Air Pollution-2

- Air Pollution and Meteorology
- Plume Calculations and Indoor Air Quality

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Air Pollution and Meteorology

√ **To discuss air pollution we need to understand how air moves around in the atmosphere**

- Are there strong winds?
- Is the air moving vertically?
- Is there a lot of sunlight?
- When was the last precipitation event?

Vertical Air Movement

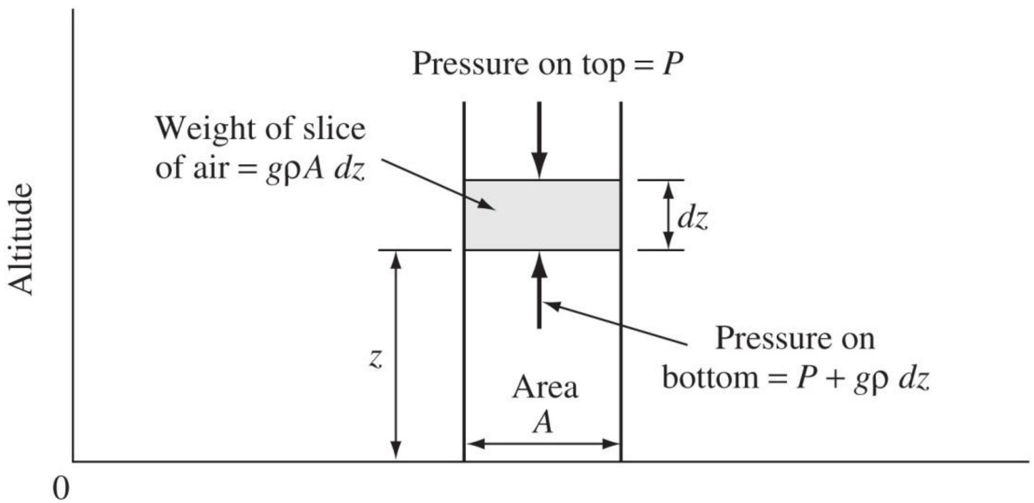
√ Temperature change for the vertical air movement

- **Start with basics, does hot air sink or rise?**
  (related to density, lighter air rises)

- **The Barometric Equation:**

$$\frac{dP}{dz} = -\rho g$$

  - Pressure decreases with elevation



Force by weight

$$P(z) = P(z+dz) + \frac{g\rho A dz}{A}$$

But

$$dP = P(z+dz) - P(z) = -g\rho dz$$

$$\frac{dP}{dz} = -\rho g \text{ (The Barometric Equation)}$$

Vertical Air Movement

- **1st Law of Thermodynamics**

$$dQ = C_p\, dT - V\, dP$$

dQ : heat (or energy) added to an air parcel (J/kg)
C_p : specific heat
dT : temperature change
V : volume per unit mass (inverse of density)
dP : incremental pressure in parcel

- Assume change in parcel is adiabatic – no heat is transferred across boundary ($dQ = 0$)

$$0 = C_p\, dT - V\, dP; \quad Thus \quad \frac{dT}{dP} = \frac{V}{C_p}$$

Vertical Air Movement

- Take earlier equations:

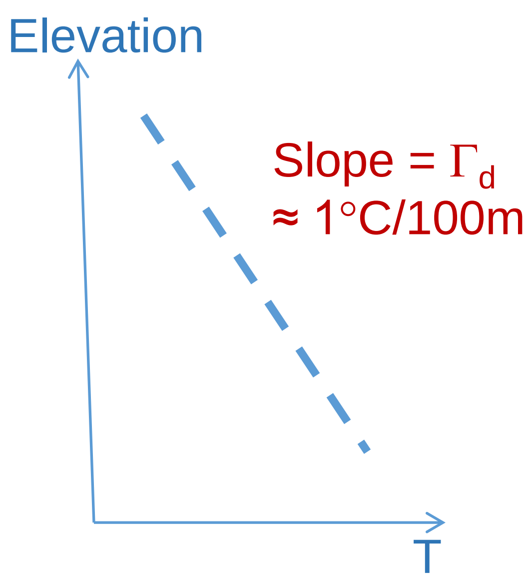
$$\frac{dT}{dP} = \frac{V}{C_p} \qquad \frac{dP}{dz} = -\rho g$$

- Interested in $\frac{dT}{dz}$

$$\frac{dT}{dz} = \frac{dT}{dP}\frac{dP}{dz} = \frac{V}{C_p}(-g\rho)$$

- V (volume per unit mass) and ρ (mass per unit volume) cancel out

$$\therefore \frac{dT}{dz} = \frac{-g}{C_p} = \Gamma_d$$



Vertical Air Movement

- This equation defines the **dry adiabatic lapse rate**:

$$\Gamma_d = -\frac{dT}{dz} = 9.76^{\circ} C / km \text{ (about } 1^{\circ}\text{C/100 m)}$$

$$= 5.4^{\circ} F / 1{,}000\, ft$$

- This is the rate of temperature change that would be experienced by a dry parcel of air moving up or down in ideal conditions.

- The adiabatic lapse rate is used as a baseline to compare with the actual atmospheric conditions and assess the stability of the atmosphere.

  - Stability means here the ability to resist the vertical movement of an air pollutant

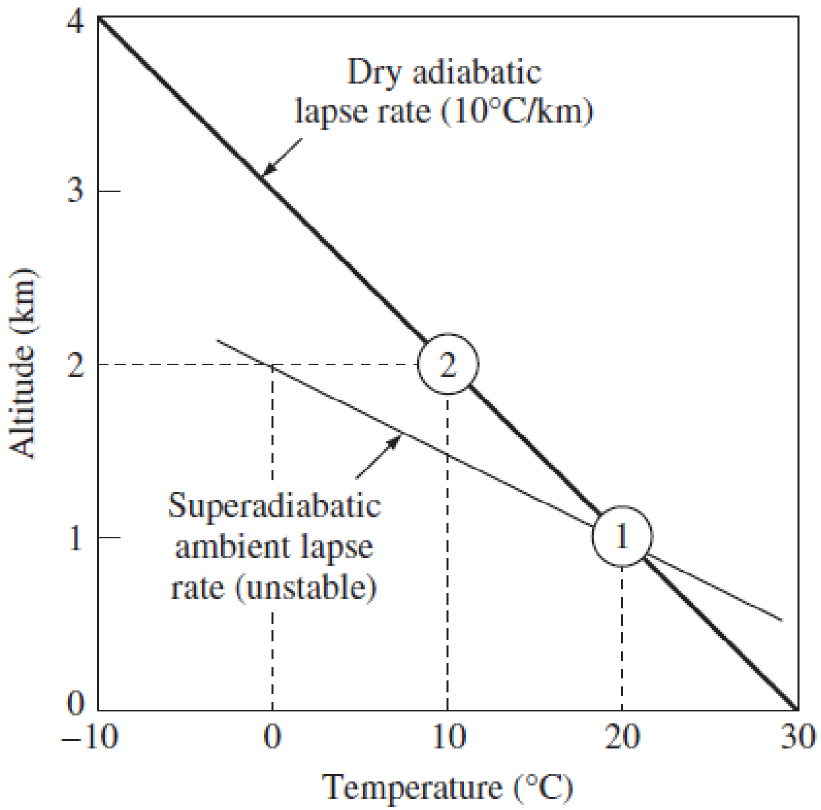
- The actual rate of temperature change with elevation is the ***ambient lapse rate***.

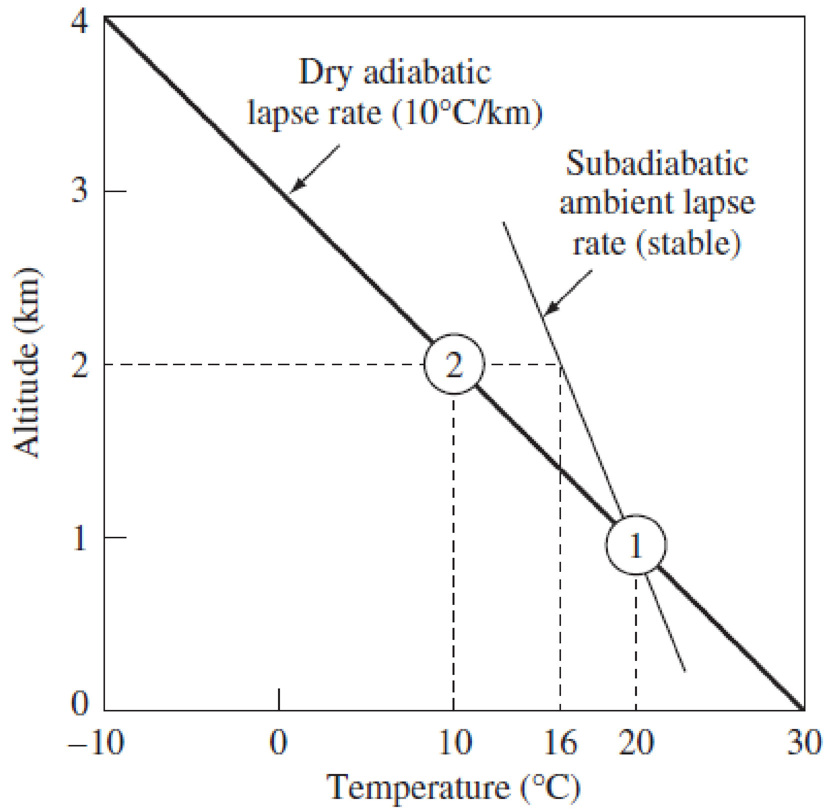
- This rate is usually different from the adiabatic rate because of wind, sunlight, water vapor in air, etc.

Vertical Air Movement

√ Ambient lapse rate and stability

$$\left(\frac{dT}{dz}\right)_{amb} > \Gamma_d \quad \text{(unstable)} \qquad \left(\frac{dT}{dz}\right)_{amb} < \Gamma_d \quad \text{(stable)}$$





Vertical Air Movement

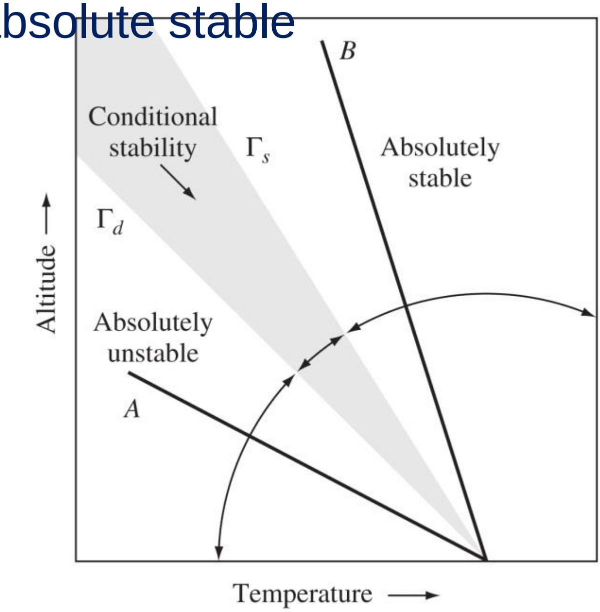
√ **Saturated adiabatic lapse rate**

- If condensation occurs: Γ_s = saturated adiabatic lapse rate
  - Average value = ~6 ºC/km (< Γ_d = ~10 ºC/km)

- If ambient lapse rate (dT/dz) > dry adiabatic = absolute unstable
  - Dispersion of pollution

- If ambient lapse rate (dT/dz) < saturated adiabatic = absolute stable
  - No dispersion of pollution

- Conditional stability:
  - Can't determine stability/instability
  - Need to know actual adiabatic profile

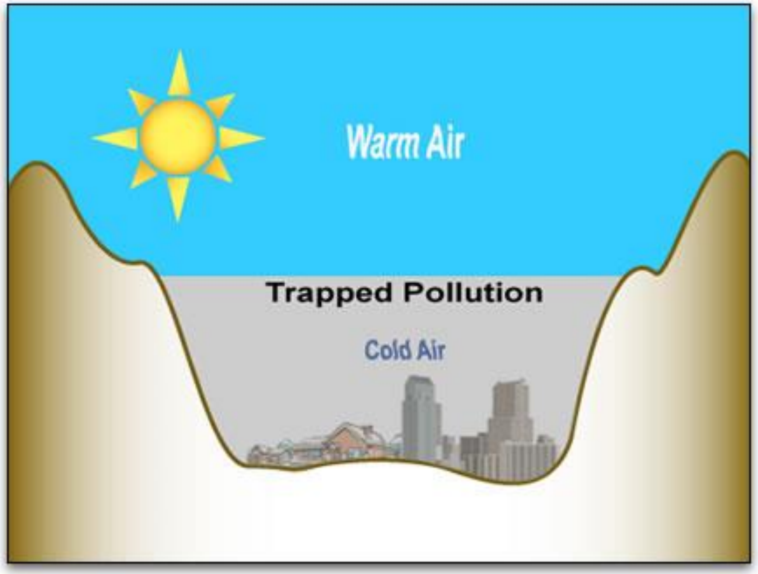


Temperature Inversions

- Ambient temperature increases with altitude
  -"Lid" on upward movement of pollution due to stability

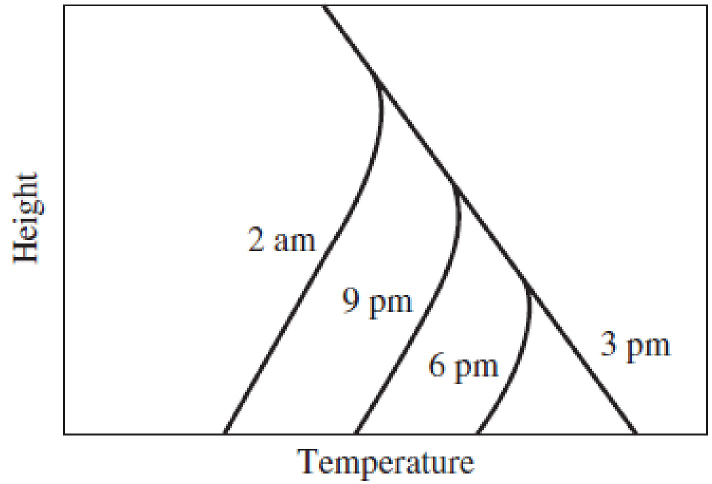
- Radiation inversion – from cooling of surface at night

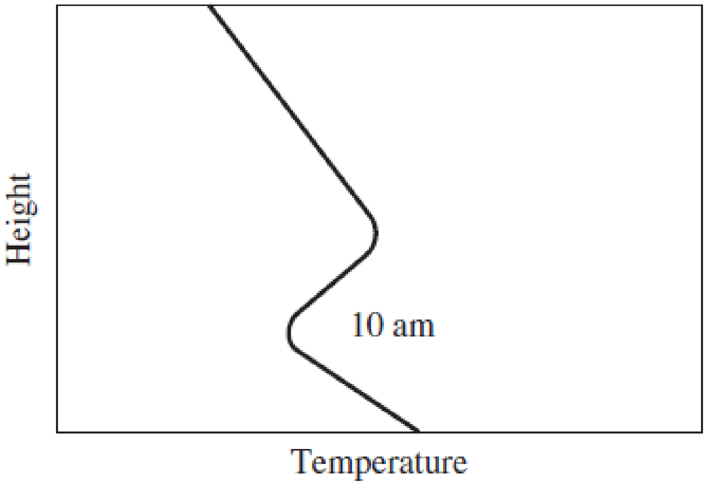
- Subsidence inversion – compressive heating (descending air under pressure)



Radiation Inversion

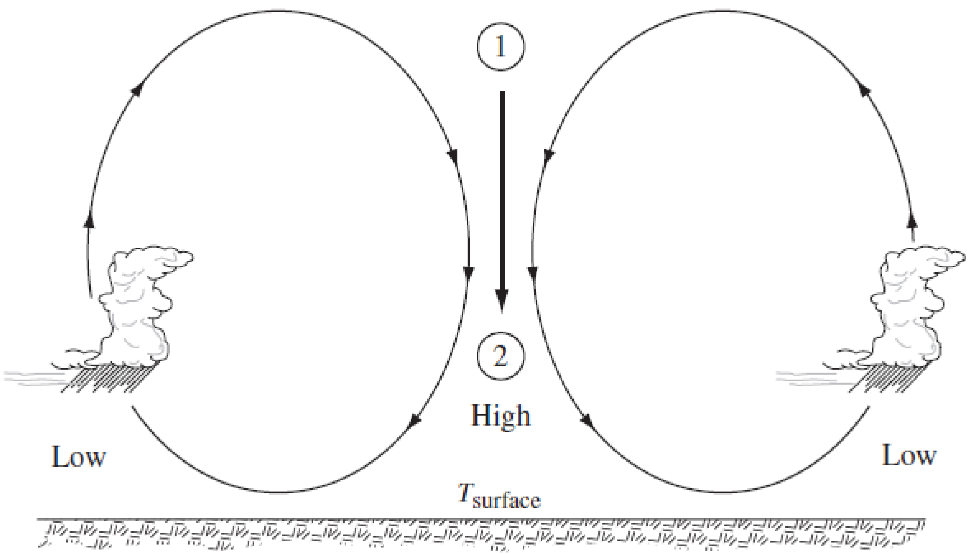
- After sunset, earth's surface cools and radiates energy
- On clear nights, surface cools quickly (easier to lose radiation to space)
  - Air closest to surface cools before air higher up
- Eventually inversion forms
  - Air near surface is cooler and denser than air above
- Frequently occurs at winter nights for a few hours
- Sun eventually warms up the ground and breaks up the inversion

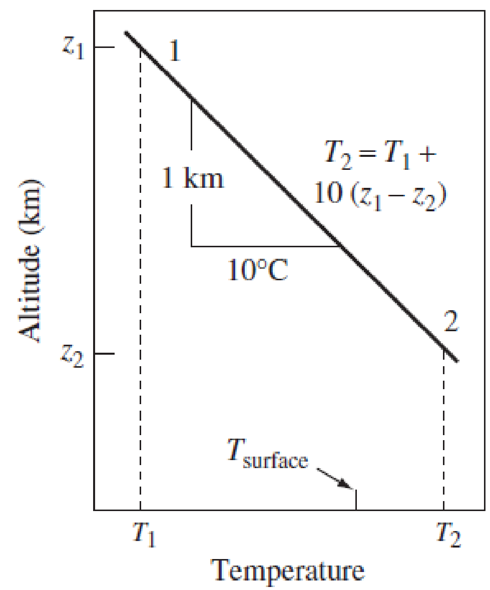




Subsidence Inversion

- Long lasting inversions
- Common in summer months
- Associated with high pressure weather (anticyclones)
  - Air in the middle sinks, edges rise
- Sinking air is compressed and heated → inversion

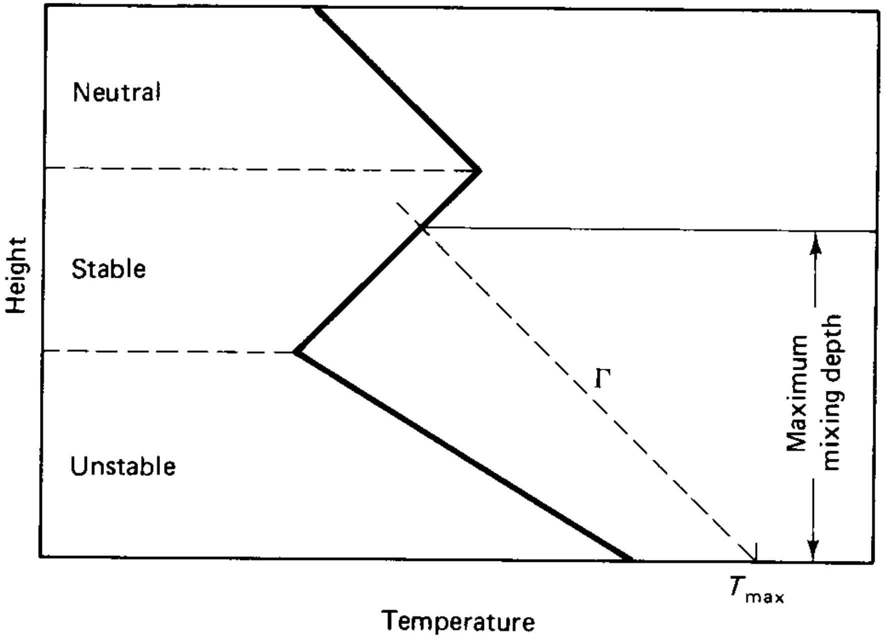




Maximum Mixing Depth (MMD)

- The simplest model to relate emissions to ambient concentrations would be to assume
  - There is a 'box' over some area
  - Air in this box mixes completely

- The height of complete mixing = Maximum Mixing Depth (MMD)
  - Defines highest level of mixing in the atmosphere
  - Found by comparing adiabatic lapse rate to real temp. profile
  - Intersection of these two lines locate height where parcels would no longer rise adiabatically



T at which pollutant is emitted

Ventilation Coefficient (VC)

- Ventilation coefficient: a function of the mixing depth and the wind speed
  - Indicator of atmosphere's dispersive capability

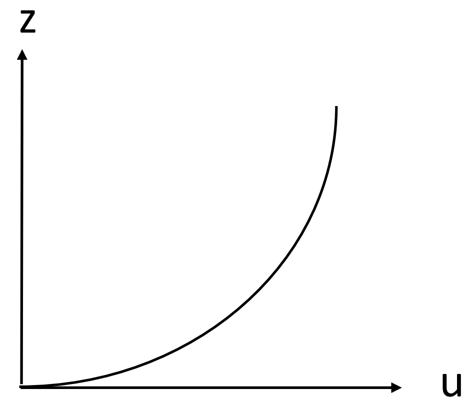
VC (m^2/s) = MMD (m) x Average wind speed (m/s)

- <6,000 m^2/s = high air pollution potential
- Average wind speed = average wind speed within the mixing layer
- Actual wind speed measurements usually made at 10 m elevation

Ventilation Coefficient (VC)

- Can predict other wind speeds with power law function

$$\frac{u_1}{u_2} = \left(\frac{z_1}{z_2}\right)^p$$



u = wind speed at elevations 1 and 2
z = elevations
p = dimensionless parameter

- Value of p depends on atmospheric stability
  - Stability class A (very unstable) p = 0.15
  - Stability class B (moderate unstable) p = 0.15
  - Stability class C (slightly unstable) p = 0.2
  - Stability class D (neutral) p = 0.25
  - Stability class E (slightly stable) p = 0.4
  - Stability class F (stable) p = 0.60

Example

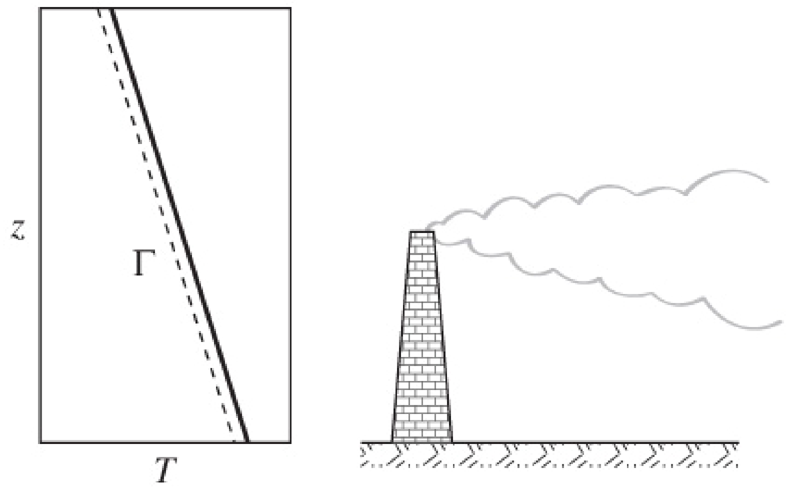
- Suppose the atmospheric temperature profile is isothermal (constant temperature) at 20^{o}C and max daily surface temperature (emission temp.) is 25 ^{o}C.

  The weather station anemometer is at a height of 10 m in the city. It indicates an wind speed of 3.0 m/s.

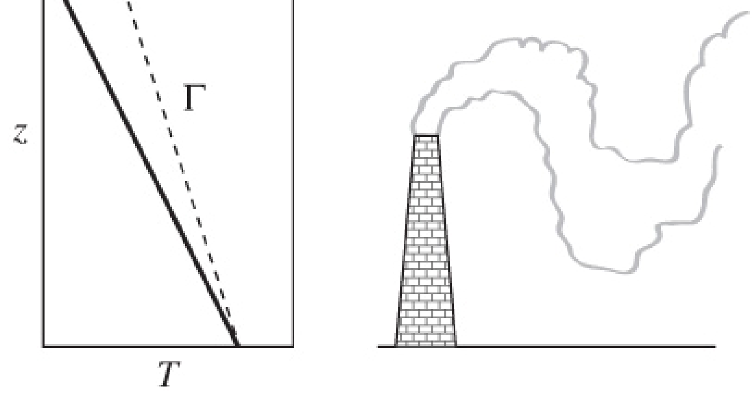
Estimate the maximum mixing depth and the ventilation coefficient

Assume ‘slightly stable’ stability class due to isothermal temperature profile

Plume Shapes



Coning
(a)

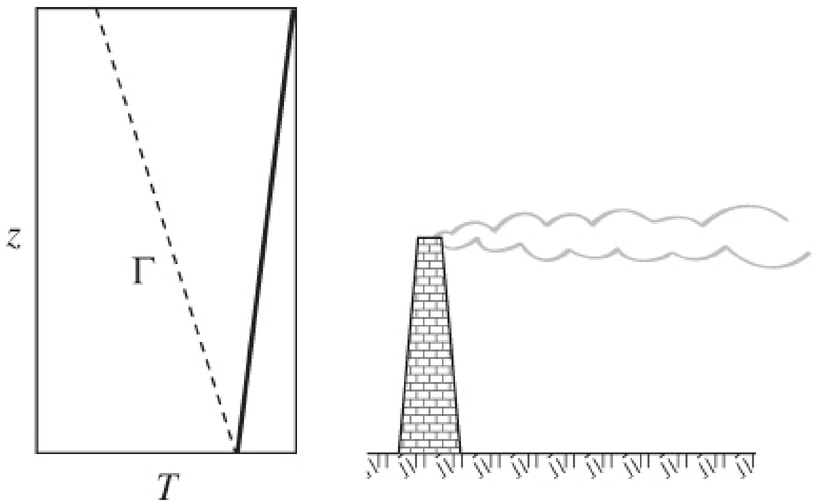


Looping
(b)

Coning: neutrally stable atmosphere

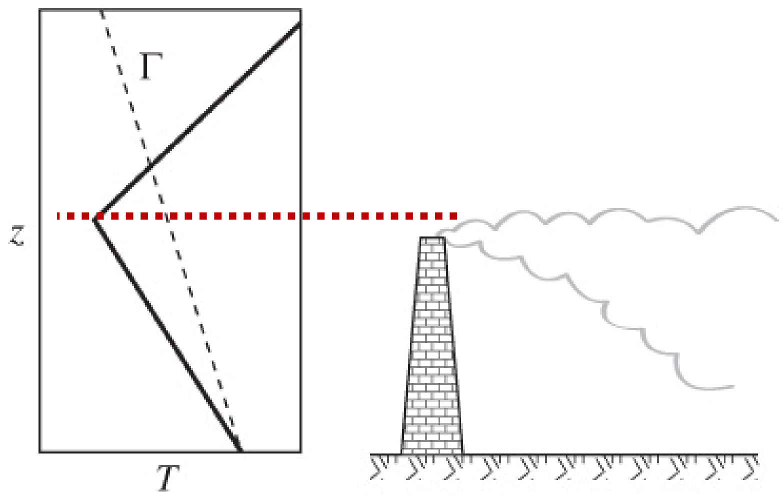
Looping: very unstable atmosphere - superadiabatic

Plume Shapes



Fanning

(c)



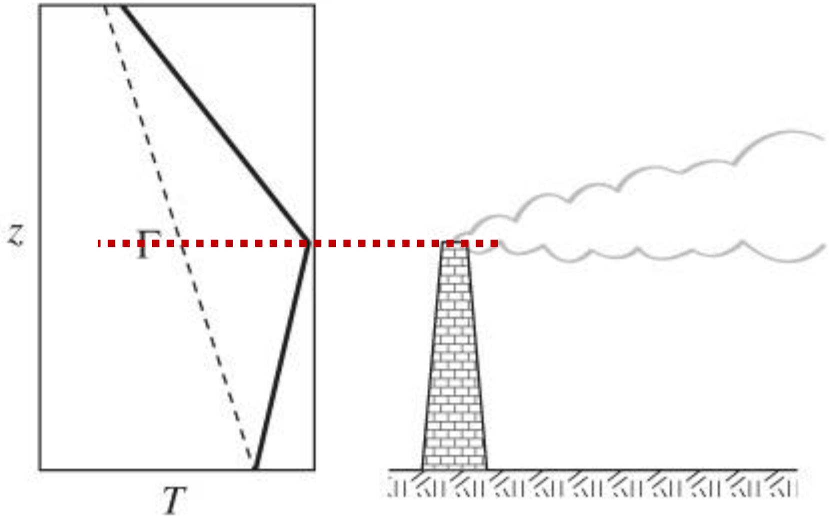
Fumigation

(d)

Fanning: stable atmosphere – subadiabatic – restricted vertical dispersion

Fumigation: stack under inversion layer – pollutants move downwards

Plume Shapes



Lofting

(*e*)

Lofting: stack above inversion layer –
keeps pollutants high above ground

The Point Source Gaussian Plume Model

√ Point Sources and the Gaussian Plume

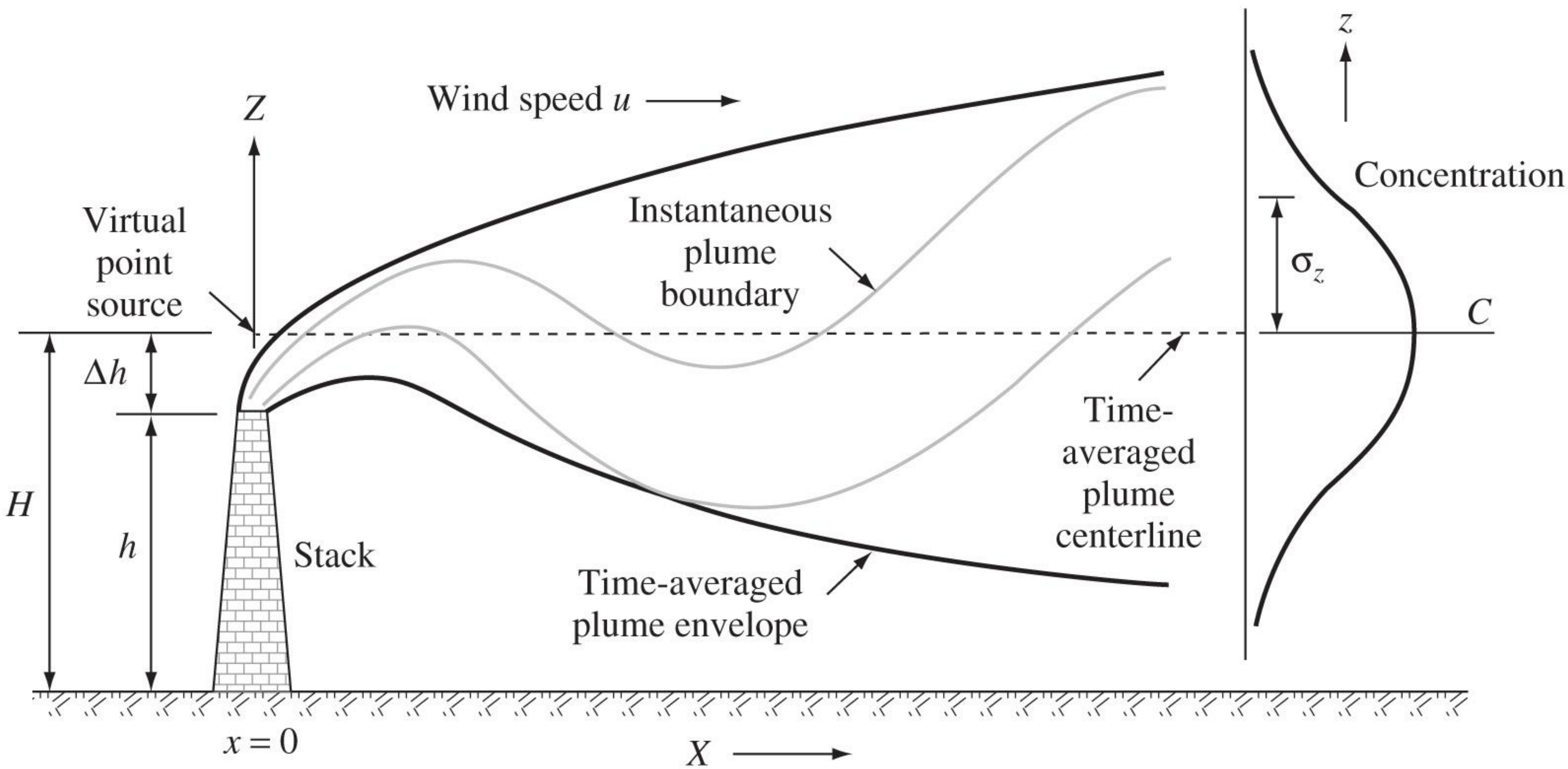
- Single facilities or smokestacks are point sources
- If we know what the atmospheric stability class is, we can model the migration and dispersion of such emissions
- Stacks may emit gas at a high velocity, or gases at high temperature. To account for both the physical location or stack height, and the energy that the plume has when it is released from the stack,

  we use an effective stack height, H.

$H = h + \Delta h$, h = stack height, Δh = plume rise

There are empirical equations for predicting Δh ($\sim 1/u$)

The Point Source Gaussian Plume Model



The Point Source Gaussian Plume Model

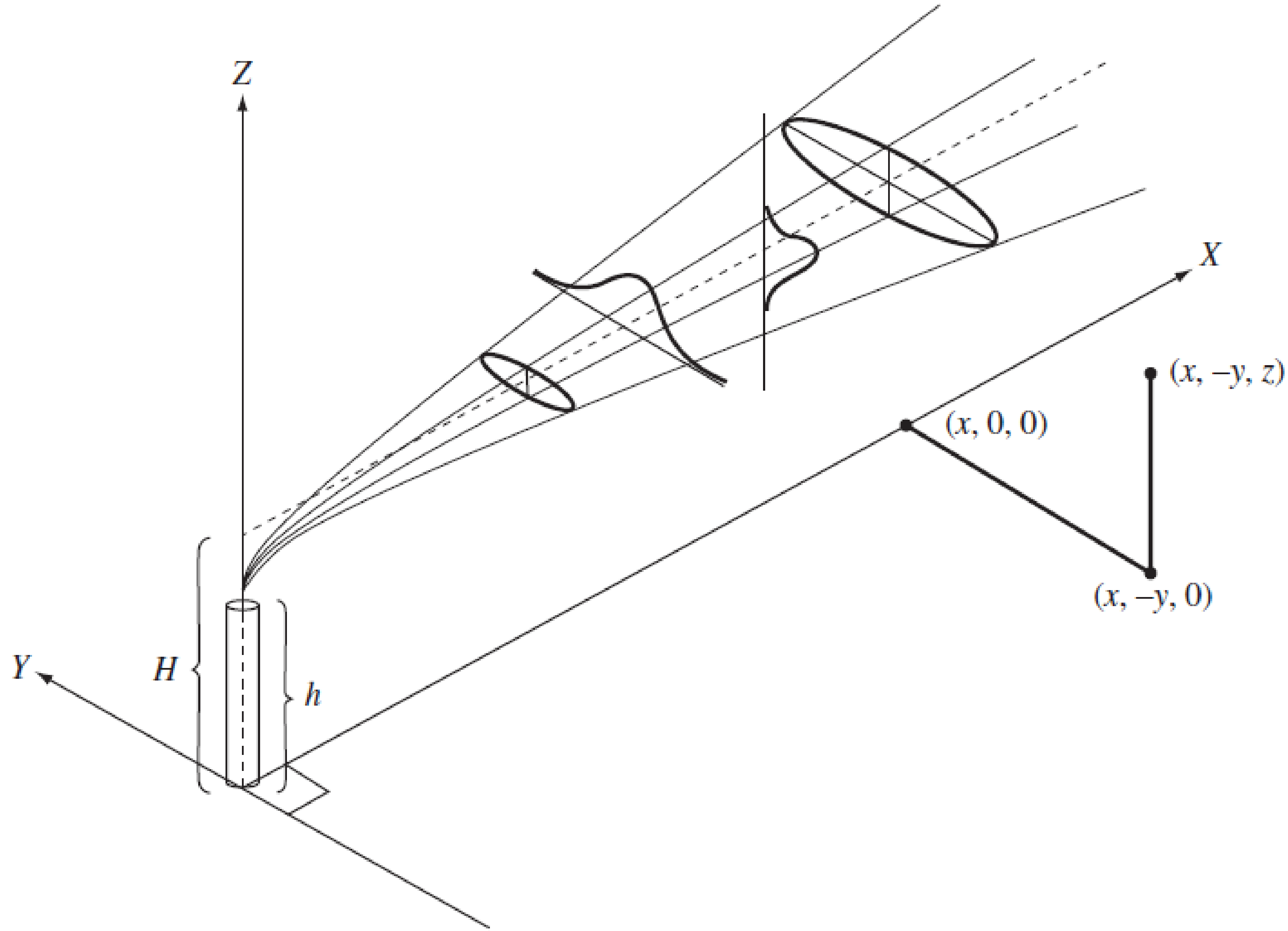
- **Assumptions:**

1) Rate of emission is constant
2) Wind speed is constant (time and elevation)
3) Conservative pollutant (NO REACTION)
4) Flat terrain

- Over time, in relatively steady conditions (constant wind speed and wind directions), point source emissions form a plume.

- The concentration of material in the plume can be described by a Gaussian equation (normal distribution)

The Point Source Gaussian Plume Model



The Point Source Gaussian Plume Model

- We are frequently interested in the ground level concentration, since that is where the people are (z = 0).

$$C(x,y) = \frac{Q}{\pi u_H \sigma_y \sigma_z} \exp\left(\frac{-H^2}{2\sigma_z^2}\right) \exp \frac{-y^2}{2\sigma_y^2}$$

C(x,y) = concentration at ground level at point x,y

x = distance directly downwind (m)

y = horizontal distance from plume centerline (m)

Q = Emission rate (ug/s)

H = Effective stack HEIGHT (H=h+Δh) (m)

u_H = Average wind speed at the stack HEIGHT (m/s)

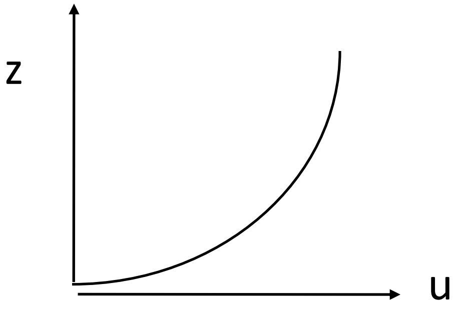
σ_y = Horizontal dispersion coefficient (standard deviation) (m)

σ_z = Vertical dispersion coefficient (standard deviation) (m)

The Point Source Gaussian Plume Model

√ Estimating wind speed

$$\left(\frac{u_H}{u_a}\right) = \left(\frac{H}{z_a}\right)^p$$



u_H = Wind speed at the Elevation H

u_a = Wind speed at the anemometer height (usually 10 m)

H = Effective Height of Plume

z_a = Anemometer Height above ground

p = Dimensionless correction factor for surface roughness and stability (addressed previously)

The Point Source Gaussian Plume Model

√ **Gaussian dispersion coefficients**

σ_y - Standard deviation of horizontal dispersion
σ_z - Standard deviation of vertical dispersion

Smaller σ = narrower plumes

$$\sigma_y = ax^{0.894}$$

$$\sigma_z = cx^d + f$$

*The values of a, c, d, and f depend on the stability class.

Values of the Constants *a*, *c*, *d*, and *f*

		$x \leq 1$ km			$x \geq 1$ km		
Stability	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

The Point Source Gaussian Plume Model

√ **Downwind ground level centerline concentrations**

- This concentration is largest at the centerline of the plume.
- To evaluate the Gaussian plume at the centerline, simply set y = 0 (directly downwind from stack).

$$Thus:$$

$$C(x,0) = \frac{Q}{\pi u_H \sigma_y \sigma_z} \exp\left(\frac{-H^2}{2\sigma^2{}_z} \right)$$

Example

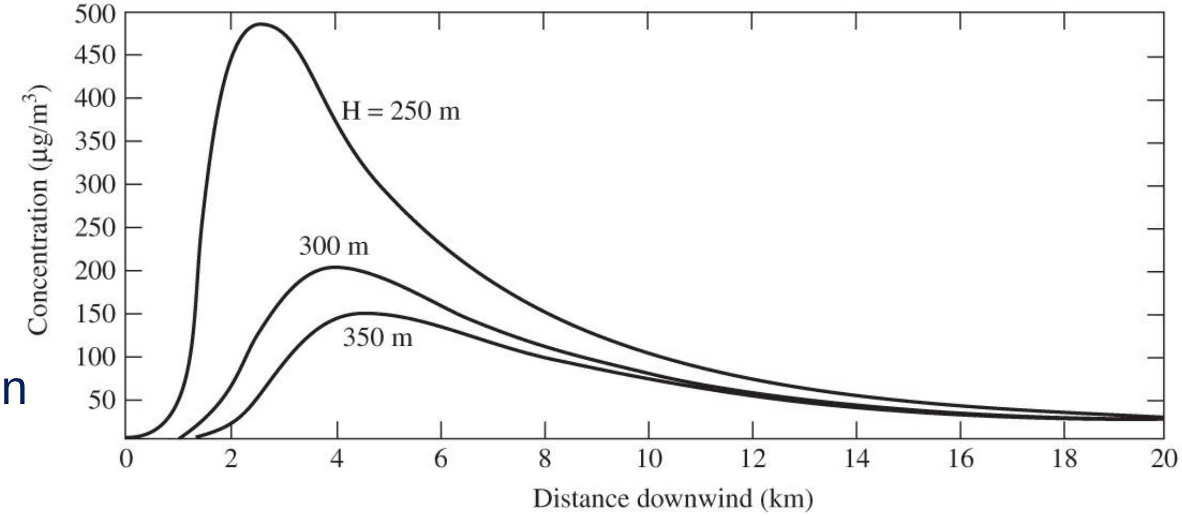
- A 40% efficient 1,000 MW (10^6 kW) coal fired power plant emits SO_2 at 0.6 lb SO_2 per million Btu of heat into the plant. The stack has an effective height of 300 m. An anemometer on a 10-m pole measures 2.5 m/s of wind and it is a cloudy summer day. Predict the ground level concentration of SO_2 4-km directly downwind. The atmosphere is slightly unstable.

The Point Source Gaussian Plume Model

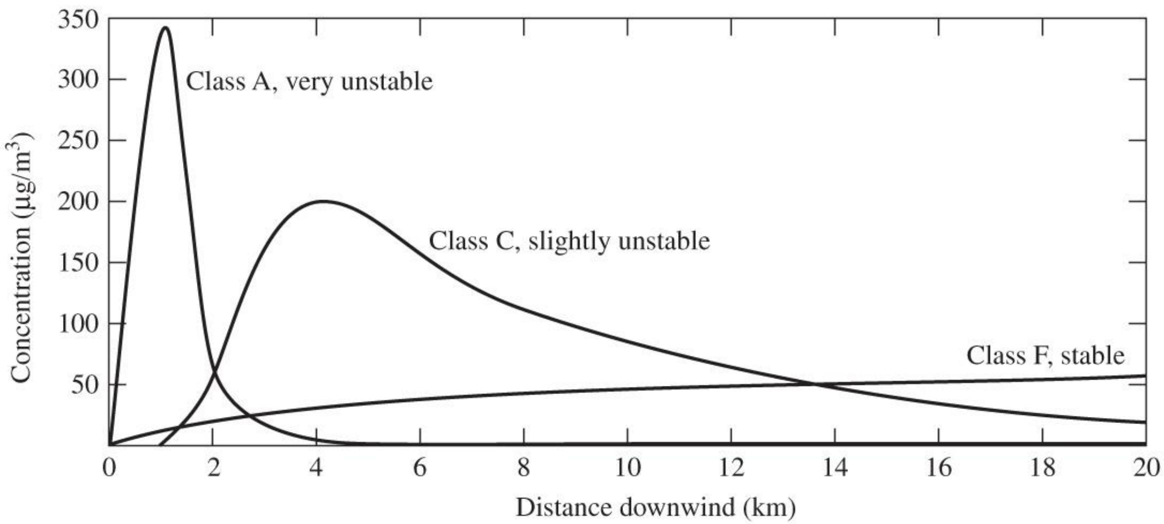
√ **Peak downwind concentration**

- Depending on all variables, the peak ground concentration varies downwind

(C$_{max}$ Increases with lower H and unstable atmosphere)



(a)



Line Sources

√ Line Sources

To study how the emissions from a heavily traveled roadway disperse, we can modify the plume equation.

A roadway can be thought of as a continuous line of single point sources.

- **Assumptions:**

1. Wind blows perpendicular to roadway (simpler geometry)
2. Car emissions occur with an effective stack height H = 0
3. Non-reacting (conservative) pollutant

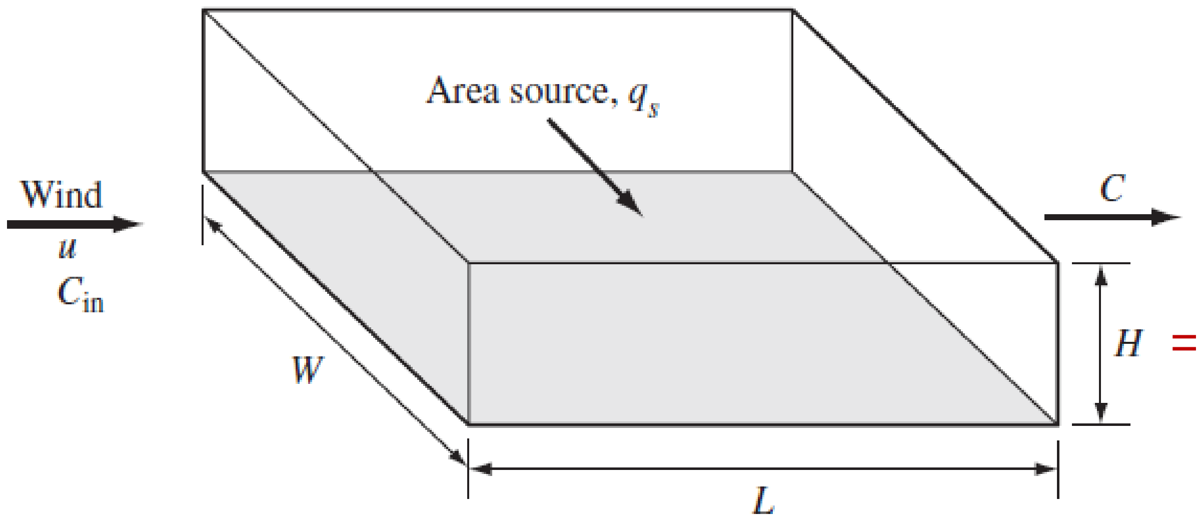
Using the special properties of normal distributions, get

$$C(x) = \frac{2q}{\sqrt{2\pi} u \sigma_z} \quad \text{(q in g/s-m)}$$

Area Sources

√ **Area Sources**

Assume that the dispersion of an area source takes place within an imaginary box. Then write a material balance to describe the concentration of pollutants within the box

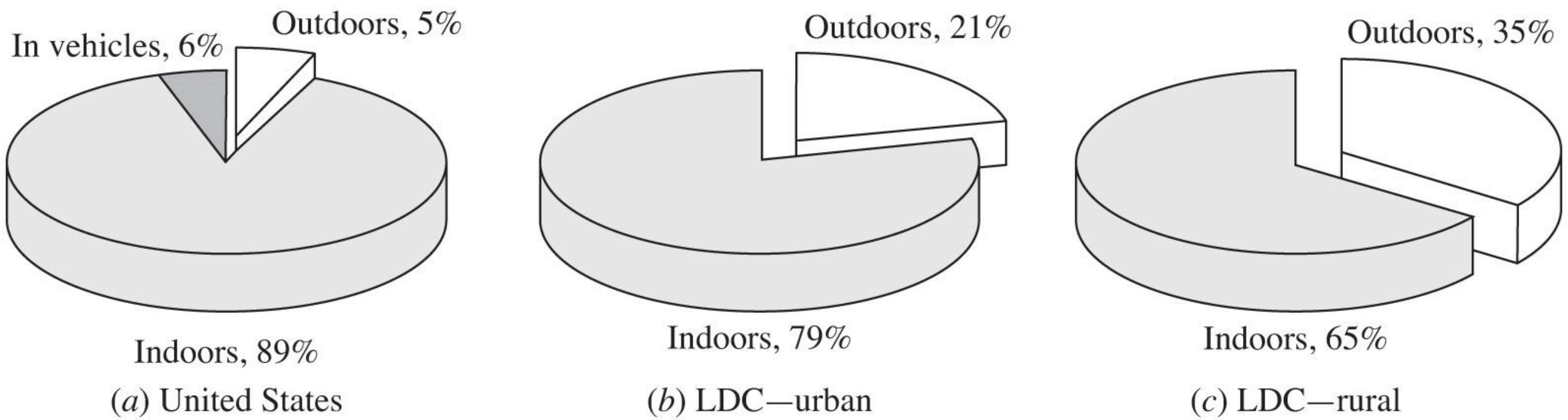


= Max. Mixing Depth

Steady state solution: $$C_{\infty} = \frac{q_s L}{uH} + C_{in}$$

q_s in g/s.m^2

Indoor Air Quality



We spend a LOT of time indoors.

Every year, indoor air pollution is responsible for the death of 1.6 million people (WHO).

Some Indoor air pollution sources are from outdoors.

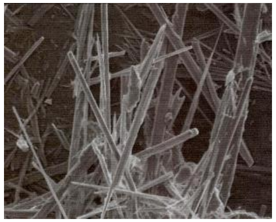
Indoor Air Quality

√ Sources & Exposure Guidelines for IAQ

• Asbestos	Fireproofing, insulation, vinyl floors (0.2 fibers/ml)
• Carbon monoxide	Combustion, space heaters, gas stoves, smoking (10mg/m^3 8 hr, 40 mg/m^3 1 hr)
• Formaldehyde	Particle board, foam insulation (120ug/m^3)
• Particulates	Smoking, wood stoves 55-110 ug/m^3 yr, 150-350 ug/m^3day
• NOx	Space heaters, stoves (100 ug/m^3 yr)
• O_3	Electrostatic cleaners, copy machines (235/m^3/yr)
• Radon	Soils, groundwater (0.01 working level per yr) EPA criterion @ 4 pCi/L = 150 Bq/m^3
• SO_2	Kerosene space heaters 80 ug/m^3 yr, 365 ug/m^3 d
• VOCs	Cooking, smoking, cleaning solvents (who knows)

Asbestos

√ Asbestos



- *Asbestinon*, latin, meaning "unquenchable"
- Amazing insulator / fireproofing material
- Exist as a naturally occurring mineral:

  - e.g. Chrysotile as $Mg_3(Si_2O_5)(OH)_4$

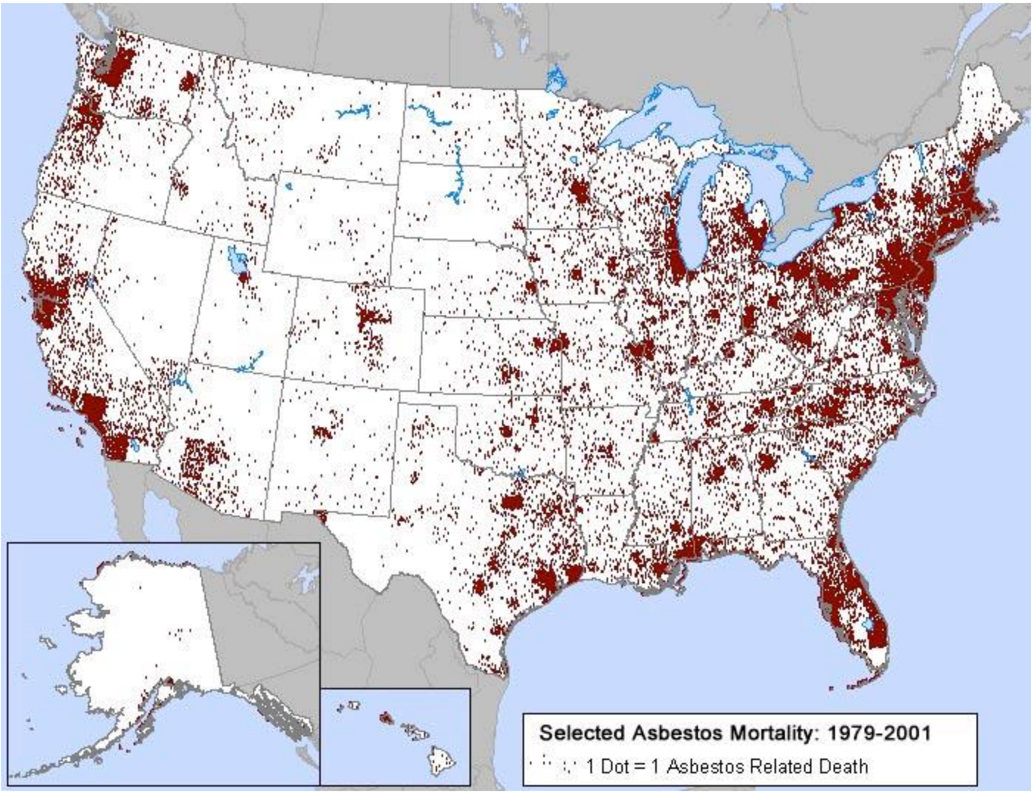
- 2006, 2.3 million tons were mined worldwide
- Causes Mesothelioma, Lung Cancer, Asbestosis

- Artificial Christmas snow, known as flocking, was previously made with asbestos

Asbestos

√ **Deaths Related to Asbestos Exposure**

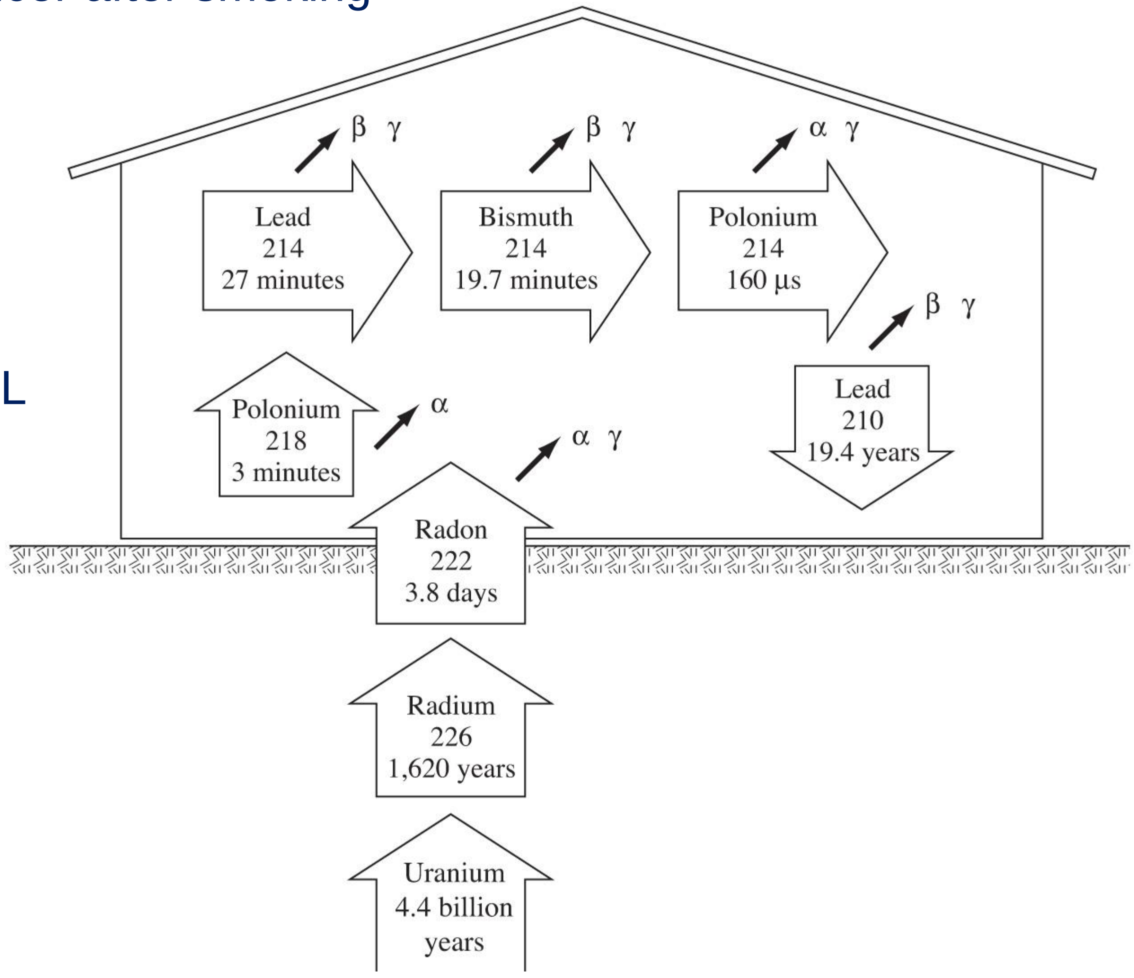
Hard to estimate the total effects…significant though..
ca. 10,000 people per year in US



Radon

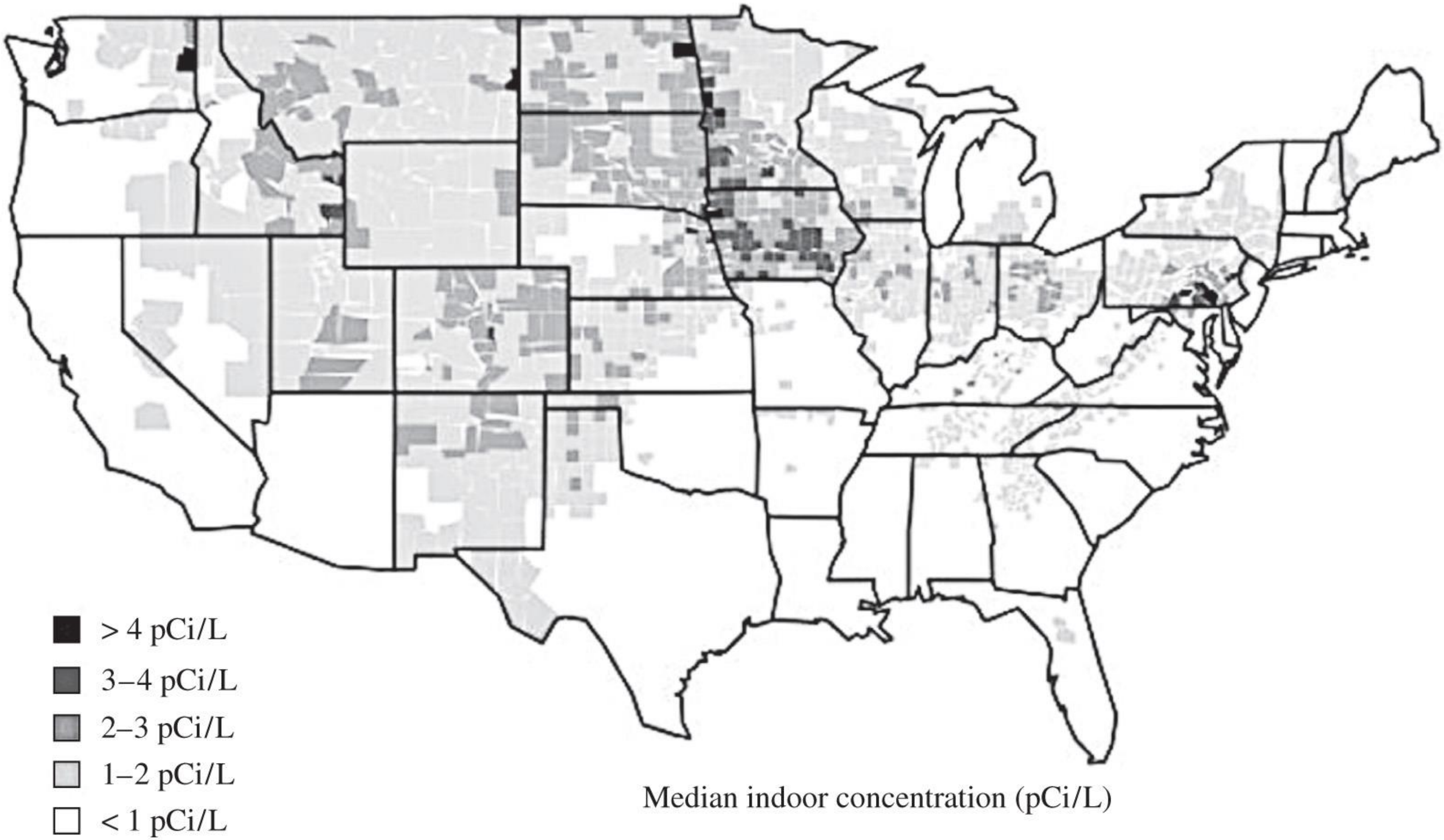
√ Radon

- Second leading cause of cancer after smoking
- Decay product from Uranium
- Soils under homes is most significant source
- Average US home = 1.3 pCi/L
- US outdoors = 0.4 pCi/L



Radon

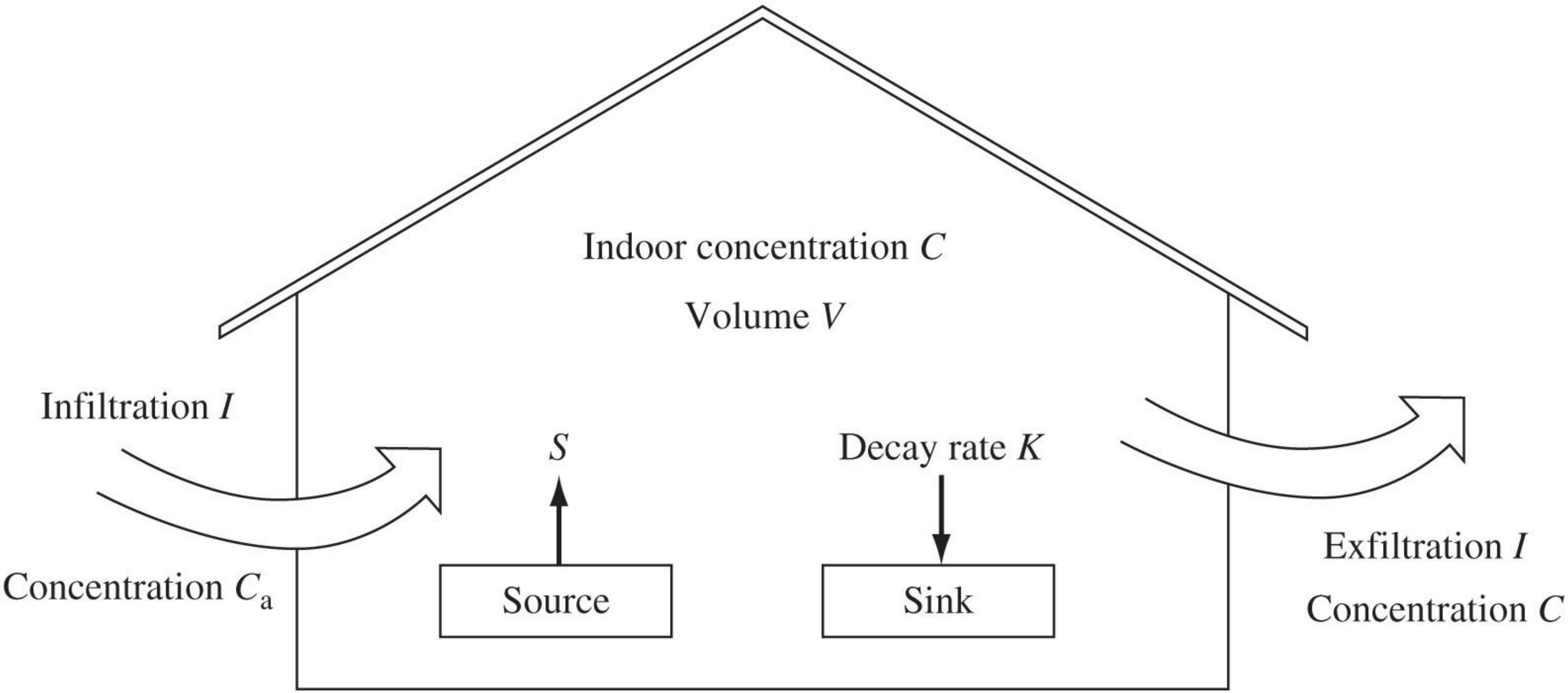
√ **Radon Exposure in the US**



Median indoor concentration (pCi/L)

Indoor Air Quality Model

√ **Indoor air quality model**



Indoor Air Quality Model

√ Indoor model – mass balance

Same as before:

(rate of accum.) = (rate entering)-(rate leaving)-(rate of decay)

$$V\frac{dC}{dt} = (S + C_a nV) - CnV - KCV$$

V = volume of space

n = number of air changes per hour (ach) (Q = nV)

S = Source emission rate (mg/hr)

C = Indoor Concentration (mg/m^3)

C_a = ambient concentration (mg/m^3)

K = pollutant decay rate (reactivity) (1/hr)

Indoor Air Quality Model

√ Indoor model – mass balance

Steady State: Set dC/dt = 0

$$C(\infty) = \frac{(S/V) + C_a n}{n + K}$$

$$C(t) = \left[\frac{(S/V) + C_a n}{n + K}\right]\left[1 - e^{-(n+K)t}\right] + C(0)e^{-(n+K)t}$$

When:
$C_a = 0$
$K = 0$

$$C(t) = \left(\frac{S}{nV}\right)(1 - e^{-nt})$$

Example

- Consider a 300 m^3 home with 0.2 ach infiltration rate. The only source of CO in the home is the gas range equipped with ovens and burners, and the ambient concentration of CO is always zero and CO does not decay.

  One oven emits 1,900 mg CO/hr, one burner emits 1,840 mg CO/hr.

  Suppose there is no CO in the home at 6 PM, but then the oven and two burners are on for one hour. Assume that the air is well mixed in the house.

  Estimate the CO concentration in the home at 7 PM and again at 10 PM

Example (solution)

$$C(t) = \left(\frac{S}{nV}\right)(1-e^{-nt}) \text{ since } C_a = C_0 = k = 0$$

6-7pm emissions: oven + 2 burners

$$S = 1{,}900 \text{ mg/hr} + 2 \times 1{,}840 \text{ mg/hr} = 5{,}580 \text{ mg/hr}$$

$$C(1 \text{ hr}) = \left(\frac{5{,}580 \text{ mg/hr}}{0.2 \text{ ach} \times 300 \text{ m}^3}\right)(1-e^{-0{,}2/h\times 1hr}) = 16.8 \text{ mg/m}^3$$

Now turn off the burners (S=0) and 3 h later:

$$C(t) = \cancelto{0}{\left[\frac{(S/V)+C_a n}{n+K}\right]\left[1-e^{-(n+K)t}\right]} + C(0)e^{-(n+K)t}$$

$$C(3 \text{ hr}) = C(7 \text{ PM})(e^{-nt}) = 16.8 \text{ mg/m}^3 (e^{-0.2/h\times 3hrs}) = 9.3 \text{ mg/m}^3$$