripper tower is represented as a stack of transfer units:

$$L = HTU \cdot NTU$$

$$HTU = \text{height of transfer unit} = \frac{Q_W}{A_T K_L a}$$

$$\text{Generally} \quad \frac{Q_W}{A_T} \leq 20 \ \frac{gpm}{ft^2} = 0.014 \ \frac{m}{s}$$

Manufacturer can supply $K_L a$ values vs. temperature and flow rate (but best to test in pilot studies before final design) $K_L a = 0.01$ to $0.05 \ sec^{-1}$ for VOCs

Use $\frac{Q_W}{A_T} = 20 \ \frac{gpm}{ft^2}$, known Q_W to find A_T

Use $K_L a$ data, Q_W/A_T to find HTU

NTU = number of transfer units

$$= \frac{S}{S-1} \ln\left[\frac{C_{in}}{C_{out}}\left(\frac{S-1}{S}\right) + \frac{1}{S}\right]$$

Design graph (pg. 10) gives fraction removed $\left(\frac{C_{in} - C_{out}}{C_{in}}\right)$ vs. S and NTU

Note marginal decrease in NTU for $S > 3$

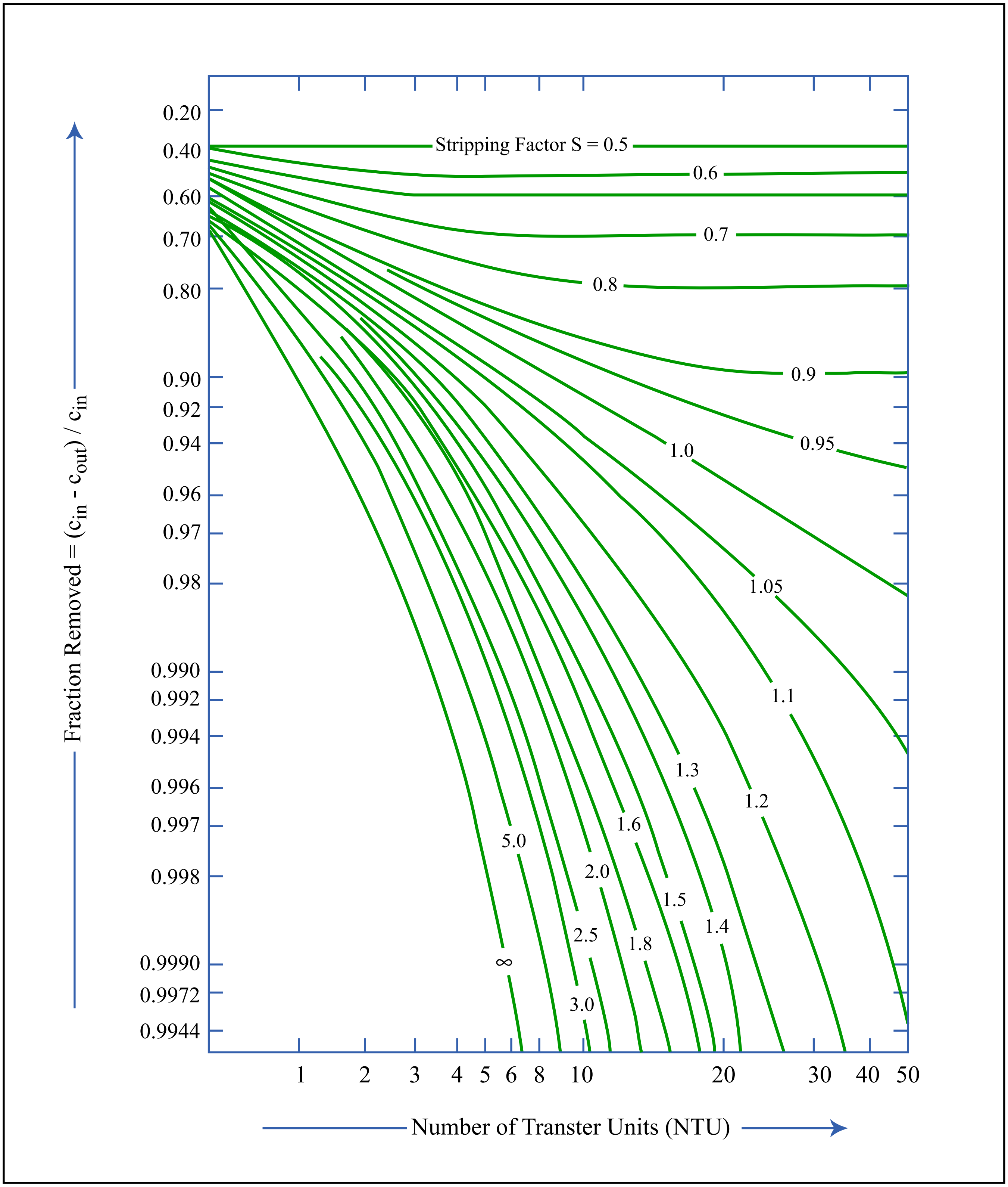


Figure by MIT OCW.

Adapted from: AWWA, 1999. Water Quality & Treatment, A Handbook of Community Water Supplies, Fifth Edition. McGraw-Hill, New York.

Full design procedure is given by:

Kavanaugh, M.C. and Trussell, R.R., 1980. Design of aeration towers to strip volatile contaminants from drinking water. Journal AWWA Vol 72 No 12 pp 684-692, December 1980.

MWH, 2005 gives same procedure

Design procedure considers pressure drop for air flow through tower, a cost factor in that blower adds to power consumption.

Kuo, 1999 (handout) gives simplified procedure:

Get H' for contaminant of concern

Select S between 2 and 10 – $S = 3.5$ is good estimate

Compute $\frac{Q_a}{Q_w} = \frac{S}{H'}$

From known Q_w find A such that $\frac{Q_w}{A} \leq 20 \frac{\text{gpm}}{\text{ft}^2} = 0.014 \frac{\text{m}}{\text{s}}$
$= 14\ \text{L/sec/m}^2$

Determine desired treated water conc, C_{out}

From known C_{in}, desired C_{out} and estimated S, compute

$$NTU = \left(\frac{S}{S-1}\right) \ln\left[\frac{C_{in}}{C_{out}}\left(\frac{S-1}{S}\right) + \frac{1}{S}\right]$$

From manufacturer data for $K_L a$, compute

$$HTU = \frac{Q_W}{A K_L a}$$

Compute tower height $L = NTU \cdot HTU$