University of Asia Pacific
Department of Civil Engineering
Course Lecture Plan (Tentative)

Course Code: CE 433 **Credit Hour: 2.0**

Corse Title: Environmental Engineering IV (Environmental Pollution and Its Control)

Course Teacher: Kazi Shamima Akter, Assistant Professor

Topics	**No of classes**
Air Pollution	**12**
Sources and types of pollutants	
Effects of various pollutants on human health, materials and plants	
Air pollution meteorology	
Global warming and green house effects	
Air pollution monitoring and controlling measures	
Water pollution	
Water pollution, sources and types of pollutants	**15**
Waste assimilation capacity of streams	
Dissolved oxygen modeling	
Ecological balance of streams	
Industrial pollution	
Heavy metal contamination	
Groundwater pollution	

Grading Policy:

Class Assessment & Attendance	**10%**
Class tests	**20%**
Mid -term exam	**20%**
Final exam	**50%**

Note: **2** out of **3** class tests will be counted.

CE 433
Environmental Pollution and Its Control
(Credit 2.0, Class Period 2 hours/week)

What is Air pollution?

Air pollution may be defined as any atmospheric condition in which substances are present at concentrations, above their normal ambient levels, to produce measurable adverse effect on human, animal, vegetations or materials.

Key features for air pollution/pollutants:

- Types of pollutants
- Concentrations of pollutants in air
- Time of exposure towards the pollutants

$$\text{Emission sources} \xrightarrow[\text{Pollutants}]{} \text{Atmosphere} \xrightarrow[\text{Mixing and chemical transformations}]{} \text{Receptors}$$

Components of air pollution problem:

Composition of atmospheric gases in clean, dry air at ground level:

Gas	Concentration (ppm by volume) (* at 2005)	Concentration (% by volume)
Nitrogen (N_2)	780,000	78.09
Oxygen (O_2)	209,500	20.95
Argon (Ar)	9,300	0.93
Carbon dioxide (CO_2)	320 (379)*	0.032
Neon	18	0.0018
Helium (He)	5.2	0.00052
Methane (CH_4)	1.5 (1.774)*	0.00015
Krypton (Kr)	1.0	0.0001
Hydrogen (H_2)	0.5	0.00005
Dinitrogen Oxide (N_2O)	0.2 (0.319)*	0.00002
Carbon Monoxide (CO)	0.1	0.00001
Zenon (Xe)	0.08	0.000008
Ozone (O_3)	0.02	0.000002

Ammonia (NH_4)	0.006	0.0000006
Nitogen dioxide (NO_2)	0.001	0.0000001
Nitric Oxide (NO)	0.0006	0.00000006
Sulfur dioxide (SO_2)	0.0002	0.00000002
Hydrogen sulfide (H_2S)	0.0002	0.00000002

Source: Peavy et al. (1985)

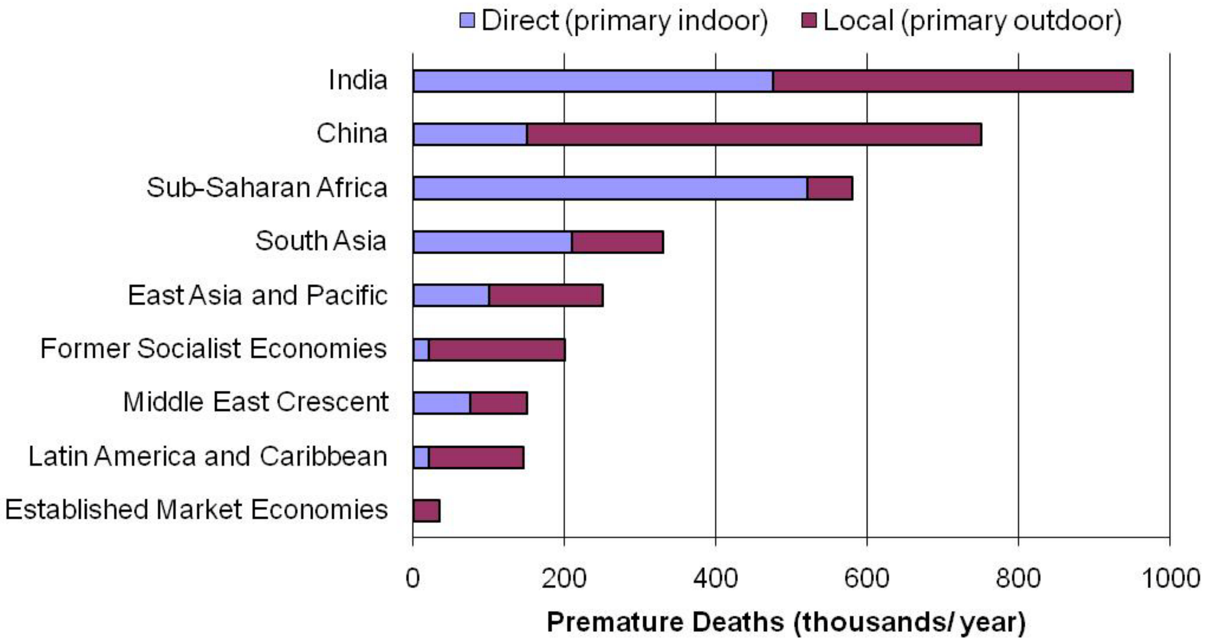
Historical Perspectives of Air Pollution Impacts on Human Health

Table 1.2: Reported disease morbidity and mortality occurrences during air pollution episodes

Year and Month	Location	Excess deaths reported	Reported illness
1873, Dec. 9-11	London, England		
1880, Jan. 26-29	London, England		
1892, Dec. 28-30	London, England		
1930, December	Meuse Valley, Belgium	63	6000
1948, October	Donora, Pennsylvania	17	6000
1948, Nov. 26 – Dec. 1	London, England	700 - 800	
1952, Dec. 5-9	London, England	4000	
1953, November	New York, USA		
1956, Jan. 3-6	London, England	1000	
1957, Dec. 2-5	London, England	700 - 800	
1958	New York, USA		
1959, Jan. 26-31	London, England	200 - 250	
1962, Dec. 5-10	London, England	700	
1963, Jan. 7-22	London, England	700	
1963, Jan. 9 – Feb. 12	New York, USA	200 - 400	
1966, Nov. 23-15	New York, USA		

Source: Peavy et al. (1985)

Premature Deaths Estimated due to Air Pollution



(Source: Gordon Hughes, 2000)

Indoor Air Pollution

Sources of Indoor Air Pollution:

- Cooking (especially using biomass fuel in traditional cooking stoves in developing countries
- Tobacco smoking
- Heating appliances
- Vapors from building materials, paints, furniture etc
- Radon (natural radioactive gas released from earth)

Pollution exposure at home and workplace is often greater than outdoors.

Outdoor Air Pollution

Classification of Major Sources for Outdoor Pollution:

(1) Mobile sources/ transportation – include motor vehicle, rail, ship, aircraft

(2) Stationary sources – include utility, industrial, institutional and commercial facilities. Examples include power plants, heating plants, paper pulp industries, petroleum refineries, municipal waste combustors etc.

(3) Area sources – include many individually small activities, like gasoline service stations, small paint shops, open burning associated with solid waste, agriculture and forest management, cooking in slum areas etc.

(4) Incineration/burning of wastes – household and commercial waste; agricultural burning; industrial and hazardous waste incineration

(5) Miscellaneous – re-suspension from road; domestic fuel, wood burning; forest fire, volcanic eruption, pollen grain, certain bacteria, viruses (natural sources);

Classification of Pollutants

(A) According to origin –

- ***Primary pollutants:*** emitted directly into the atmosphere and are found in form in which they were emitted, e.g. SO_x, NO_x, HC (Hydro carbon)
- ***Secondary pollutants***: derived from the primary pollutants by chemical or photo-chemical reactions in the atmosphere, e.g. Ozone (O_3), peroxyacetyle nitrate (PAN)

(B) According to chemical composition –

- ***Organic***: Hydrocarbons (H. C), Aldehydes and Ketones (H, C, O), VOCs, PCBs, PAHs
- ***Inorganic***: NO_x, SO_x, CO, HCl, H_2SO_4, H_2S, NH_3

Inorganic pollutants are often classified as –
- S containing compounds
- N containing compounds
- C containing compounds
- H compounds

(C) According to state of matter –

- ***Gaseous***: CO, SO_x, NO_x (Inorganic) ; Benzyne, Methane (Organic)
- P***articulates/Aerosols***: dust, smoke, fume, fly ash (solid); mist, spray (Liquid); pollen, bacteria, virus (natural)

Important Terms to Describe Air Pollutants

Criteria pollutants – Six major air pollutants identified as causing health effects at concentrations above thresholds established at levels known to be safe. These are:

- CO
- Pb
- NO_2
- O_3
- SO_2
- Particulate Matter (PM)

Air toxins – Pollutants that are known or suspected to cause cancer or other serious health effects. Air toxins can come from natural sources (e.g. radon gas coming from the ground) or man-made sources, such as motor vehicles and industrial processes.

Examples include benzyne (from gasoline), perchloroethylene (fromdry cleaners) and methylene chloride (used as a solvent and paint stripper).

Units of measurements –

- Particulate matter (PM): mass/unit vol. of air (e.g. mg/m^3, $\mu g/m^3$)
- Gaseous pollutants:
- (a) mass/unit vol. (e.g. mg/m^3, $\mu g/m^3$)
- (b) ppm= ppmv= volume of pollutant per million volume of air mixture

$$1 \text{ ppm} = 1\text{ppmv} \quad \frac{1 \text{ vol. of gaseous pollutant}}{106 \text{ vol. of air}} =$$

Relationship between two units for gaseous pollutants:

- Ideal gas law: PV = nRT

Where, R = 0.082056 L atm mol^{-1} k^{-1} (Gas Law constant)

Therefore, Volume of 1 mole of an ideal gas at STP (P = 1 atm, T = 273.25 k),

$$V = \frac{nRT}{P} = 22.414 \text{ L}$$

$$\text{Now, } 1 \text{ ppm} = \frac{1 \text{ m}^3 \text{ of pollutant}}{10^6 \text{ m}^3 \text{ air}}$$

$$1 \text{ mg/m}^3 = \frac{1 \text{ mg pollutant}}{1\text{m}^3 \text{ air}} = \frac{10^6 \text{ mg pollutant}}{10^6 \text{ m}^3 \text{ air}}$$

Now at STP,

10^6 mg pollutant = 10^6 mg × 10^{-3} (g/mg × mol/ MW g) × 22.414 (L/mol) × 10^{-3} (m^3/L)
= 22.414 m^3/ MW
Here, MW = mol. wt.

Therefore, at STP, 1 mg/m^3 = (22.414 /MW) ppm
At any other temp (T) and pressure (P),
10^6 mg pollutant = (22.414/ MW) × (T/273.15 P) [as P1 V1/T1 = P2 V2/T2]
Therefore, 1 mg/m^3 = [(22.414/ MW) × (T/273.15 P)] ppm

In other words,
Concentration in mg/m^3 = conc. in ppm × (MW/22.414) × (273.15 P/T)
Since 1 mol. of all ideal gas occupies the same volume under same temperature and pressure,

$$1 \text{ ppm V} = \frac{1 \text{ mole pollutant}}{10^6 \text{ mole air}}$$

Similarly, since each mole contains the same number of molecules (6.02 × 10^{23} molecules/mol),

$$1 \text{ ppm V} = \frac{1 \text{ molecule of pollutant}}{10^6 \text{ molecule air}}$$

Regulations/ Standards

Two types of standards:
(a) Emission standard
(b) Air quality standard

Emission standard: Source cannot emit more than a specified mass of pollutant (over a period of time).

This is based on the technology, economics, relation to air borne concentration.

The objective is to control pollutant sources so that ambient pollutant concentrations are reduced to levels considered to be safe from public health point of view.

Bangladesh Environmental Conservation Rules (ECR) 1997 set emission standards for motor vehicles, industries etc. The motor vehicle standard has been revised in July 2005.

Example 1: Petrol/ Gas driven motor vehicle (< 8 seater) standards at the time of registration –

CO : 2.2 gm/km
HC, NO_x : 0.5 gm/km

Example 2: From Gas-fired power plants – Gaseous discharge, NO

≥ 500 MW	: 50 ppm
200 -500 MW	: 40 ppm
< 200 MW	: 30 ppm

(b) **Air Quality Standards**: Airborne concentration of a pollutant cannot exceed a specified value over a certain "averaging period".

Air quality standards are based only on effects.

Why averaging period?

Because higher the concentration, shorter the exposure time required for undesirable effects.

A pollutant at a certain concentration may be harmful over longer exposure time but relatively harmless over shorter exposure time.

Example: Bangladesh standard for CO:

$10\ mg/m^3$ (averaging period: 8 hr)

$40\ mg/m^3$ (averaging period: 1 hr)

Measurement and reporting of a particular air pollutant should be consistent with the "averaging period" of that particular air pollutant.

Bangladesh Air Quality Standards

- Environmental Conservation Rules (ECR) 1997
- Air quality standard contained in ECR revised in July 2005

Table 1.3: Revised National Ambient Air Quality Standard (ECR 1997, Revised in July 2005)

Pollutant	Standard	Averaging Period
CO	$10\ mg/m^3$ (9 ppm)	8 hr
	$40\ mg/m^3$ (35 ppm)	1 hr
Pb	$0.5\ \mu g/m^3$	Annual
NO_2	$100\ \mu g/m^3$ (0.053 ppm)	Annual
SPM	$200\ \mu g/m^3$	8 hr
PM_{10}	$50\ \mu g/m^3$	Annual
	$150\ \mu g/m^3$	24 hr
$PM_{2.5}$	$15\ \mu g/m^3$	Annual
	$65\ \mu g/m^3$	24 hr
O3	$235\ \mu g/m^3$ (0.12 ppm)	1 hr
	$157\ \mu g/m^3$ (0.08 ppm)	8hr
SO2	$80\ \mu g/m^3$ (0.03 ppm)	Annual
	$365\ \mu g/m^3$ (0.14 ppm)	24 hr

Note:
SPM – Suspended Particulate Matter
PM_{10} – Particulate matter of size $\leq 10\ \mu m$
$PM_{2.5}$ – Particulate matter of size $\leq 2.5\ \mu m$

Air Quality Index (AQI)

Table 1.4: AQI Categories (USEPA)

AQI value	Descriptor	Color Code
0 – 50	Good	Green
51 – 100	Moderate	Yellow
101 – 150	Unhealthy for sensitive group	Orange
151 – 200	Unhealthy	Red
201 – 300	Very unhealthy	Purple
> 301	Hazardous	Maroon

Purposes of AQI:

To inform people about air quality conditions in a single format

Promote public interest and action to reduce emissions

Table 1.5: AQI Categories from Bangladesh perspectives (adopted from USEPA)

AQI value	Descriptor	Color Code
0 – 100	Good	Green
101 – 200	Unhealthy	Orange
201 – 300	Very unhealthy	Violet
301 – 500	Extremely unhealthy	Red

AQI is calculated based on concentrations of 5 criteria pollutants:

- O_3 (1-hr, 8-hr)
- PM (PM_{10}, 24-hr; $PM_{2.5}$, 24-hr)
- CO (8-hr)
- SO_2 (24-hr)
- NO_2 (annual)

- Each pollutant concentration is converted into an AQI number using the method developed by USEPA.
- The highest AQI number is the AQI value of the day.
- For example: On a particular day, if a certain area has an AQI value of 120 for $PM_{2.5}$ and 88 for SO_2, then the AQI for that particular day is 120 and the critical pollutant is $PM_{2.5}$ for that area.

Calculation of Air Quality Index (AQI)

AQI is the highest value calculated for each pollutant as follows:

- Identify the highest concentration among all the monitors within each reporting area
- Using Table 1.6, find the breakpoints that contain the concentrations
- Using Eq. 1, calculate the index for each pollutant and round the value to nearest integer

Table 1.6: Breakpoint concentration of criteria pollutants and AQI categories

Breakpoints							**AQI**	**Category**
O_3 (ppm) 8-hr	**O_3 (ppm) 1-hr (i)**	**$PM_{2.5}$ (µg/m^3) 24-hr**	**PM_{10} (µg/m^3) 24-hr**	**CO (ppm) 8-hr**	**SO_2 (ppm) 24-hr**	**SO_2 (ppm) Annual**		
0.000-0.064	---	0.0-15.4	0-54	0.0-4.4	0.000-0.034	(ii)	0-50	Good
0.065-0.084	---	15.5-40.4	55-54	4.5-9.4	0.035-0.144	(ii)	51-100	Moderate
0.085-0.104	0.125-0.164	40.5-65.4	155-254	9.5-12.4	0.145-0.224	(ii)	101-150	Unhealthy for sensitive group
0.105-0.124	0.165-0.204	65.5-150.4	255-354	12.5-15.4	0.225-0.304	(ii)	151-200	Unhealthy
0.125-0.374	0.205-0.404	150.5-250.4	355-424	15.5-30.4	0.305-0.604	0.65-1.24	201-300	Very unhealthy
(iii)	0.405-0.504	250.5-350.4	425-504	30.5-40.4	0.605-0.804	1.25-1.64	301-400	Hazardous
(iii)	0.505-0.604	350.5-500.4	505-604	40.5-50.4	0.805-1.004	1.65-2.04	401-500	Hazardous

(i) In some cases, in addition to calculating the 8-hr ozone index, the 1-hr ozone index may be calculated and the maximum of the two values is reported

(ii) NO_2 has no short term air quality standard and can generate an AQI only above 200

(iii) 8-hr O_3 values do not define higher AQI values (≥ 301). AQI values of 301or higher are calculated with 1-hr O_3 concentrations.

Important Points about AQI

- AQI values (reported in Table 1.6) is related to the air quality standard
- In most cases, the index value of 100 is associated with the numerical level of the short-term standard (i.e., averaging period 24-hr or less)
- The index value 50 is associated with the numerical level of the annual standard for a pollutant, if there is one, at one-half the level of the short-term standard of the pollutant, or at the level at which it is appropriate to begin to provide guidance on cautionary language.
- Higher categories of the index are based on increasingly serious health effects and increasing proportions of the population that are likely to be affected.
- The pollutant responsible for the highest index value (the reported AQI) is called the "critical pollutant".

AQI for a particular pollutant, I_p is given by:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo} \quad \text{.........................} \text{ (Eq. 1)}$$

where,

I_p = the index value for pollutant p

C_p = the concentration of pollutant p

BP_{Hi} = the breakpoint ≥ C_p

BP_{Lo} = the breakpoint ≤ C_p

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

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

(Note: If the concentration is larger than the highest breakpoint in Table 1.6, then you may use the last two breakpoints in the Table 1.6 while applying Eq. 1)

The AQI report should contain:

- Reporting area
- Reporting date
- The critical pollutant
- The AQI (i.e., the highest index value)
- The category descriptor (and the color format, if appropriate)
- The pollutant specific sensitive group according to Table 1.7
- Where appropriate, the name and index value of other pollutants, particularly those with index value > 100

Table 1.7: Pollutant specific sensitive groups

Pollutant AQI > 100	Sensitive groups/ groups at the most risk
O_3	Children and the people with asthma
$PM_{2.5}$	People with respiratory or heart disease, the elderly and children
PM_{10}	People with respiratory disease
CO	People with heart disease
SO_2	People with asthma

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Air Pollution and Meteorology

Air quality often depends on the dynamics of the atmosphere, the study of which is called "meteorology".

Lapse Rates

The case with which pollutants can disperse in the atmosphere is largely determined by the rate of change of air temperature with altitude.

In the troposphere, the temperature of ambient air usually decreases with an increase in altitude. This rate of temperature change is called "lapse rate" or "ambient lapse rate, Λ"

A specific parcel of air whose temperature is greater than that of the ambient air tends to rise until it reaches a level at which its own temperature and density equal that of the atmosphere that surround it. Thus a parcel of artificially heated air (e.g., automobile exhaust) rises, expands, becomes lighter and cools. The rate, at which the temperature of the parcel decreases (i.e., lapse rate), may be considerably different from the ambient lapse rate (Λ) of the air.

The lapse rate for the rising parcel of air may be determined theoretically. For this calculation, the cooling process within a rising parcel of air is assumed to be "adiabatic" (i.e., occurring without the addition or loss of heat). This is called "adiabatic lapse rate" (Γ).

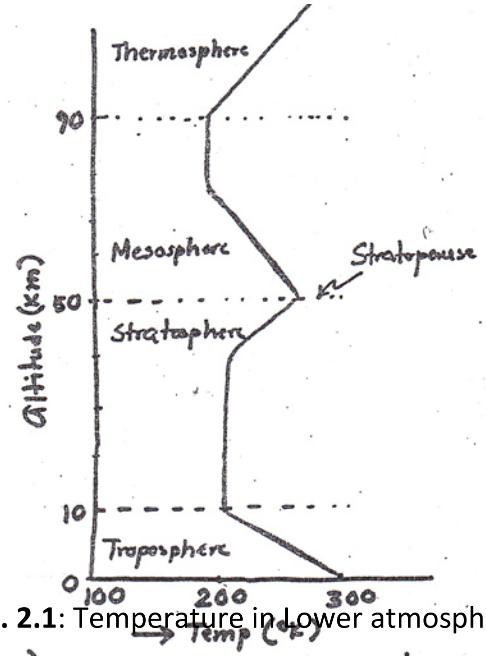


Fig. 2.1: Temperature in Lower atmosphere

Determination of Adiabatic Lapse Rate (Γ)

"Γ" serves as a reference temperature profile against which we compare the actual profiles of temperature.

For determination of Γ, we require:
(i) Ideal gas law
(ii) Hydrostatic equation
(iii) 1st law of thermodynamics

Considering air as an ideal gas, we can write

$$P = \frac{\rho RT}{M_a} \text{ .... (1)}$$

here,
ρ = mass density of air (kg/m^3)
R = universal gas constant = 8.134 J/°K/mole
M_a = molecular weight of air = 28.97 gm/mole

The pressure at any height is due to the weight above. The change in pressure with height is given by the "hydrostatic equation" as follows:

$$\frac{dP}{dz} = -\rho g \text{ .... (2)}$$

Combining equations (1) and (2), we get

$$\frac{dP}{dz} = -\frac{gM_aP}{RT} \text{ ..... (3)}$$

Now, from the first law of thermodynamics:
$du = dQ - dW$ ..... (4)

Where,
du = change in internal energy = C_v. dT
C_v = heat capacity of system at constant volume
dQ = heat input to the system across its boundaries
= 0 for adiabatic condition
dW = energy lost by the system to the surroundings as a result of work done to alter the volume of the system
= P. dV
From ideal gas law,

$$P = \frac{m}{V} \cdot \frac{RT}{M_a} \text{ .... (5)}$$

$$\Rightarrow PV = \frac{mRT}{M_a}$$

$$\Rightarrow d(PV) = \frac{mR}{M_a} .dT$$

$$\Rightarrow PdV + VdP = \frac{mR.dT}{M_a}$$

$$\Rightarrow dW + VdP = \frac{mR.dT}{M_a}$$

$$\Rightarrow dW = \frac{mR.dT}{M_a} - V.dP$$

Now, replacing the value of dW in eq. (4),

$$du = dQ - dW$$

$$\Rightarrow C_v.dT = 0 - \left(\frac{mRdT}{M_a} - V.dP\right)$$

$$\Rightarrow C_v.dT = V.dP - \frac{mRdT}{M_a}$$

Replacing the value of V from eq. (5),

$$C_v.dT = \frac{mRT.dP}{P.M_a} - \frac{mRdT}{M_a}$$

$$\Rightarrow dT\left(C_v + \frac{mR}{M_a}\right) = dP\left(\frac{mRT}{M_aP}\right)$$

$$\therefore \frac{dT}{dP} = \frac{mRT/(M_aP)}{C_v + mR/M_a} \text{ .... (6)}$$

Combining eq. (3) and (6),

$$\frac{dT}{dz} = \frac{dT}{dP}.\frac{dP}{dz} = -\frac{mg}{C_v + mR/M_a}$$

$$\Rightarrow \frac{dT}{dz} = -\frac{g}{\hat{C}_v + R/M_a}$$

Here, $\hat{C}v$ = heat capacity of constant volume per unit mass of air

$\hat{C}_V + R/M_a = \hat{C}_P$ = heat capacity at constant pressure per unit mass of air

$\therefore \dfrac{dT}{dz} = -\dfrac{g}{\hat{C}_p} = -\Gamma$ = the rate of temperature change for a parcel of “dry” air rising adiabatically

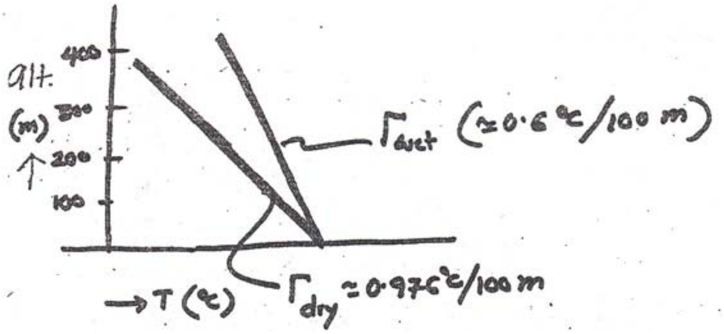
$$\Gamma = -\frac{dT}{dz} = \frac{9.8 m/\sec^2}{1004 J\,^{o}K^{-1} kg^{-1}}$$

$$\left.\begin{aligned} \therefore \Gamma &= 0.976\ ^{\circ}\text{C}/100\text{ m} \\ &= 9.76\ ^{\circ}\text{C/ km} \\ &= 5.4\ ^{\circ}\text{F}/1000\text{ ft} \end{aligned}\right\}$$

Dry adiabatic lapse rate
(often taken as 1°C/100 m)

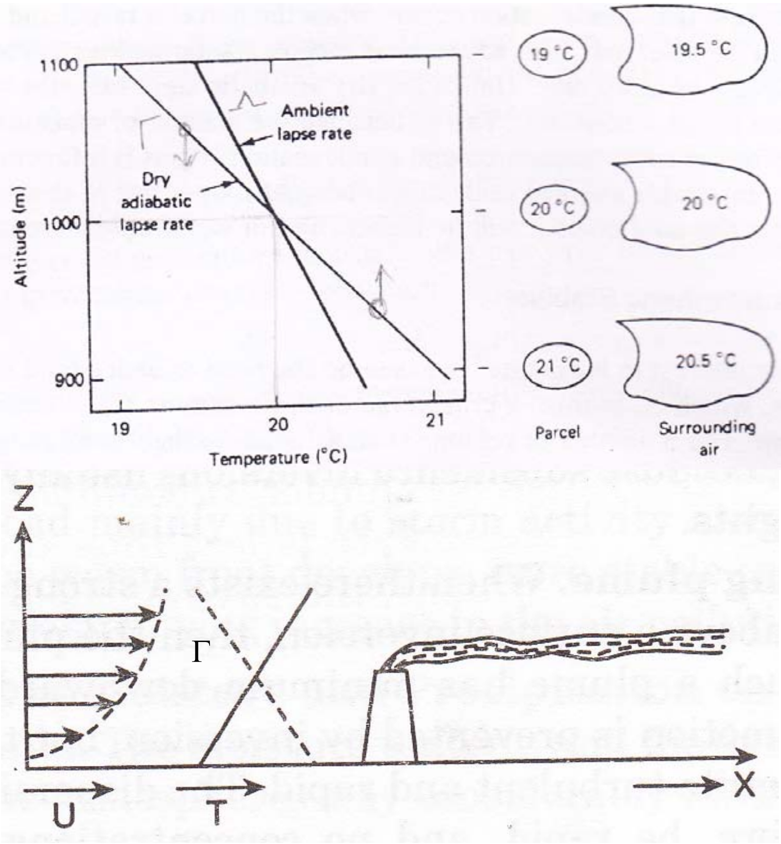
In moist atmosphere, because of the release of latent heat of vaporization, a saturated parcel cools on rising at a slower rate than a dry parcel.

$\therefore \Gamma_{dry} > \Gamma_{wet}$



Atmospheric Stability:

(a) $\Lambda < \Gamma$ - stable atmosphere

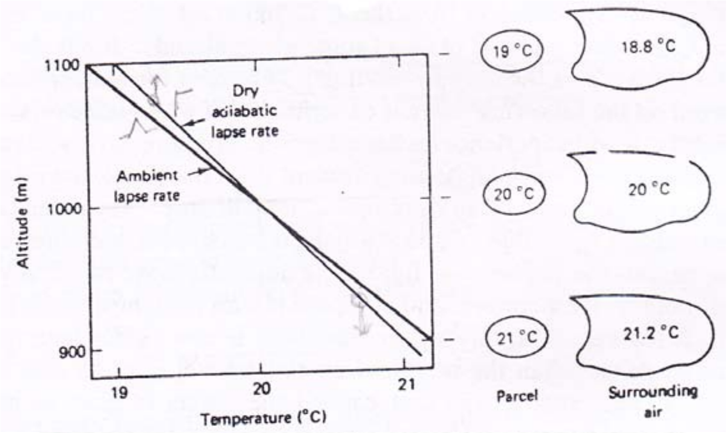


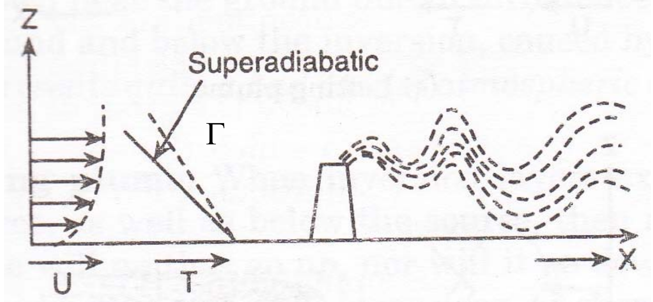
Fanning plume

In figure (a), the ambient temperature cools less rapidly than the adiabatic lapse rate. Assume a 20° C air parcel at 1000 m to be just like the air surrounding it. If that parcel is raised by 100 m, it will cool adiabatically by about 1° C, thus residing at a temperature of 19° C. The surrounding air temperature at 1100 m is shown to be 19.5° C. Thus the air parcel is cooler as well as denser than its surroundings, so it sinks, i.e. goes down.

On the other hand, if the air parcel goes down by 100 m below from its initial elevation, it warms adiabatically to 21° C. Thus at 900 m, the parcel is of 21° C and the surrounding air is at 20.5° C. The parcel is warmer than the surrounding and hence it is buoyant and wants to move upward (warm air rises). This temperature profile therefore corresponds to a ***stable atmosphere***. The ambient lapse rate is called ***sub-adiabatic***.

(b) $\Lambda > \Gamma$ - unstable atmosphere

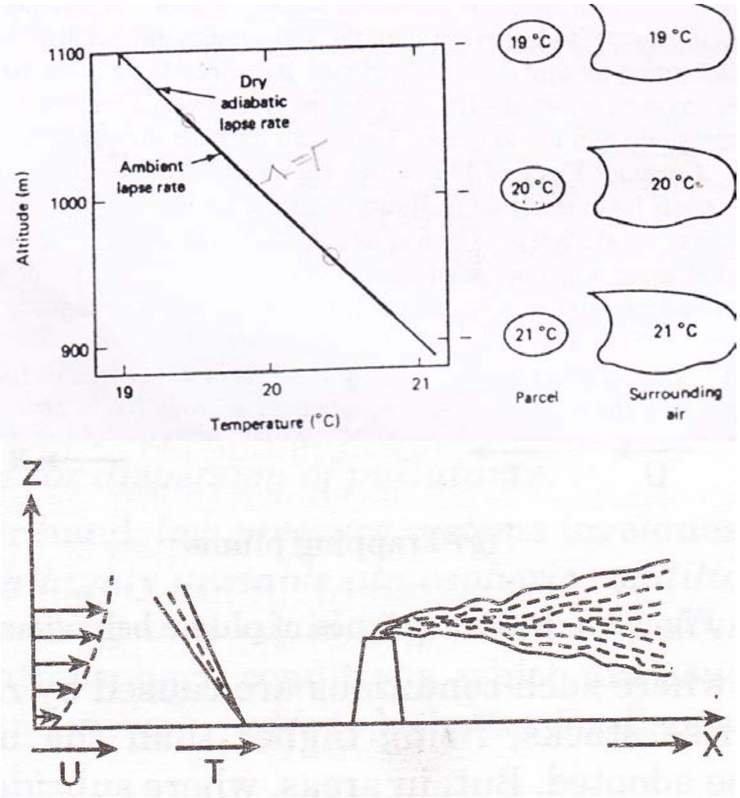




Looping plume

In figure (b), the ambient temperature cools more rapidly than the adiabatic lapse rate. If we consider the air parcel at 1000 m and 20° C, it will find itself warmer than the surrounding air. At its new elevation, it experiences the same pressure as the air around it, but it is warmer, so it will be buoyant and continue to climb. Conversely, a parcel starting at 1000 m and 20° C that starts moving downward will get cooler and denser than its surroundings. It will continue to sink. The ambient air is ***unstable*** and the ambient lapse rate is called ***super-adiabatic***.

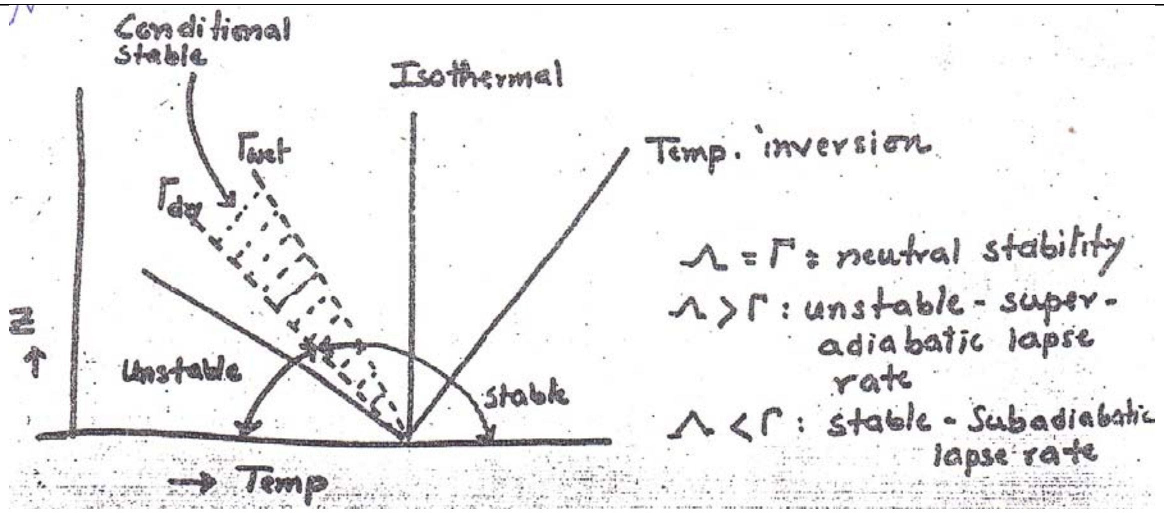
(c) $\Lambda = \Gamma$ - neutral atmosphere



Coning plume

In figure (c), when the ambient lapse rate is equal to the adiabatic lapse rate, the upward or downward movement of air parcel results in its temperature changing by the same amount of its surroundings. In any new position, it experiences no force that makes it either continue its motion or return to its original elevation. Such an atmosphere is called ***neutrally stable***.

Since, $\Gamma_{dry} > \Gamma_{wet}$, a moist atmosphere is inherently less stable than a dry atmosphere. Thus a stable situation with reference to Γ_{dry} may actually be unstable for upward displacement of a saturated air parcel.



Temperature Inversion:

Temperature inversions represent the extreme cases of stable atmosphere, when the lapse rate become negative, i.e. the ambient air temperature increases with the increase of altitude. In this case, the warmer air lies over the cooler one.

Types of Inversion:

(i) ***Radiation Inversion***:

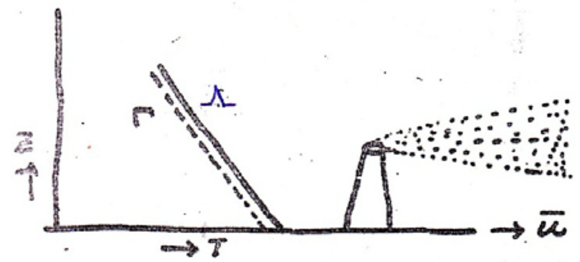
- Arises from unequal cooling rates of the earth and the air above the earth.
- The earth cools more rapidly than the air above it.
- Usually a nocturnal phenomenon that occurs generally on clear winter nights and breaks up easily with the rays of the morning sun.
- Radiation inversion prompts the formation of fog and simultaneously taps gases and particulates, creating a concentration of pollutants in our close environment.
- Valley areas may also have radiation inversion because of the absence of horizontal movement of air due to surrounding high ground.

(ii) ***Subsidence Inversion***:

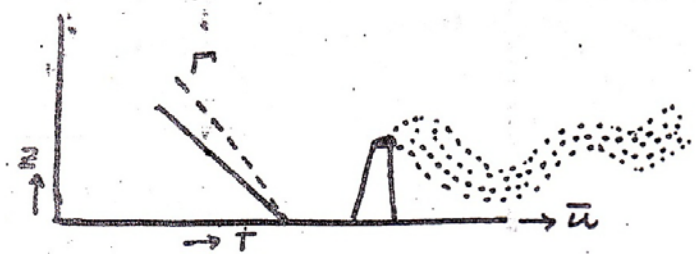
- Usually associated with a high pressure system.
- Caused by the subsiding/ sinking motion of air in a high pressure area surrounded by low pressure area.
- As the high pressure air descends, it is compressed and heated, forming a blanket of warm air over the cooler air below and thus creating an inversion that prevents further vertical movement of air.
- Thicker subsidence inversion layer may cause extreme pollution in our immediate environment, which may persist for several days, thus making it more dangerous than radiation inversion.

Lapse Rates and Dispersion of Air Pollutants:

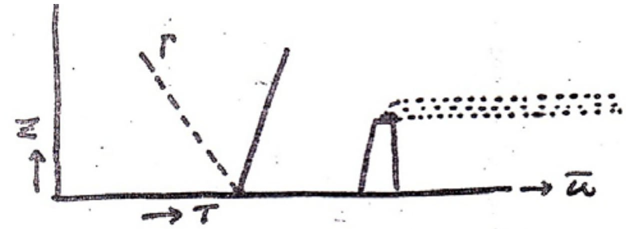
By comparing the ambient lapse rate (Λ) to the adiabatic lapse rate (Γ), it may be possible to predict what will happen to gases emitted from a stack. The emitted gases being known as ***plume***, while their source of origin is called ***stack***.



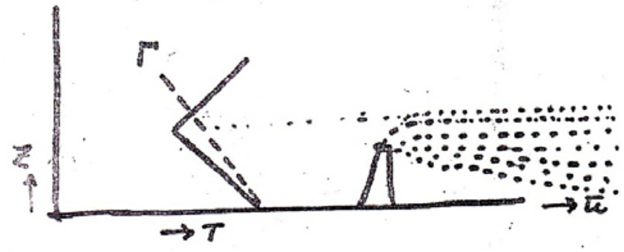
(a) neutrally stable atmosphere
"coning"



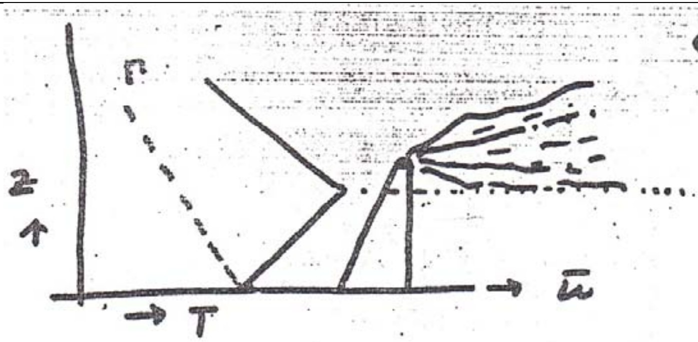
(b) unstable atmosphere
"looping"



(c) stable atmosphere
"Fanning"

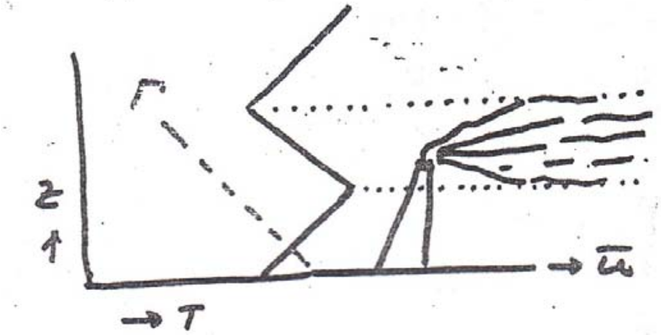


(d) Inversion:
smokestack under inversion layer.
"Fumigating"



(e) Smokestack above inversion layer.

"Lofting"



(f) Smokestack between two stable layers

"Trapping"

(a) Coning Plume:

- The plume makes a cone shape about the plume line
- Occurs in neutral atmosphere
- The environment is slightly stable and there is limited vertical mixing
- Probability of air pollution

(b) Looping Plume:

- The plume has a wavy character and occurs in super-adiabatic atmosphere
- Rapid mixing make the environment quite unstable
- High degree of turbulence causes rapid dispersion of the plume, even can cause higher pollutant concentration near the ground before the dispersion is finally completed
- Higher stacks are recommended to prevent premature contact of pollutants with the ground
- Automobile exhausts cannot be dispersed as they are released at lower levels

(c) Fanning Plume:

- Under extreme inversion conditions, caused by negative environmental lapse rate, from the ground and up to a considerable height, extending even above the top of stack
- The emission spreads only horizontally, as it cannot lift due to extremely stable environment
- No vertical mixing occurs
- The plume simply extends horizontally over large distance

(d) Fumigating Plume:

- In this case, the inversion layer occurs at a short distance above the top of the stack and super-adiabatic condition prevails below the stack
- The pollutants cannot escape above the top of the stack because of inversion layer
- The pollutants are brought down near the ground due to air turbulence in the region above the ground and below the inversion, caused by the strong lapse rate
- This represents quite a bad case of atmospheric condition for dispersion

(e) Lofting Plume:

- In this case, a strong super-adiabatic lapse rate exists above the surface inversion layer
- This plume has minimum downward mixing, as its downward motion is prevented by inversion, whereas the upward movement is quite turbulent and rapid.
- Dispersion of pollutant is rapid, no concentration will touch the ground
- The most ideal case for dispersion of emissions

(f) Trapping Plume:

- Inversion layers exist above as well as below the stack
- The plume neither goes up nor goes down and remains confined between two inversions
- Bad condition for dispersion, as the dispersion cannot go above a certain height

Notes:

- Fumigating plumes can lead to greatly elevated down-wind ground level concentration.
- Lofting plumes are helpful in terms of exposure to people at ground level.
- Thus a common approach to air pollution control has been to build taller stacks to emit pollutants, above inversion layer.
- However, pollutants released from tall stacks can travel long distances, so that effects such as acid deposition can be felt hundreds of miles from the source.

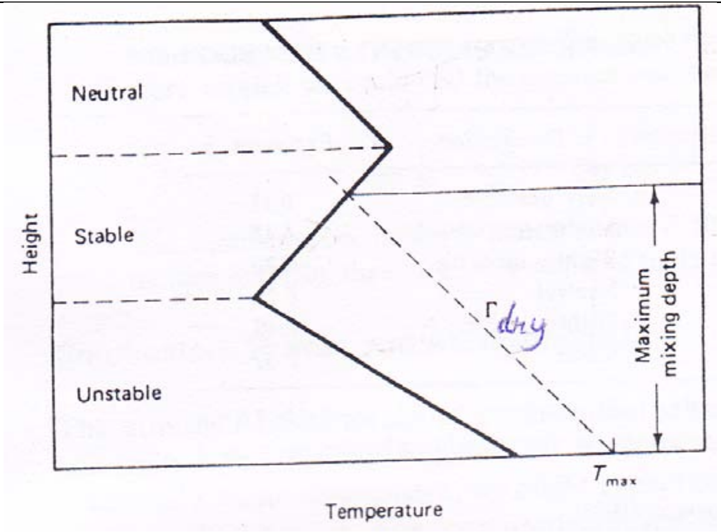
Atmospheric Stability and Mixing Depth:

The amount of air available to dilute pollutants is related to the wind speed and to the extent to which emissions can rise into the atmosphere.

An estimate of this (dilution process) can be obtained by determining “maximum mixing depth”.

Estimation of Maximum Mixing Depth (MMD) and Ventilation Coefficient:

The air pollutants induced to air tends to rise or fall in relation to the difference of their temperature with the ambient air temperature. Following this logic, the maximum mixing depth can be estimated by plotting maximum surface temperature and drawing a line parallel to the average adiabatic lapse rate from the point of maximum surface temperature to the point at which the line intersects the ambient or natural temperature profile (usually of early morning or night).



Ventilation coefficient (m^2/s) = MMD (m) × Avg. wind speed within mixing depth (m^2/s)

This parameter is used as an indicator of the atmosphere's dispersive capacity.

If ventilation coefficient < 6000 m^2/s, air pollution potential is considered to be high.

Wind speed generally increases with altitude and the following power law expression is helpful to estimate wind speed at an elevation higher than the standard 10 m weather station anemometer. This expression is valid for elevations less than a few hundred meters above the ground.

$$\mathbf{u_1 / u_2 = (z_1 / z_2)^p}$$

where, u_1 and u_2 = wind speed at higher and lower elevation respectively
z_1 and z_2 = higher and lower elevation respectively
p = a dimensionless parameter that varies with atmospheric stability

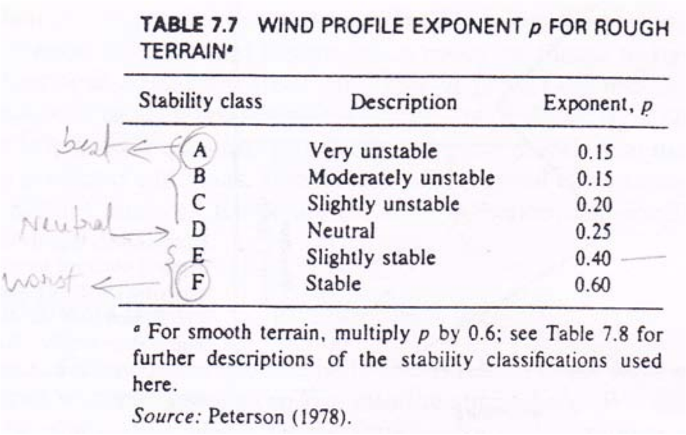


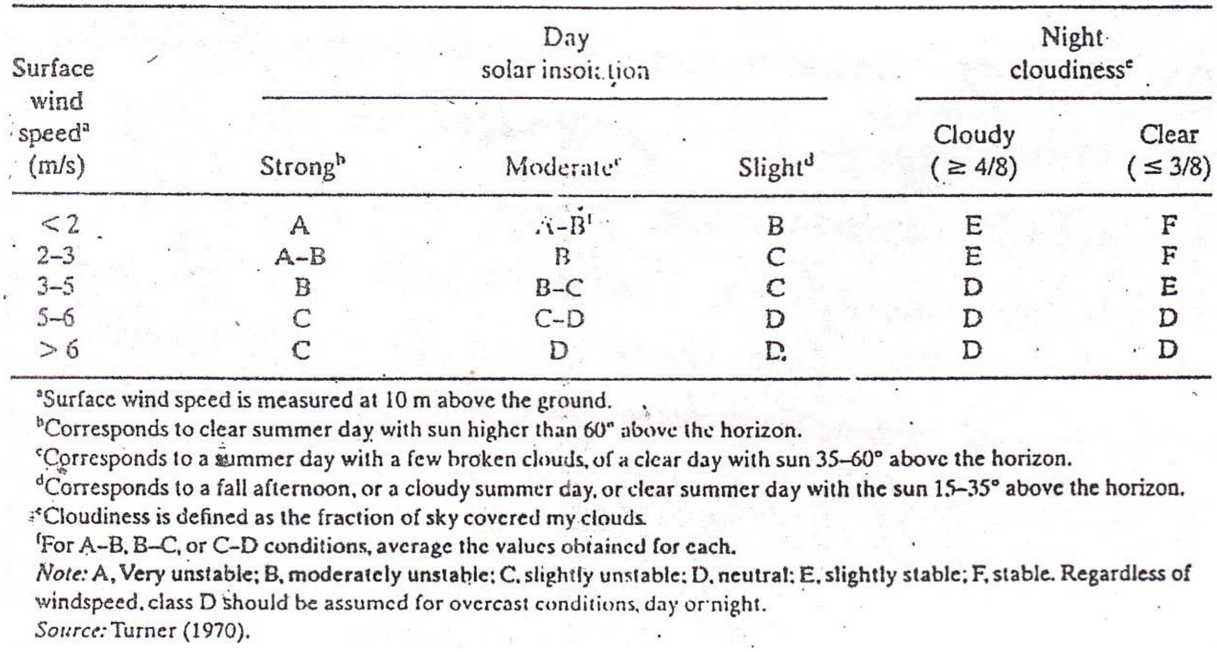
TABLE 7.7 WIND PROFILE EXPONENT *p* FOR ROUGH TERRAIN[a]

	Stability class	Description	Exponent, *p*
best ←	A	Very unstable	0.15
	B	Moderately unstable	0.15
	C	Slightly unstable	0.20
Neutral →	D	Neutral	0.25
	E	Slightly stable	0.40
worst ←	F	Stable	0.60

[a] For smooth terrain, multiply *p* by 0.6; see Table 7.8 for further descriptions of the stability classifications used here.

Source: Peterson (1978).

Classification of Atmospheric Stability



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

[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° above the horizon.

[e] Cloudiness is defined as the fraction of sky covered my clouds.

[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

Source: Turner (1970).

Atmospheric Stability Classes: (According to Turner, 1970)

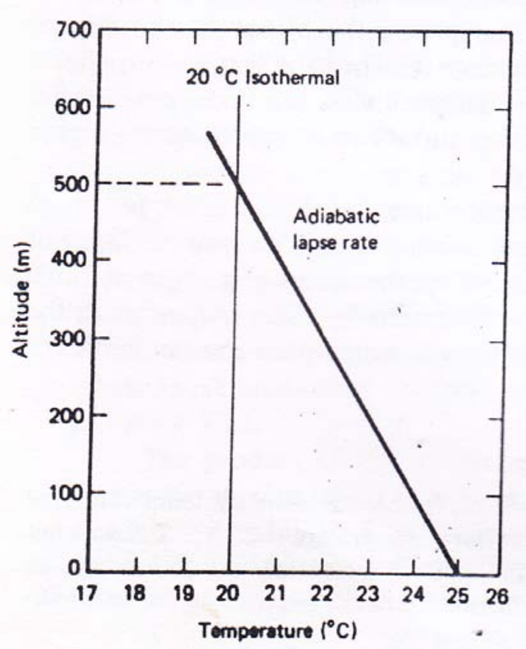
A – Very unstable
B – Moderately unstable
C – Slightly unstable
D – Neutral
E – Slightly stable
F - Stable

<u>Problem:</u>

Suppose the atmospheric temperature profile is isothermal (constant temperature) at 20° C and the estimated maximum daily surface temperature is 25° C. The weather station anemometer (wind speed measuring instrument) is at a height of 10 m in the city (rough terrain). It indicates an average wind speed of 3 m/s. Estimate the ***mixing depth*** and the ***ventilation coefficient***.

<u>Solution:</u>

The dry adiabatic lapse rate is 1° C/100 m, so projecting that lapse rate from 25° C at the surface until it reaches the 20° C isothermal means the mixing depth will be 500 m as shown in following figure.



Since the temperature profile is isothermal, lets choose the "slightly stable" stability class, with p = 0.4 (from Table 7.7)

We need to estimate the average wind speed at 500 m mixing depth. As a quick estimate, we might use the wind speed at the half-way point, 250 m

$u_1 / 3 = (250/10)^{0.4} = 3.6$

$u_1 = 3 * 3.6 = 10.9$ m/s at 250 m

Therefore, ventilation coefficient = 500 * 10.9 = 5450 m^2/s

To be more appropriate, we can apply integration to estimate wind speed as follows:

$$\bar{u}_1 = \frac{1}{500}\int_0^{500} u_1\, dz = \frac{1}{500}\int_0^{500} 3.0\left(\frac{z}{10}\right)^{0.4} dz = 10.2 \text{ m/s}$$

Then, ventilation coefficient = 500 * 10.2 = 5100 m^2/s, not so different from the previous case.

CE 433
Environmental Pollution and Its Control
(Credit 2.0, Class Period 2 hours/week)

Air Quality Modeling

(1) *Dispersion/ Diffusion Modeling*

- Uses mathematical formulations to characterize atmospheric processes that disperse a pollutant emitted by a source.

(2) *Photochemical Modeling*

- Long-range air quality models that stimulate the changes of pollutant concentrations in the atmosphere due to the chemical and physical processes in the atmosphere.

(3) ***Receptor modeling***

- Mathematical or statistical processes for identifying as well as qualifying the source of air pollutants at a receptor location.
- Example – Chemical Mass Balance method (CMB)
    - Other USEPA receptor models
        - UNMCX model
        - Positive Matrix Factorization (PMF) method

Dispersion/ Diffusion Model

- Behavior of gases and particles in turbulent flow (in the atmosphere) is referred to as atmospheric diffusion
- Goal of diffusion model is to describe mathematically the spatial and temporal distribution of contaminants released into the atmosphere
- Two idealized source types –

(i) Instantaneous Point Source (Puff)
(ii) Continuous Point Source (Plume)

- Other source types – Line Source, Area Source

Atmospheric Diffusion Theory

- Goal – to be able to describe mathematically the spatial and temporal distribution of contaminants released into the atmosphere

Point Source Gaussian Plume Model:

Assumptions –

(i) Pollutant material takes on Gaussian distribution in both y and z directions

(ii) Steady state condition

(iii) Ideal gas condition

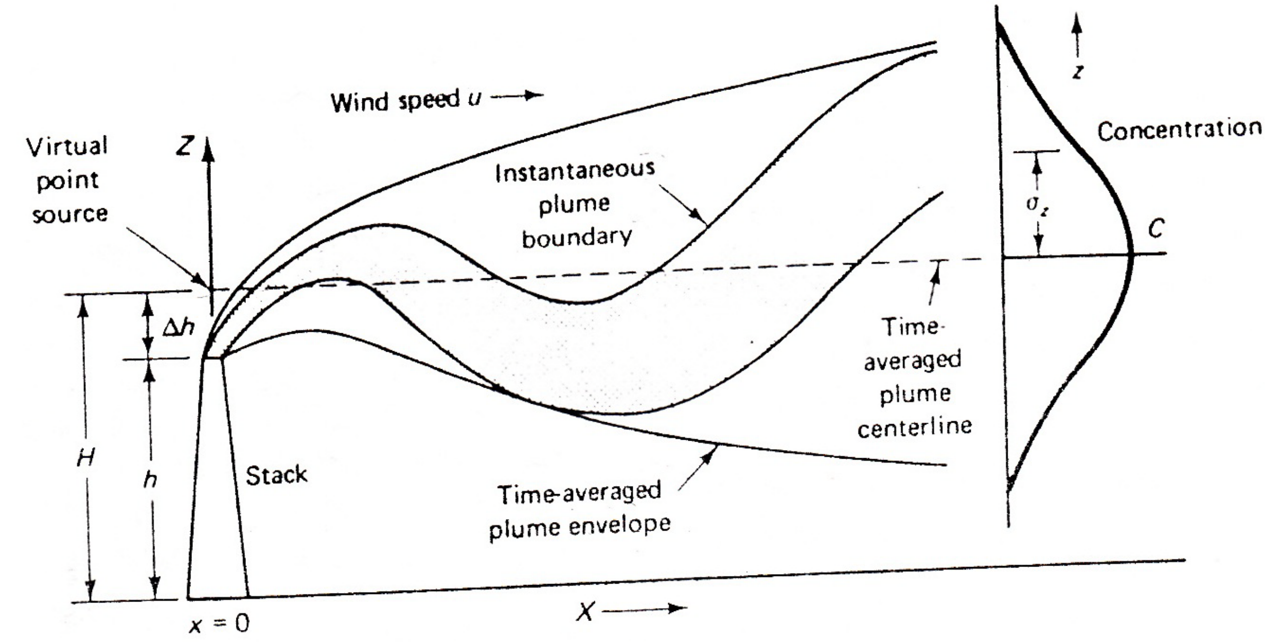
(iv) Uniform continuous emission rate

(v) No diffusion in x direction

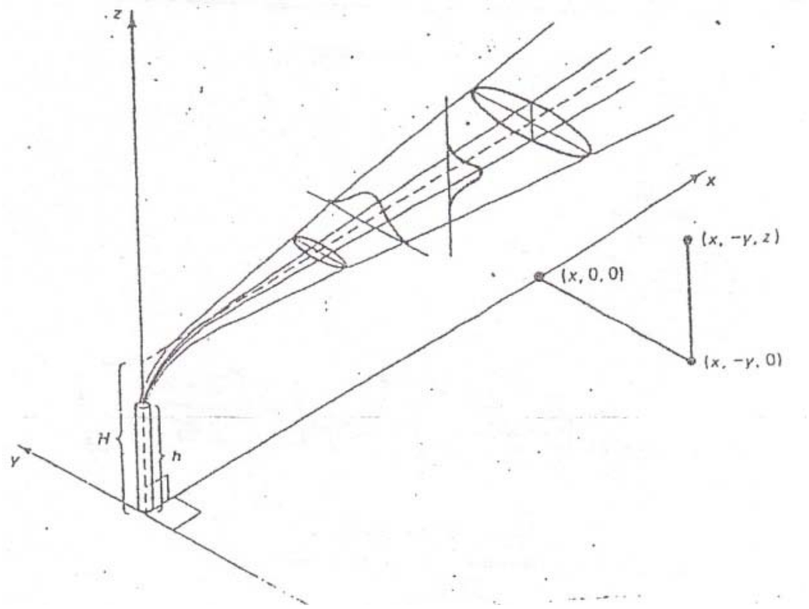
(vi) Homogeneous, horizontal wind field

(vii) Constant wind speed with time and elevation

(viii) Flat terrain



The basic Gaussian model applies to a single "***point source***" (e.g., a smoke stack), but it can be modified to account for the "***line source***" (e.g., emission from motor vehicles along a highway) or "***area source***".



Point Source Gaussian Plume Model under different considerations

<u>(a) No ground reflection (PM, Nitric acid, Vapor)</u>

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

where,

C = pollutant concentration (g/m^3, μg/m^3)

Q = uniform continuous emission rate (g/s, μg/s)

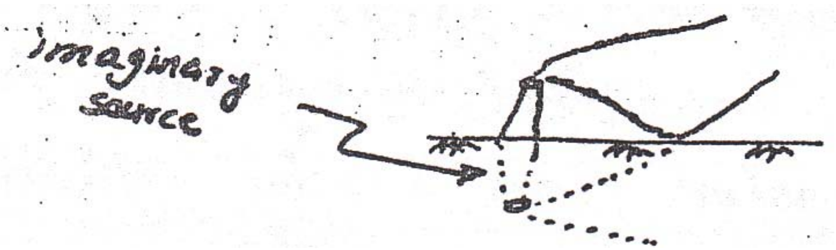
u = mean wind speed at plume height (m/s)

σ_y = cross-wind dispersion parameter (m)

σ_z = vertical dispersion parameter (m) x, y, z = location of receptor

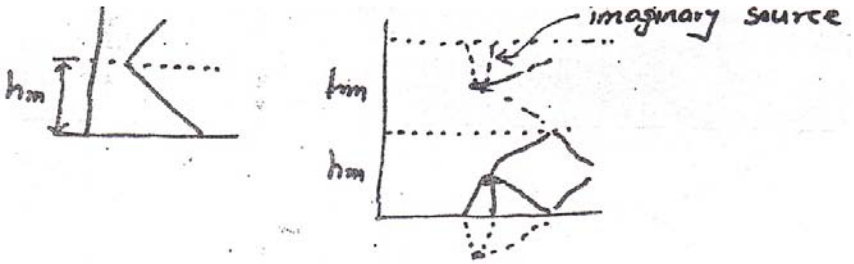
H = effective stack height (= stack height + plume rise = $h_s + \Delta h$)

(b) Ground reflection (CO, SO_2, NO_2)



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

(c) Ground reflection and temperature inversion



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

Simplification of *Gaussian Plume Equations*

(i) Concentration at ground level (z = 0) with no h_m (with ground reflection)

$$c(x,y,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

(ii) Concentration at ground level (z = 0), in the downwind horizontal direction along the centerline of the plume (y = 0) with no h_m (with ground reflection)

$$c(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

(iii) z = 0, y = 0, no h_m and emission at ground level (h = 0) (with ground reflection)

$$c(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z}$$

Estimation of Parameters of *Gaussian Plume Equations*

(i) Q = emission rate (usually expressed in g/s)

(ii) H = effective stack height

$= h_s + \Delta h$

= stack height + plume height

Plume rise is caused primarily by buoyancy and momentum of exhaust gas and stability of atmosphere

Buoyancy results when exhaust gases are warmer than the ambient and/or when the molecular weight of the exhaust is lower than that of air

Momentum is caused by the mass and velocity of the gases as they leave the stack

(iii) **Plume rise estimation** – Different techniques have been proposed for estimation of plume rise. The USEPA recommends the following model.

$$F = gr^2 v_s \left(1 - \frac{T_a}{T_s}\right)$$

Where, F = buoyancy flux parameter (m^4/s^3)

g = gravitational acceleration (9.8 m/s^2)

r = inner radius of stack (m)

v_s = stack ga exit velocity (m/s)

T_a = stack gas temperature (k)

T_s = ambient air temperature (k)

For neutral or unstable conditions (stability class A – D)

$$\Delta h = \frac{1.6 F^{1/3} x_f^{2/3}}{u}$$

Where, h = plume rise (m)

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

x_f = distance downwind to point of final plume rise

$x_f = 120\ F^{0.4}$ if $F \geq 55\ m^4/s^3$

$x_f = 50\ F^{5/8}$ if $F < 55\ m^4/s^3$

For stable conditions (stability class E and F)

$$\Delta h = 2.6\left(\frac{F}{us}\right)^{1/3}$$

The quantity of **S** is a stability parameter with units of s^{-2} and is given by –

$$S = \frac{g}{T_a}\left(\frac{\Delta T_a}{\Delta z} + \Gamma\right) = \frac{g}{T_a}\left(\frac{\Delta T_a}{\Delta z} + 0.01°C/m\right)$$

$\frac{\Delta T_a}{\Delta z}$ represents the actual rate of change of ambient temperature with altitude (+ve value indicates the temp. is increasing with altitude)

(iv) $\overline{u}$ = mean wind speed at plume height

$$\overline{u}(z) = \overline{u_0}\left(\frac{z}{z_0}\right)^{\rho}$$

(valid for few hundred meters)

Where, $\overline{u}(z)$ = wind speed at plume ht, z

$\overline{u_0}$ = wind speed instrument height

z = plume ht

z_0 = instrument ht (usually 10 m)

ρ = factor, depends on stability condition of atmosphere and can be taken from Table 7.7

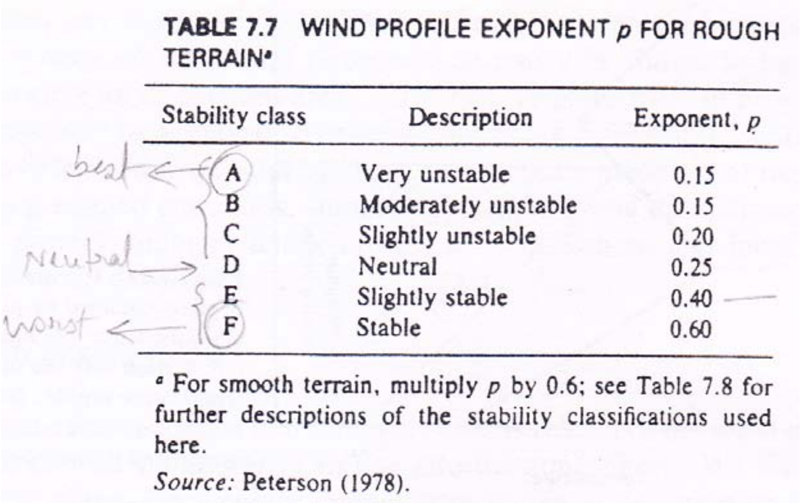


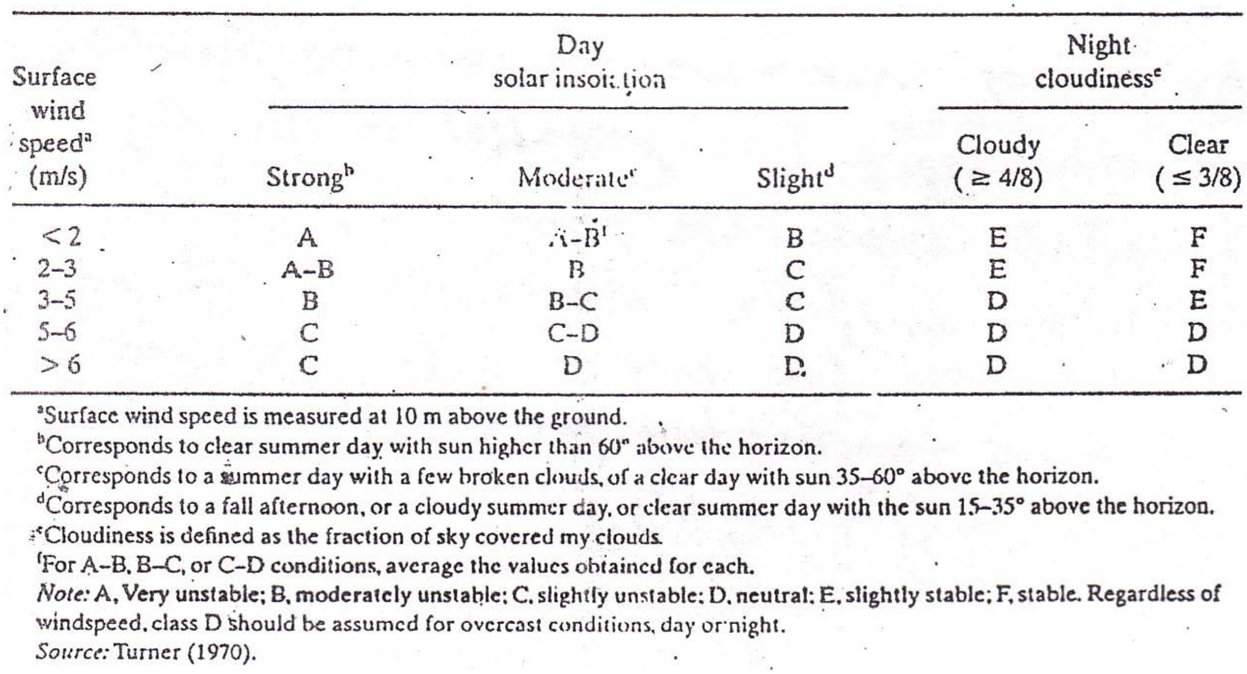
TABLE 7.7 WIND PROFILE EXPONENT p FOR ROUGH TERRAIN[a]

Stability class	Description	Exponent, p
best ← A	Very unstable	0.15
B	Moderately unstable	0.15
C	Slightly unstable	0.20
Neutral → D	Neutral	0.25
E	Slightly stable	0.40
worst ← F	Stable	0.60

[a] For smooth terrain, multiply p by 0.6; see Table 7.8 for further descriptions of the stability classifications used here.

Source: Peterson (1978).

Classifications of Atmospheric Stability



Surface wind speed[a] (m/s)	Day solar insolation			Night cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy ($\geq$ 4/8)	Clear ($\leq$ 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

[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, of 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° above the horizon.

[e] Cloudiness is defined as the fraction of sky covered my clouds.

[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

Source: Turner (1970).

(v) σ_y and σ_z = f (distance and stability condition)

These are standard deviations. Can be obtained from plots of σ_y and σ_z versus distance downwind for different stability conditions.

- as x increases, σ_y and σ_z increase
- for a given x, σ_y and σ_z increase as we move to more unstable condition
- There are several approaches for estimating σ_y and σ_z

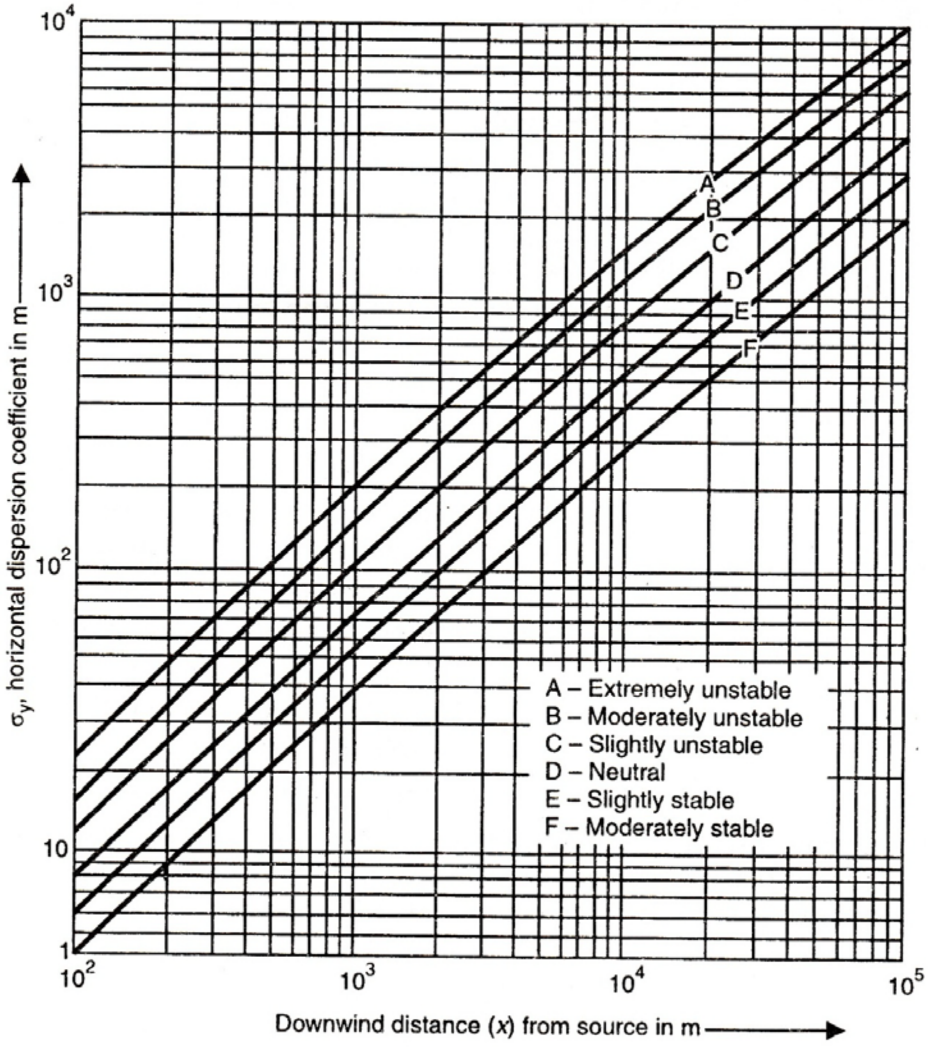


Fig 4.1: σ_y vs x for different atmospheric stabilities

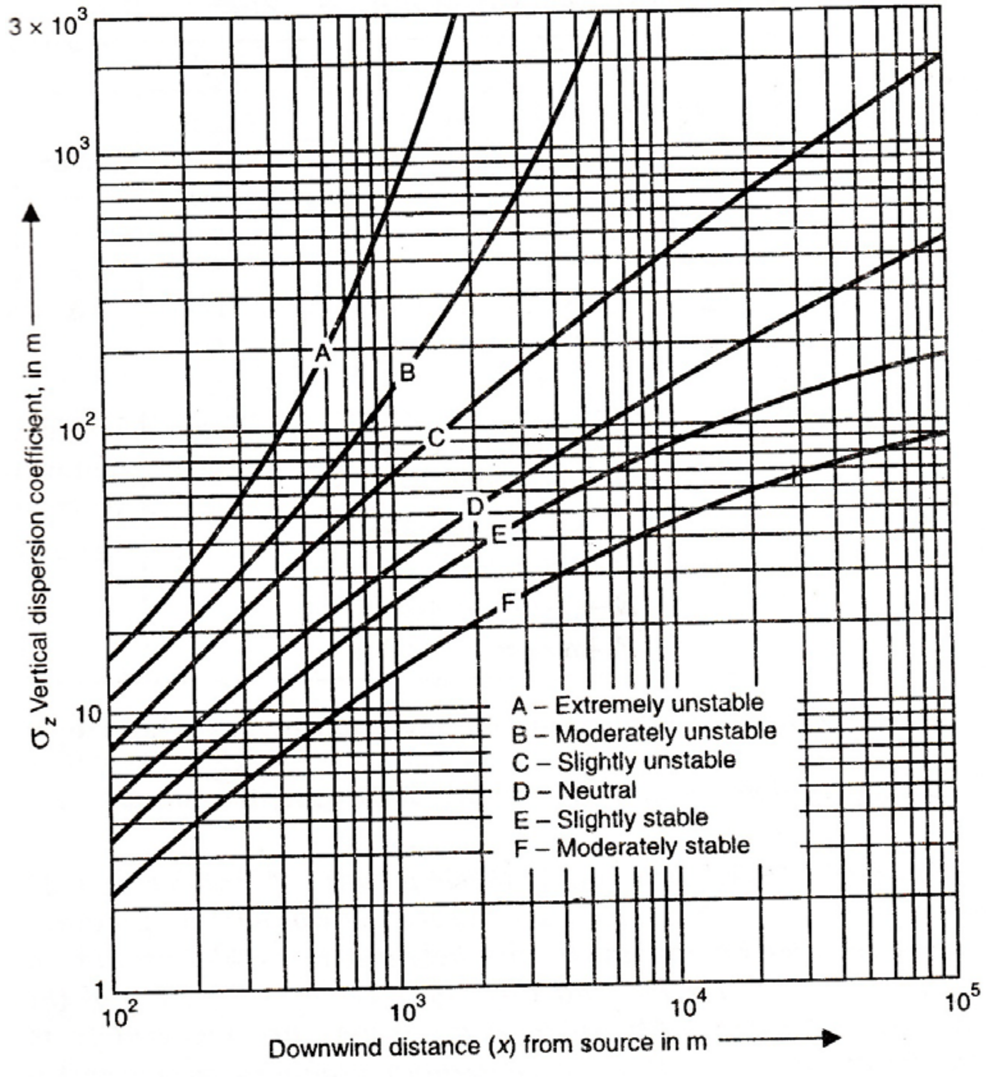


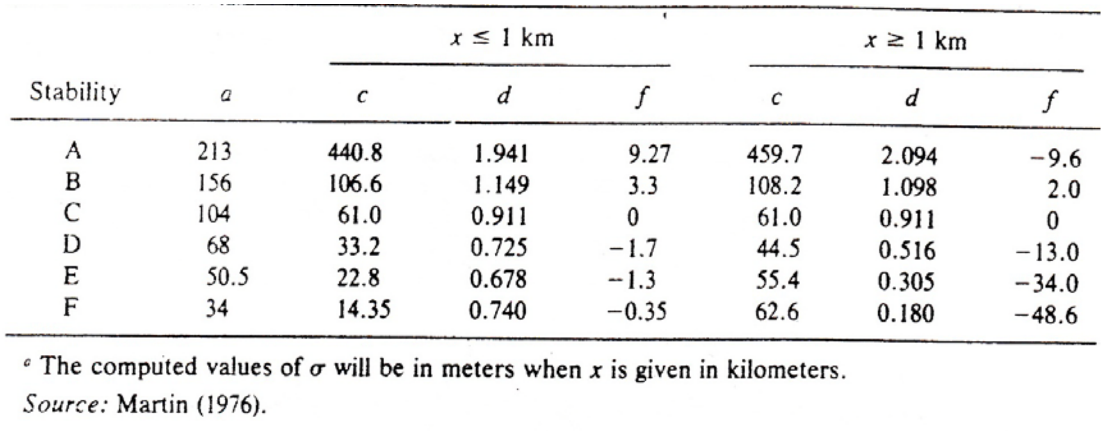
Fig 4.2: σ_z vs x for different atmospheric stabilities

According to Martin (1976) :

$\boldsymbol{\sigma_y = a.\ x^{0.894}}$

and $\boldsymbol{\sigma_z = c.\ x^{d} + f}$

Table: Values of constant a, c, d and f in equation for σ_y and σ_z



Stability	a	$x \le 1$ km			$x \ge 1$ km		
		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

[a] The computed values of σ will be in meters when x is given in kilometers.

Source: Martin (1976).

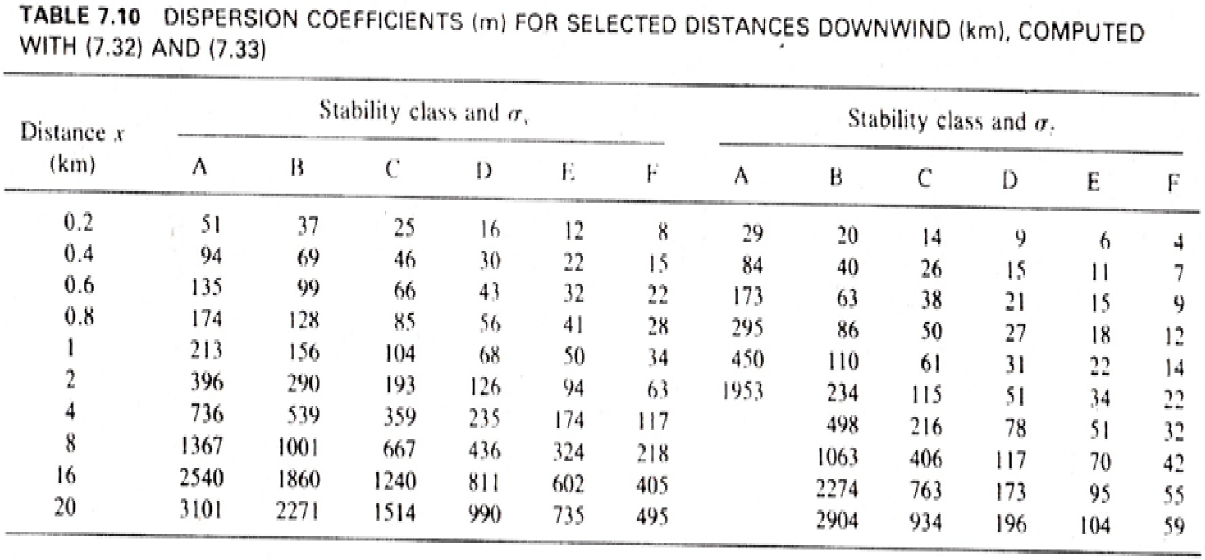


TABLE 7.10 DISPERSION COEFFICIENTS (m) FOR SELECTED DISTANCES DOWNWIND (km), COMPUTED WITH (7.32) AND (7.33)

Distance x (km)	Stability class and σ_y						Stability class and σ_z					
	A	B	C	D	E	F	A	B	C	D	E	F
0.2	51	37	25	16	12	8	29	20	14	9	6	4
0.4	94	69	46	30	22	15	84	40	26	15	11	7
0.6	135	99	66	43	32	22	173	63	38	21	15	9
0.8	174	128	85	56	41	28	295	86	50	27	18	12
1	213	156	104	68	50	34	450	110	61	31	22	14
2	396	290	193	126	94	63	1953	234	115	51	34	22
4	736	539	359	235	174	117		498	216	78	51	32
8	1367	1001	667	436	324	218		1063	406	117	70	42
16	2540	1860	1240	811	602	405		2274	763	173	95	55
20	3101	2271	1514	990	735	495		2904	934	196	104	59

Downwind (Along the wind direction) Ground level Concentration

The ground level concentrations directly downwind are of great interest, since pollution will be the highest along this axis.

$$c\,(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

Let us examine :

(i) Effect of effective stack height (H)

(ii) Effect of atmospheric stability

------------------------ on downwind ground level concentration

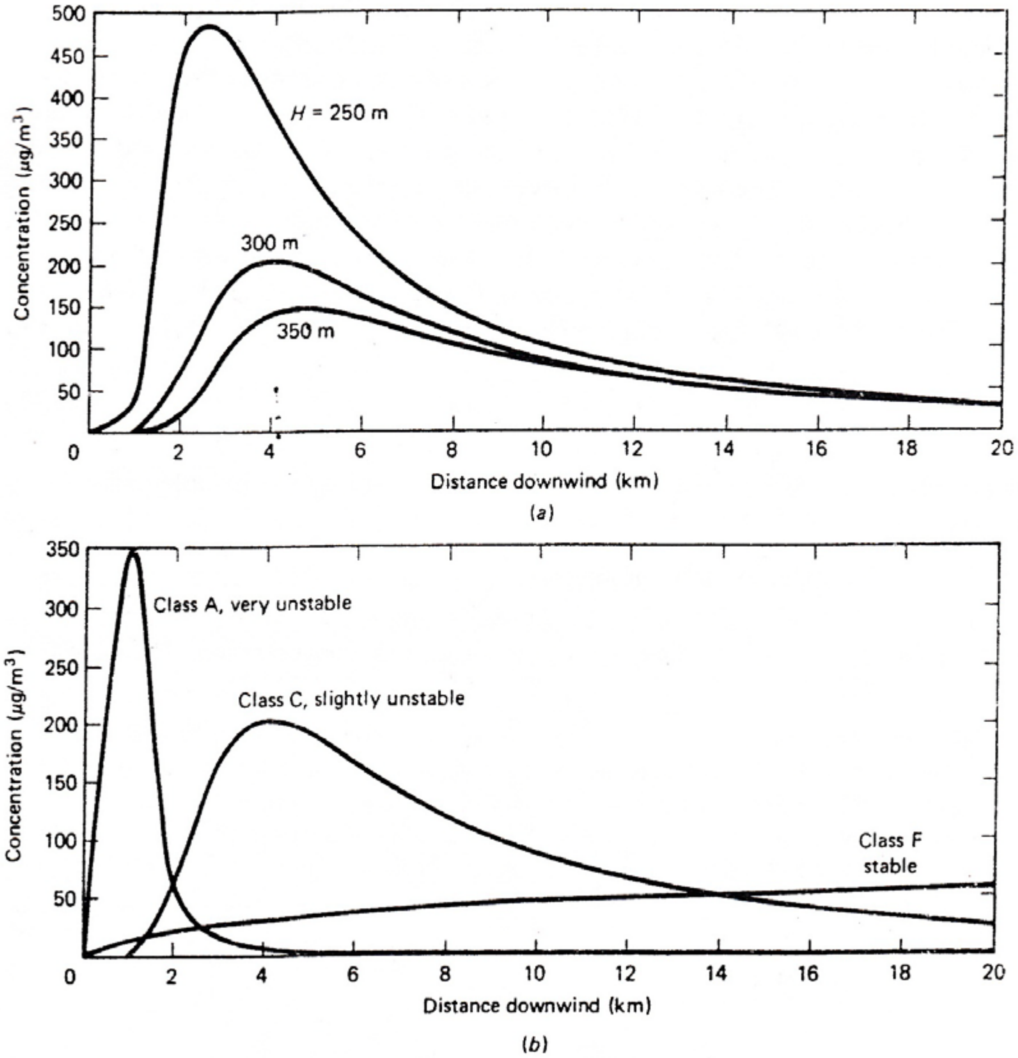


Figure 7.29 The effect of variations in key parameters on SO_2 plume for the 1000-MW coal plant of Example 7.7. (*a*) Effect of effective stack height for constant stability classification, and (*b*) effect of stability classification given a constant effective stack height.

(a) Q = 647 g SO2/s
$\bar{u}$ = 4.9 m/s
Stability class "C"
H = 250 m, 300 m, 350 m

(b) Q = 647 g SO_2/s
$\bar{u}$ = 4.9 m/s
H = 300 m
Stability class:
A = extremely unstable
C = Slightly unstable
F = Moderately stable

The highest peak downwind concentration is produced by the unstable atmosphere, not by the stable atmosphere.

Explanation: The turbulence in an unstable atmosphere brings the plume to earth very quickly, resulting in high peak values near the stack. Downwind, however concentrations drop off very quickly.

The plume rise is itself a function of stability class, thus less stable atmosphere have higher effective stack height, producing somewhat lower ground concentrations than shown in the above figure.

Estimation of Peak Downwind Concentration

The simplest way would be using a spreadsheet program to calculate C (x,0,0) as a function of x, using the following equation -

$$c(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

And finding peak downwind concentration.

When a computer is not readily available, peak downwind concentration can be estimated using the following chart and the equation –

$$C_{\max} = \frac{Q}{\bar{u}}\left(\frac{C_u}{Q}\right)_{\max}$$

If stability class and H are known, then one can estimate - (i) distance of peak and $(C_u/Q)_{\max}$ from the chart. Then using the above equation, $C_{\max}$ can be estimated.

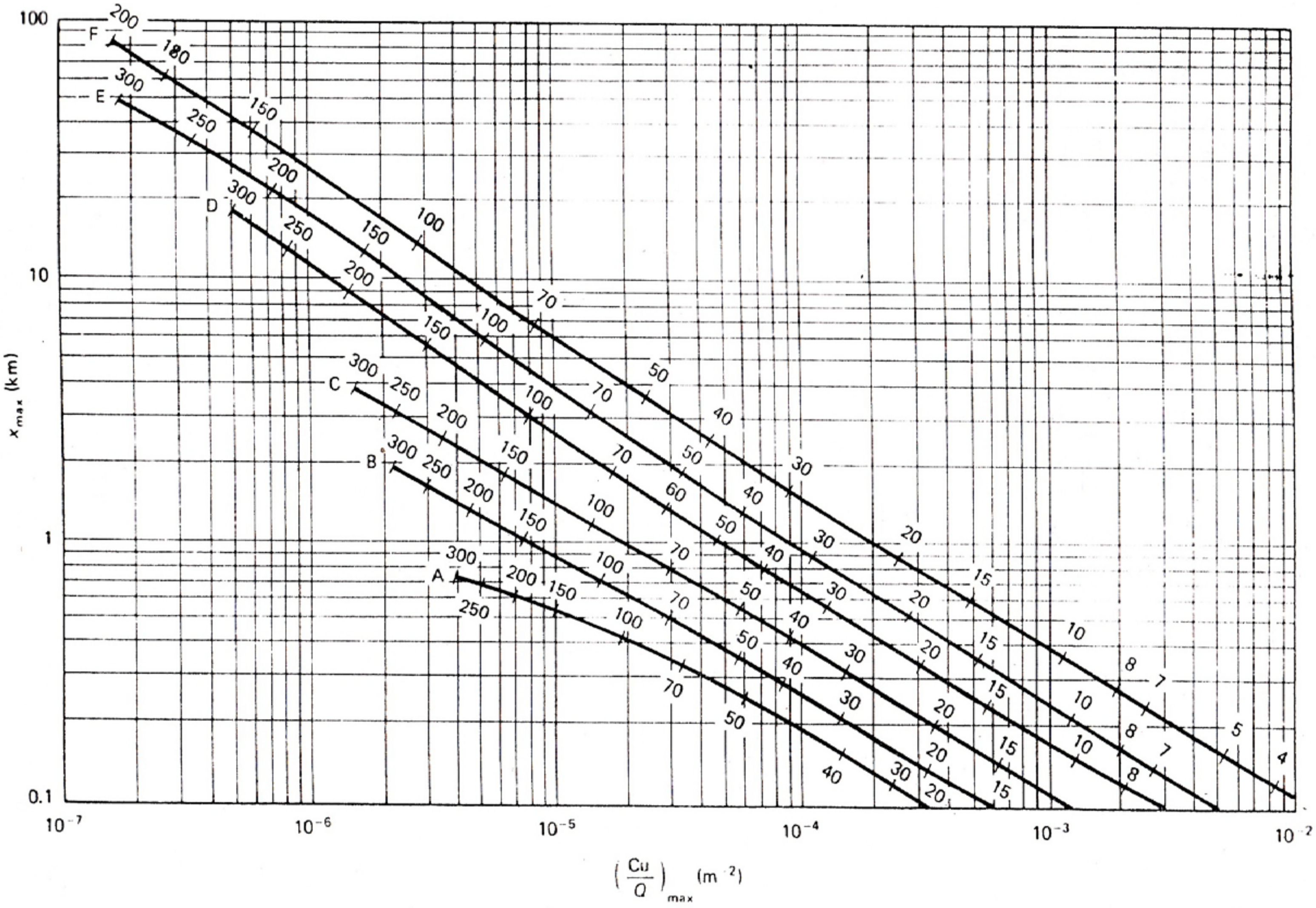
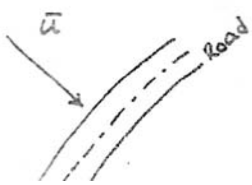
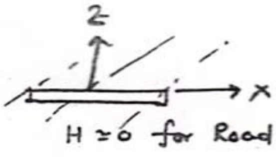


Figure 7.30 To determine the peak downwind plume concentration, enter the graph at the appropriate stability classification and effective stack height (numbers above the lines, in meters) and then move across to find the distance to the peak, and down, to find a parameter from which the peak concentration can be found (Turner, 1970).

Gaussian Plume Model for Line Sources (e.g. Road)





For simplicity, consider –
(i) infinite length source at ground level
(ii) Wind blowing perpendicular to the line.

(a) <u>No ground reflection</u>

$$C(x,z) = \frac{Q_L}{\sqrt{2\pi}\,\sigma_z \cdot \bar{u}} \exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right]$$

(b) <u>With ground reflection</u>

$$C(x,z) = \frac{Q_L}{\sqrt{2\pi}\,\sigma_z\,\bar{u}} \left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

where,
Q_L = source emission rate per unit length of road (g/sec-m)

Examples of Line Sources

(i) Motor vehicles travelling along a straight section of a highway
(ii) Agriculture burning along the edge of a field
(iii) A line of industrial sources on the bank of a river

CE 433
Environmental Pollution and Its Control
(Credit 2.0, Class Period 2 hours/week)

Problem on AQI

On January, 10, 2009, the following air quality data have been recorded at CAMS (Continuous Monitoring Stations/Systems) in Dhaka.

$PM_{2.5} = 190\ \mu g/m^3$ (24 hr)

$PM_{10} = 280\ \mu g/m^3$ (24 hr)

$O_3 = 0.095$ ppm (8 hr)

Calculate AQI for that day. Also, prepare the AQI report.

Breakpoints							**AQI**	**Category**
O_3 (ppm) 8-hr	**O_3 (ppm) 1-hr (i)**	**$PM_{2.5}$ ($\mu g/m^3$) 24-hr**	**PM_{10} ($\mu g/m^3$) 24-hr**	**CO (ppm) 8-hr**	**SO_2 (ppm) 24-hr**	**SO_2 (ppm) Annual**		
0.000-0.064	---	0.0-15.4	0-54	0.0-4.4	0.000-0.034	(ii)	0-50	Good
0.065-0.084	---	15.5-40.4	55-54	4.5-9.4	0.035-0.144	(ii)	51-100	Moderate
0.085-0.104	0.125-0.164	40.5-65.4	155-254	9.5-12.4	0.145-0.224	(ii)	101-150	Unhealthy for sensitive group
0.105-0.124	0.165-0.204	65.5-150.4	255-354	12.5-15.4	0.225-0.304	(ii)	151-200	Unhealthy
0.125-0.374	0.205-0.404	150.5-250.4	355-424	15.5-30.4	0.305-0.604	0.65-1.24	201-300	Very unhealthy
(iii)	0.405-0.504	250.5-350.4	425-504	30.5-40.4	0.605-0.804	1.25-1.64	301-400	Hazardous
(iii)	0.505-0.604	350.5-500.4	505-604	40.5-50.4	0.805-1.004	1.65-2.04	401-500	Hazardous

(i) In some cases, in addition to calculating the 8-hr ozone index, the 1-hr ozone index may be calculated and the maximum of the two values is reported

(ii) NO_2 has no short term air quality standard and can generate an AQI only above 200

(iii) 8-hr O_3 values do not define higher AQI values (≥ 301). AQI values of 301or higher are calculated with 1-hr O_3 concentrations.

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

Solution

AQI for $PM_{2.5}$ = $\frac{300-201}{250.4-150.5}(190-150.5)+201=240.1$

Similarly, AQI for PM_{10}= $\frac{200-151}{354-255}(280-250)+151=163.4$

AQI for O_3 = $\frac{150-101}{0.104-0.085}(0.098-0.085)+101=126.8$

Now, the AQI report

Reporting area: Dhaka

Reporting date: 10/01/2009

Criteria pollutant: $PM_{2.5}$

AQI: 240.1

Descriptor: Very unhealthy (Purple -USEPA)

Very unhealthy (Violet -BD)

Severity group: people with respiratory/ heart disease – elderly children

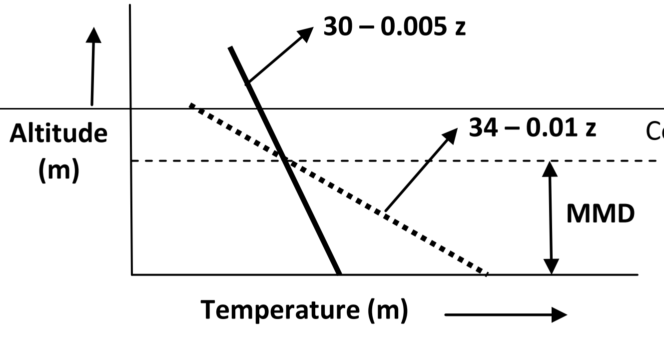
Other pollutants with index >100 : PM_{10} (163.4), O_3 (126.8)

Problem on VC

Suppose, the ambient atmospheric temperature profile of an area is given by the following equation:

$\wedge$ (°C) = 30 – 0.005 z, where, z = altitude in m. If maximum surface temperature is 34°C and average wind speed is 5.7 m/s, estimate the variation coefficient (VC) and comment on the pollution potential.

Solution



At the point of intersection,

$30 - 0.005z = 34 - 0.01\,z$ (as dry adiabatic lapse rate = $1^\circ C$ / 100m)

Therefore, z = 800 m = MMD

Now, VC = MMD × $\bar{u}$

$= 800 \times 5.7 = 4560\ m^2/sec < 6000\ m^2/sec$

Therefore, the area has high pollution potential.

Problem on Emission Rate Estimation

1. A power plant consumes 250 tons of coal (containing 1% sulfur) each day. Assuming 10% of this sulfur is emitted as SO_2, estimate the emission rate of SO_2 in g/sec from the power plant.

Solution

Quantity of S, emitted as SO_2 = 250 × 1000 × 1000 × 0.01 × 0.1 = 250000 g/day = 2.894 g/sec

Now, $\mathbf{S \quad + \quad \rightarrow O_2 \qquad SO_2}$

$(32) \quad (2 \times 16) \quad (32+32 = 64)$

$\therefore$ Emission rate of $\mathbf{SO_2}$ = 2.894 × (64/32) = 5.79 g SO_2/sec

2. The following information is available on emission of NOx for the proposed 335 MW combined cycle (CC) power plant to be constructed at siddhirganj power generation complex.

Flow rate of exhaust gas = 589.4 kg/sec

Maximum NOx in exhaust gas = 25 ppm V

Estimate the NOx emission rate from the power plant in g/sec

[given, MW of exhaust gas = 28.01 g/mol, assume all NOx emitted as NO_2]

Solution: Approach 1

Concentration in mg/m^3 = $\frac{ppm \times MW}{22.414} \times \frac{273P}{T}$

$\therefore$ NO$_2$ in exhaust gas (mg/m^3) = $\frac{25 \times 46}{22.414} \times \frac{273 \times 1}{273}$ at STP

= 51.30 mg/m^3 or mg/Nm3 (Nm^3 = m^3 of air at STP)

From Ideal gas law: PV = nRT

Assuming ideal gas, volume of 1 kg exhaust gas , $V = \frac{nRT}{P}$

$$= \left(\frac{1000g}{kg} \times 1kg \times \frac{mol}{28.01g}\right) \times \frac{0.082 \times 10^{-3} m^3 atm}{mol \times k} \times \frac{273k}{1atm} = 0.799m^3$$

$\therefore$ Flow rate of exhaust gas = 589.4 ×0.799 = 47.06 m^3/sec

Maximum NO$_2$ in exhaust = 51.30 × 471.06/1000 = 24.2 g/sec

Solution: Approach 2

Considering ideal gas, $1ppmV = \frac{1 mol Pollutant}{10^6 mol Exhaust Gas}$

$\therefore$ NO2 in exhaust gas = 25 ppmV = $\frac{25 mol NO_2}{10^6 mol Exhaust Gas}$

$$= \frac{25 mol NO_2 \times 46 g/mol}{10^6 mol Exhaust Gas \times 28.01 g/mol}$$

= 4.106 × 10^{-5} g NO_2/g exhaust gas

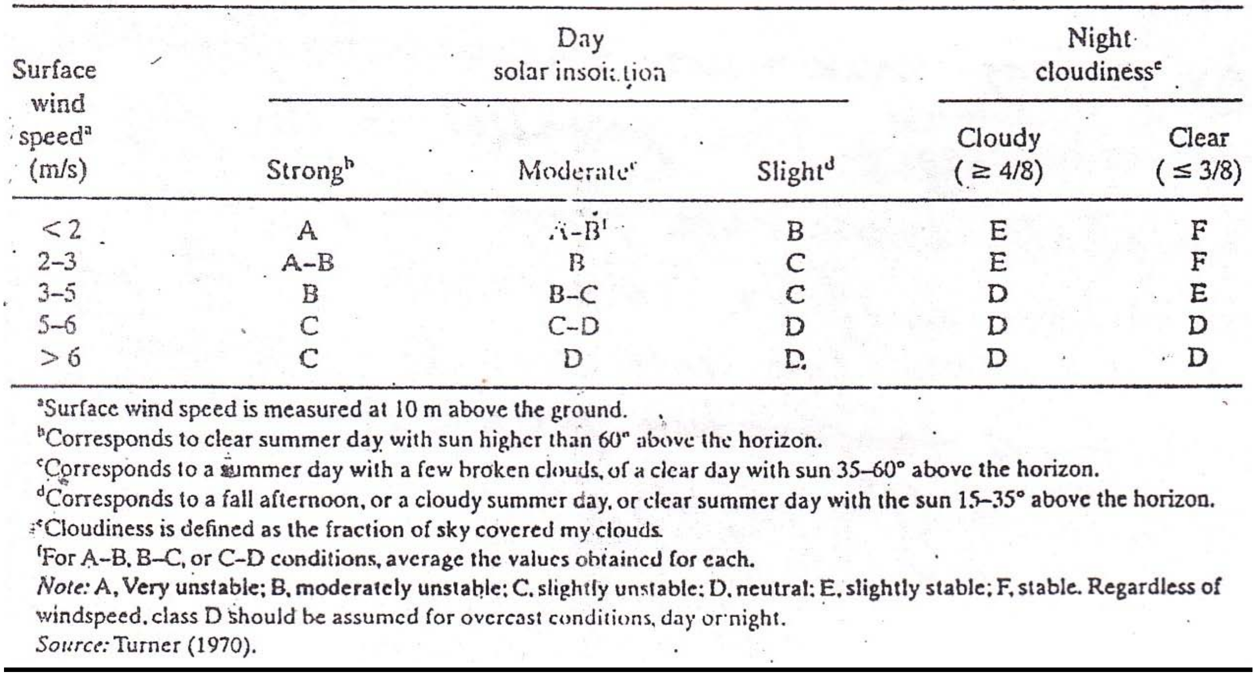
Exhaust flow rate = 589.4 kg/sec

$\therefore$ NO2 emission = 4.106 × 10^{-5} g NO_2/g exhaust gas × 589.4 kg/sec× 10^3 g/kg

= 24.2 g/sec

Problem on Stack Height Estimation

1. A power plant has a 100 m stack with inside radius of 1m. The exhaust gases leave the stack with an exhaust velocity of 10m/s at a temperature of 220°C. Ambient temperature is 6°C. Wind speed at effective stack height is estimated to be 5m/s, surface wind speed is 3m/s and it is a cloudy summer day. Estimate the effective height of this stack.



Surface wind speed[a] (m/s)	Day solar insolation			Night cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy ($\geq 4/8$)	Clear ($\leq 3/8$)
< 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

[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, of 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° above the horizon.

[e] Cloudiness is defined as the fraction of sky covered my clouds.

[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

Source: Turner (1970).

Solution

Here, $T_s = 220 + 273 = 493$ K   Surface wind speed = 3m/s and cloudy summer day

$T_a = 6 + 273 = 279$ K $\therefore$ Stability class = C

Now, $F = gr^2v_s\,(1 - T_a/T_s)$

$= 9.8 \times 1^2 \times 10 \times (1 - 279/493) = 42.54\ m^4/s^3 < 55\ m^4/s^3$

$\therefore X_f = 50\ F^{5/8} = 50 \times (42.54)^{5/8} = 521.16$ m

For stability class C,

$$\therefore \Delta h = \frac{1.6 F^{1/3} x_f^{2/3}}{u} = \frac{1.6 \times (42.54)^{1/3} \times (521.16)^{2/3}}{5} = 72m$$

$\therefore$ Effective stack height, $H = h + \Delta h = 100 + 72 = 172$ m

2. A 750 MW coal fired power plant has a 250 m stack with inside radius of 4 m. The exit velocity of the stack gases is estimated at 15m/s, at a temperature of 140°C (413K). Ambient temperature is 25°C (298K) and wind at stack height is estimated to be 5 m/s. Estimate the effective height of the stack if –

(a) the atmosphere is stable with temperature increasing at the rate of 2°C/km

(b) the atmosphere is slightly unstable, class C.

<u>Solution</u>

$F = g r^2 v_s (1 - T_a/T_s)$

$= 9.8 \times 4^2 \times 15 \times (1 - 298/413) = 655\ m^4/s^3 < 55\ m^4/s^3$

(a) For stable conditions, $\Delta h = 2.4 \times (F/uS)^{1/3}$

Here, $S = (g/Ta)\ (dTa/dz + \Gamma)$

$= (9.8/298)\ (0.002 + 0.01) = 0.0004/s^2$

Now, $\Delta h = 2.4 \times (F/uS)^{1/3}$

$= 2.4 \times \{655/(5\times 0.0004)\}^{1/3}$

$= 165$ m

Therefore, H = 250 + 165 = **415 m**

(b) For unstable atmosphere, class C,

$$\Delta h = \frac{1.6F^{1/3}x_f^{2/3}}{u}$$

For $F>55\ m^4/s^3$, $x_f = 120\ F^{0.4} = 120 \times (655)^{0.4} = 1600$ m

$\Delta h = 1.6\ F^{1/3}\, x_f^{2/3} / u = 1.6 \times (655)^{1/3}\, (1600)^{2/3} / 5 = 380$ m

Therefore, H = 250 + 380 = **630 m**

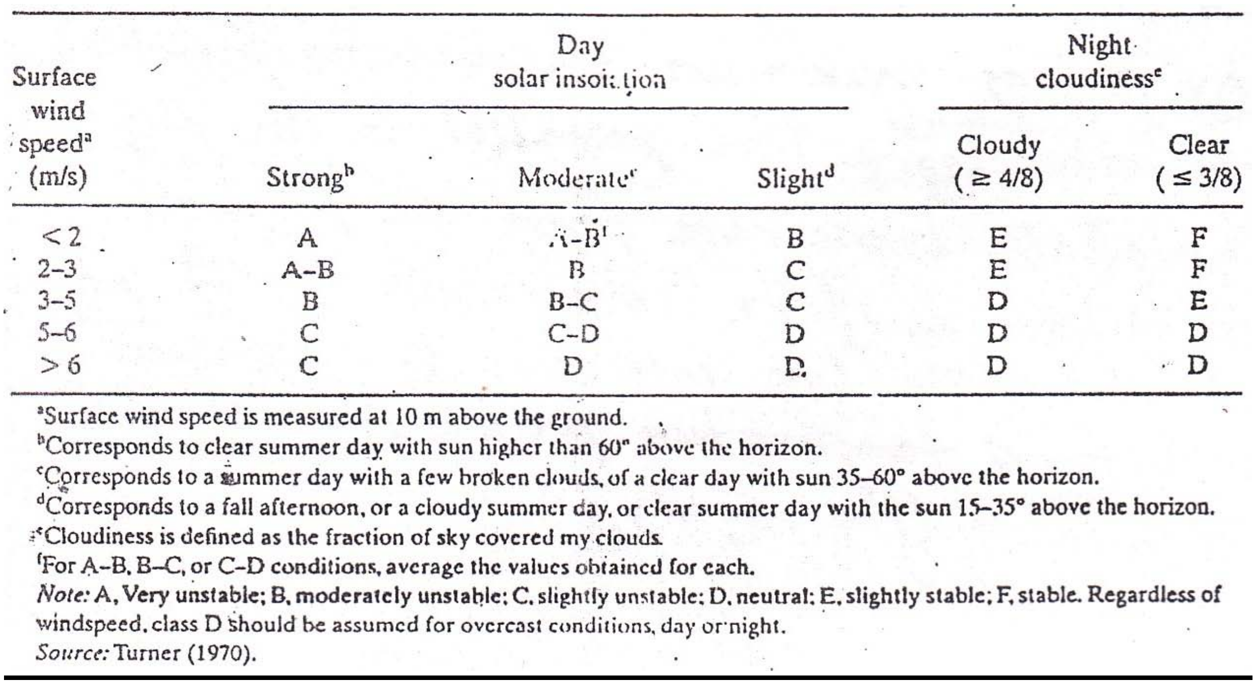
Problem on Ground Level Concentration

A stack emitting 80 g/s of NO_2 has an effective stack height of 100m. The wind speed is 4m/s at 10m, and it is a clear summer day with the sun nearly overhead. Estimate the ground level NO_2 concentration –

(a) directly downwind at a distance of 2km

(b) at a point downwind where NO_2 is maximum

(c) at a point located 2 km downwind and 0.1 km of cross-downwind axis



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

[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, of 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° above the horizon.

[e] Cloudiness is defined as the fraction of sky covered my clouds.

[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

Note: A, Very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable. Regardless of windspeed, class D should be assumed for overcast conditions, day or night.

Source: Turner (1970).

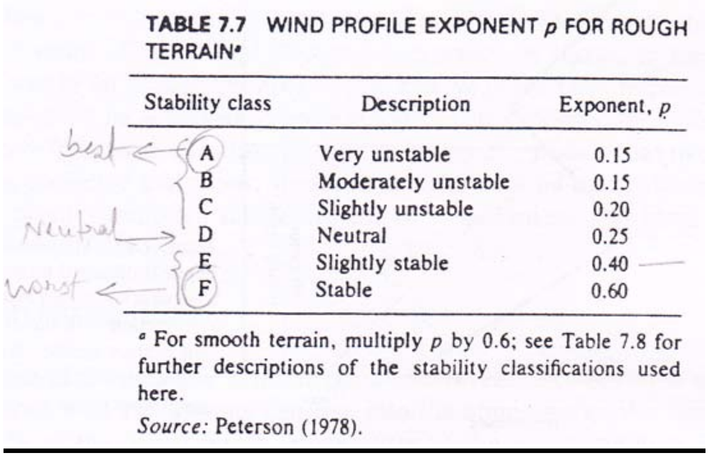


TABLE 7.7 WIND PROFILE EXPONENT *p* FOR ROUGH TERRAIN[a]

	Stability class	Description	Exponent, *p*
best ←	A	Very unstable	0.15
	B	Moderately unstable	0.15
	C	Slightly unstable	0.20
Neutral →	D	Neutral	0.25
	E	Slightly stable	0.40
worst ←	F	Stable	0.60

[a] For smooth terrain, multiply *p* by 0.6; see Table 7.8 for further descriptions of the stability classifications used here.

Source: Peterson (1978).

		$x \leq 1$ 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

[a] The computed values of σ will be in meters when x is given in kilometers.

Source: Martin (1976).

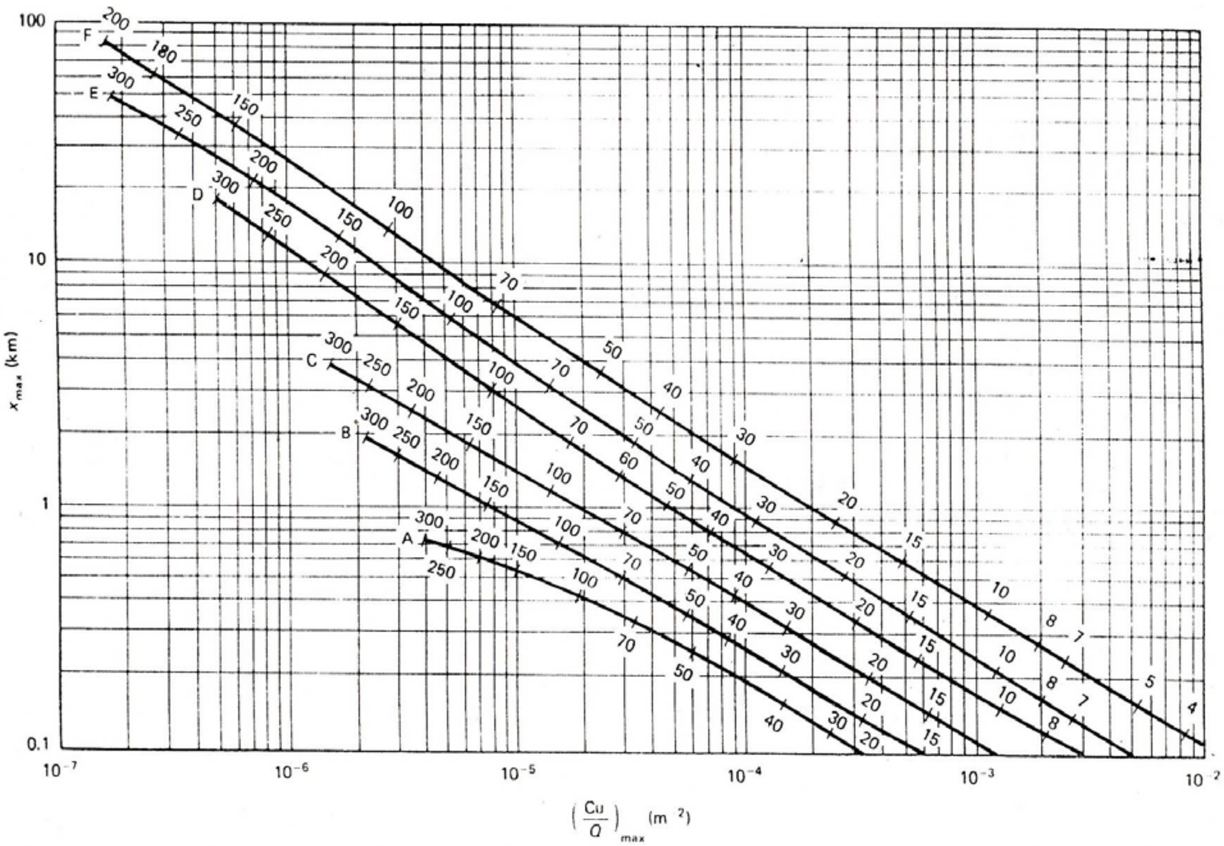


Figure 7.30 To determine the peak downwind plume concentration, enter the graph at the appropriate stability classification and effective stack height (numbers above the lines, in meters) and then move across to find the distance to the peak, and down, to find a parameter from which the peak concentration can be found (Turner, 1970).

Solution

(a) Here, Q = 80 g/sec

H = 100m

V_0 = 4.0 m/s and clear summer day, $\therefore$ Stability class B and p = 0.15

Now, $v_z = 4\times(100/10)^{0.15} = 5.65$ m/s

X = 2 km

$\therefore \sigma_y = ax^{0.894} = 156 \times (2)^{0.894} = 289.9$ m

$\sigma_z = cx^d + f = 108.2\times (2)^{1.098} + 2 = 233.6$ m

For Ground reflection (CO, SO_2, NO_2)

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

Now,

$$C(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \times \exp\left(\frac{-H^2}{2\sigma_z^2}\right) = \frac{80}{\pi \times 5.65 \times 289.9 \times 23.6} \times \exp\left(\frac{-100^2}{2\times 233.6^2}\right)$$

$= 6.07 \times 10^{-5}$ g/m^3

$= 60.7$ μg/m^3

(c) $C(x, y, 0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \times \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \times \exp\left(\frac{-H^2}{2\sigma_z^2}\right)$

$$C(2km, 0.1km, 0) = \frac{80}{\pi \times 5.65 \times 289.9 \times 233.6} \times \exp\left(\frac{-100^2}{2 \times 289.9^2}\right) \times \exp\left(\frac{-100^2}{2 \times 233.6^2}\right)$$

$= 57.2$ μg/m^3

(b) For stability class B and H = 100 m, we get

$X_{max} = 0.7$ km

$(C_u/Q)_{max} = 1.6 \times 10^{-5}$ m^{-2}

Now, $C_{max} = (Q/u) \times (C_u/Q)_{max}$

$= (80/5.65) \times 1.6 \times 10^{-5} = 226.5$ μg/m^3

Check:

$\sigma_y = 156 (0.7)^{0.894} = 113.4$ m

$\sigma_z = 1082 (0.7)^{1.098} + 2 = 75.1$ m

$\therefore$

$$C(0.7km,0,0) = \frac{80}{\pi \times 5.65 \times 113.4 \times 75.1} \times \exp\left(\frac{-100^2}{2 \times 78.1^2}\right) = 2.18 \times 10^{-4}\, g/m^3 = 218 \mu g/m^3$$

Problem on Ground Level Concentration of line source

Cars travelling at 55 mph speed at 75 m apart are emitting 5g/mile of CO. The wind speed is 3.5 m/s and perpendicular to the road. Estimate ground level; concentration of CO at a distance 300m downwind. Consider atmosphere to be adiabatic.

Solution

As the atmosphere is adiabatic, that means the atmosphere is neutral, hence stability class is D. For x = 300 m, σ_z = 15 m

Q = (5g/mile) × (55 mile/hr) ×(1hr/3600 sec) × (1car / 75 m) = 1.018×10^{-3} g/m^3

H = 0

$\bar{u}$ = 3.5 m/s

Now, considering ground reflection,

$$C(x,z)=\frac{Q_L}{\sqrt{2\pi}\sigma_z\bar{u}}\times\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right]+\exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\}$$

$$C(x,0)=\frac{2Q_L}{\sqrt{2\pi}\sigma_z\bar{u}}$$

$$C(300,0)=\frac{2\times1.018\times10^{-3}\,g/m-s}{\sqrt{2\pi}\times15m\times3.5m/s}=1.55\times10^{-5}\,g/m^3=15.5\mu g/m^3$$

CE 433
Environmental Pollution and Its Control
(Credit 2.0, Class Period 2 hours/week)

Effects of Air Pollution

(1) Effects on atmospheric properties

(2) Effects on materials

(3) Effects on vegetation

(4) Effects on human health

(1) Effects on atmospheric properties

- Visibility reduction
- Fog formation and precipitation
- Solar radiation reduction
- Temperature and wind direction alteration
- Possible effect on global climate changes

(2) Effects on materials

- Air pollutants can affect materials by soiling or chemical deterioration. High smoke and particulate levels are associated with soiling of clothing and structures.
- Acid or alkaline particles, especially those containing sulfur corrode materials, such as paint, masonary, electrical contacts and textiles.
- Ozone is particularly effective in deteriorating rubber. Residents of Los Angles in USA with high O_3 levels must replace automobile tires and windshield wiper blades most frequently than residents in cities where O_3 concentrations are low.

(3) Effects on vegetation

- Pollutants that are known phytotoxins (substances harmful to vegetation) are SO2, peroxyacetyl nitrate and ethane of somewhat lesser severity are cholrine, hydrogen chloride, ammonia and mercury.
- Gaseous pollutants enter plant through stomata in the cause of normal respiration of plant. Once in the leaf, pollutants destroy chlorophyll and disrupt photosynthesis.
- Damage can range from a reduction in growth rate to complete death of plant.
- Symptoms of damage are usually manifested in the leaf.

(4) Effects on human health

- Extremely high concentrations of (for several hours/ days) have resulted in serious “air pollution episodes:, causing significant deaths in injuries.
- Diseases of respiratory system are generally correlated with air pollution. Effects are particularly severe on vulnerable population, e.g., older people, infants, people suffering from other diseases.
- In general, two types of reaction of respiratory system to air pollution:
  (i) acute (eg., irritative bronchitis)
  (ii) chronic (e.g., chronic bronchitis, pulmonary emphysema)

Sources and Effects of Criteria Pollutants

Particulates/ Particulate Matter (PM) / Aerosol

Consists of any dispersed matter in the air, solid or liquid (except pure water), with size ranging from molecular clusters of 0.005 µm to coarse particles of up to 100 µm.

Terms used to describe PM:

Dust – solid particles are called dust, if they are caused by grinding and crushing operations.

Fumes – solid particles are called fumes, if they are formed when vapors condenses.

Mist, Fog – liquid particulates

Smoke, Soot – composed primarily of carbon that results from incomplete combustion.

Smog – derived from smoke and fog

The black smoke or soot emitted from diesel engines and smokestacks (e.g. brickfields) consist mostly of solid particles made up of vast numbers of carbon particles fused together in benzene rings.

While these particles themselves can irritate lung, most often it is the larger organic molecules that stick to the surface of soot [mostly Polycyclic/ Polynuclear Aromatic Hydrocarbons (PAHS), e.g., benzo-a-pyrene, a human carcinogen] that are responsible for most serious health effects. PAHs are formed when C-containing hydrocarbons are not completely oxidized during combustion.

Size of PM: Aerodynamic Diameter:

Although particles may have irregular shapes, their size can be described by an equivalent "aerodynamic diameter" determined by comparing them with perfect spheres having the same settling velocity. Stokes law can be used to estimate settling velocity (e.g., a 10µm particle has a settling velocity of approximately 20 cm/min). $PM_{2.5}$ indicates PM with aerodynamic diameter $\leq$ 2.5µm.

Particles of most interest have aerodynamic diameter in the range of 0.1 to 10 µm. Particles smaller these undergo random (Brownian) motion and through coagulation generally grow to size > 0.1 µm. Particle larger than 10 µm, settles quickly.

Distribution and Characteristics of PM:

About 90% of all respirable particles in the Earth's atmosphere are natural; about 10% are anthropogenic.

However, most natural particles are relatively harmless (e.g., soil, sea-spray, biological materials). Particles of anthropogenic origin, on the other hand, are often toxic.

Particulates of anthropogenic origin are considered more harmful because of their, (a) non-uniform distribution; (b) chemical composition; and (c) size distribution (smaller).

(a) Non-uniform distribution: Anthropogenic particulates are concentrated in cities and industrial areas.

(b) Chemical composition: about 40% elements can be found in particulates. Most important elements include – Al, Fe, Na (Sea spray), Si. These are mostly of natural origin (e.g. soil contains 8% Al, 6% Fe)

(c) Size distribution:

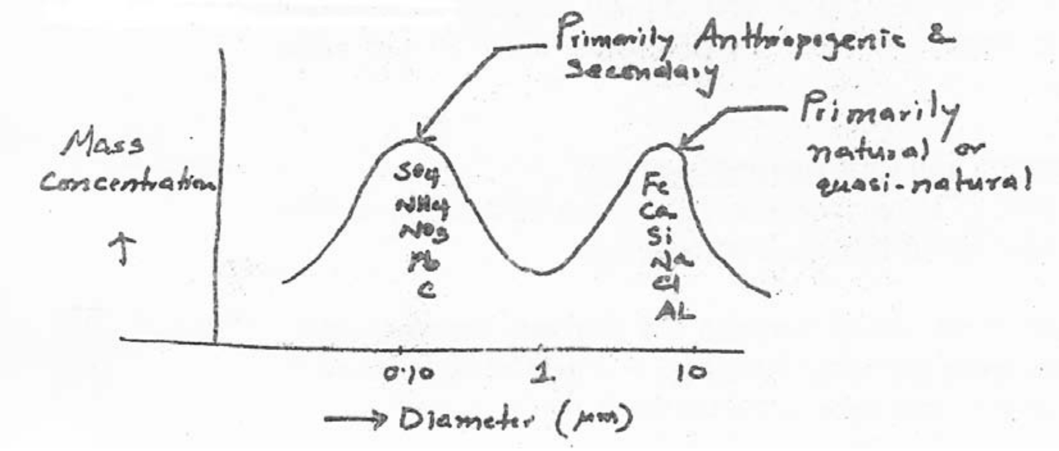


Fig: Idealized aerosol mass distribution showing a typical segmentation of chemical species into fine and coarse fractions

Source Apportionment of Particulate Matter in Dhaka

Average mass contribution of PM pollution in Dhaka (%) in 1993-1994

Source type	Coarse (PM_{10})	Fine ($PM_{2.5}$)
Re-suspended soil	64.7	8.88
2-stroke engine	6.07	2.03
Construction works	7.09	-
Motor vehicles	3.12	29.1
Sea salt	0.22	4.11
Refuse burning	0.74	-
Natural gas/diesel burning	-	45.7
Metal smelting	-	10.2

(Source: Biswas et al., 2000)

From other studies

Major sources of **$PM_{2.5}$**:

- Motor vehicle
- Brick kiln
- Road dust/ soil dust

Major sources of **PM_{10}**:

- Motor vehicle
- Road dust
- Soil dust
- Sea salt

Health Effects of PM

Particles (aerosols) suspended in the air enter our body when we breathe.

These particles include:

- Natural particles (e.g., bacteria, viruses, pollen, sea salt, road dust)
- Anthropogenic emissions (e.g., cigarette smoke, vehicle exhaust etc)

The hazard pose by these particles depend on their chemical composition as well as where they deposit within our respiratory system.

Hence we need to learn about our respiratory system.

Deposition of Particles in the Respiratory System

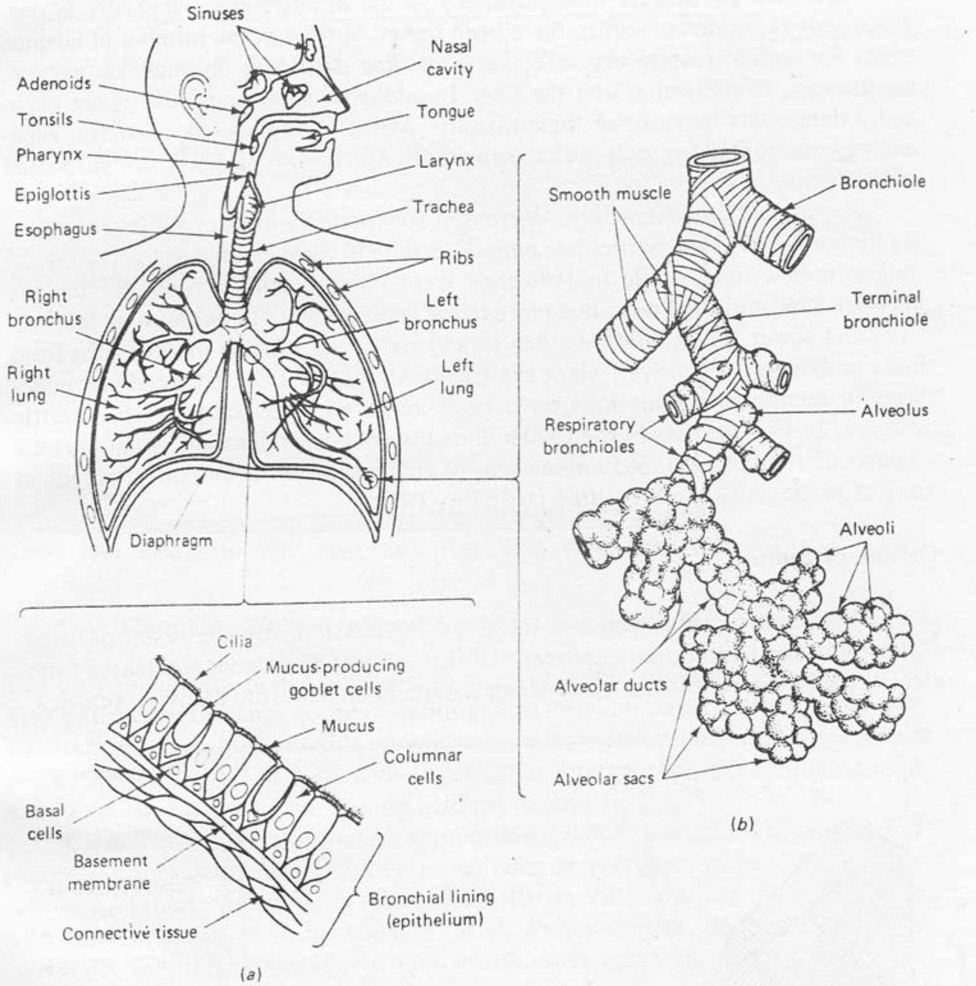


Figure 7.10 The human respiratory system: (*a*) the system as a whole and a cross section of the bronchial lining showing the cilia; (*b*) details of the lower respiratory system terminating in the alveoli. (*Source:* Williamson, S. J. *Fundamentals of Air Pollution*. © 1973 by Addison-Wesley Publishing Co. Reprinted by permission of Addison-Wesley Publishing Co., Inc., Reading, MA.)

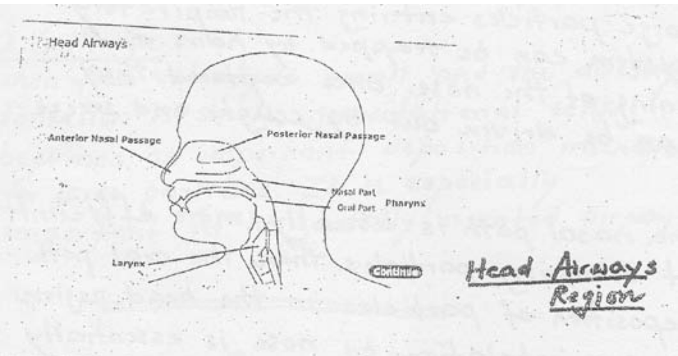
- Upper respiratory system – Nasal cavity, Trachea
- Lower respiratory system – Bronchial tubes, Lungs

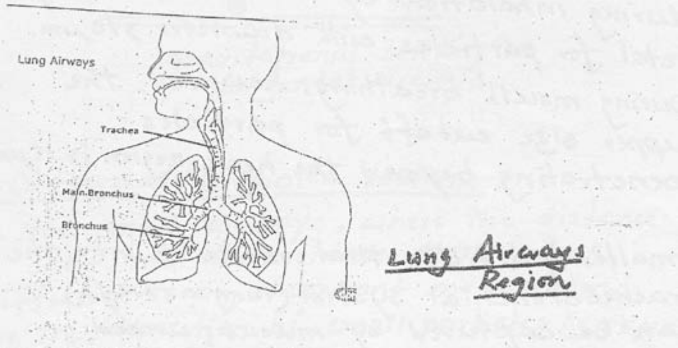
From the viewpoint of respiratory deposition of particulates, the respiratory system can be divided into three regions:

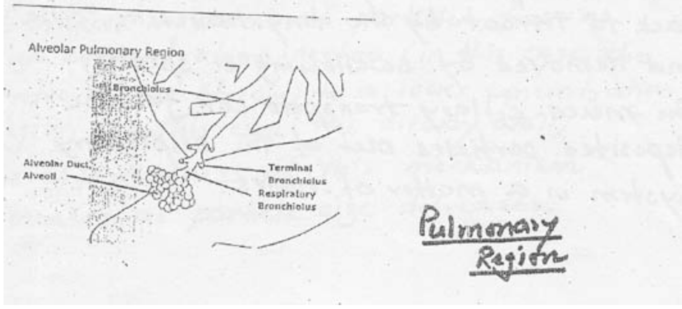
(i) **Head Airways Region** – nasal airway, oral airway

(ii) **Lung Airways Region (Trancheobronchial Region)** - from trachea to terminal bronchioles (23 branchings)

(iii) **Pulmonary Region (Alveolar Region)** – across the alveolar membrane O_2 and CO_2 counter-diffuse; surface area is about 75 m^2, if fully unfolded







Respiratory Deposition

- Large particles entering the respiratory system can be trapped by hairs and lining of the nose. Once captured, they can be driven out by caugh and sneeze.
- The nasal path is usually more efficient at removing particles than the oral path. Deposition of particles in the head region during inhalation by nose is essentially total for particles with diameter > 10 µm. During mouth breathing, however, the upper size cut off for particles penetrating beyond the head region is 15 µm.
- Smaller particles that make it into the tracheobronchial system (lung airways) can be captured by mucus, worked back to throat by the tiny hair-like "cilia" and removed by swallowing or spitting. The muco-ciliary transport can get the deposited particles out of the respiratory system in a matter of hours.
- Smaller particles are often able to traverse deeper without being captured in the mucus lining, but depending on their size, they may or may not be deposited there. Some particles are so small that they tend to follow the airstream into the lung and right back out again.
- The alveolar region does not have the muco-ciliary mechanism (because it is designed for gas exchange). It takes months or years to clear the insoluble particles deposited in this region. Fibrogen dust, such as silica, asbestos and coal dust interfere with the cleaning mechanism resulting in "fibrosis" of the region. Insoluble radioactive materials deposited in this region may cause subsequent damage due to long retention time and subsequently continuous radiation.
- Soluble materials can pass through the alveolar membrane and be transported to other parts of the body. Hence, it is the region where viruses invade and it is also the target region for therapeutic aerosol delivery.

Particle Deposition Mechanism

Most important deposition mechanisms are:

(i) Impaction

(ii) Settling

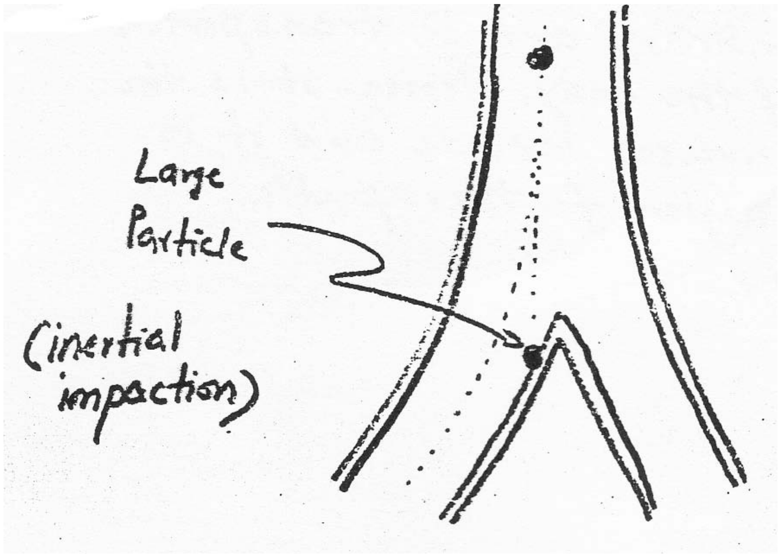
(iii) Diffusion/ Brownian motion

(iv) Interception

(i) **Impaction:**

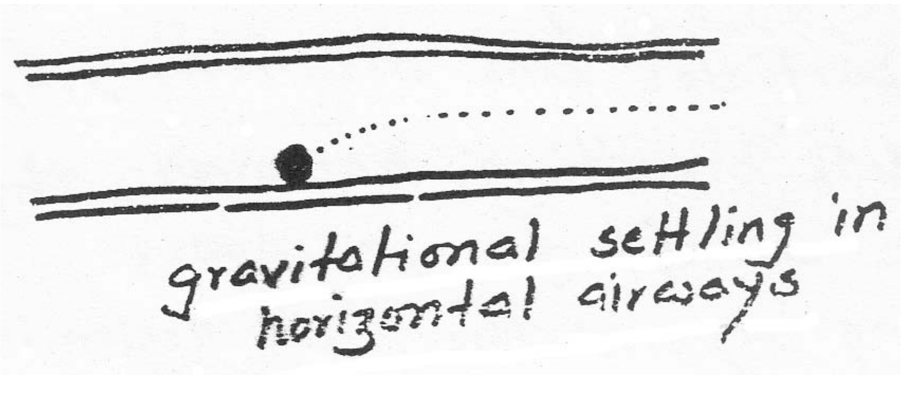
Collection by impaction is due to a particle's inertia that makes the particle deviate from the air stream when the air stream makes a turn.

Impaction is important when the particle size or the velocity is large in a curved pathway. Hence, it is important mechanism in bronchial region.



(ii) **Settling:**

When flow velocity is small and the airway dimension is small, gravitational settling becomes an important deposition mechanism for large particles. It is especially important for horizontally oriented airways.

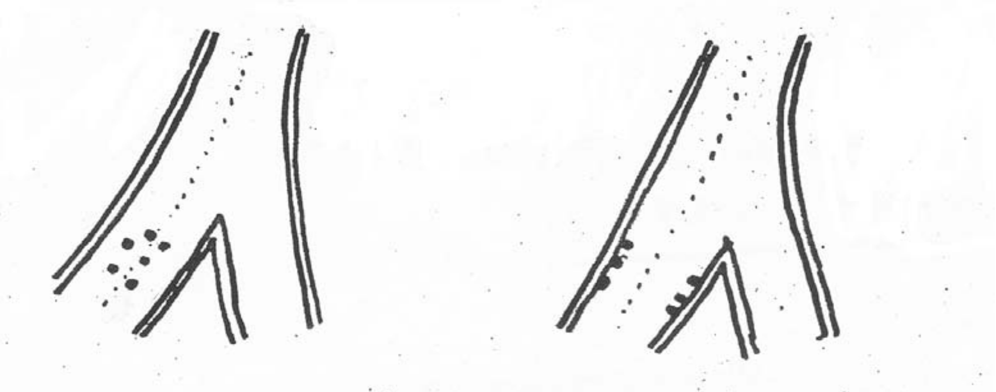


(iii) **Diffusion/ Brownian motion:**

In the small airways, where the distance is short and the residence time is long, diffusion is an important mechanism for the deposition of small particles (<0.5 µm).

It induces movement of particles from a higher concentration region (in this case, the center of air stream) to a lower concentration region (in this case, the airway wall).

The effectiveness of this mechanism increases as particle size decreases.

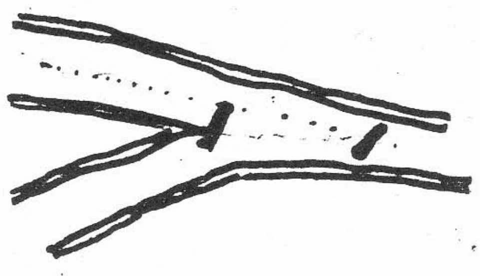


Deposition of particles by diffusion

(iii) **Interception:**

When a particle follows the air stream without deviation, it can still contact the airways surface because of its physical size. This mechanism is called interception.

Usually, interception is not critically important in our respiratory system, except for long fibers that are long in one dimension.



Deposition by interception

Total Deposition of Particles

Particle entering respiratory system are subject to all the deposition mechanisms. Several models have been developed to predict the deposition based on experimental data.

The total deposition fraction (DF) in the respiratory system according to International Commission on Radiological Protection (ICRP) model is:

$$DF = IF\left(0.0587 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln d_p)} + \frac{0.943}{1 + \exp(0.503 + 2.58 \ln d_p}\right)$$

where, dp = particle size in µm

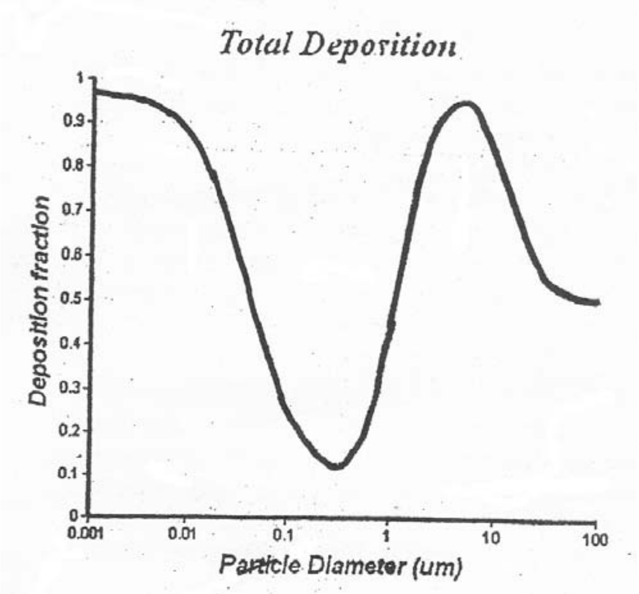
IF = inhalable fraction, defined as follows –

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076 \ln d_p^{2.8}}\right)$$

Large particles have a high deposition fraction due to impaction and settling. The fraction decreases for particles larger than 3 µm and is due to the reduced entry into the mouth or nose.

Small particles also get a high deposition fraction due to diffusion.

The minimum efficiency is between 0.1 to 1.0 µm, where none of the above mechanisms dominates.



Regional Deposition

Regional deposition is of more interest because it is more relevant in assessing the potential hazard of inhaled particles and the effectiveness of therapeutic delivery.

The deposition fraction in the three regions can be approximated by the following equations –

For the Head Airways (HA)

$$DF_{HA} = IF\left(\frac{1}{1+\exp(6.84+1.183\ln d_p} + \frac{1}{1+\exp(0.924-1.88\ln d_p}\right)$$

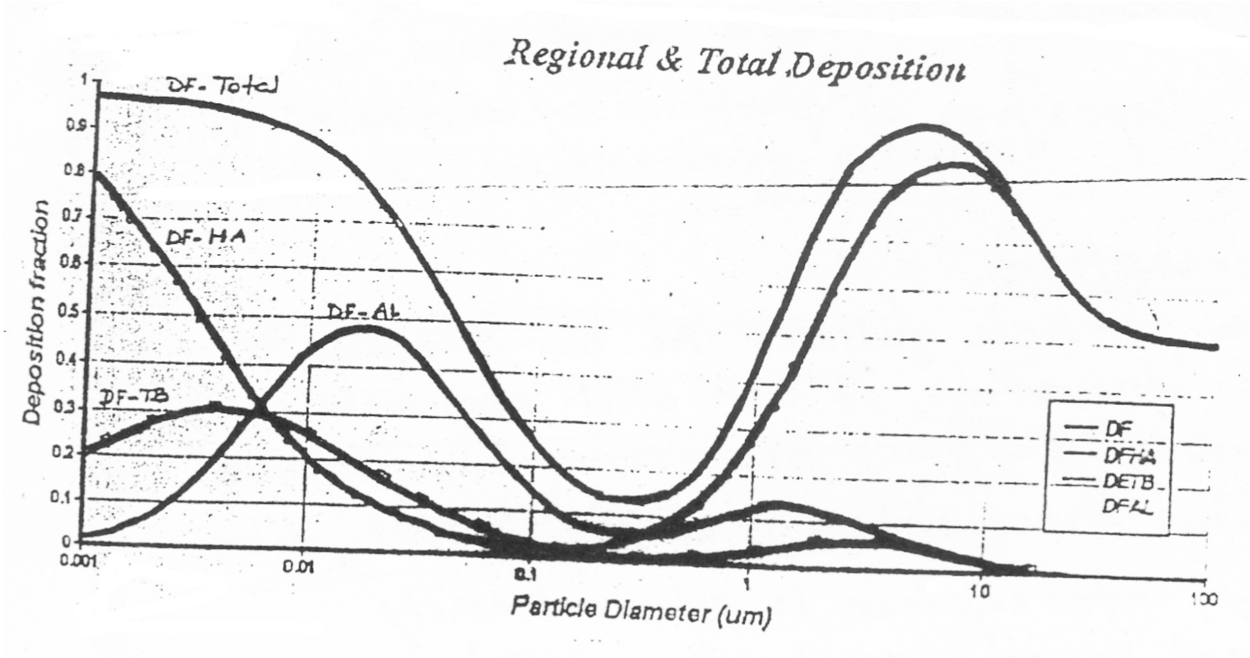
For the Tracheobronchial region (TB)

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)[\exp(-0.234(\ln d_p + 3.40)^2 + 63.9\exp(-0.819(\ln d_p - 1.61)^2)]$$

For the Alveolar region (AL)

$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)[\exp(-0.416(\ln d_p + 2.84)^2 + 19.11\exp(-0.482(\ln d_p - 1.362)^2)]$$

Regional deposition of particles in the respiratory system



HA

- The largest particles are removed by settling and impaction in the Head Airways.
- Ultrafine particles less than 0.01 µm can also have significant deposition in this region due to their high diffusivity.

TB

- In the TB region, impaction and settling are important for particles larger than 0.5 µm although the overall deposition fraction in this size range is quite small. This is because the majority has been removed in the preceding head airways.

- Ultrafine particles also have a high deposition efficiency in this region due to their rapid Brownian motion

AL

- Particles entering the Alveolar region have high deposition efficiency, no matter they are large or small; settling for large particles and diffusion for small particles.
- As seen in the figure, Alveolar deposition is not significant whenever head airways and tracheobronchial airways deposition is high.
- Again, these two rapid cleared regions (i.e. head and lung airways) are very important in protecting the more vulnerable alveolar region from irritating or harmful particles.

CE 433
Environmental Pollution and Its Control
(Credit 2.0, Class Period 2 hours/week)

Sources and Effects of Criteria Pollutants

Lead (Pb)

- Most lead emissions come from vehicles burning gasoline containing the antiknock additive, tetraethyl lead $(C_2H_5)_4Pb$.
- Lead is emitted to the atmosphere primarily in the form of inorganic particulates.
- Human exposure to airborne lead primarily results from inhalation. It can also be ingested after lead has deposited onto food stuff.
- About $1/3^{rd}$ of lead particles inhaled are deposited in the respiratory system, and about ½ of those are absorbed by blood stream.
- Adverse effects of lead poisoning include aggressive, hostile and destructive behavioral change, learning disabilities, seizures, severe and permanent brain damage and even death.
- Vulnerable groups include children and pregnant women.

Other sources of Pb

- Paint
- Food processing
- Coal combustion / metal smelting
- Plumbing
- Plants manufacturing lead acid batteries

Carbon Monoxide (CO)

Formation of CO

(i) Incomplete combustion of carbon/ carbon containing fuel

$2C + O_2 = 2CO$

$2CO + O_2 = 2CO_2$

Incomplete combustion results when any of the following 4 variables are not kept sufficiently high: (a) Oxygen supply, (b) combustion temperature, (c) gas residence time at high temperature and (d) combustion chamber temperature.

(ii) Industrial production of CO by high temperature reaction between CO2 and carbon containing material.

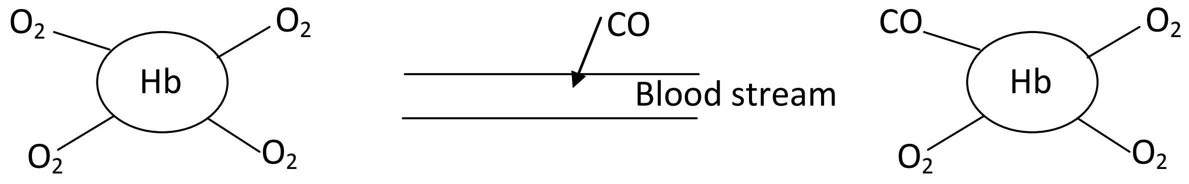
$CO_2 + C = 2CO$

Sources of CO

- Transportation (most significant often accounts of most of the CO emission in urban areas)
- Industrial processes
- Natural (e.g., volcanic activity)

Health Effects of CO

- The effects of CO exposure are reflected in the O_2 carrying capacity of blood.
- In normal functioning condition, hemoglobin (Hb) molecules carry oxygen which is exchanged for CO_2 in the capillaries connecting arteries and veins.
- Co diffuses through the alveolar wall and competes with O2 for one of the 4 iron sites in hemoglobin molecule. Affinity of the iron site for CO is about 210 times greater than for O_2.
-



O_2 Hb (Transport vehicle for O_2)

CO Hb

- When a hemoglobin molecule acquires a CO molecule, it is called carboxy hemoglobin.
- Formation of COHb causes two problems as follows –
    - Less sites for O_2

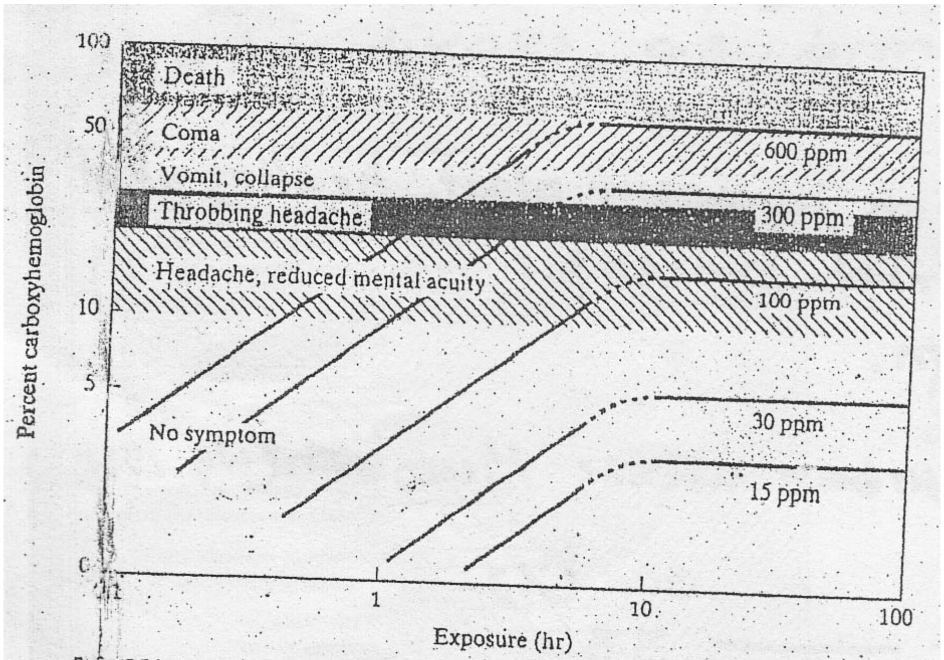
  - Greater amount of energy binding 3 O_2 molecule to Hb, so that they cannot be released easily (to be exchanged for CO_2)

- Formation of COHb is a reversible process, with a half-life for dissociation after exposure of about 2 to 4 hr for low concentration.

- When blood stream carries less O_2, brain functions are affected and heart rate increases in an attempt to offset O_2 deficit.

- Sensitive groups include elderly, fetus, individuals with heart disease.

- The health effects of CO exposure are summarized in the following figure.



F[illegible]RE 7:6 Effects of exposure to carbon monoxide. (*Source*: Seinfeld, 1986)

- The amount of COHb in blood is related to CO concentration and exposure time, often related by empirical equations, e.g.,

- **$\%COHb = \beta(1-e^{-\gamma t})\,(CO)$**
  where, %COHb = COHb as a percent of saturation
  (CO) = CO concentration in ppm
  $\gamma = 0.402\ hr^{-1}$, $\beta = 0.15\%$ per ppm of CO
  t = exposure time in hr

- CO concentration in busy roadways often range from 5 to 50 ppm, CO concentration of about 100 ppm has also been recorded.
- CO is an important indoor air pollutant.
- Cigarette smoke contains about 20000 ppm of CO, which is diluted to 400 – 500 ppm during inhalation; cigarette smoking often raises CO in restaurants to 20 – 30 ppm (close to 1-hr standard)
- 24-hr average indoor CO concentration due to wood and charcoal combustion in developing countries can be between 100 to 200 ppm, with peak concentration as high as 400 ppm lasting for several hours.
- People who are consistently exposed to high level of CO, like heavy smokers or women in traditional rural kitchen, often adjust to compensate for lower levels of oxygen in blood stream, but they still risk developing chronic health effects.
- People who are not accustomed to CO exposure could easily become acutely ill from high concentrations of CO.

Sulfur Oxides (SO_x)

Formation

Combustion of S-containing materials, e.g., oil and coal, which typically contain high quantities of sulfur (0.5 – 0.6%)

$$S + O_2 = SO_2 \xrightarrow[\text{Air}]{} SO_2 + OH\cdot = HOSO_2\cdot$$

$2SO_2 + O_2 = SO_3$ $\qquad$ $HOSO_2\cdot + O_2 = SO_3 + HO_2$

(small amount)

$$SO_3 + HO_2 = H_2SO_4 \xrightarrow[\text{Existing particles}]{\text{Condensation on}} SO_4 \text{ particles}$$

Transformation of SO_2 gas to sulfate particles is gradual, usually taking days.

Sources

- Fuel combustion in power plant, heating plant
- Other industrial processes
- Transportation

Sources of Sox in urban areas: Mumbai (WB, 1996)

Sources	**SO_X (%)**
Power plant	33
Gasoline vehicle	1
Diesel vehicles	4
Industrial fuel	48
Domestic kerosene	2
Marine	12

Health Effects of SO_x

- SO_2 is highly soluble and consequently is absorbed in the moist passages of the upper respiratory system. Exposure to SO_2 levels of the order of ppm leads to constriction of the airways in the respiratory tract
- SO_2 causes significant bronco-constrictions in asthmatics at relatively low concentrations (0.25 to 0.50 ppm)
- SO_2, H_2SO_4 and sulfate salts tend to irritate the mucus membranes of respiratory tract and faster development of chronic respiratory diseases, e.g., bronchitis.

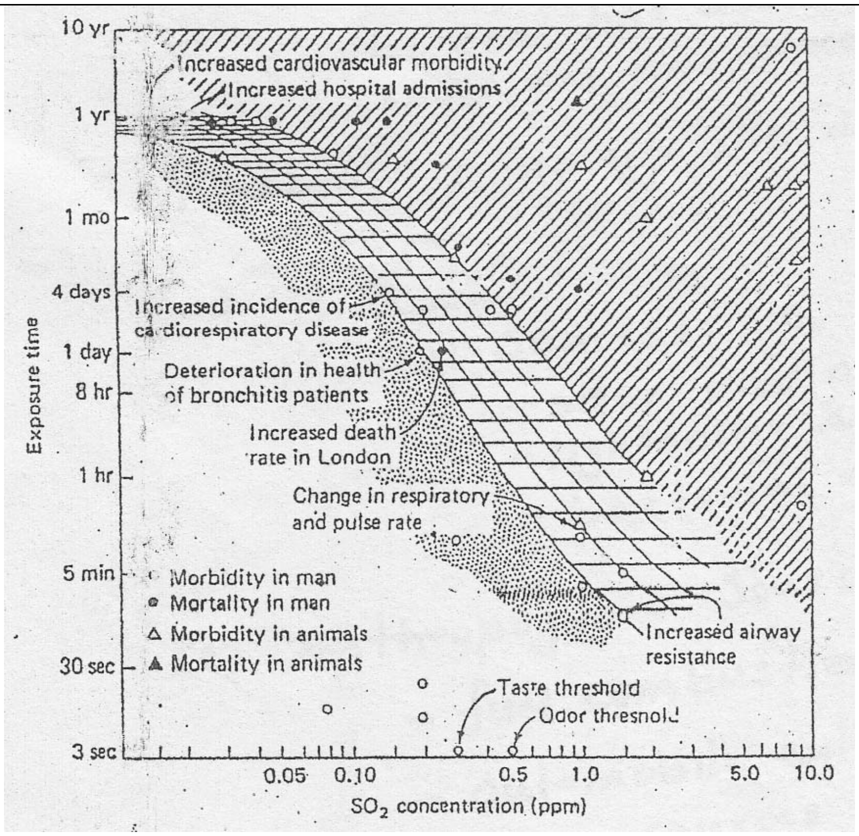


Fig: Health effects due to various exposure to SO_2

- In industry atmosphere, Sox is particularly harmful, because both SO_2 and H_2SO_4 paralyze the hair-like cilia which line the respiratory tract. Without regular sweeping action o cilia, particulates may penetrate to the lung and settle there. These particulates usually carry absorbed/ adsorbed SO_2, thus bringing this irritant into direct prolonged contact with delicate lung tissues.

- The SO_2-particulate combination has been cited as cause of death in several air pollution tragedies.

Effects of SO_x on materials

- H_2SO_2 aerosols readily attack building materials especially those containing carbonates such as marble, limestone, roofing slate and mortar.

- The carbonates are replaced by sulfates, which are water soluble according to the following equation:

- $CaCO_3 + H_2SO_4 = CaSO_4 + CO_2 + H_20$
- The $CaSO_4$ formed in this process is washed away by rain water, leaving a pitted, discolored surface.
- Corrosion rates of most metals, especially iron, steel, zinc, copper, nickel are accelerated by SO_x polluted environment.
- H_2SO_4 mist can also damage cotton, linen, rayon and nylon.
- Leather weakens and disintegrates in the presence of excess Sox by-products.
- Paper absorbs SO_2, which is oxidized to H_2SO_4; the paper turns yellow and becomes brittle. This is why many industrialized cities store historic documents in carefully controlled environment.

Oxides of Nitrogen (NO_x)

Nitric oxide (NO) and Nitrogen dioxide (NO_2) are of primary concern in atmospheric pollution.

Formation of NO_x

Two sources of NO_x during combustion of fossil fuel.

(i) Thermal NO_x: created with N and O, if the combustion air are heated to high temperature (>1000 K) to oxidize N.

(ii) Fuel NO_x: results from oxidation of nitrogen compounds that are chemically bound in the fuel molecules themselves. (Note: coal has about 3% N by weight, natural gas has almost none).

Fuel NO_x is usually the dominant source.

Sources of NO_x

(i) Natural sources – No_x is produced by

- Solar radiation
- Lightening and forest fire
- Bacterial decomposition of organic matter

(ii) Anthropogenic sources: Global scale

- Fuel combustion in stationary sources (49%)
- Automobile exhaust (39%)
- Other sources, e.g., industrial processes (nitric acid plant) etc

NO_x in Urban Environment

Source contribution to emission of NO_x in greater Mumbai (1992) (WB, 1996)

Sources	**NO_X (%)**
Power plant	30
Gasoline vehicle	18
Diesel vehicles	34
Industrial fuel	11
Domestic fuel	4
Marine	3

Effects of NO_x

- Almost all NO_x emissions are in the form of NO, which has no known adverse health effects at concentrations found in atmosphere (<1 ppm).
- NO can be oxidized to NO_2 ($NO + \frac{1}{2} O_2 = NO_2$), which may react with hydrocarbon in the presence of sunlight to form photochemical smog, which is injurious.
- NO_2 also reacts with hydroxyl radical ($HO\cdot$) in the atmosphere to form nitric acid (HNO_3), which is washed out of the atmosphere as acid rain.
- NO_2 irritates lung
- Persistent low level concentration of NO_2 increases respiratory illness.

- NO_2 can cause damage to plants and when converted to HNO_3, it leads to corrosion of metal surface.

Photochemical Smog and Ozone

- When NO_x, various hydrocarbons and sunlight come together , they can initiate a complex set of reactions to produce a number of secondary pollutants known as "photochemical smog".
- Hydrocarbons + NO_x + Sunlight $\longrightarrow$ Photochemical Smog
- Constituent of smog: ozone (most abundant), formaldehyde, peroxy benzyl nitrate (PBzN), peroxy acetyl nitrate (PAN), acrolein etc
- Ozone (O_3) is primarily responsible for chest constriction, irritation of mucus membrane, cracking of rubber, damage to vegetation.
- Eye irritation, the most common complaint about smog, is caused by the other components of smog listed above [especially formaldehyde (HCHO) and acrolein (CH_2CHCHO), PANs]
- Photochemical smog mainly occurs in highly motorized areas in large metropolitan cities.

Persistent Organic Pollutants (POPs)

POPs are organic substances that –

- possess toxic characteristics
- are persistent
- bioaccumulate
- are prone to long range trans-boundary atmospheric transport and deposition
- are likely to cause significant adverse human health or environmental effects near to and distant from their sources.

The Stockholm Convention identifies 12 substances as POPs, which include:

(a) 9 substances used as pesticides, namely Aldrin, Chlordane, Dieldrin, Endrin, Heptachlor, Mires, Toxaphone, DDT and Hexachlorbenzene (HCB)

(b) Polychlorinated biphenyl (PCBs) – are chlorinated hydrocarbons that have been widely used as industrial chemicals since 1930. There are 209 varieties of PCBs. Large quantities of PCBs were produced for use as a cooling and dielectric fluid in electric transformers and in large capacitors. PCBS are linked to reproductive failure and suppression of the immune system in various wild animals, severe human intoxication occurred due to accidental consumption of PCB-containing oils. IARC (International Agency for Research on Cancer) classified PCBs into group 2B (possibly carcinogenic to human). International production of PCBs was ended in most countries by 1980.

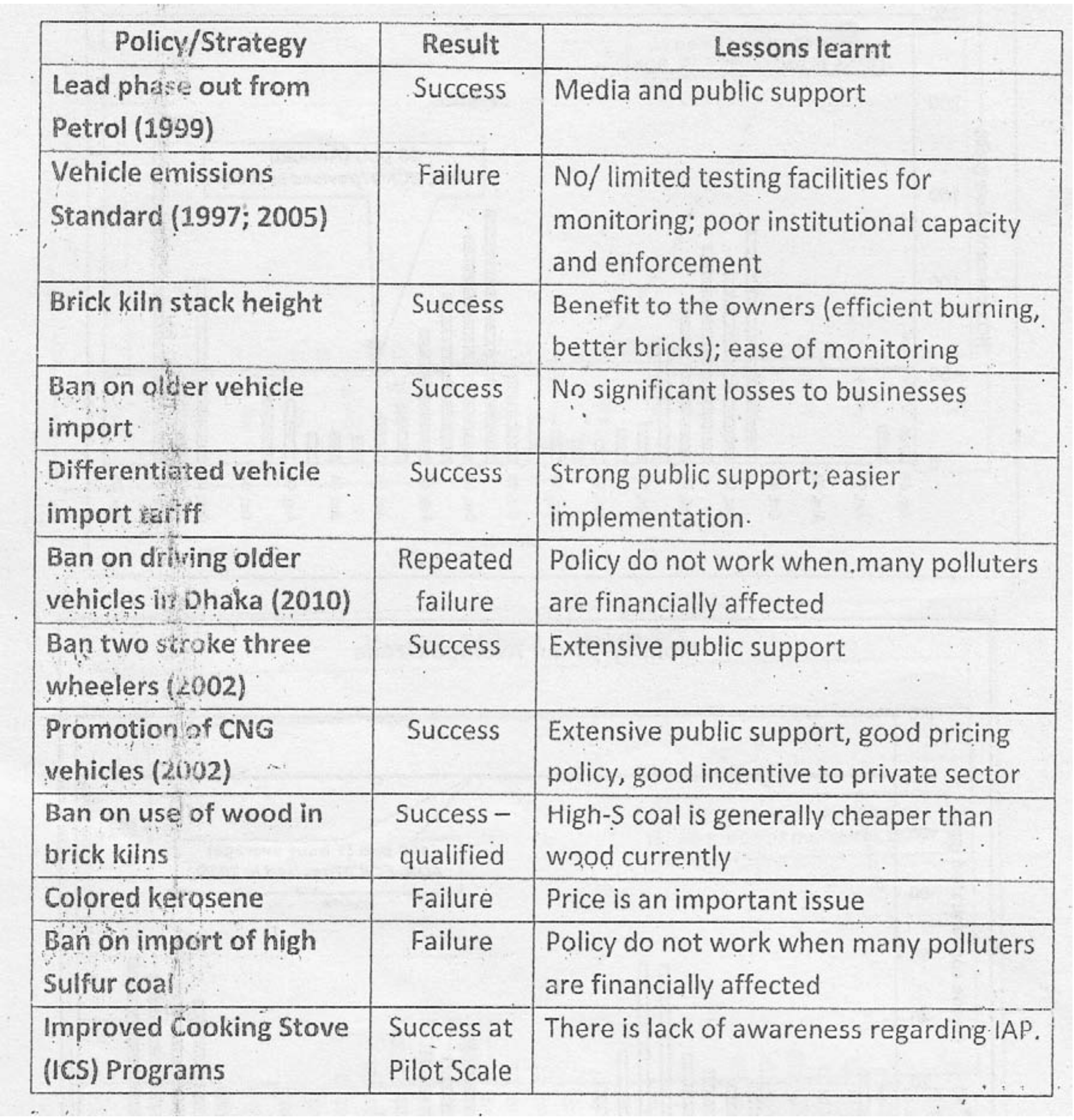
(c) Dioxins and Furans – are class of chlorinated hydrocarbons and are generated as unwanted by-products in a variety of combustion and chemical process. The major sources include waste incinerators combusting municipal wastes, hazardous wastes, medical waste, sewage sludge etc. Kilns firing of cement/tiles industries, open burning of wastes etc may also generate dioxins and furans. Other sources are: pulp and paper mills using chlorine bleach processes, certain thermal processes in metallurgic industry and chemical production process. Dioxins are considered "more toxic than cyanide and the most toxic of manmade chemicals".

There are 75 different dioxin congeners and 135 different furan congeners. IARC classified one congener of dioxin as human carcinogen; all others are carcinogenic in animals. Non carcinogenic effects on the immune, the reproductive, the developmental and the nervous systems are considered to be of great concern.

Effects of POPs on human health and environment

- Reproduction failure and population declines
- Abnormal functioning of thyroid and other hormone system
- Feminization of males and masculization of females
- Weakening of immune system
- Abnormalities in behavior
- Tumors and cancers
- Birth defects

Air Quality Measurement (AQM) Experience in Bangladesh



Policy/Strategy	Result	Lessons learnt
Lead phase out from Petrol (1999)	Success	Media and public support
Vehicle emissions Standard (1997; 2005)	Failure	No/ limited testing facilities for monitoring; poor institutional capacity and enforcement
Brick kiln stack height	Success	Benefit to the owners (efficient burning, better bricks); ease of monitoring
Ban on older vehicle import	Success	No significant losses to businesses
Differentiated vehicle import tariff	Success	Strong public support; easier implementation
Ban on driving older vehicles in Dhaka (2010)	Repeated failure	Policy do not work when many polluters are financially affected
Ban two stroke three wheelers (2002)	Success	Extensive public support
Promotion of CNG vehicles (2002)	Success	Extensive public support, good pricing policy, good incentive to private sector
Ban on use of wood in brick kilns	Success – qualified	High-S coal is generally cheaper than wood currently
Colored kerosene	Failure	Price is an important issue
Ban on import of high Sulfur coal	Failure	Policy do not work when many polluters are financially affected
Improved Cooking Stove (ICS) Programs	Success at Pilot Scale	There is lack of awareness regarding IAP.

Air Quality Scenario in Bangladesh

Air Quality Monitoring in CAMS

- Two Continuous Air Monitoring Stations (CAMS) in Dhaka –
  - (a) Shangshad Bhaban CAMS: since April 2002
  - (b) BARC CAMS; since June 2008
- Chittagong CAMS: since January 2008
- Rajshahi CAMS: since April 2008

- Khulna CAMS: since January 2010
- Satkhira CAMS (Trans-boundary)

Limitations

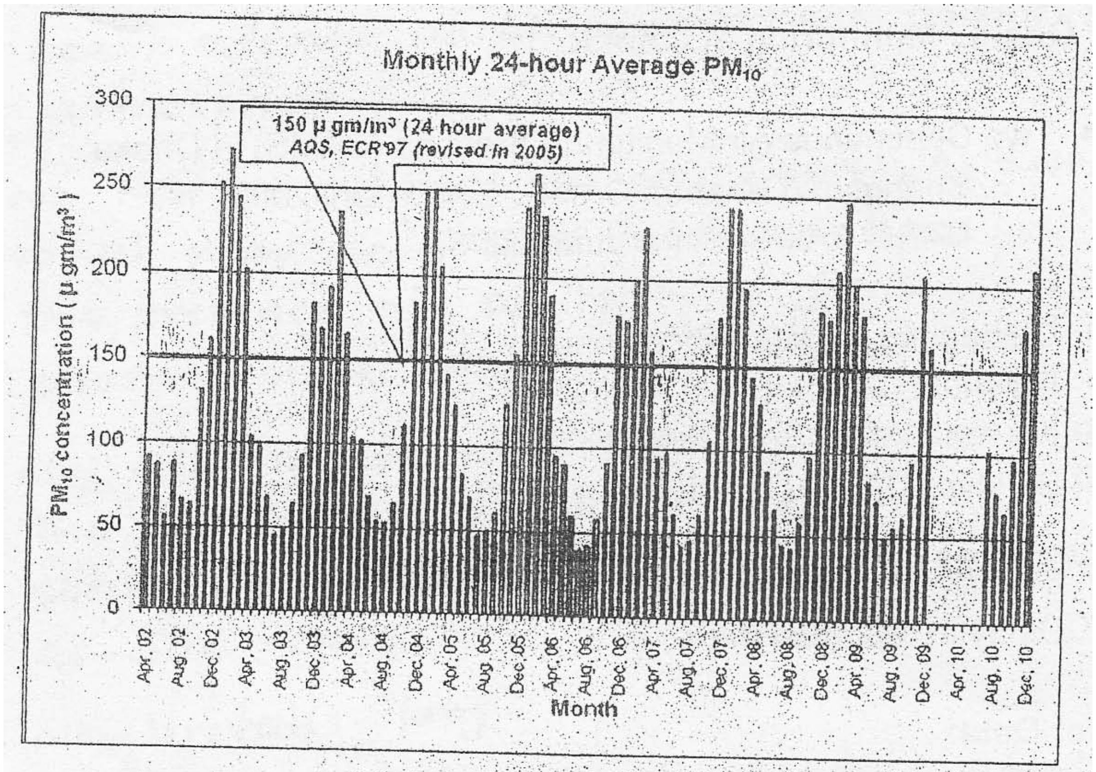
- Significant data gaps due to equipment malfunction
- Delay in reporting data

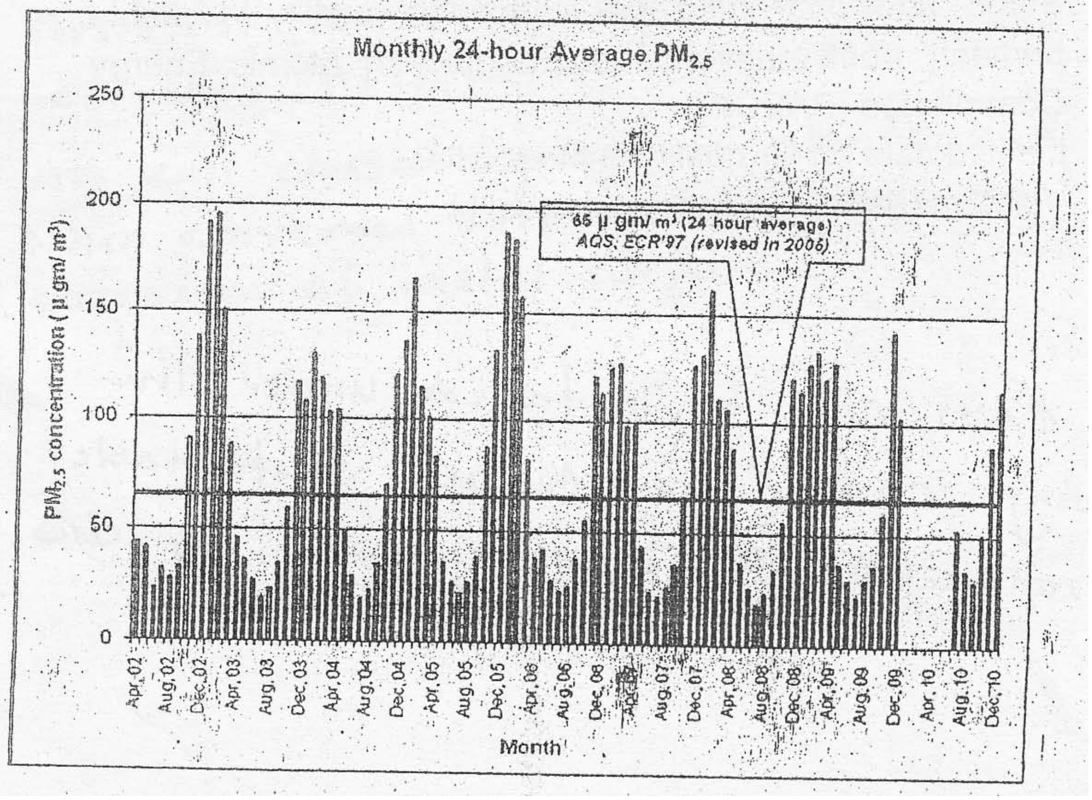
Other Data

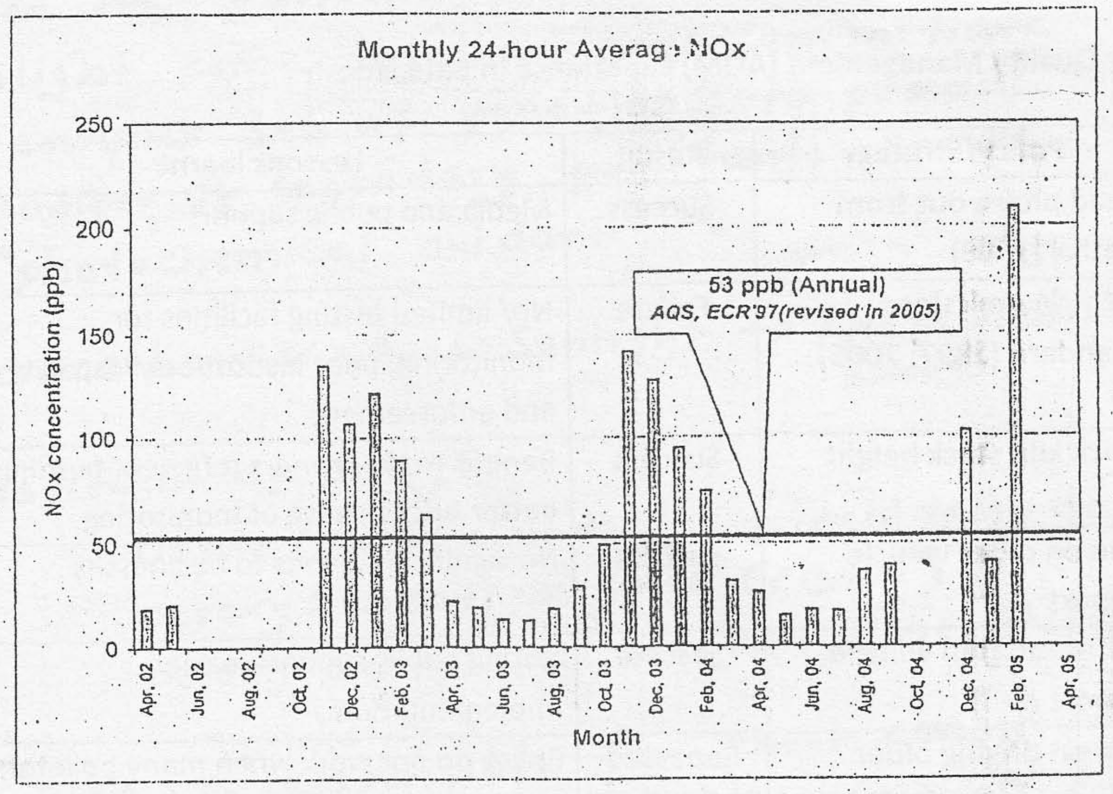
- Some additional data on Dhaka air quality available primarily from monitoring of Bangladesh Atomic Energy Commission (BAEC)
- Limited data on air quality in other cities
- Very limited data on indoor air quality

More CAMS will be installed under the ongoing CASE (Clean Air and Sustainable Environment) Project being implemented by GoB.

Dhaka Air Quality (Shangshad Bhaban CAMS)

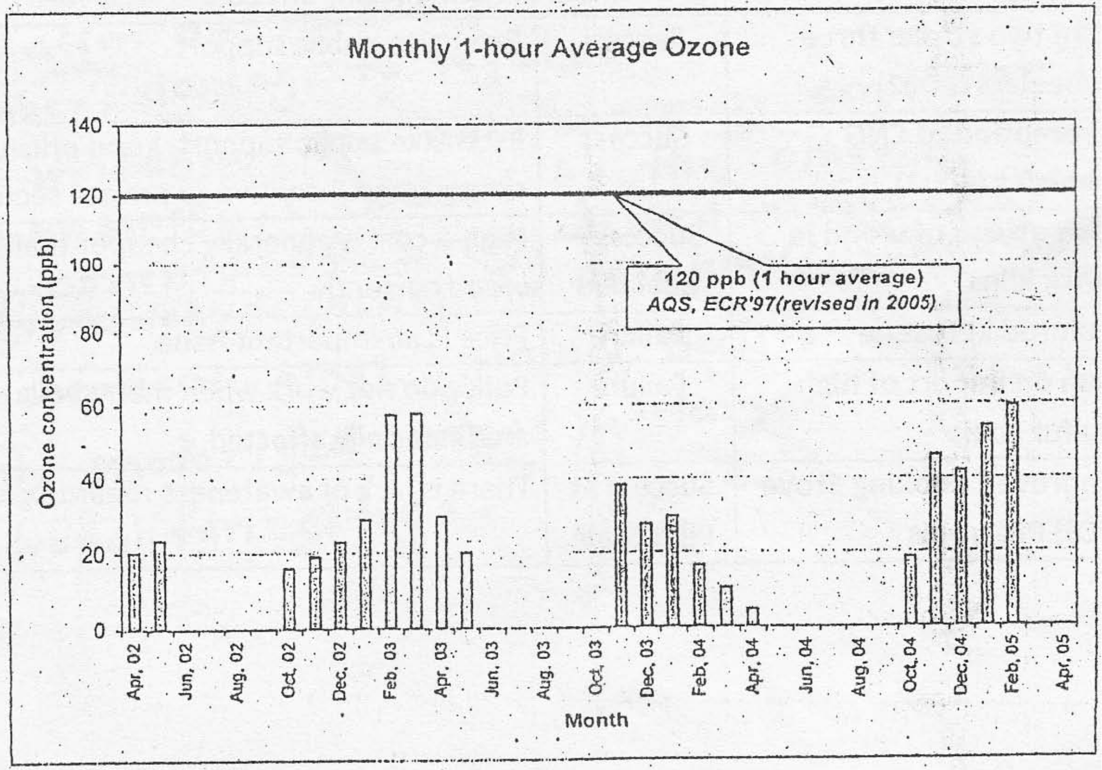






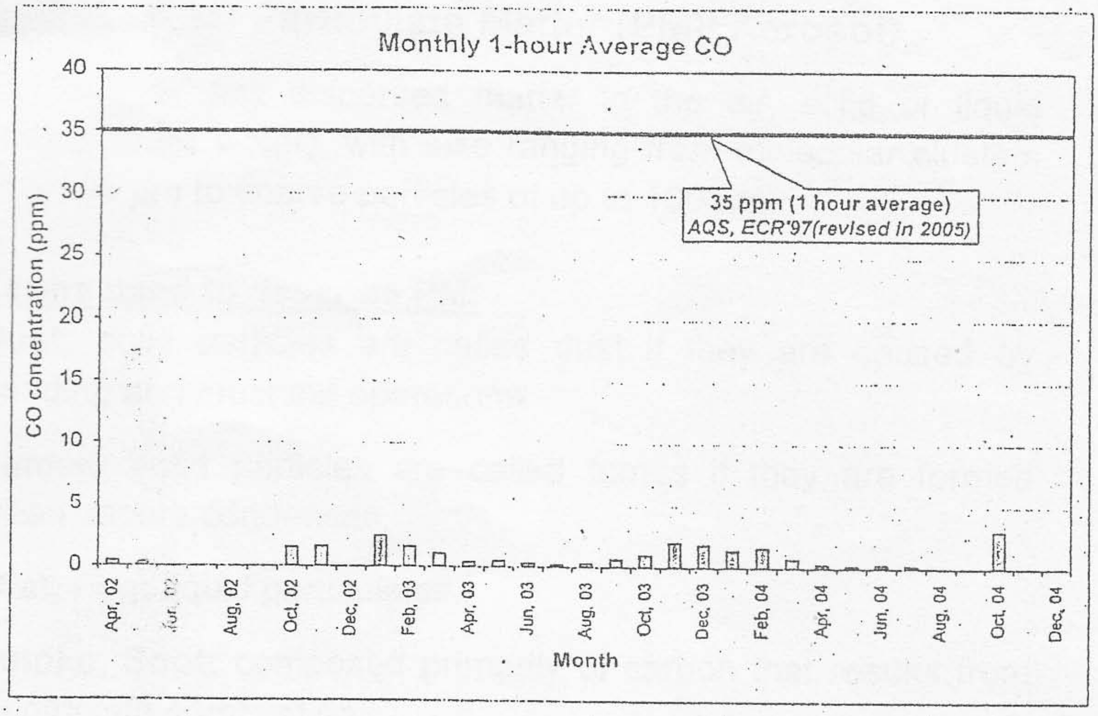
Monthly 24-hour Average NOx

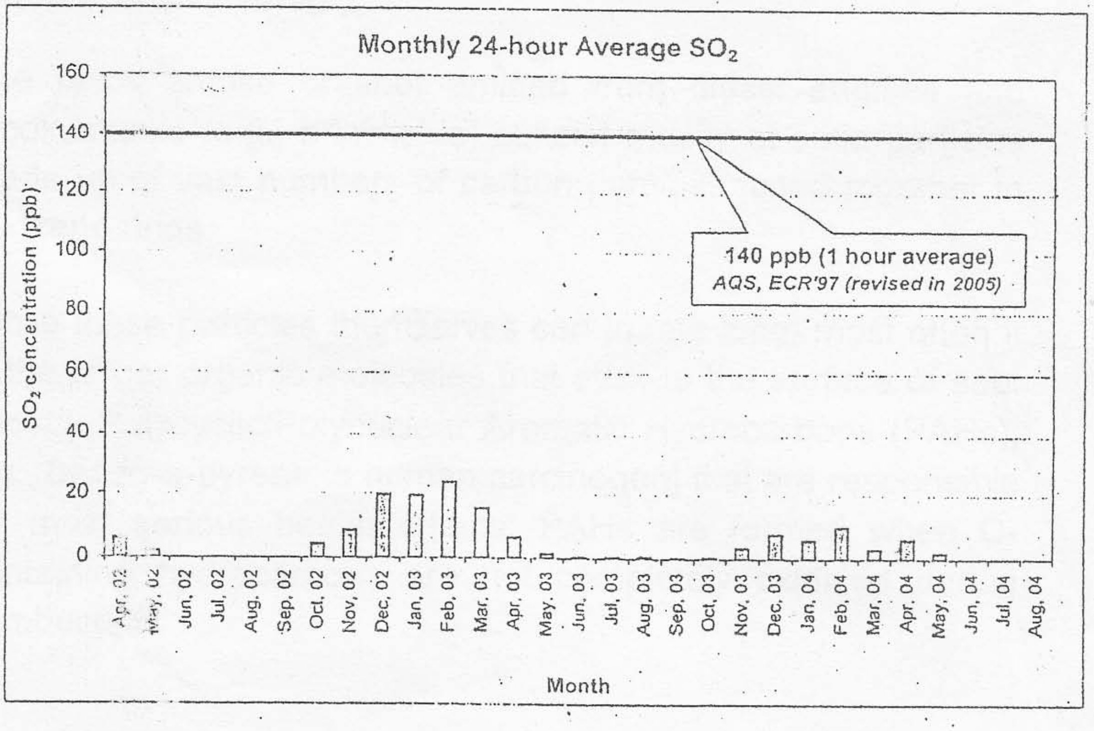
53 ppb (Annual)
AQS, ECR'97(revised in 2005)



Monthly 1-hour Average Ozone

120 ppb (1 hour average)
AQS, ECR'97(revised in 2005)


Monthly 1-hour Average CO
CO concentration (ppm)
40
35
30
25
20
15
10
5
0
35 ppm (1 hour average)
AQS, ECR'97(revised in 2005)
Apr, 02
Jun, 02
Aug, 02
Oct, 02
Dec, 02
Feb, 03
Apr, 03
Jun, 03
Aug, 03
Oct, 03
Dec, 03
Feb, 04
Apr, 04
Jun, 04
Aug, 04
Oct, 04
Dec, 04
Month


Monthly 24-hour Average SO_2
SO_2 concentration (ppb)
160
140
120
100
80
60
40
20
0
140 ppb (1 hour average)
AQS, ECR'97 (revised in 2005)
Apr, 02
May, 02
Jun, 02
Jul, 02
Aug, 02
Sep, 02
Oct, 02
Nov, 02
Dec, 02
Jan, 03
Feb, 03
Mar, 03
Apr, 03
May, 03
Jun, 03
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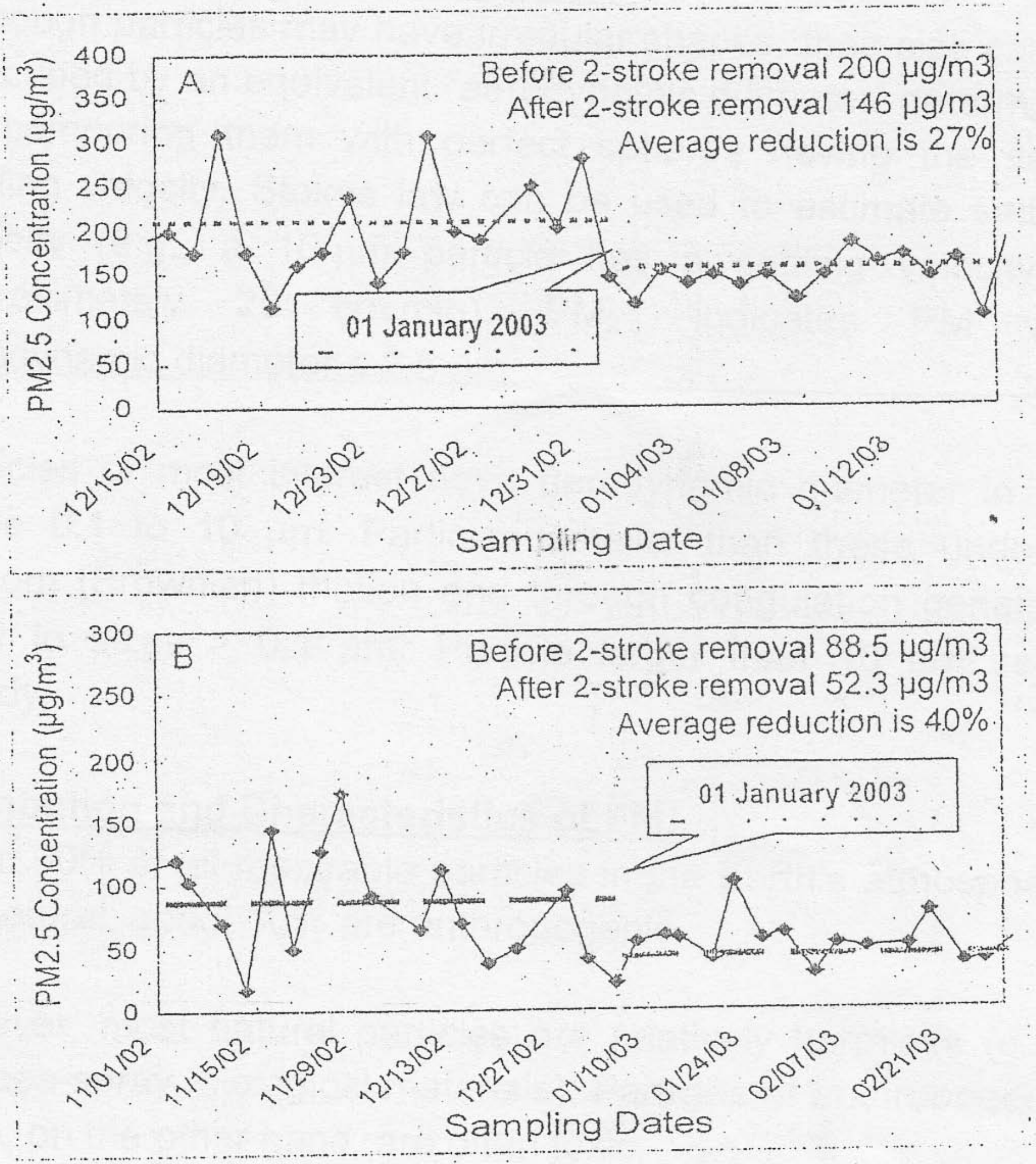
Nov, 03
Dec, 03
Jan, 04
Feb, 04
Mar, 04
Apr, 04
May, 04
Jun, 04
Jul, 04
Aug, 04
Month



Effect of banning two-stroke baby taxi on air quality of Dhaka city
(A: Data from CAMS, DoE; B: Data from Farmgate, BAEC)