Meteorology and Dispersion Modeling
Air Quality and Meteorology

- Primary Metrological Parameter
  - Wind speed, Wind Direction, Atmospheric Stability
- Secondary Metrological Parameter
  - sunlight
  - temperature
  - precipitation and humidity
  - Topography
  - Energy from the sun and earth’s rotation drives atmospheric circulation

Stability

- Dry adiabatic lapse rate – temperature decreases due to lower pressure (ideal gas law)

$$\Gamma = -\frac{dT}{dz} = -1.00\ ^{\circ}\text{C/100 m} = \text{-}5.4\ ^{\circ}\text{F} / 1000\ \text{ft}$$

- Ambient (actual) lapse rate

  < Γ (temperature falls faster) unstable or superadiabatic

  > Γ (temperature falls slower) stable or subadiabatic

  = Γ (same rate) neutral

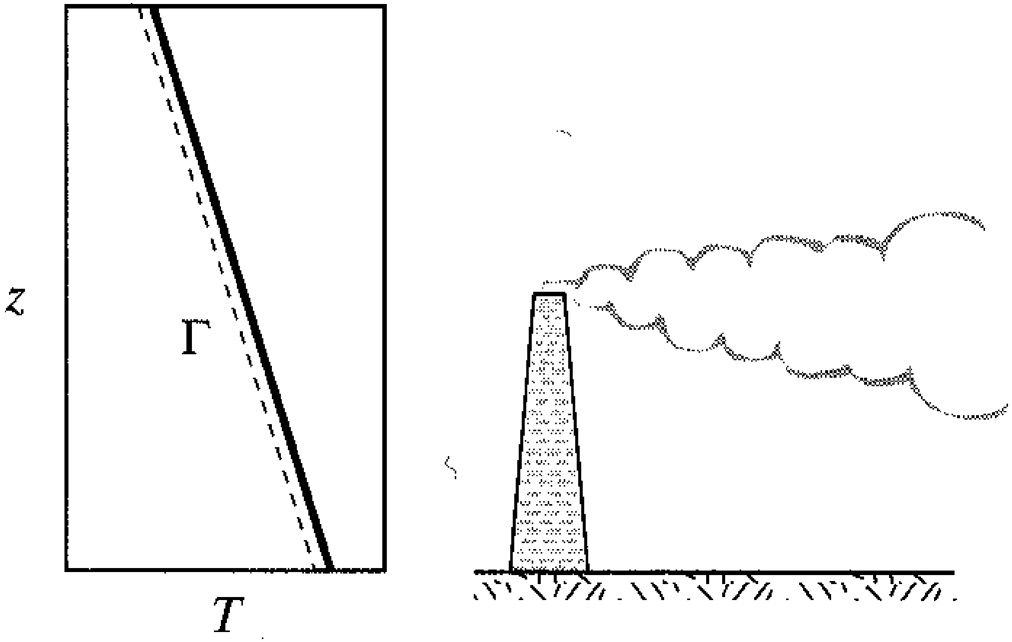
Example

Z(m)	T(ºC)
2	-3.05
318	-6.21

$$\frac{\Delta T}{\Delta z} = \frac{T_2 - T_1}{z_2 - z_1} = \frac{-6.21 - (-3.05)}{318 - 2} = -0.0100\ ^\circ\text{C/m}$$

$$= -1.00\ ^\circ\text{C/100 m}$$

Since lapse rate = Γ, atmosphere is neutral



Coning

- Standard Plume: Moderate wind speed:
- Moderate radiation, night time
- Horizontal dispersion at a right angle to the wind is due to turbulence and diffusion, which occurs at the same rate as the vertical dispersion, which is not being opposed nor encouraged by the stability (or lack of it) in the atmosphere.
- Plume spreads equally in the vertical and horizontal as it propagates downstream, forming a coning plume

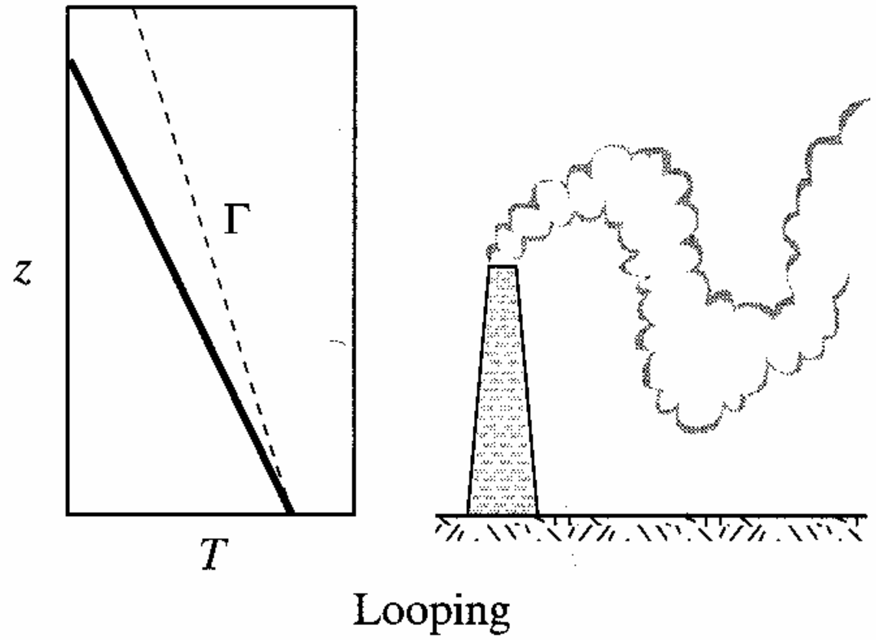
Example

Z(m)	T(ºC)
10	5.11
202	1.09

$$\frac{\Delta T}{\Delta z} = \frac{T_2 - T_1}{z_2 - z_1} = \frac{1.09 - 5.11}{202 - 10} = -0.0209\ ^\circ\text{C/m}$$

$$= -2.09\ ^\circ\text{C/100 m}$$

Since lapse rate is more negative than Γ, (-1.00 ºC/100 m), atmosphere is <u>unstable</u>



•In unstable air, the plume will whip up and down as the atmosphere mixes around (whenever an air parcel goes up, there must be air going down someplace else to maintain continuity, and the plume follows these air currents). This gives the plume the appearance that it is looping around.

•Vertical dispersion is very high.

•Less wind speed: Strong & Moderate radiation, day time Mechanical Turbulence is enhanced.

•High probability of high concentrations sporadically at ground level close to stack.

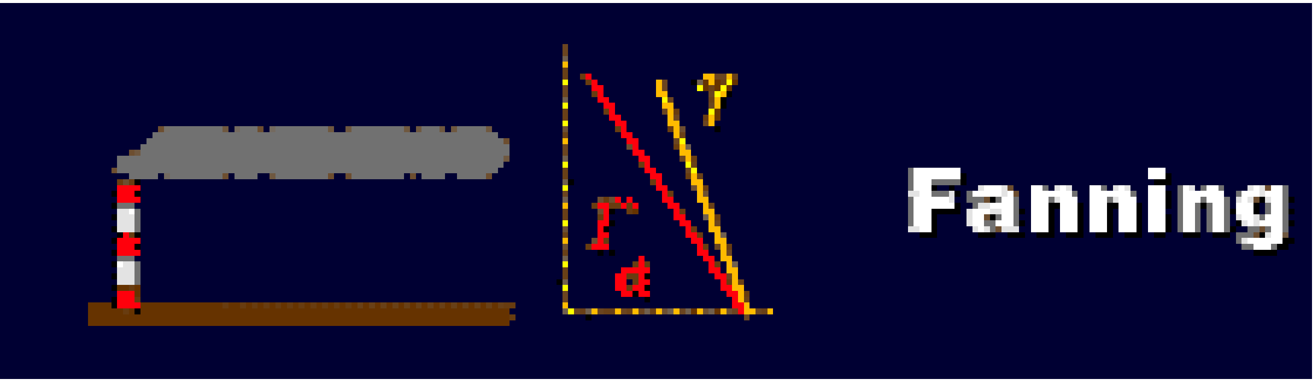
Example

Z(m)	T(ºC)
18	14.03
286	12.56

$$\frac{\Delta T}{\Delta z} = \frac{T_2 - T_1}{z_2 - z_1} = \frac{12.56 - 14.03}{286 - 18} = -0.0055\ °\text{C/m}$$

$$= -0.55\ °\text{C/100 m}$$ Suppress Vertical Dispersion

Since lapse rate more positive than Γ, atmosphere is <u>stable</u>

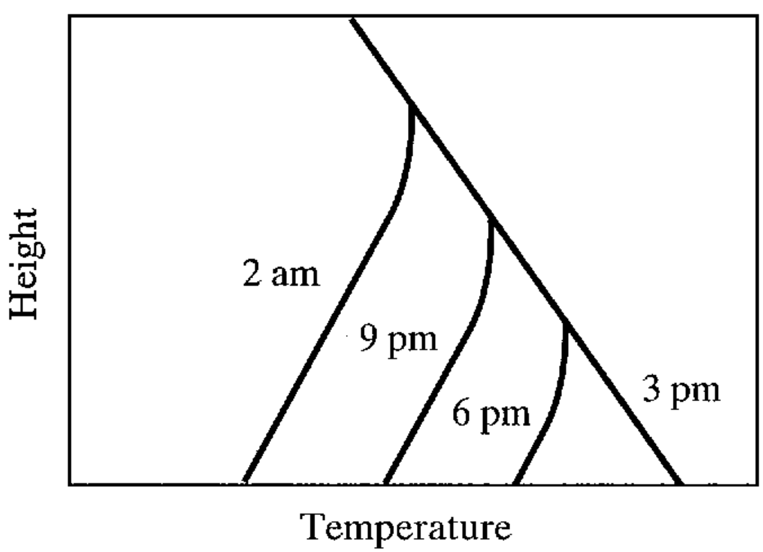


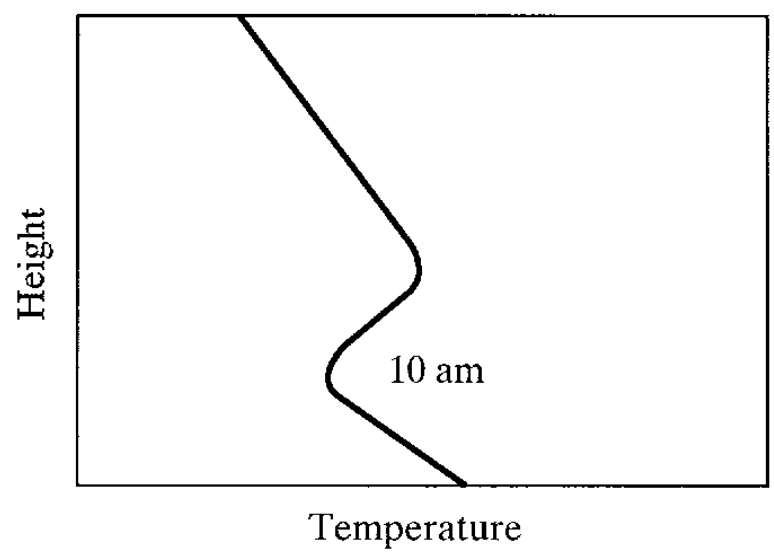
•High wind speed: Night time, High horizontal dispersion, Vertical dispersion is suppresses by stable atmosphere.

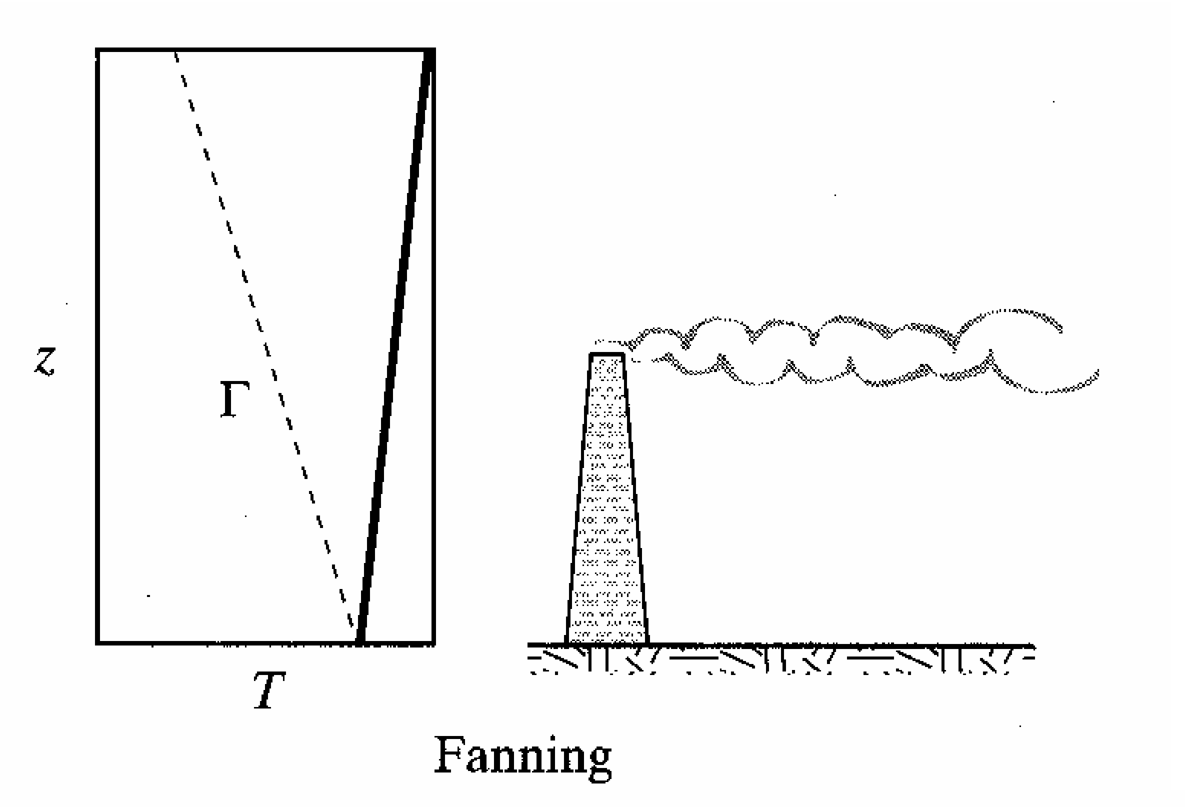
•In the vertical, dispersion is suppressed by the stability of the atmosphere, so pollution does not spread toward the ground. This results in very low pollution concentrations at the ground

Temperature Inversions

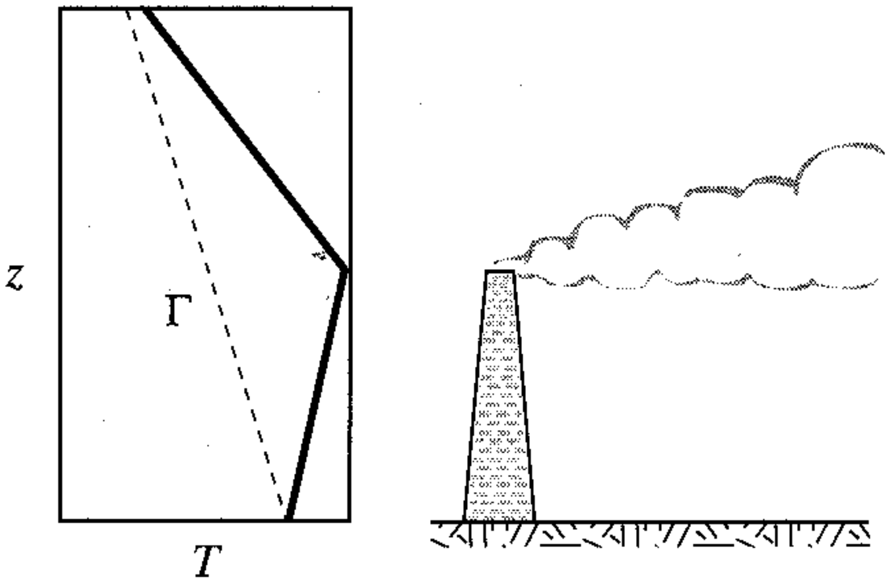
- Extreme case of stability when lapse rate is actually positive, i.e. temperature increases with altitude
- Resulting temperature inversion prevents nearly all upward mixing





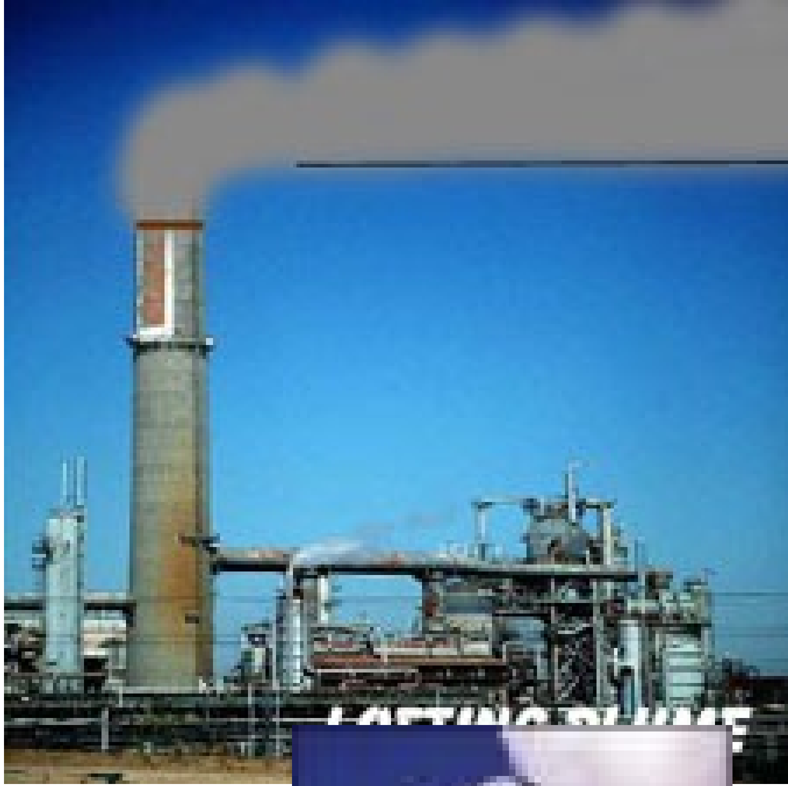


Fanning Plume:
Usually occurs at night, or 1200m-1800m above ground. There is high ground concentration if stack is short or if plume moves through rugged terrain. Occurs in stable inversion atmospheric conditions.

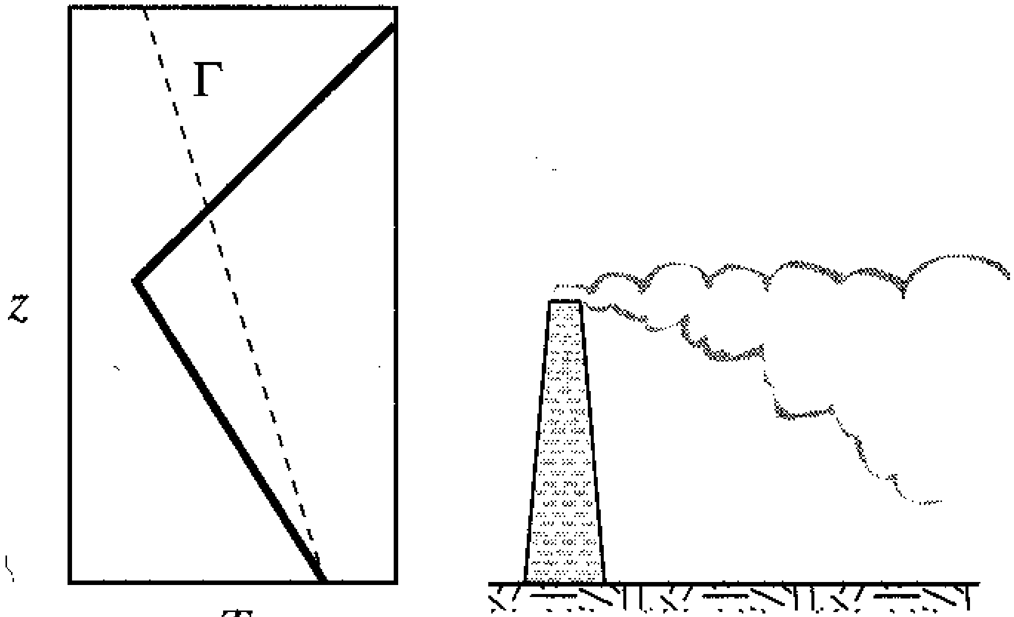


Lofting

(e)



Lofting Plume: favorable in the sense that fewer impacts at ground level. Pollutants go up into environment. They are created when atmospheric conditions are unstable above the plume

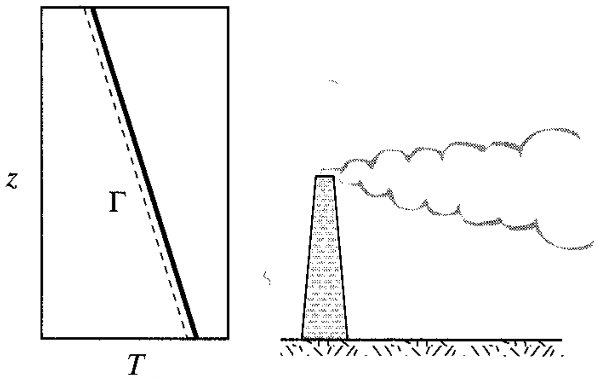


Fumigation

Fumigation:

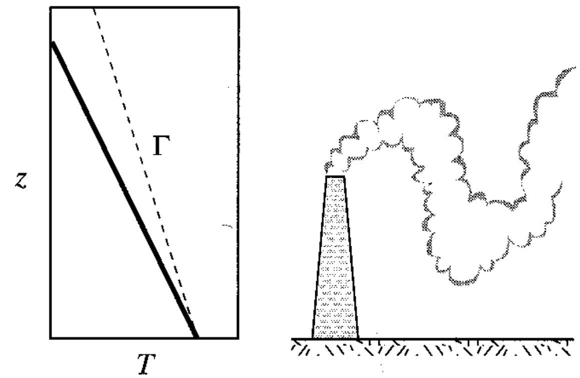
most dangerous plume: contaminants are all coming down to ground level. They are created when atmospheric conditions are inversion stable above the plume and unstable below. This happens most often after the daylight sun has warmed the atmosphere, which turns a night time fanning plume into fumigation for about a half an hour.

Effect of Lapse Rate on Plumes



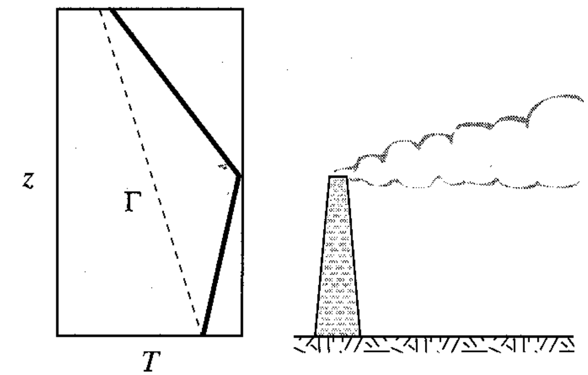
Coning

(*a*)



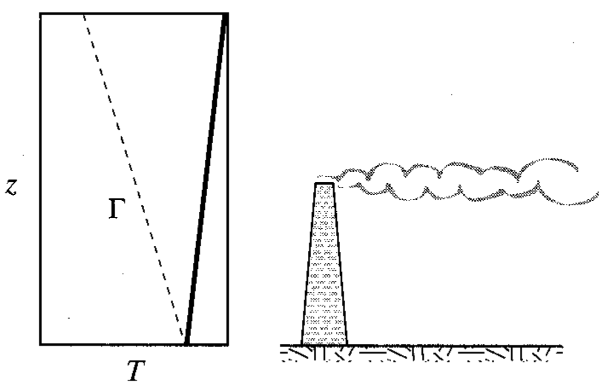
Looping

(*b*)



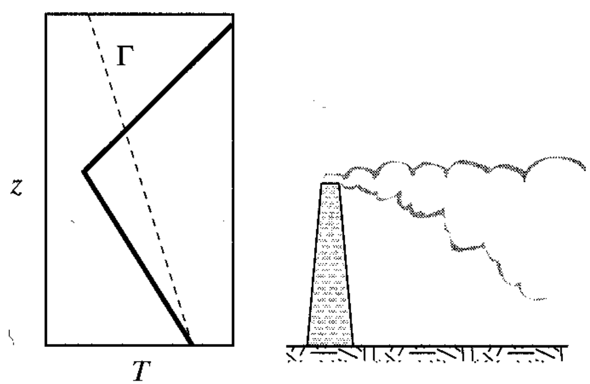
Lofting

(*e*)



Fanning

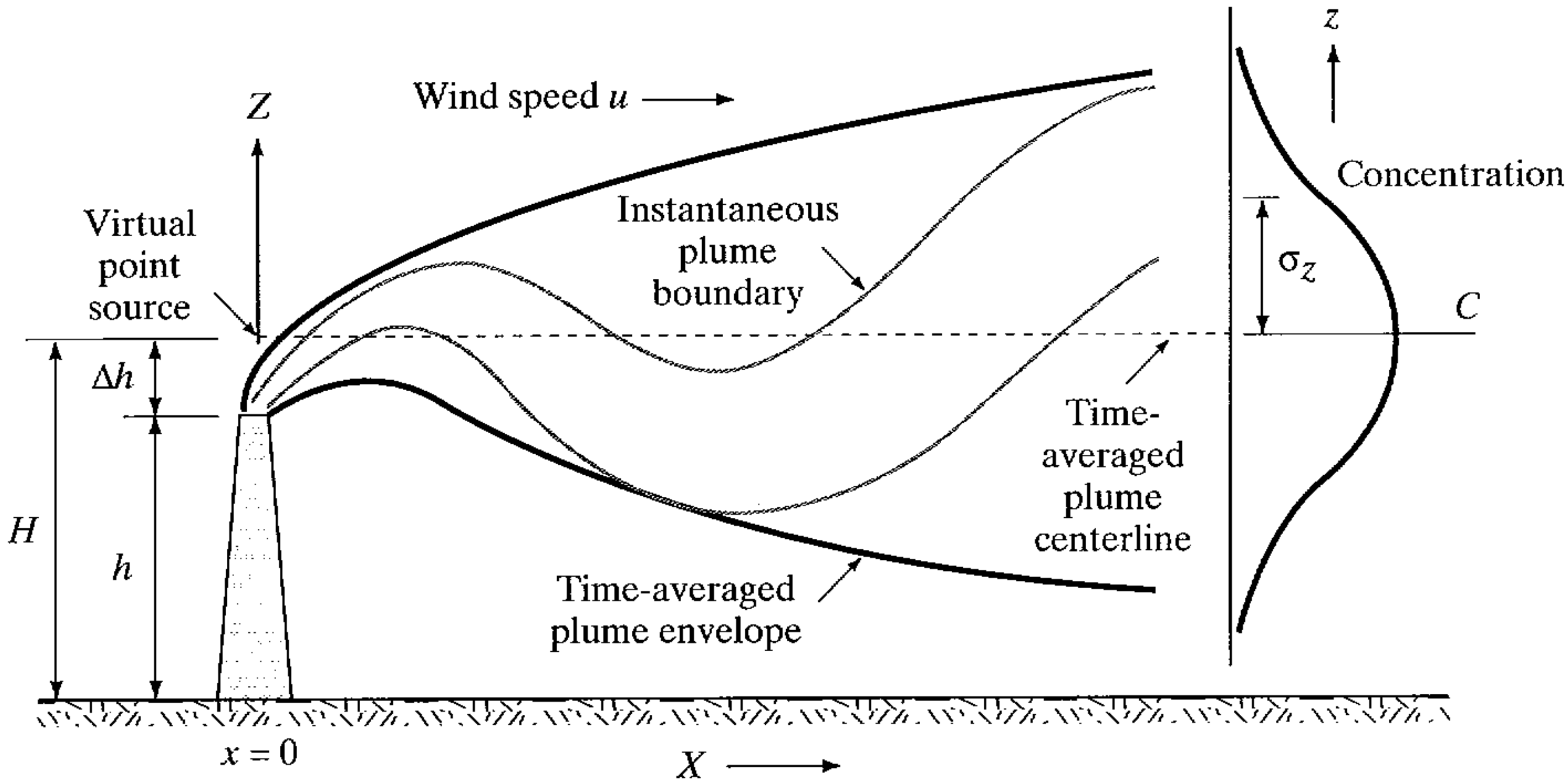
(*c*)



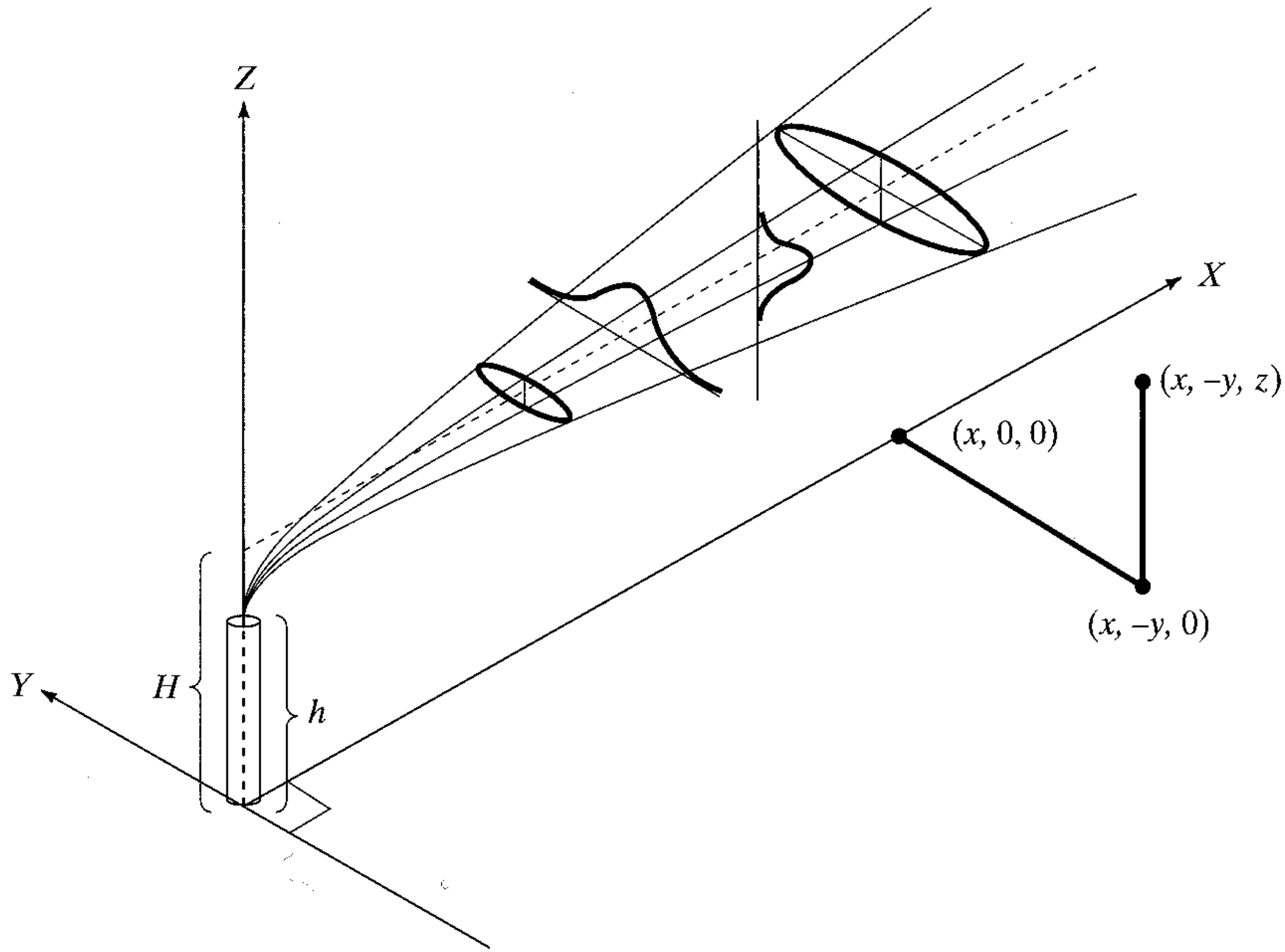
Fumigation

(*d*)

Point Source Gaussian Plume Model



Point Source Gaussian Plume Model



Point Source Gaussian Plume Model

- Model Structure and Assumptions
  - pollutants released from a “virtual point source”
  - advective transport by wind
  - dispersive transport (spreading) follows normal (Gaussian) distribution away from trajectory
  - constant emission rate

Point Source Gaussian Plume Model

- Model Structure and Assumptions (cont)
  - wind speed constant with time and elevation
  - pollutant is conservative (no reaction)
  - pollutant is “reflected by ground”
  - terrain is flat and unobstructed
  - uniform atmospheric stability

Point Source Gaussian Plume Model

$$\chi(x, y, 0, H) = \left[\frac{E}{\pi s_y s_z u}\right]\left[\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]\right]\left[\exp\left[-\frac{1}{2}\left(\frac{H}{s_z}\right)^2\right]\right]$$

Where χ = downwind concentration at ground level (g/m^3)

E = emission rate of pollutant (g/s)

s_y, s_z = plume standard deviations (m)

u = wind speed (m/s)

x, y, z, H = distances (m)

Point Source Gaussian Plume Model – Effective Stack Height

$$H = h + \Delta H$$

where

H = Effective stack height (m)

h = height of physical stack (m)

ΔH = plume rise (m)

Point Source Gaussian Plume Model – Effective Stack Height

- Holland's formula

$$\Delta H = \frac{v_s}{u}\left[1.5 + \left(2.68 \times 10^{-2}\left(P\right)\left(\frac{T_s - T_a}{T_a}\right)d\right)\right]$$

where v_s = stack velocity (m/s)

d = stack diameter (m)

u = wind speed (m)

P = pressure (kPa)

T_s = stack temperature (ºK)

T_a = air temperature (ºK)

Point Source Gaussian Plume Model – Stability Categories

TABLE 11–6 Key to Stability Categories

Surface Wind Speed (at 10 m) $(m \cdot s^{-1})$	Day[a] Incoming Solar Radiation			Night[a]	
	Strong	Moderate	Slight	Thinly Overcast or $\geq \frac{4}{8}$ Low Cloud	$\leq \frac{3}{8}$ Cloud
<2	A	A–B	B		
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

A Extremely Unstable

B Moderately Unstable

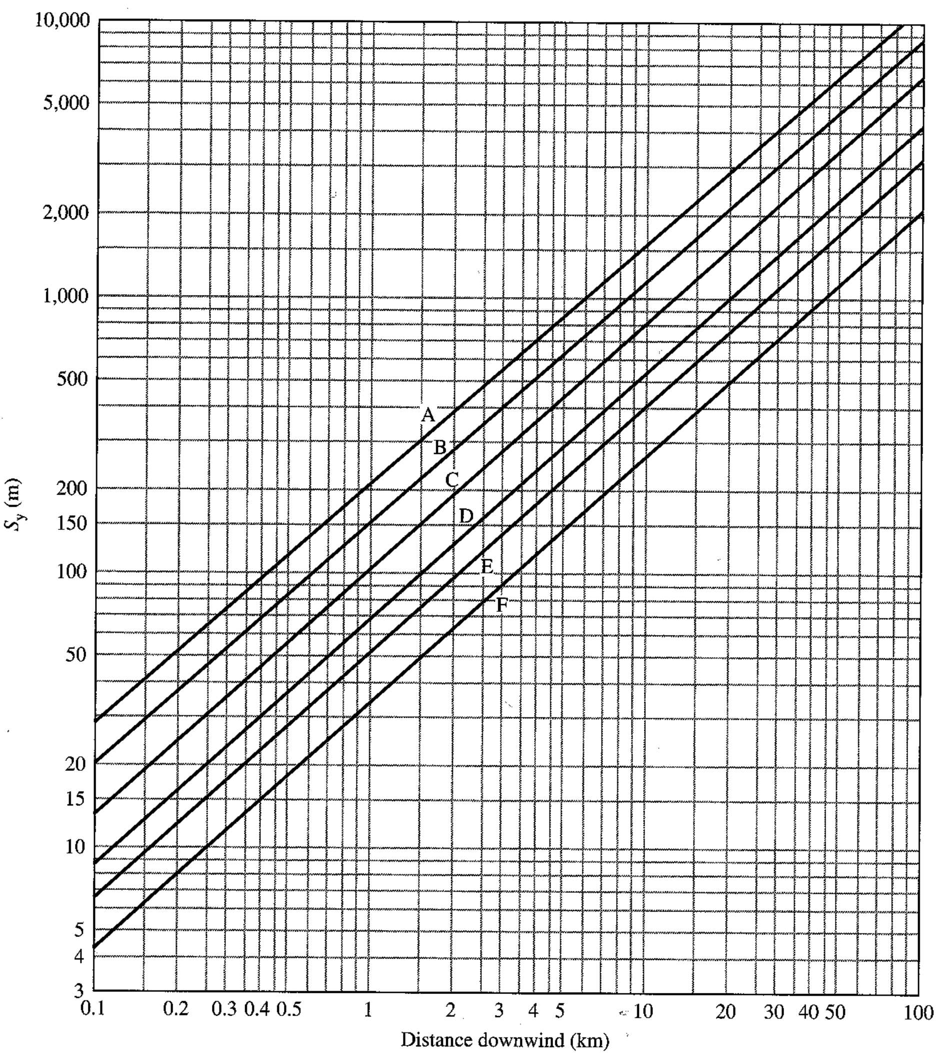
C Slightly Unstable

D Neutral

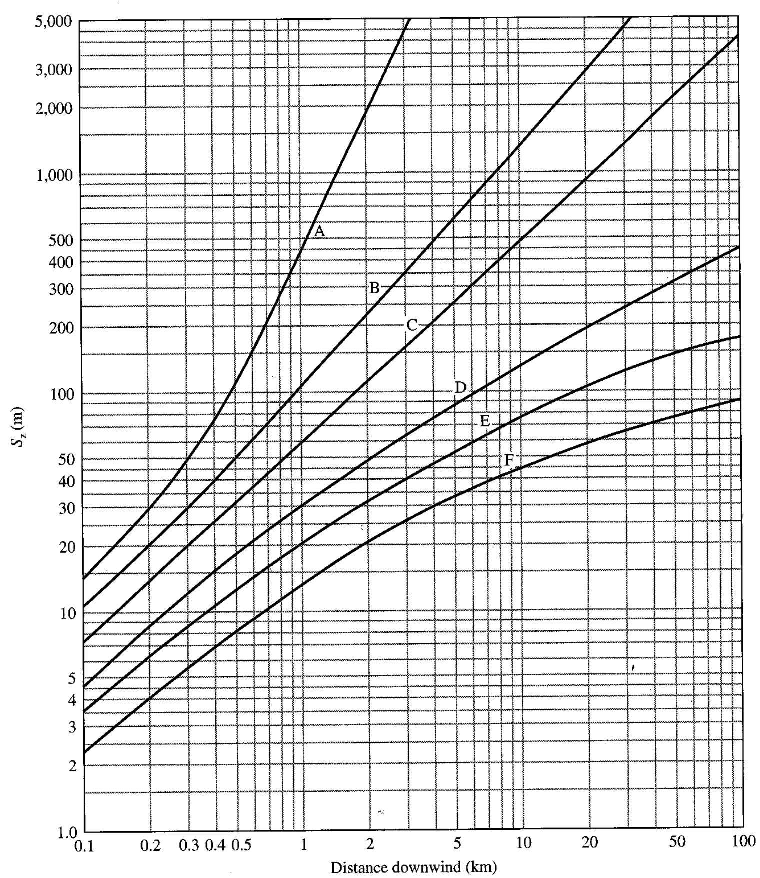
E Slightly Stable

F Moderately Stable

Point Source Gaussian Plume Model – Horizontal Dispersion



Point Source Gaussian Plume Model – Vertical Dispersion



Point Source Gaussian Plume Model – Wind Speed Correction

- Unless the wind speed at the virtual stack height is known, it must be estimated from the ground wind speed

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

where u_x = wind speed at elexation z_x

p = empirical constant

TABLE 11–8 Exponent *p* Values for Rural and Urban Regimes

Stability Class	Rural	Urban	Stability Class	Rural	Urban
A	0.07	0.15	D	0.15	0.25
B	0.07	0.15	E	0.35	0.30
C	0.10	0.20	F	0.55	0.30

Example

- A stack in an urban area is emitting 80 g/s of NO. It has an effective stack height of 100 m. The wind speed is 4 m/s at 10 m. It is a clear summer day with the sun nearly overhead. Estimate the ground level concentration at a) 2 km downwind on the centerline and b) 2 km downwind, 0.1 km off the centerline.

Example

1. Determine stability class

   Assume wind speed is 4 km at ground surface. Description suggests strong solar radiation.

   <u>Stability class B</u>

TABLE 11–6 Key to Stability Categories

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<2	A	A–B	B		
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

Example

2. Estimate the wind speed at the effective stack height

   Note: effective stack height given – no need to calculate using Holland's formula

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A	0.07	0.15	D	0.15	0.25
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C	0.10	0.20	F	0.55	0.30

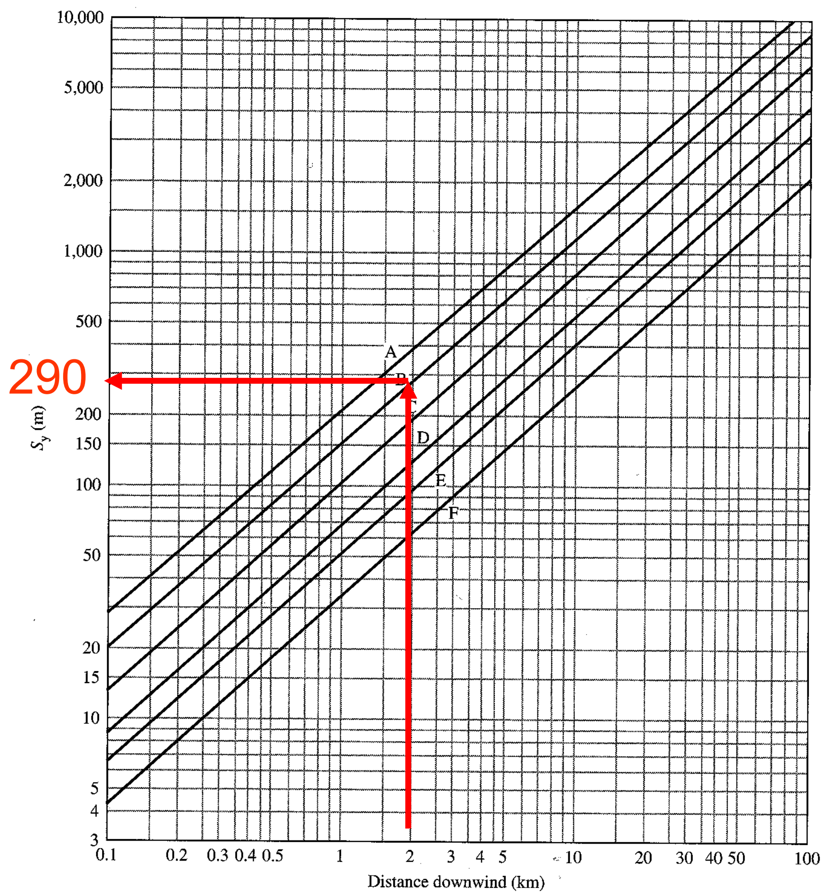
$$u_2 = u_1\left(\frac{z_2}{z_1}\right)^p = 4\left(\frac{100}{10}\right)^{0.15} = 5.65\ \text{m/s}$$

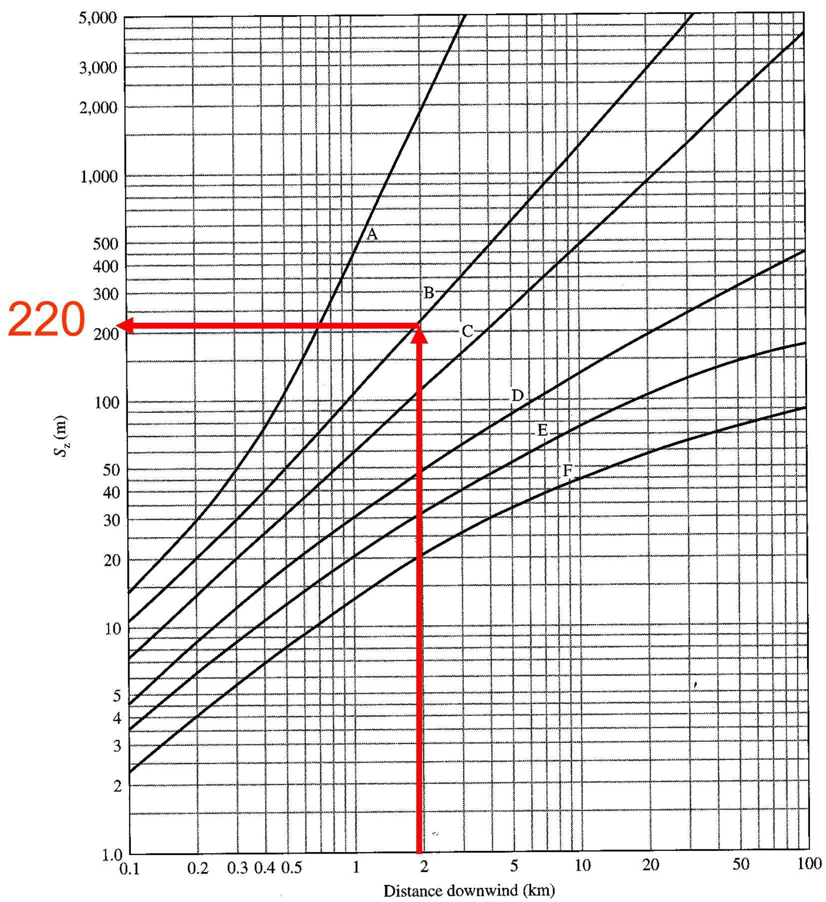
Example

3. Determine σ_y and σ_z

σ_y = 290

σ = 220





Example

4. Determine concentration using Eq
   a. x = 2000, y = 0

$$C(2000,0) = \frac{80}{\pi(290)(220)(5.6)} \exp\left[-\frac{1}{2}\left(\frac{0}{290}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{100}{220}\right)^2\right]$$

$$C(2000,0) = 6.43 \times 10^{-5} \text{ g/m}^3 = 64.3\ \mu\text{g/m}^3$$

Example

b. x = 2000, y = 0.1 km = 100 m

$$C(2000{,}100) = \frac{80}{\pi(290)(220)(5.6)} \exp\left[-\frac{1}{2}\left(\frac{100}{290}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{100}{220}\right)^2\right]$$

$$C(2000{,}0) = 6.06\times10^{-5}\ \text{g/m}^3 = 60.6\ \mu\text{g/m}^3$$