

CE666A

Air Pollution and Its Control

References:

1. Noel DE Nevers (2000). Air Pollution Control Engineering. McGraw Hill International, New Delhi
2. J. H. Seinfeld and S.N. Pandis (1998). Atmospheric Chemistry and Physics. Wiley Inter Science, John Wiley and Sons, New York
3. Wayne T. Davis (2000) Air Pollution Engineering Manual, Air & Waste Management Association



Technology

Mining Engg.

- Extraction
- Concentration
- Product

Chemical Engg

- Chemicals
- Petroleum
- Pesticides

Automobile Engg

- Transportation
- Machinery
- Combustion

Electrical Engg

- Power Generation

Civil Engg

- Construction
- Waterways
- Road,Railways

Environmental Engineering Science

Origin of the atmosphere

- The original atmosphere
 - Probably made up of **hydrogen and helium**.
 - These are fairly common in the universe.
- Original atmosphere stripped away by the solar wind
 - H and He are very light
 - Hydrogen and helium have the smallest atoms by mass.
 - The early earth was not protected by a magnetic field.
 - Thus the current atmosphere is secondary

The secondary atmosphere

- Formed from degassing of volcanoes
- Gasses emitted probably similar to the gasses emitted by volcanoes today.
 - H₂O (water), 50-60%
 - CO₂ (carbon dioxide), 24%
 - SO₂ (sulfur dioxide), 13%
 - CO (carbon monoxide),
 - S₂ (sulfur),
 - Cl₂ (chlorine),
 - N₂ (nitrogen),
 - H₂ (hydrogen),
 - NH₃ (ammonia) and
 - CH₄ (methane)

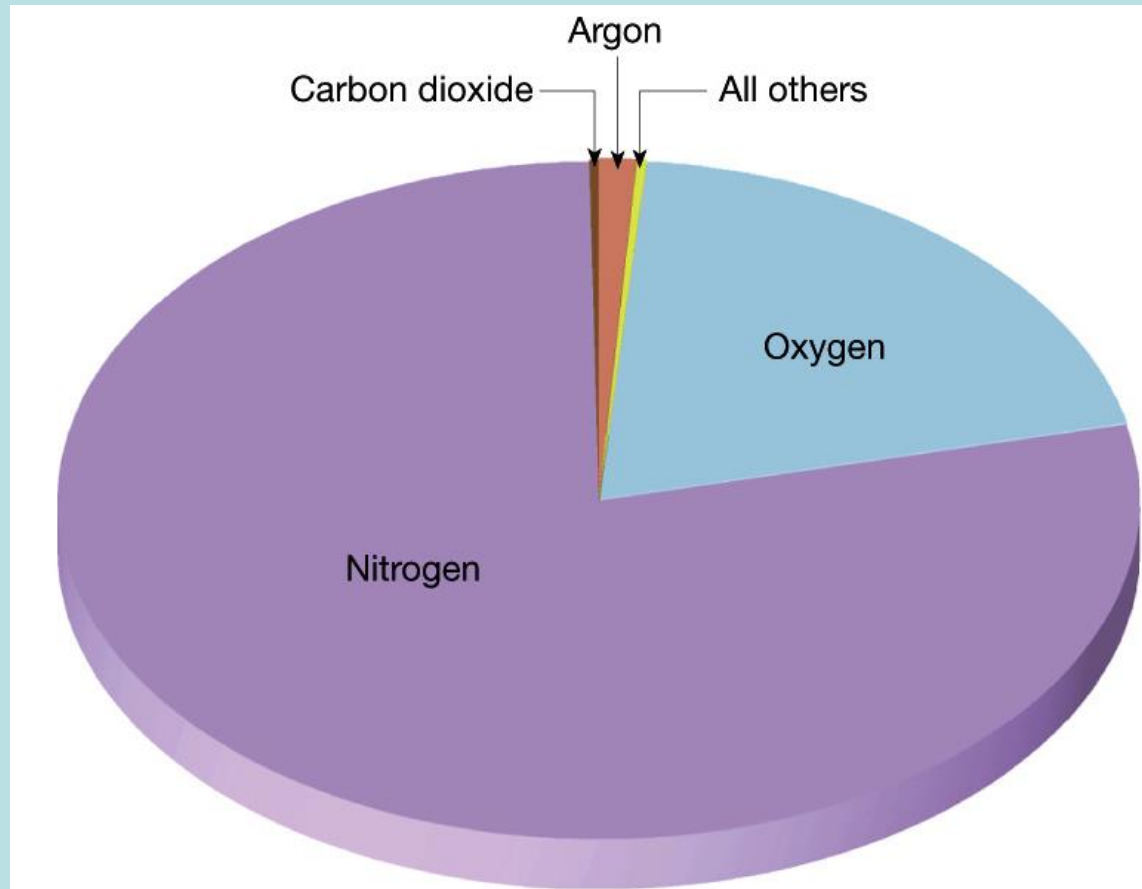


Modern atmosphere

Nitrogen (N_2)-
78%,

Oxygen (O_2)-
21%,

Carbon Dioxide (CO_2)
0.03 %,



Where did all the
oxygen come from?

Volcanic outgassing	Modern Atmosphere
H ₂ O – 50-60%	N ₂ – 78%
CO ₂ – 24%	O ₂ – 21%
SO ₂ – 13%	CO ₂ – 0.03%

1. Where did all the O₂ come from?
2. Where did all the CO₂ go?

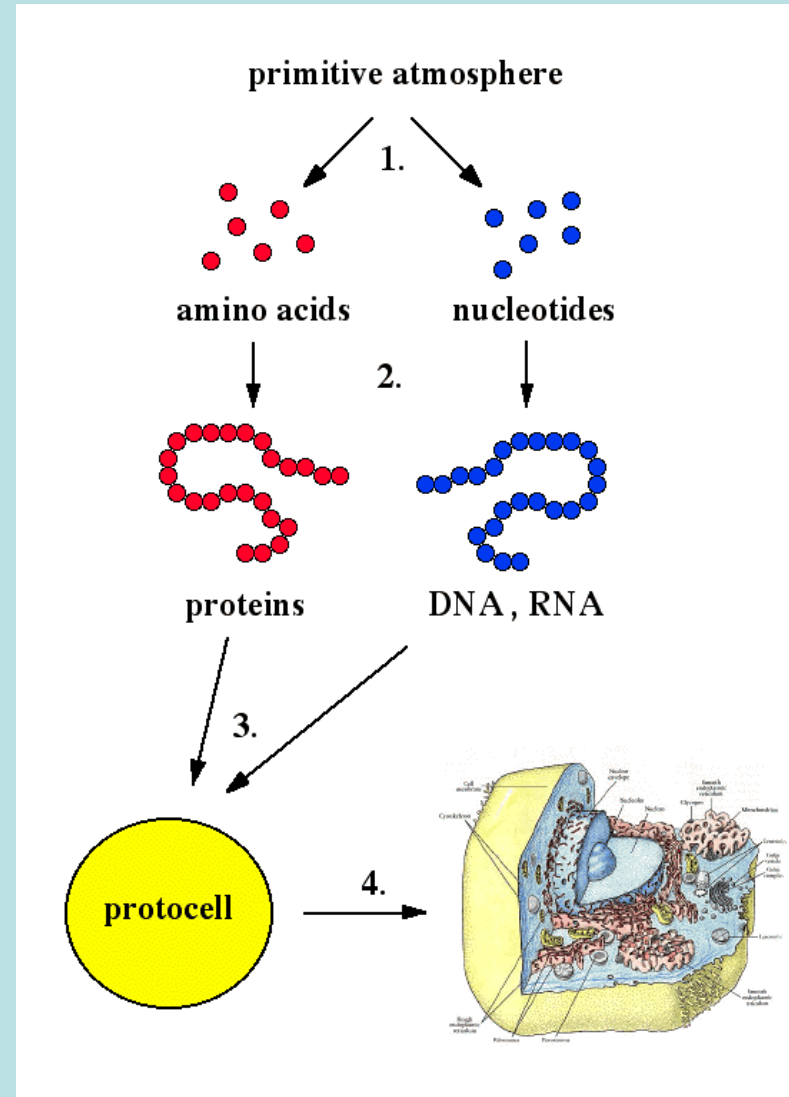
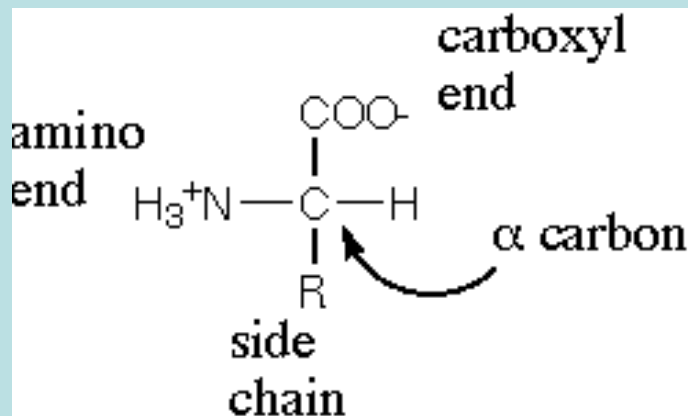
Formation of the oceans

- The earth is cool enough that H_2O condenses to form the oceans.
 - Estimates of the amount of H_2O outgassed is not enough to fill the oceans
 - It seems likely that a large volume of water was added by the impact of icy meteors on the atmosphere.
- CO_2 dissolves into the oceans.

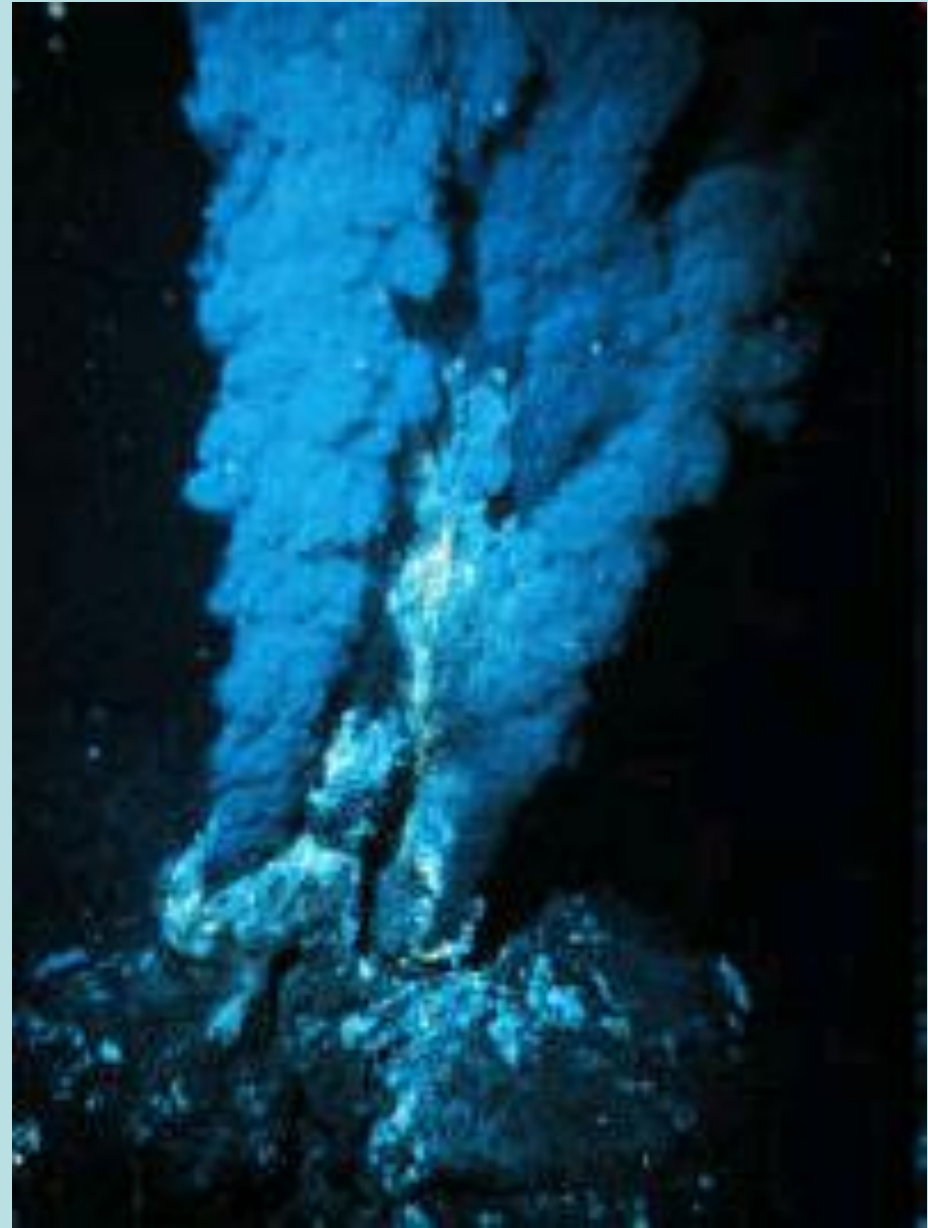


In the oceans life evolves

- Ingredients necessary for life
 - NH_3 – ammonia
 - CH_4 – Methane
 - H_2O – Water
- These can produce **amino acids**, the building blocks of life
- Nucleotides – consists nucleobase, 5-carbon sugar and phosphate



- Life may have originated
 - under the primitive atmosphere
 - or at hydrothermal vents deep in the oceans
 - or deep in the earth's crust



Life changes the atmosphere

- With the evolution of life the first cellular organisms (cyanobacteria) began to use the gasses in the early atmosphere (NH_3 – ammonia, CH_4 – methane, H_2O – water) for energy.

Photosynthetic organisms evolve.

These organisms use CO_2 and produce oxygen (O_2) as a waste product.



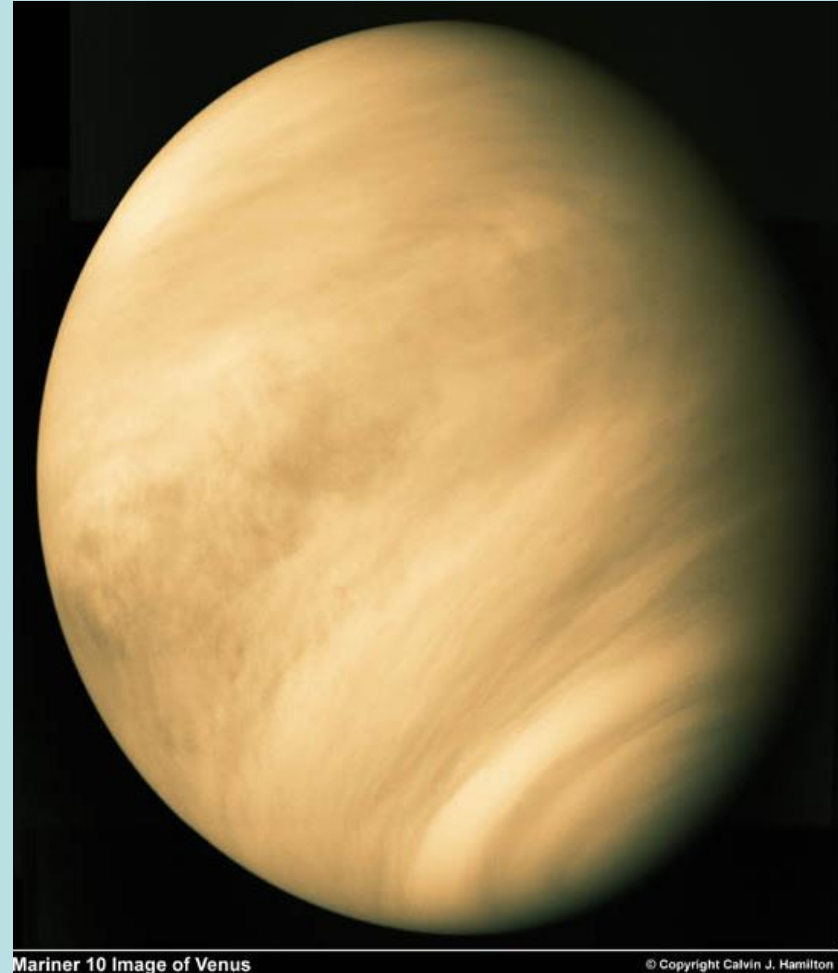
- Where did the O_2 come from?
 - Produced by photosynthetic life.
- Where did the CO_2 go?
 - Dissolves in water in the oceans
 - Used by life by photosynthesis and buried when plants and micro-organisms die.
 - The source of coal and oil

Early history of life and the atmosphere

- The Earth is about 4.5 billion years old.
- Life first appeared in the oceans at least 3.5 billion years ago.
- 0.9 billion years ago there is enough oxygen in the atmosphere to produce the ozone layer and life can finally move onto land.
 - The ozone layer protects the earth from harmful ultra violet radiation from the sun.

The other planets

- Venus
 - Closer to the sun
 - Very hot at the surface so water vapor in the atmosphere does not condense.
 - Runaway greenhouse effect (482°C, 900°F).
 - No oceans or rainfall so CO₂ does not dissolve.
 - Has a very dense atmosphere.

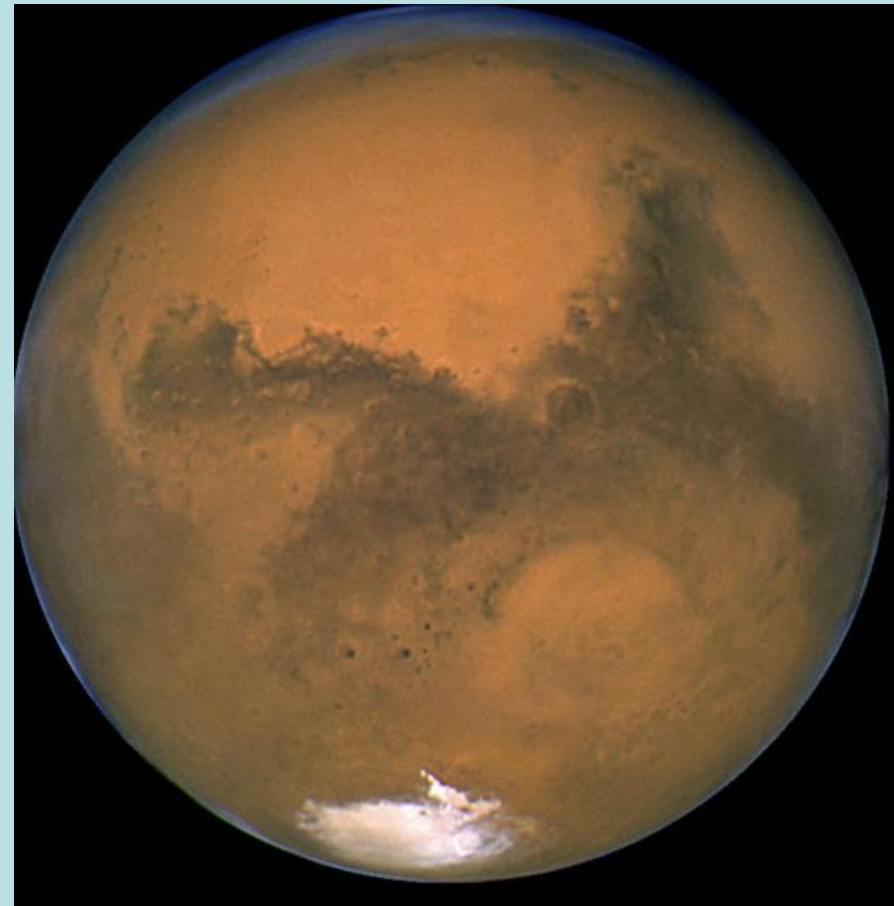


Mariner 10 Image of Venus

© Copyright Calvin J. Hamilton

The other planets

- Mars
 - Further from the sun
 - Smaller than Earth
 - So small that most of the atmosphere escaped into space.
 - No oceans or rainfall so CO₂ stays in atmosphere.
 - 98% of atmosphere is CO₂.



- Jupiter
 - Huge (318x earth's mass)
 - Kept all its original atmosphere
 - 80% Hydrogen
 - 20% Helium



Summary

1 st atmosphere	H and He from solar nebula	Lost to solar wind
2 nd atmosphere	H ₂ O, CO ₂ and SO ₂ from volcanic degassing	Transformed by photosynthesis
Current atmosphere	N ₂ , O ₂ , from photosynthesis and constant N ₂ production	

Thickness of the atmosphere

- Relative to size of the earth, the atmosphere is extremely thin
- 90% of mass below 16 km
- Given that the earth's diameter is 12,756 km, the atmosphere is about the thickness of the skin on an apple

Vertical structure of the atmosphere

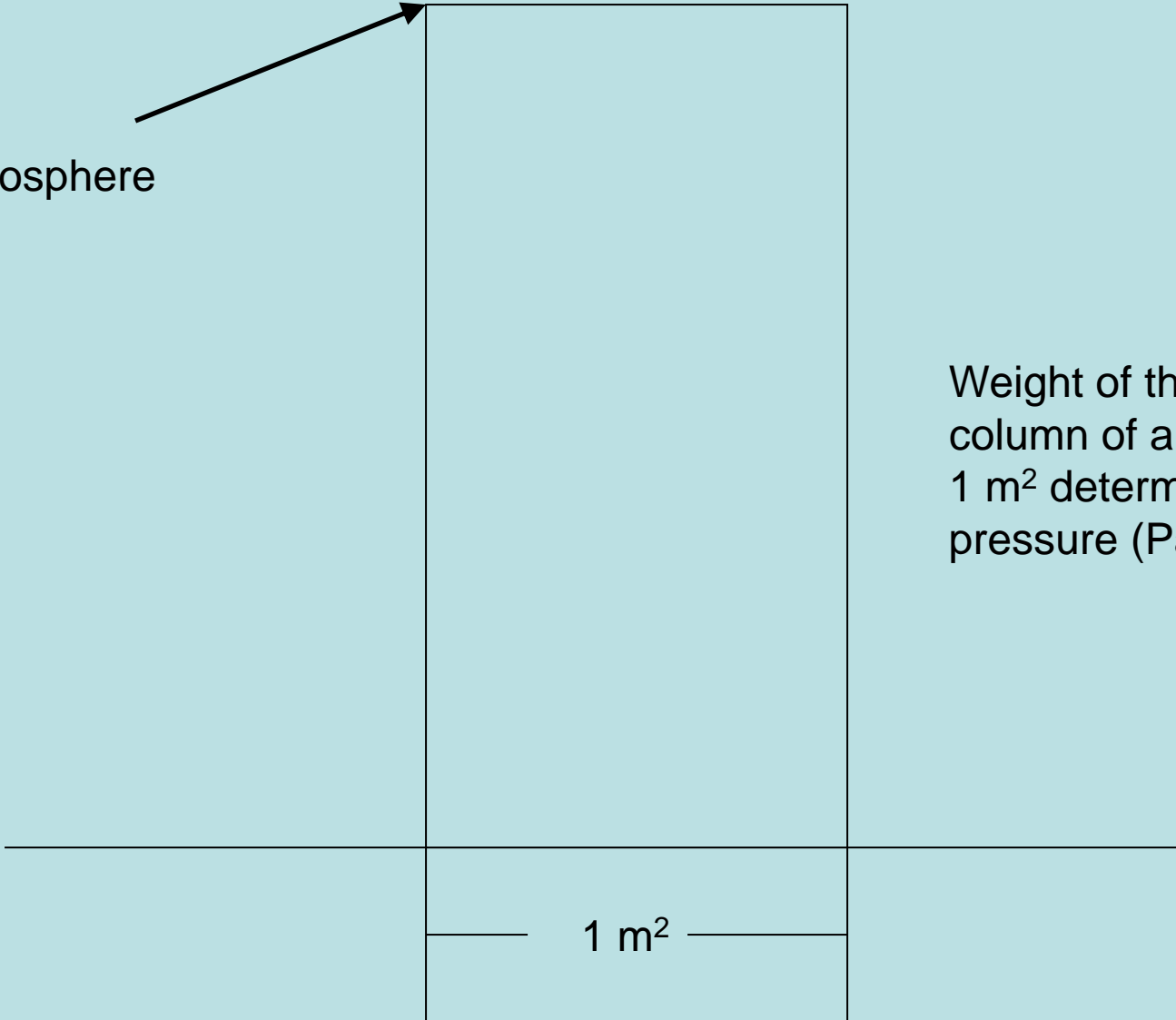
- Gravity holds the atmosphere to the earth
- Consequently, the pressure for any area can be defined by the weight (force) of a vertical column of air over the area

Top of
the atmosphere



Weight of the entire
column of air over the
 1 m^2 determines the
pressure (Pa)

1 m^2



Pressure decrease: I

- PART I

$$P = \rho gh$$

P = pressure (Pa = N m⁻² = kg m⁻¹ s⁻²)

ρ = density (kg m⁻³)

g = gravitational acceleration (9.81 m s⁻²)

h = height of air column (m)

Pressure decrease: II

- PART II
- Expressed in a differential form:
- $dP = - \rho g dz$ (negative indicates decrease with height) This is the hydrostatic law
- Or, change in pressure is equal to density times acceleration times change in height
- A parcel of air is balanced by the upward and downward forces acting upon it

Pressure decrease: III

- The ideal gas law
- $P = \rho RT$
- R is the gas constant. For air R is $287.07 \text{ J kg}^{-1} \text{ K}^{-1}$
- T is temperature in Kelvin
- Rearrange to $\rho = P/RT$ and substitute into the hydrostatic law to obtain:

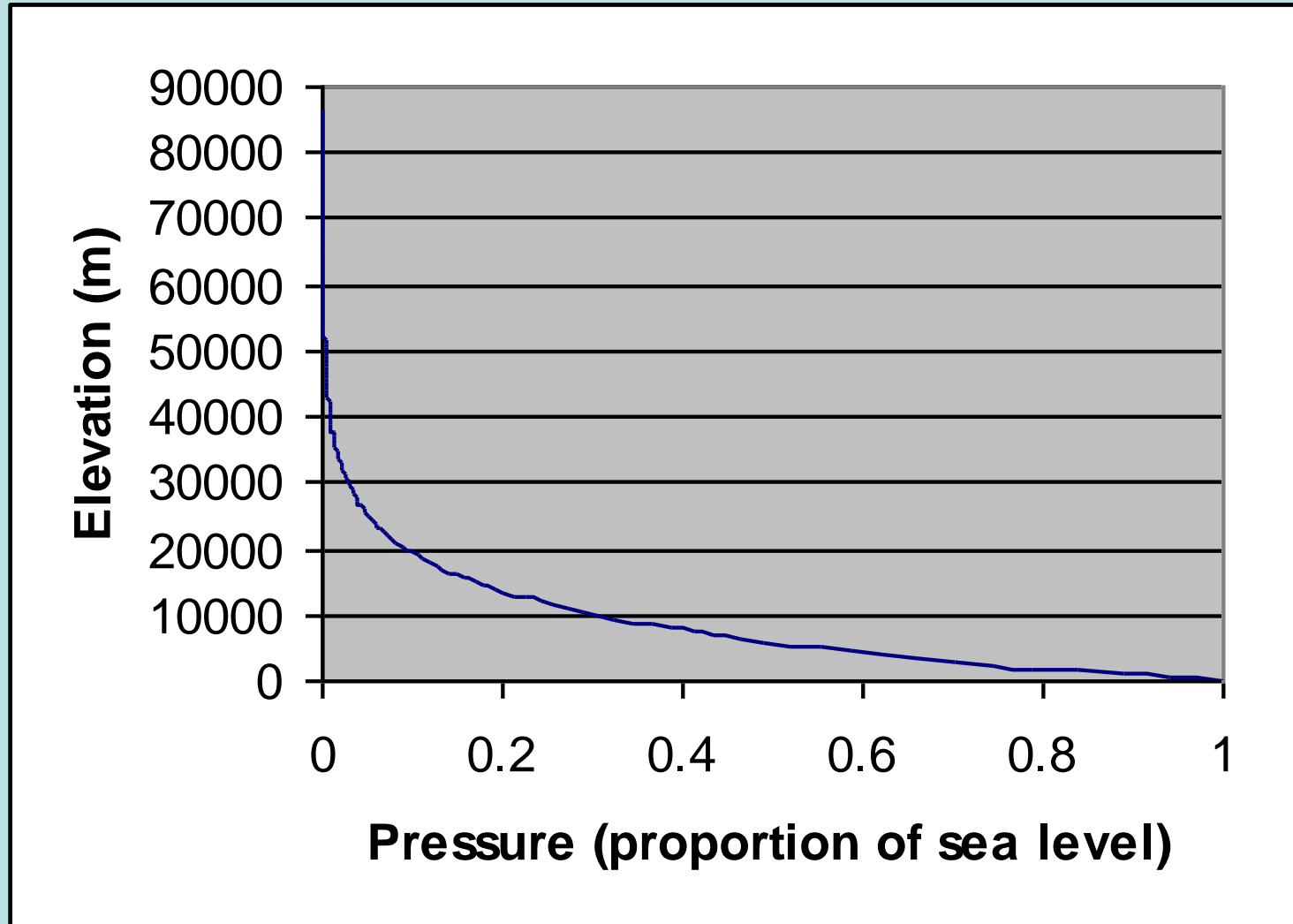
$$\frac{dP}{P} = -\frac{g}{RT} dz$$

Pressure decrease: IV

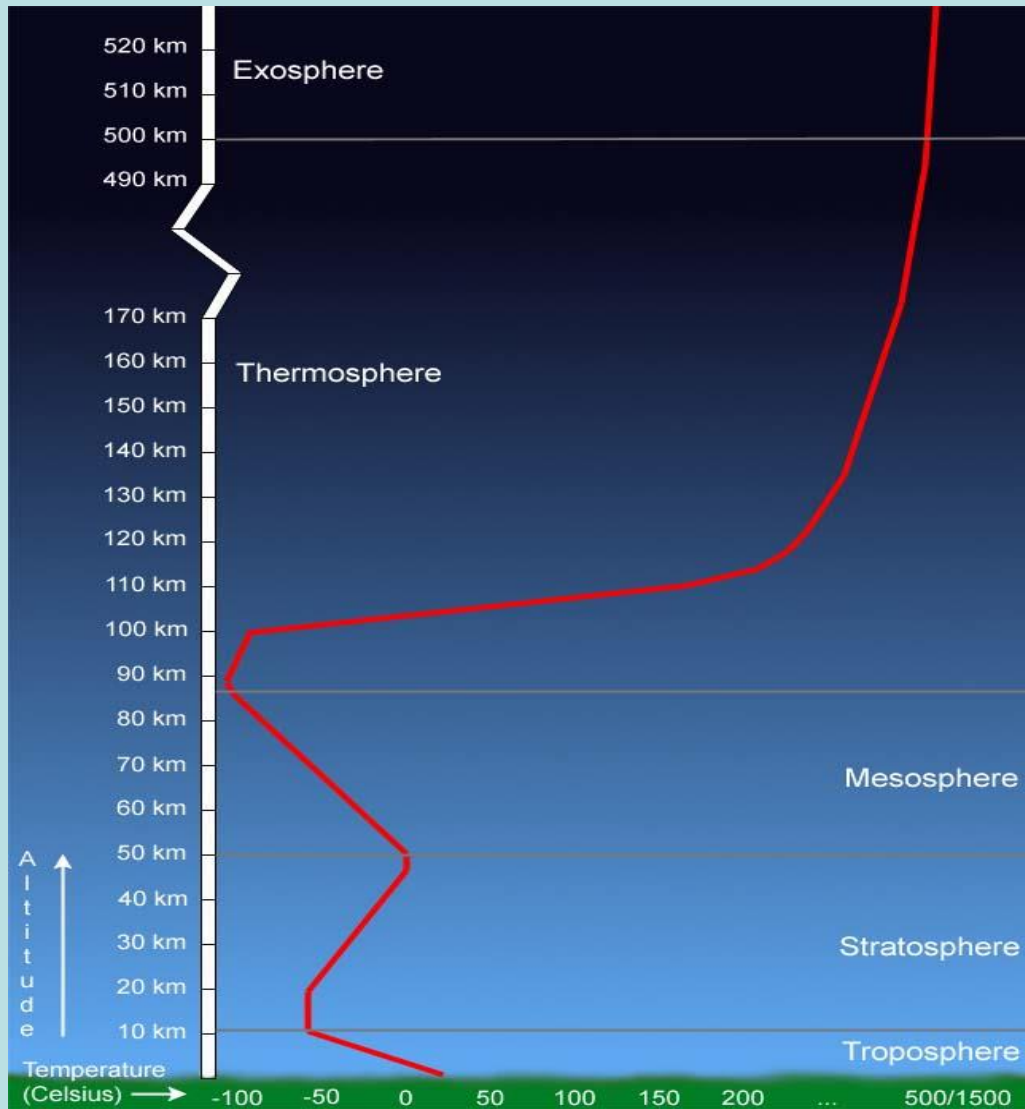
- Integration of the previous equation gives:

$$\frac{P_2}{P_1} = e^{-\frac{g}{RT}(z_2 - z_1)}$$

Vertical atmospheric structure: Pressure



Vertical atmospheric structure: Temperature



Reasons for vertical temperature profile

- Troposphere: temperature declines due to decreases in pressure causing decreases in the average kinetic energy
- Conceptually the molecules of air are moving around more slowly, causing temperature to decline
- This can be predicted mathematically

Temperature profiles

- Increasing temperature in the stratosphere
 - Caused by ozone absorption of UV radiation
- Decreasing temperature in the mesosphere
 - Caused by decreasing ozone
- In the thermosphere
 - Warming caused by absorption of UV radiation by O_2
 - since the air is so thin within the thermosphere, such temperature values are not comparable to those of the troposphere or stratosphere. Although the measured temperature is very hot, the thermosphere would actually feel very cold to us because the total energy of only a few air molecules residing there would not be enough to transfer any appreciable heat to our skin

Refresh:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$PV = nRT$$

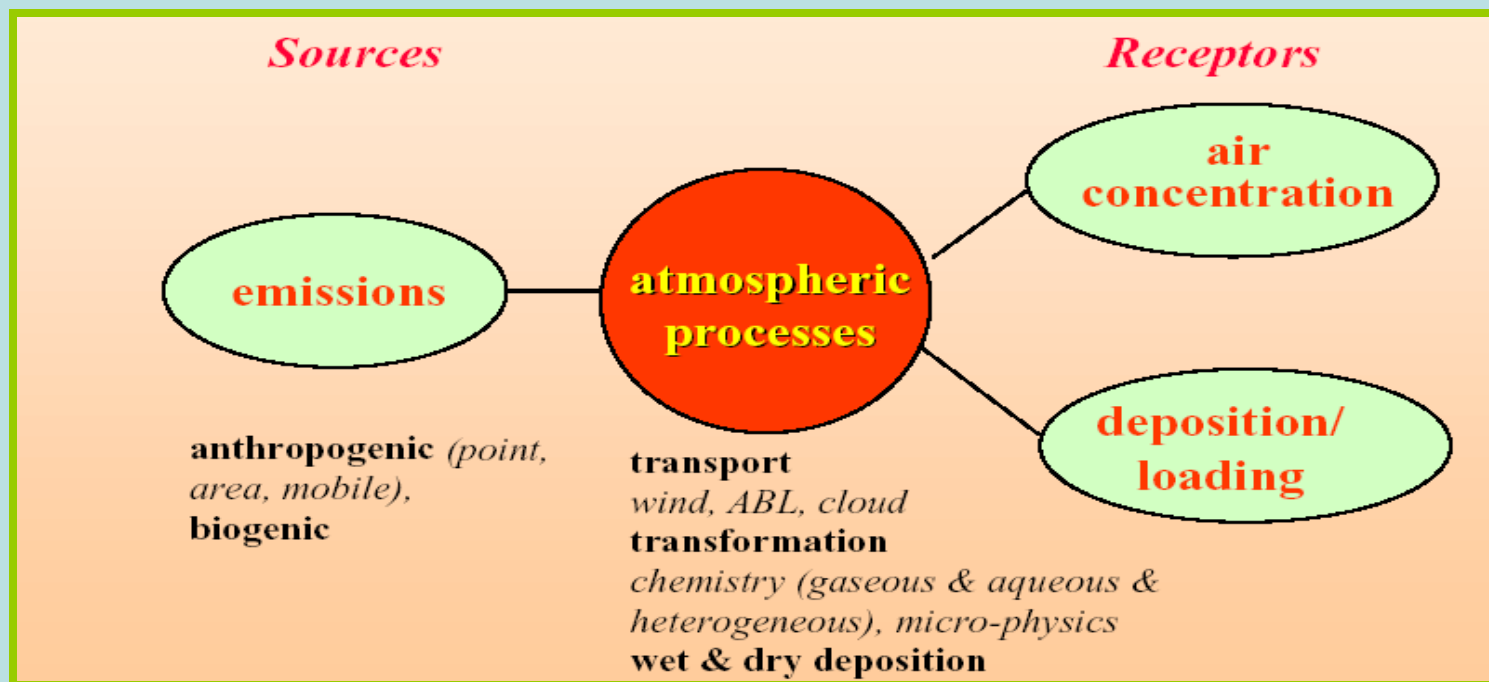
Troposphere and Stratosphere

- 0 to 15 km altitude
 - The lowest region of the atmosphere, where life & weather exist.
 - Temperature decreases with altitude.
 - Long-wave radiation emitted from Earth is absorbed by the atmosphere, the atmosphere becomes less dense with increasing altitude, less air to absorb
 - Top of the troposphere is known as the tropopause
-
- 15 to 50 km altitude
 - Temperature increases with altitude.
 - Heating occurs because ozone (O₃) absorbs ultraviolet radiation from the Sun.
 - Top of the stratosphere is known as the stratopause

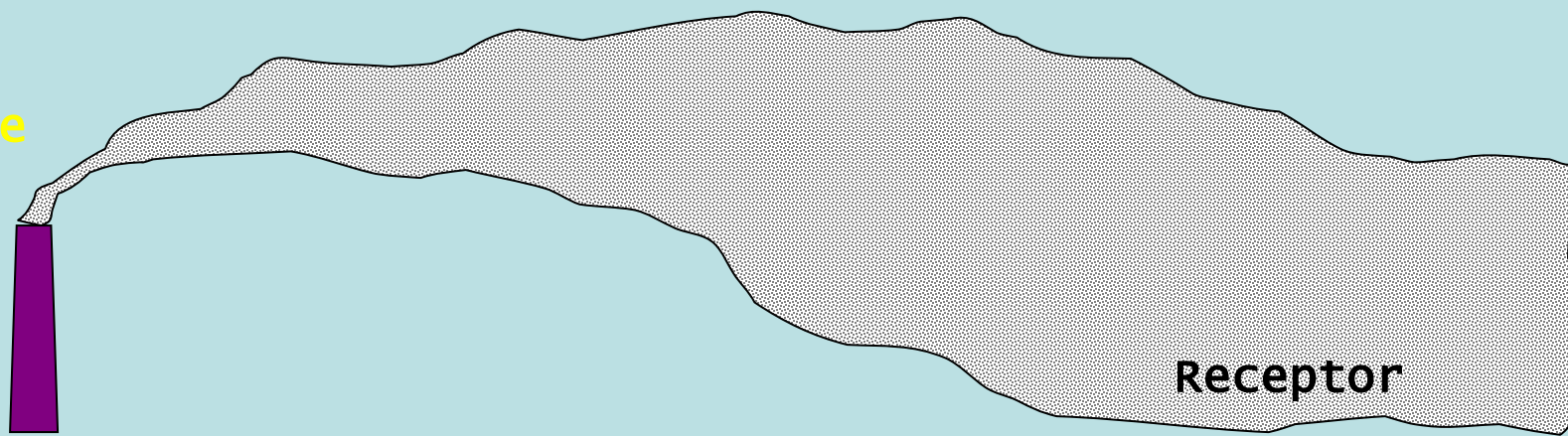
Mesosphere and Thermosphere

- 50 to 90 km altitude
 - Temperature decreases with altitude
 - The lowest temperatures in the entire atmosphere are found at the mesopause during summer at high latitudes, 130 K (-226°F) can occur
 - Top of the mesosphere is known as the mesopause
-
- 90 to 500 km altitude
 - Temperature increases with altitude above 90 km, and is constant above 200 km.
 - This heating is due to absorption of solar radiation (wavelengths less than 0.2 microns) by molecular oxygen (O₂).
 - The highest temperatures in the atmosphere can be found in the thermosphere, 2000 K can occur

Atmosphere – Major Sink for Air Pollutants



Source



Air Pollution

*“ presence of any substances, solid, liquid or gas in atmosphere in **such a concentration** that may or may tend to be injurious to the humans, animals, plants, property or the atmosphere itself, is referred to as air pollution and the substance and the substance air as air pollutant”*

Key - words :

“such a concentration”

What is that Concentration ?



Philosophy of Air Pollution Control

Reduction of pollutant(s) emission to a point such that no noticeable adverse effects associated with pollutant(s) exist.

To determine extent of reduction –

Understand / Established Linkages between sources and receptors using meteorology; and

Understand / Establish safe air quality levels for receptors

Air Quality Standards ~ to protect receptors

Primary Health Standards

Secondary Standards for vegetation/crops

Sensitive area standards

Challenges of Managing Air Pollution System

- **Problem 3-Dimensional**
- **Transport Medium beyond Control/regulation**
- **Impacts – Instant and Chronic**
- **Receptors Remediation almost Impossible**
- **Solution cannot be delayed**

Types of Remediation

- (i) Medium Remediation**
- (ii) Source Remediation**
- (iii) Receptor Remediation**

Criteria Pollutants

PM, SO₂, NO_x, and CO

Non- criteria Pollutants

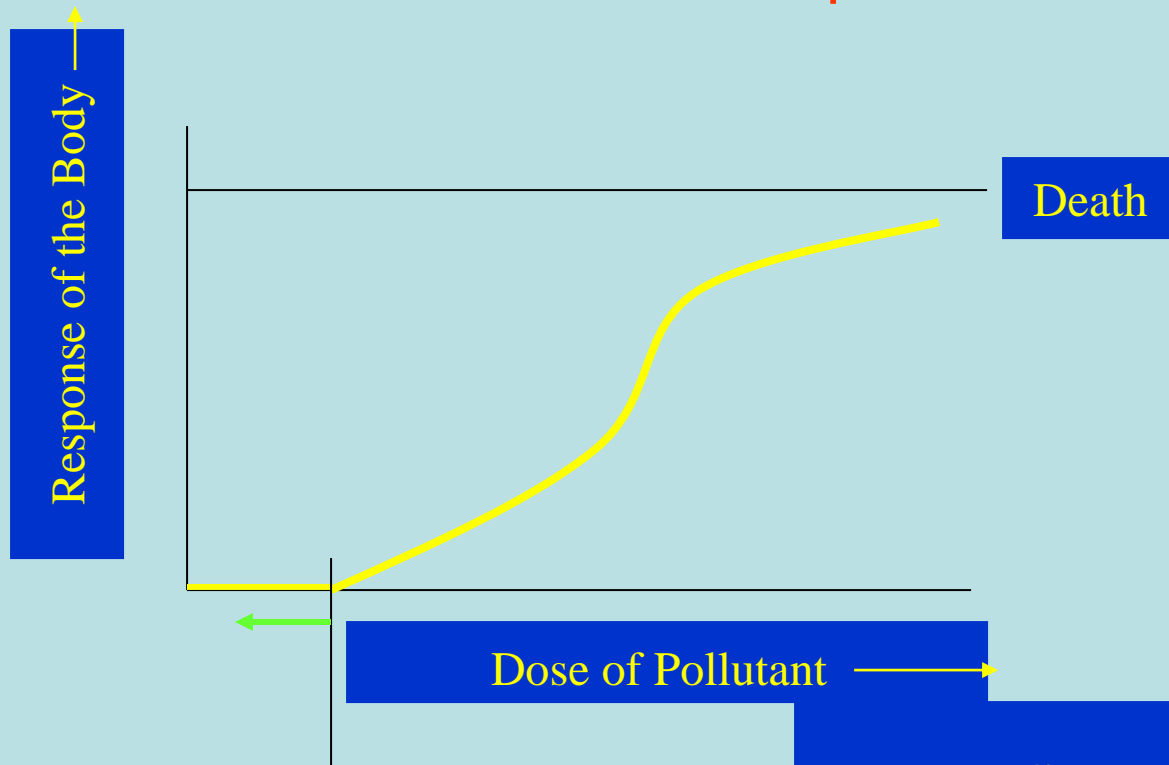
**Pb, Asbestos, Vinyl chloride, Mercury, Arsenic
TOC (Trace Organic Carbon) and others**

How much external addition ?

Develop the basis ~ Criteria

Dose-Response/Cause – Effect Knowledge (receptor specific)

Dose-Response Curve

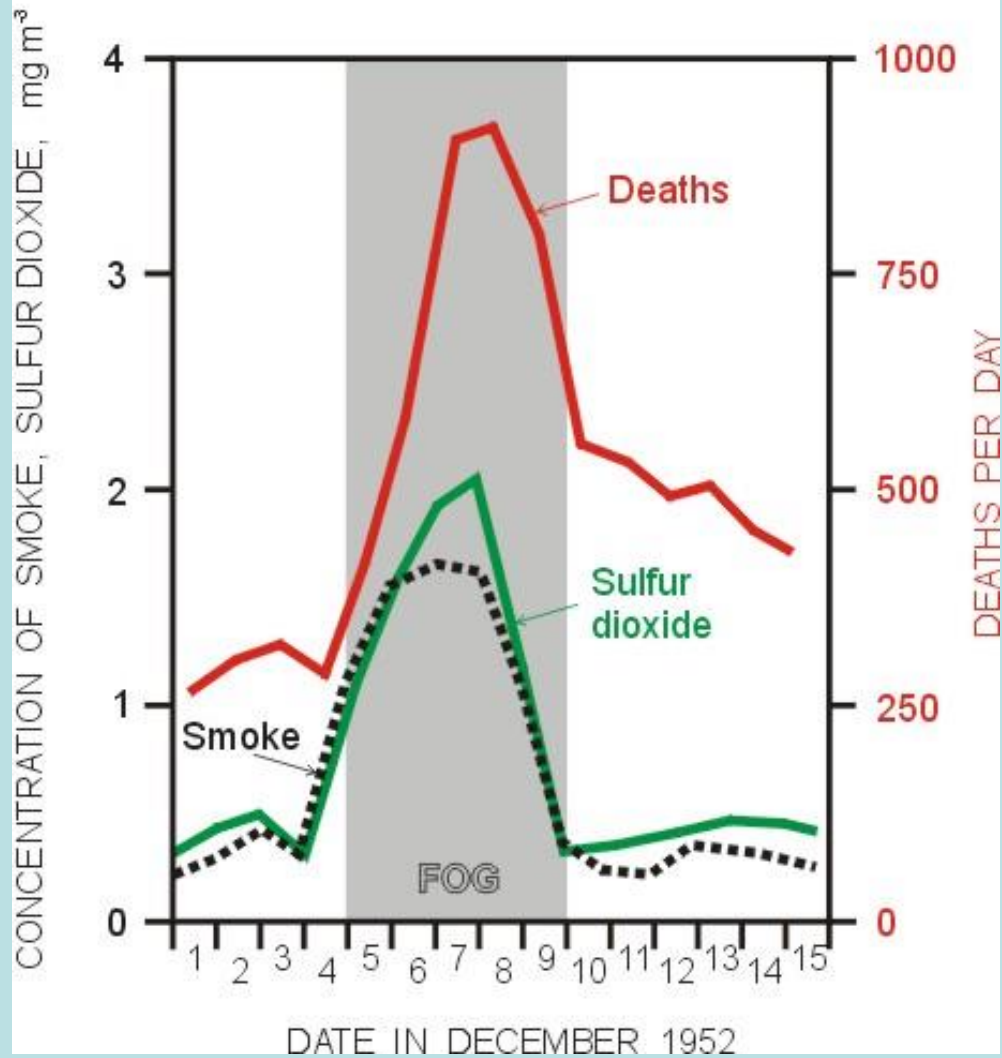


TLV_{8-h} (Threshold Limited Value)

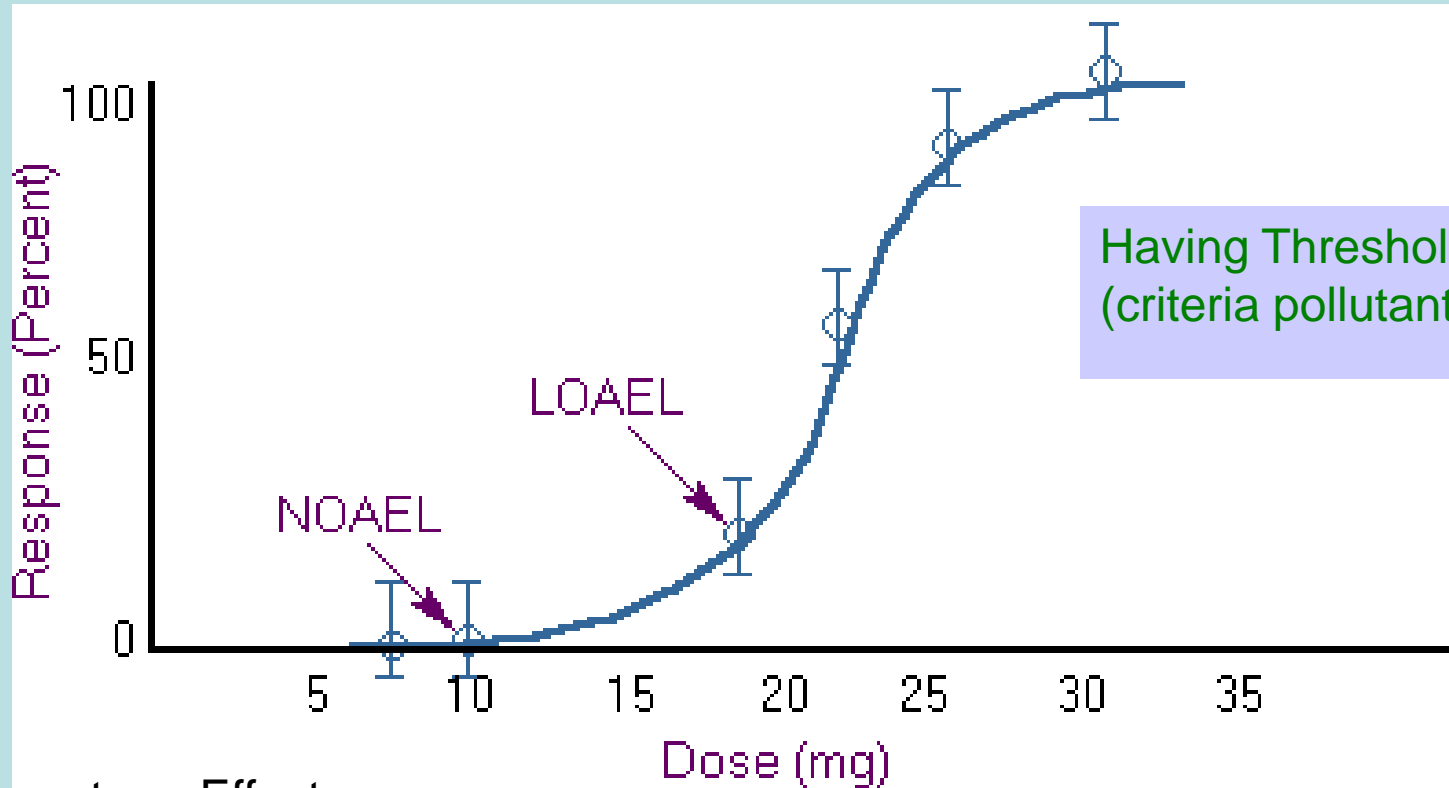
**TLV = Such a concentration ?
Permissible Concentration
= TLV / factor of safety (FS)
FS ~ 10 – 100**

**National Consensus, background levels, financial resources
Ambient Air Quality Standards, Goals, Guidelines**

THE LONDON SMOG



[BBC: London Smog 1952](#)



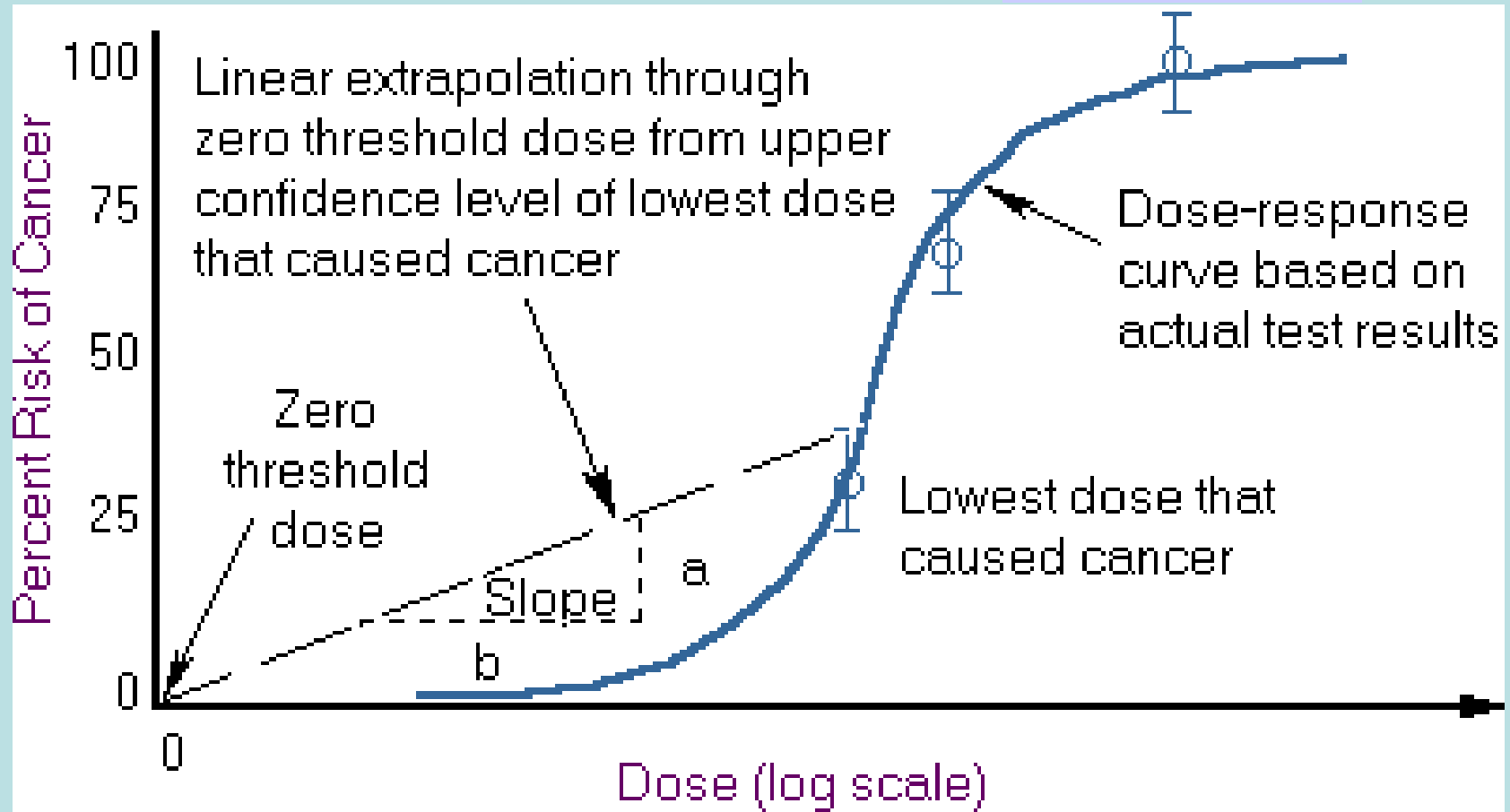
Long-term Effects

$$RfD = \frac{NOAEL}{\left(\prod_{i=1}^n UF_i \times MF \right)}$$

$$RfD = \frac{LOAEL}{\left(\prod_{i=1}^n UF_i \times MF \right)}$$

$$UF = 10H \times 10A \times 10S$$

No Threshold
(Carcinogens)



Slope factor, Cancer Potency factor or Unit Risk factor

Slope factor = $\text{risk}/(\text{mg}/\text{kg}\text{-day})$

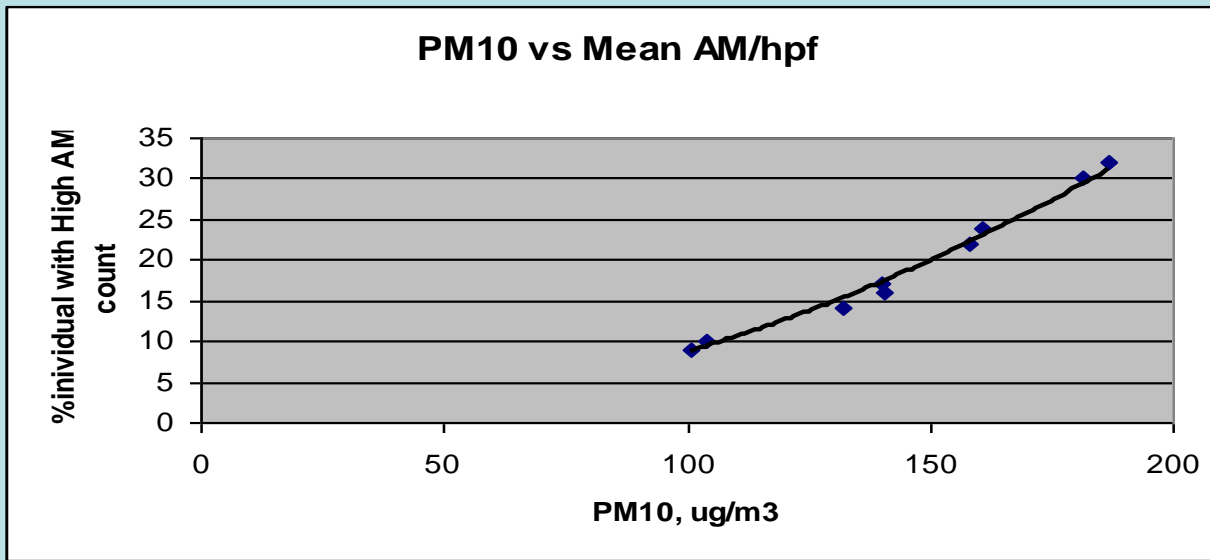
Unit Risk Factor = $\text{risk}/(\mu\text{g}/\text{m}^3)$

Example

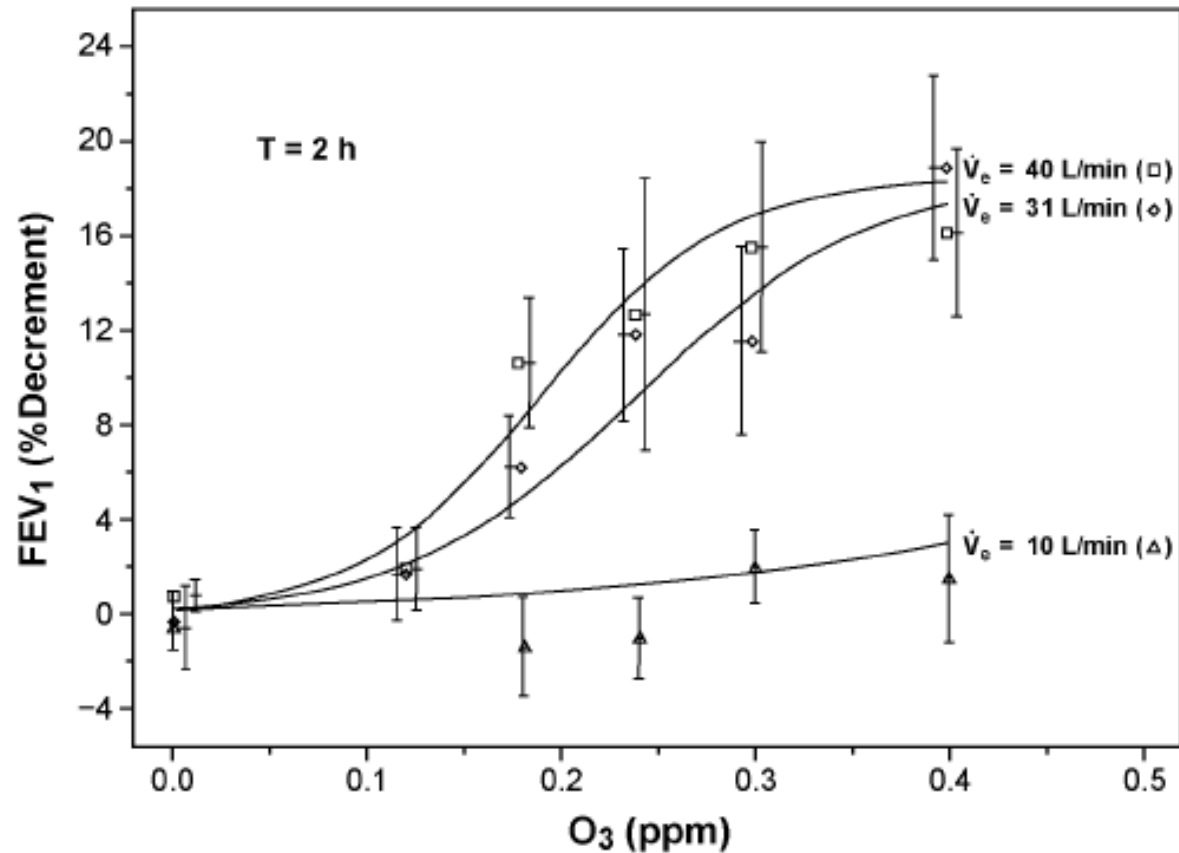
Acceptable Air Concentration = Target Risk / (Unit risk factor)

Target risk = 1×10^{-5} ; URF = $1 \times 10^{-3} (\mu\text{g}/\text{m}^3)^{-1}$

Concentration = $1 \times 10^{-5} / 1 \times 10^{-3} (\mu\text{g}/\text{m}^3)^{-1} = 0.01 \mu\text{g}/\text{m}^3$

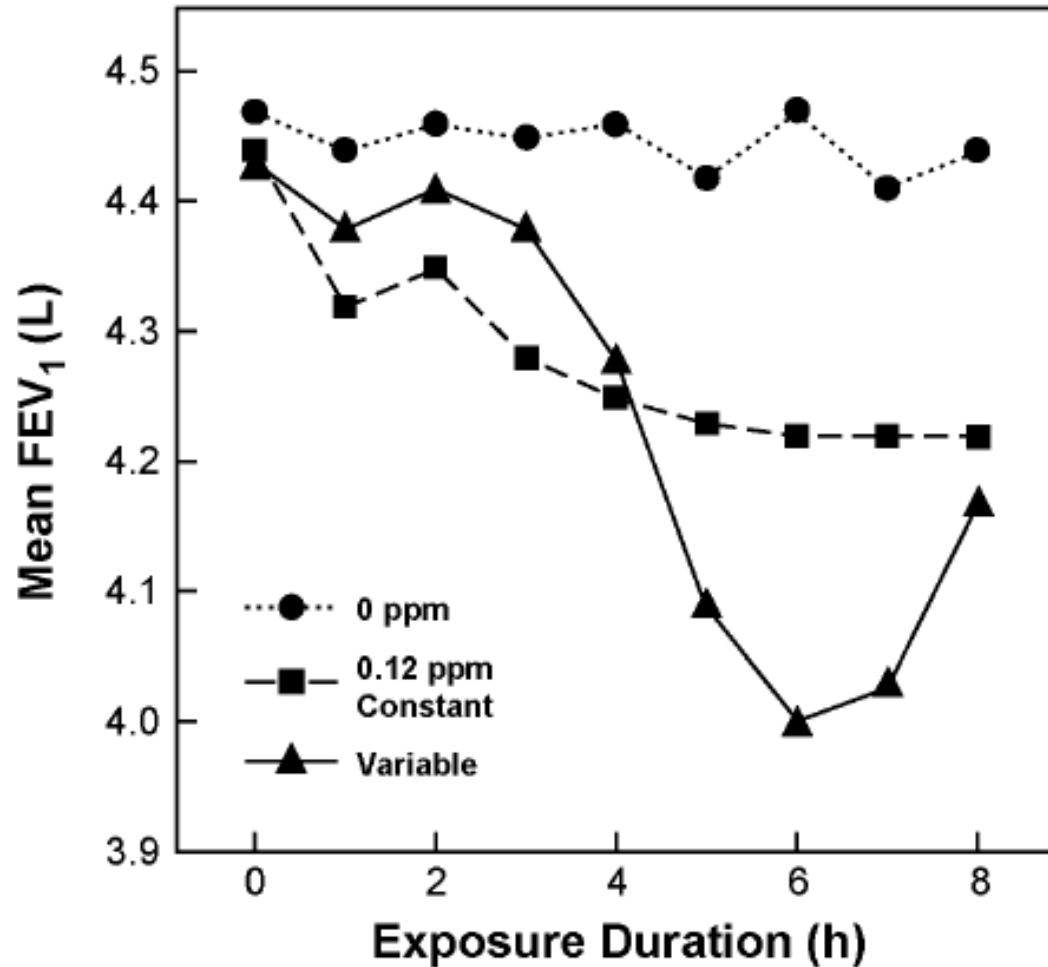


Area	Average PM ₁₀ (μg/m ³)	Mean AM/hpf	% individual with high (>10/hpf) AM count
North	140.1	11.8	17
North East	160.5	13.2	24
North West	158.2	12.8	22
Central	186.9	16.7	32
East	132.1	11.9	14
West	181.4	16.8	30
South	140.5	11.9	16
South East	104.2	7.2	10
South West	101	6.8	9

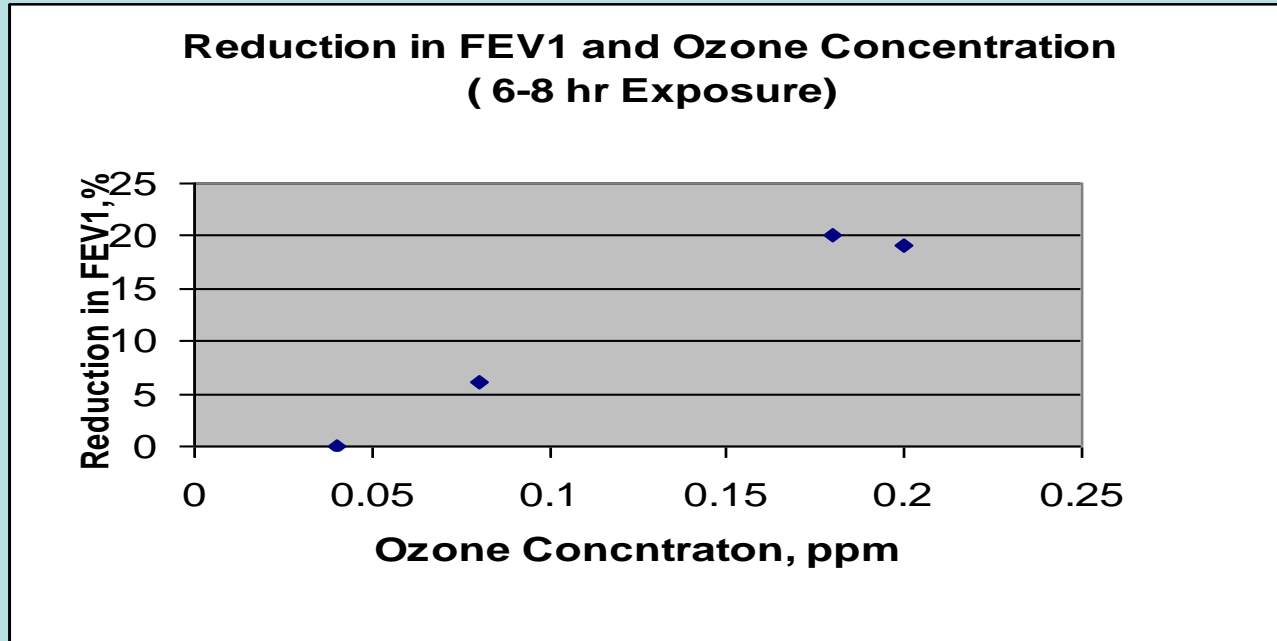


Exercise ~ Vol/min has significant bearing

FEV₁ decrements as a function of O₃ concentration following a 2 h exposure with incremental exercise (15 min intervals) or rest. Points are experimental data (mean ± SE) and lines are model predictions for each activity level. Minute ventilation (\dot{V}_E) represent average across intervals of rest and exercise.



The forced expiratory volume in 1 s (FEV₁) is shown in relation to exposure duration (hours) under three exposure conditions. Subjects exercised (minute ventilation \approx 40 L/min) for 30 min during each hour; FEV₁ was measured at the end of the intervening rest period. Standard error of the mean for these FEV₁ averages (not shown) ranged from 120 to 150 mL.

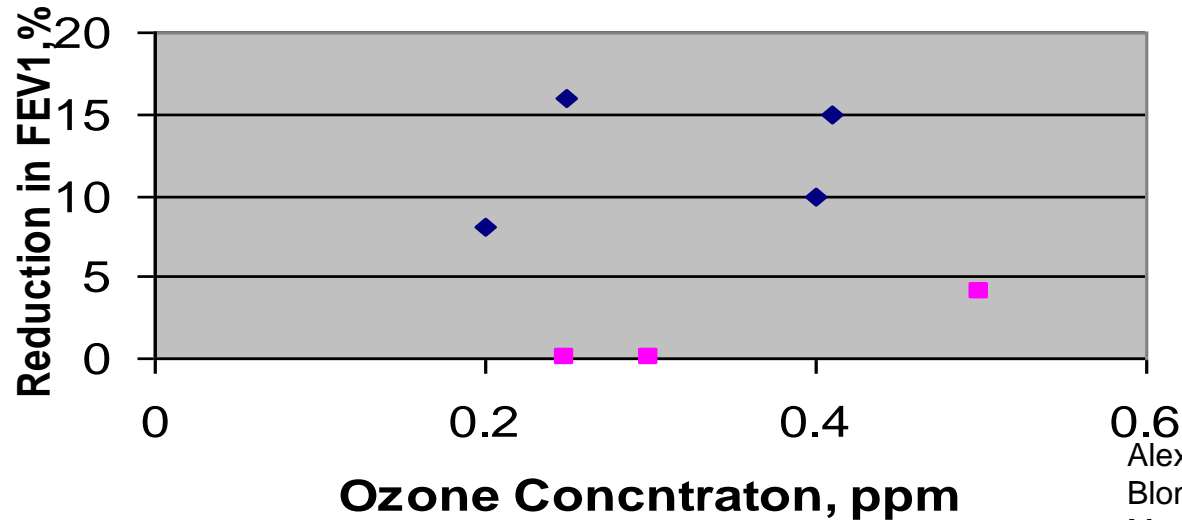


Proposed Standard (8-hr) = $[(1/10) \times 0.04] \times 2 + 0.030$ (background), ppm = 110 ppb.

Why Factor 2?

Personal Exposure = 1/2 of ambient Concentration

Reduction in FEV1 and Ozone Concentration (<2hr Exposure)



Alexis et al (2000)
Blomberg et al (1997)
Montuschi et al (2002)
McDounell et al (2002)

◆ During Exercise ■ At Rest

Proposed Standard (1-hr) = $[(1/10) \times 5] \times 2 + 0.030$ (background), ppm = 130 ppb

Why Factor 2?

Personal Exposure = 1/2 of Ambient Concentration

This also prevents ill effects during exercise and it is conservative enough as it will be 1-hr standard.

Criteria Pollutants:

- ✓ These are commonly found, show threshold in D_R curve having short term effects
- ✓ Emitted from many large diverse sources, including mobile and stationary sources
- ✓ Omnipresent and, therefore, pose the greatest overall threat to human health
- ✓ Assumption: the adverse health effects are not cancerous, and their dose-response relationship exhibits a threshold
- ✓ PM, SO₂, NO_x, CO, Pb, O₃

Non- criteria Pollutants

Asbestos, Vinyl chloride, Mercury, Arsenic, TOC (Trace Organic Carbon) and others

Criteria:

Complete knowledge about dose-response relationship for the pollutant.

Standards:

Legally binding concentration in a country arrived from criteria, factor of safety and other concentrations. The following points should be considered at the time of deciding the standards

- Averaging time (short term or long term)
- Allowable exceedance (98% of time standards must be met)
- Method of measurement must be specified (along with Accuracy and Precision)
- Local air quality levels (including background pollution levels)
- Economics of the local areas
- Precursor levels responsible for the secondary pollutant formation

Guidelines/Goal:

Desirable concentration without legal binding

Hazardous Air Pollutants (HAPs):

- Sources may be limited and industry specific
- More toxic and even carcinogenic
- ~188 chemicals
- For example, benzene, formaldehyde, cadmium, vinyl chloride
- Separate strategies exist for regulating criteria and hazardous pollutants
- HAPs are more toxic than criteria pollutants; they “. . . **may reasonably be expected to result in serious irreversible . . . disease, including cancer**”
- For examples: Heavy metals (chromium, mercury), Organics (benzene, perchloroethylene), VOCs (volatile organic compounds)

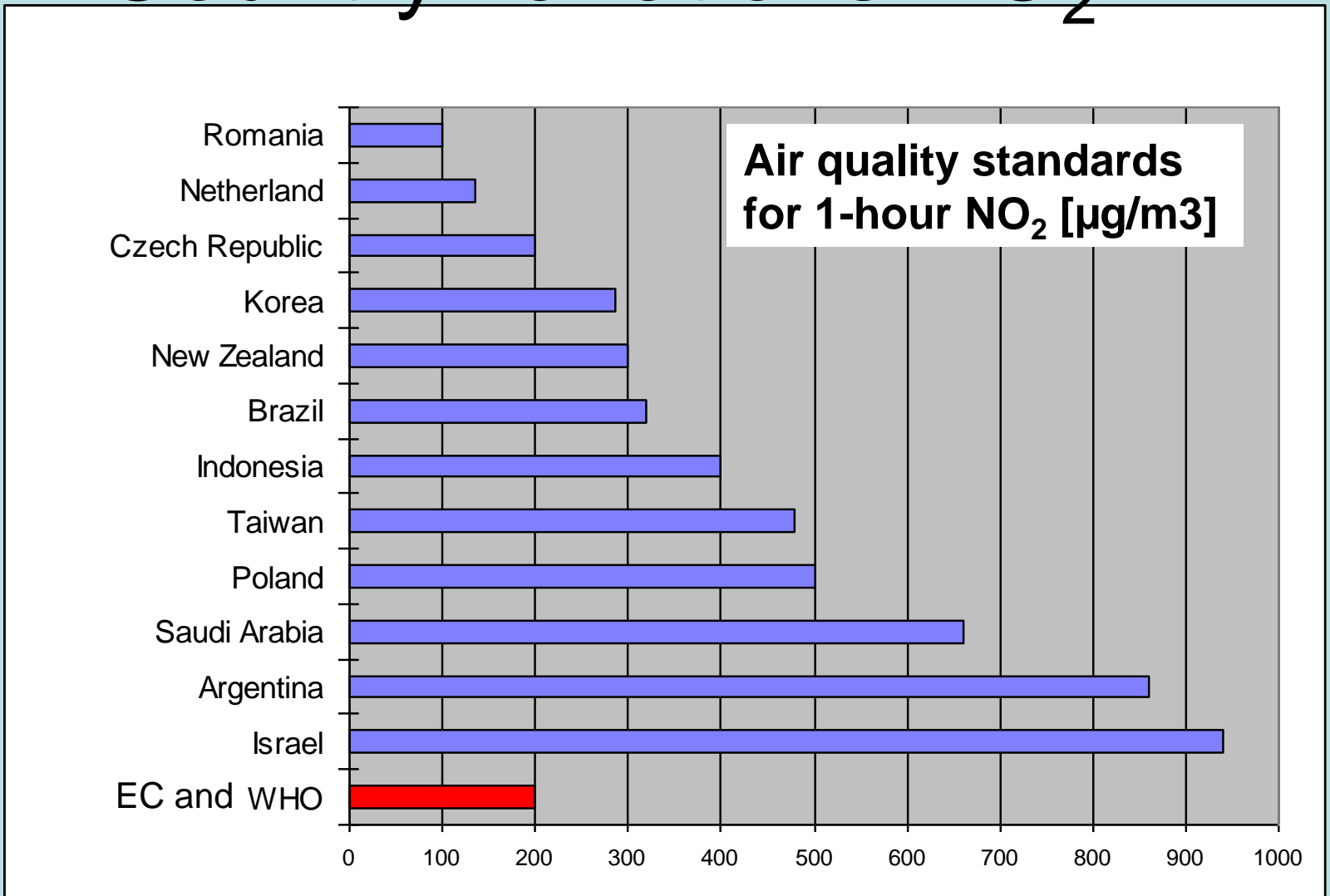
Accuracy:

It describes the relationship between the average of several repeated determinations and the goals.

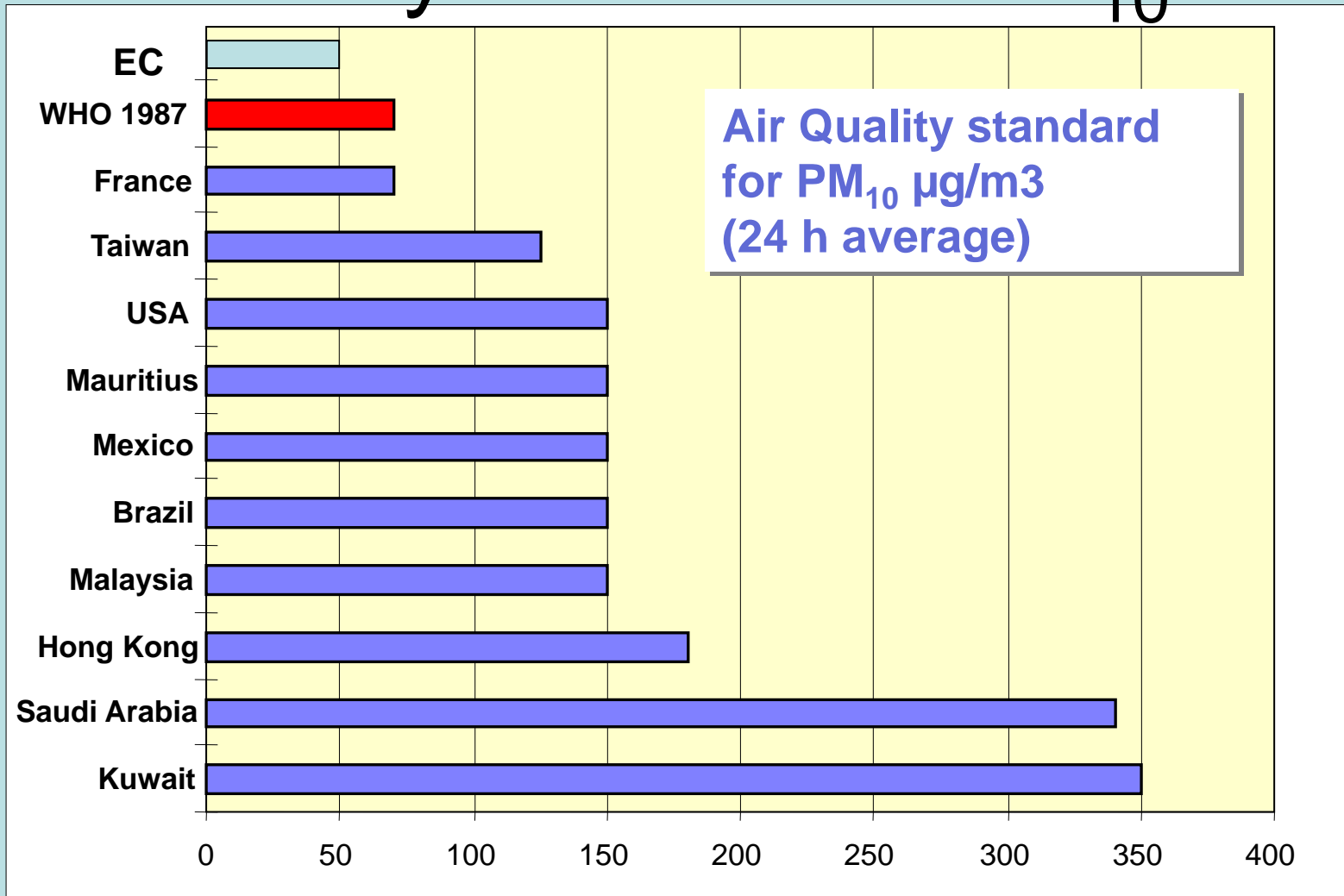
Precision:

The degree to which further measurements or calculations will show the same or similar results or it can be repeatedly determined with little variability.

Country variations NO₂



Country variations PM₁₀



NATIONAL AMBIENT AIR QUALITY STANDARDS
CENTRAL POLLUTION CONTROL BOARD
NOTIFICATION

New Delhi, the 18th November, 2009

No. B-29016/20/90/PCI-I.—In exercise of the powers conferred by Sub-section (2) (h) of section 16 of the Air (Prevention and Control of Pollution) Act, 1981 (Act No.14 of 1981), and in supersession of the Notification No(s). S.O. 384(E), dated 11th April, 1994 and S.O. 935(E), dated 14th October, 1998, the Central Pollution Control Board hereby notify the National Ambient Air Quality Standards with immediate effect, namely:-

NATIONAL AMBIENT AIR QUALITY STANDARDS

S. No.	Pollutant	Time Weighted Average	Concentration in Ambient Air		
			Industrial, Residential, Rural and Other Area	Ecologically Sensitive Area (notified by Central Government)	Methods of Measurement
(1)	(2)	(3)	(4)	(5)	(6)
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual* 24 hours**	50 80	20 80	- Improved West and Gaeke -Ultraviolet fluorescence
2	Nitrogen Dioxide (NO ₂), µg/m ³	Annual* 24 hours**	40 80	30 80	- Modified Jacob & Hochheiser (Na-Arsenite) - Chemiluminescence
3	Particulate Matter (size less than 10µm) or PM ₁₀ µg/m ³	Annual* 24 hours**	60 100	60 100	- Gravimetric - TOEM - Beta attenuation
4	Particulate Matter (size less than 2.5µm) or PM _{2.5} µg/m ³	Annual* 24 hours**	40 60	40 60	- Gravimetric - TOEM - Beta attenuation
5	Ozone (O ₃) µg/m ³	8 hours** 1 hour**	100 180	100 180	- UV photometric - Chemiluminescence - Chemical Method
6	Lead (Pb) µg/m ³	Annual* 24 hours**	0.50 1.0	0.50 1.0	- AAS /ICP method after sampling on EPM 2000 or equivalent filter paper - ED-XRF using Teflon filter
7	Carbon Monoxide (CO) mg/m ³	8 hours** 1 hour**	02 04	02 04	- Non Dispersive Infra Red (NDIR) spectroscopy
8	Ammonia (NH ₃) µg/m ³	Annual* 24 hours**	100 400	100 400	-Chemiluminescence -Indophenol blue method

(1)	(2)	(3)	(4)	(5)	(6)
9	Benzene (C ₆ H ₆) µg/m ³	Annual*	05	05	- Gas chromatography based continuous analyzer - Adsorption and Desorption followed by GC analysis
10	Benzo(a)Pyrene (BaP) - particulate phase only, ng/m ³	Annual*	01	01	- Solvent extraction followed by HPLC/GC analysis
11	Arsenic (As), ng/m ³	Annual*	06	06	- AAS /ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel (Ni), ng/m ³	Annual*	20	20	- AAS /ICP method after sampling on EPM 2000 or equivalent filter paper

* Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.

** 24 hourly or 08 hourly or 01 hourly monitored values, as applicable, shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.

Note. — Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigation.

SANT PRASAD GAUTAM, Chairman
[ADVT-III/4/184/09/Exty.]

Forms of Air Pollutants:

- Solid:

(It also includes liquid, e.g. acid mist)

example- dust, particulate matter, soot etc.

- Gases:

example: SO₂, NO_x etc.

- Partitioned between solid and gas

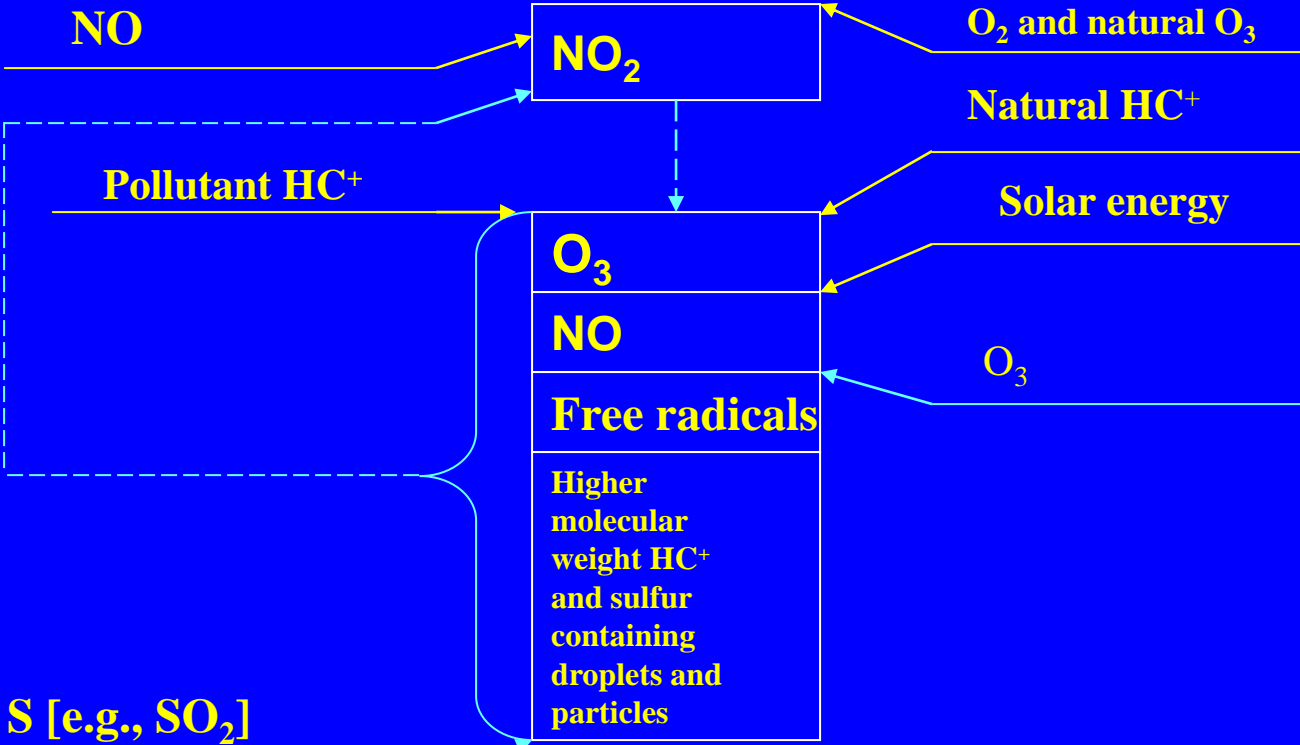
example: semivolatile hydrocarbons like PAH (Polycyclic Aromatic Hydrocarbon)

Formation of Secondary Pollutants from Primary Pollutants

Type of Reaction	Primary Pollutants	Secondary Pollutants	Unpolluted Atmosphere
Simple reaction	<p>Acid gases</p> <p>Alkaline Particles</p>	<pre>graph LR; A[Acid gases] --> C[Salt particles]; B[Alkaline Particles] --> C;</pre> <p>Salt particles</p>	

Formation of Secondary Pollutants from Primary Pollutants

Type of Reaction	Primary Pollutants	Secondary Pollutants	Unpolluted Atmosphere
Photochemical chain reaction	<p>NO</p> <p>Pollutant HC⁺</p> <p>S [e.g., SO₂]</p>	<p>NO₂</p> <p>O₃</p> <p>NO</p> <p>Free radicals</p> <p>Higher molecular weight HC⁺ and sulfur containing droplets and particles</p>	<p>O₂ and natural O₃</p> <p>Natural HC⁺</p> <p>Solar energy</p> <p>O₃</p>



Observe the pictures



Agriculture Crop Residues (Biomass) Burning

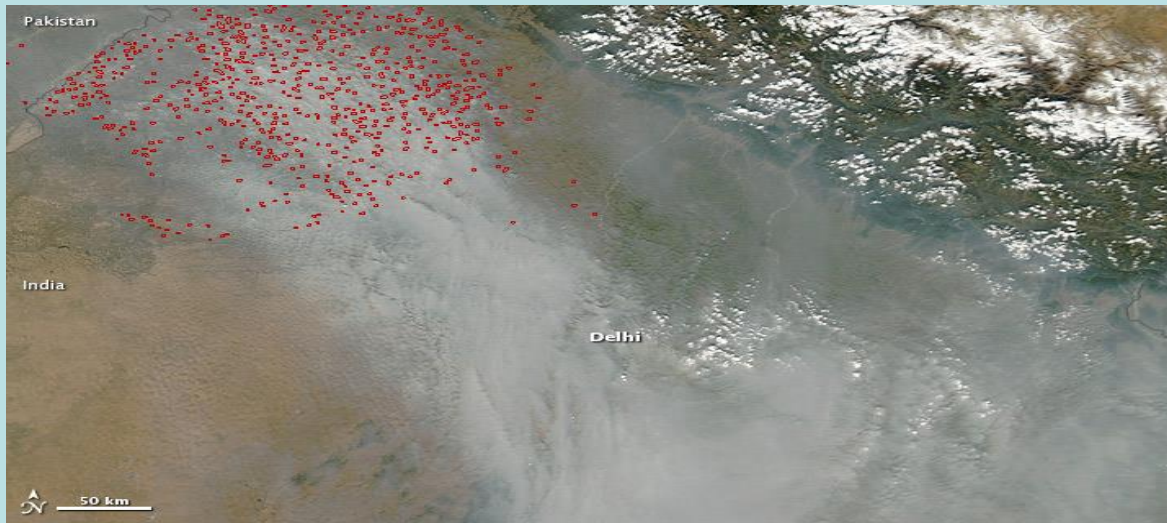
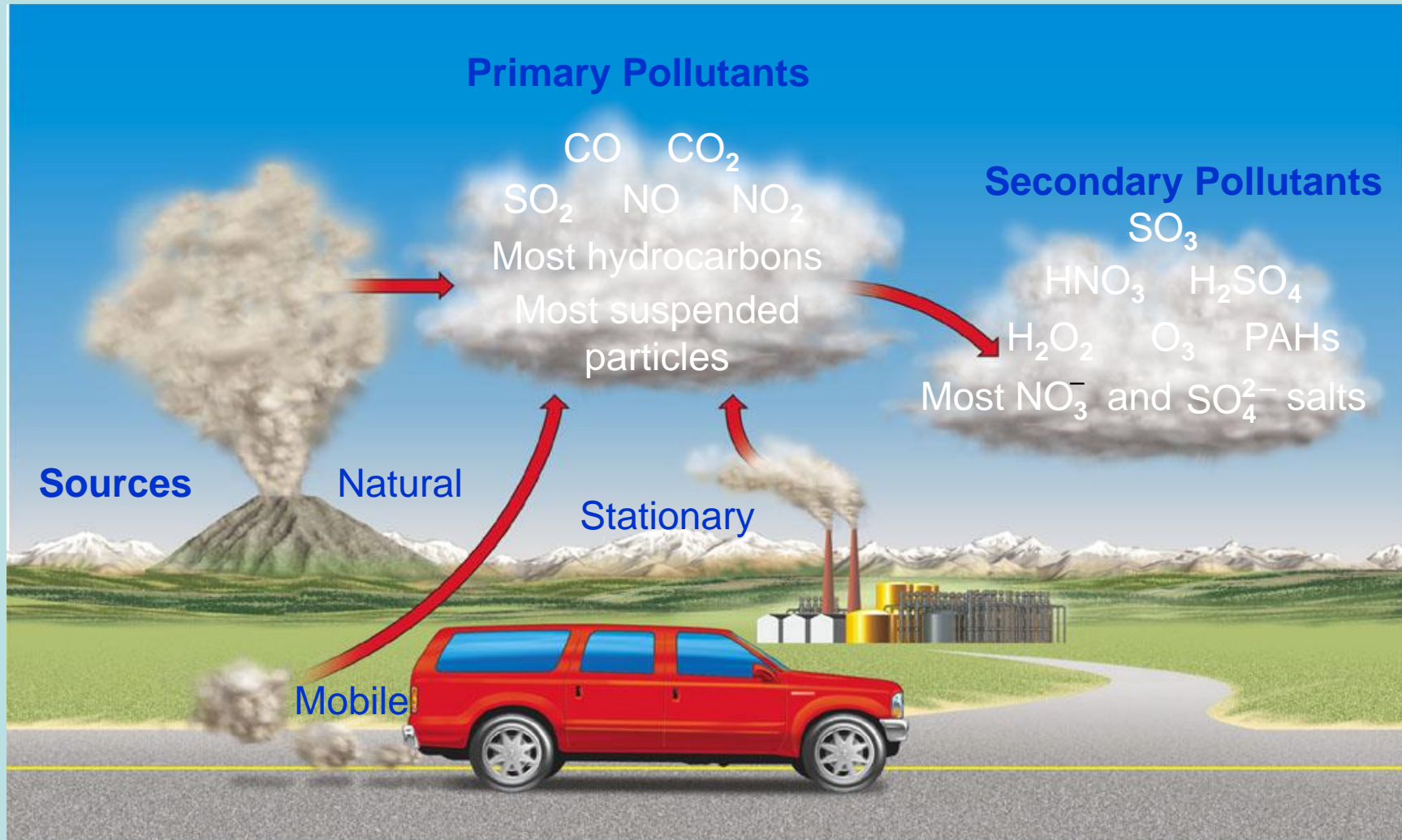


Image of biomass burning induced smoke captured by **Moderate Resolution Imaging Spectroradiometer** (MODIS) on NASA's **Aqua satellite**, November 5, 2012

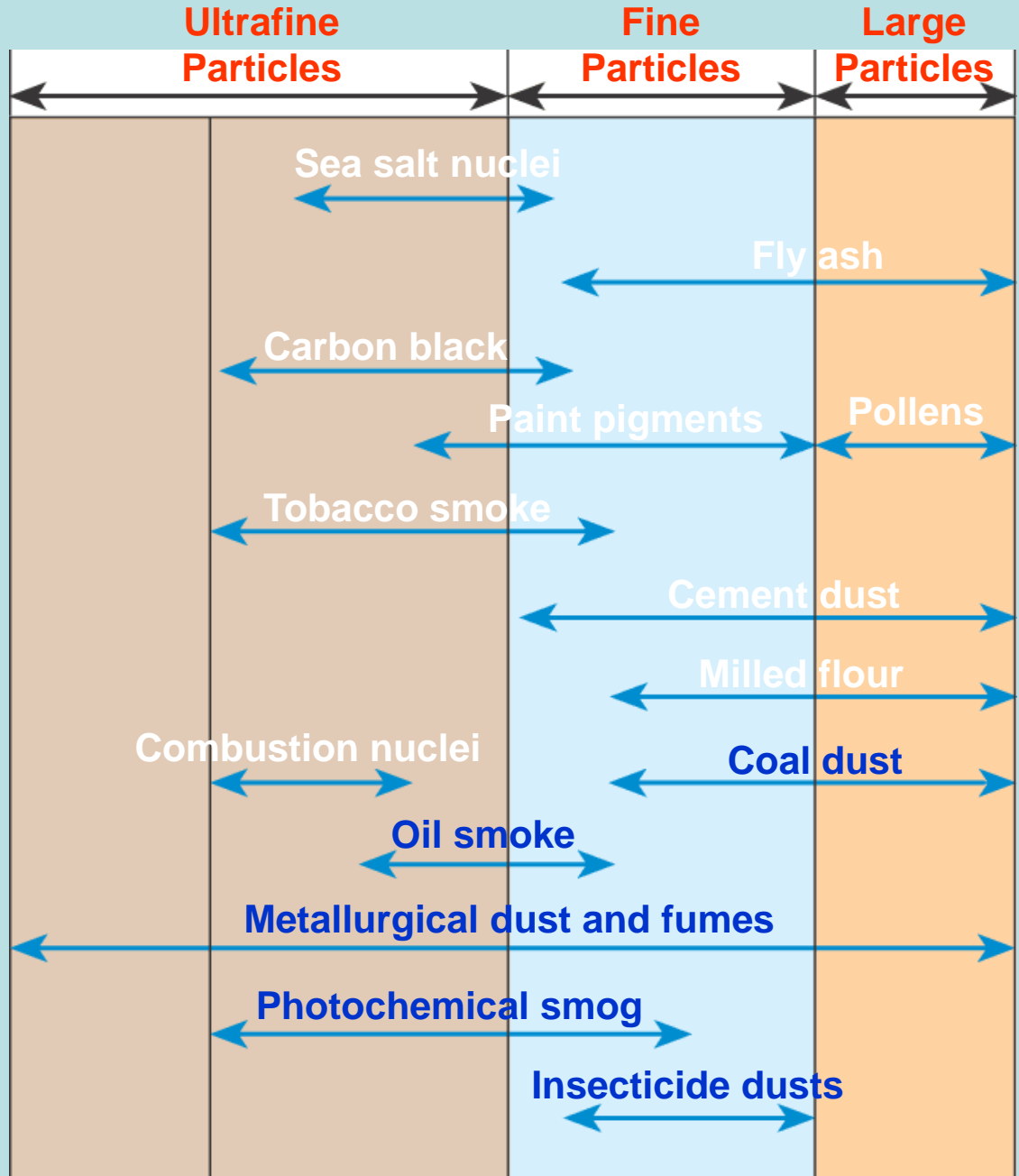
- The fire active (agricultural-waste burning) area: IGP including Punjab, Haryana and western part of Uttar Pradesh) ~ 48,400 sq. km (Justice et al., 2002)
- CRB is active for four months in a year: rice-residue burning during October–November and wheat-residue burning during April–May.

Photochemical Brown Smog



Particle Size

- >5 microns- filtered out
- 1-5 microns- trapped in lungs
- <1 micron-aveolar region



Assignment Questions

Q 1 The area of Kanpur city is $(20 \times 30) \text{ km}^2$. The height of heavily polluted air layer is assumed to be 1 Km. One solution to Kanpur problems would be to pump the contaminated air away through a pipe. Suppose it is decided to pump out the Kanpur air once in 24 hours towards the city of Lucknow, 80 km away from Kanpur. Other information:

- a) velocity of air in pipe is 5 m/sec. find the diameter of pipe?
- b) Find the pressure drop between two ends of the pipe;

Considering i) frictional losses

ii) Entrance loss

iii) Exit loss

Assume $K_{\text{exit}} = 1.5$

$K_{\text{entrance}} = 0.7$

take friction constant 0.0015 and velocity through pipe 12 m/s

- c) Estimate the power requirement of the pump?
- d) If power requirement of Kanpur people is 0.5 KW/person; what population equivalent of power will be taken by pump?
- e) Is the idea workable – Justify?

Q 2 Develop the relationship between ppm and $\mu\text{g}/\text{m}^3$ by using gas law, $PV=nRT$?

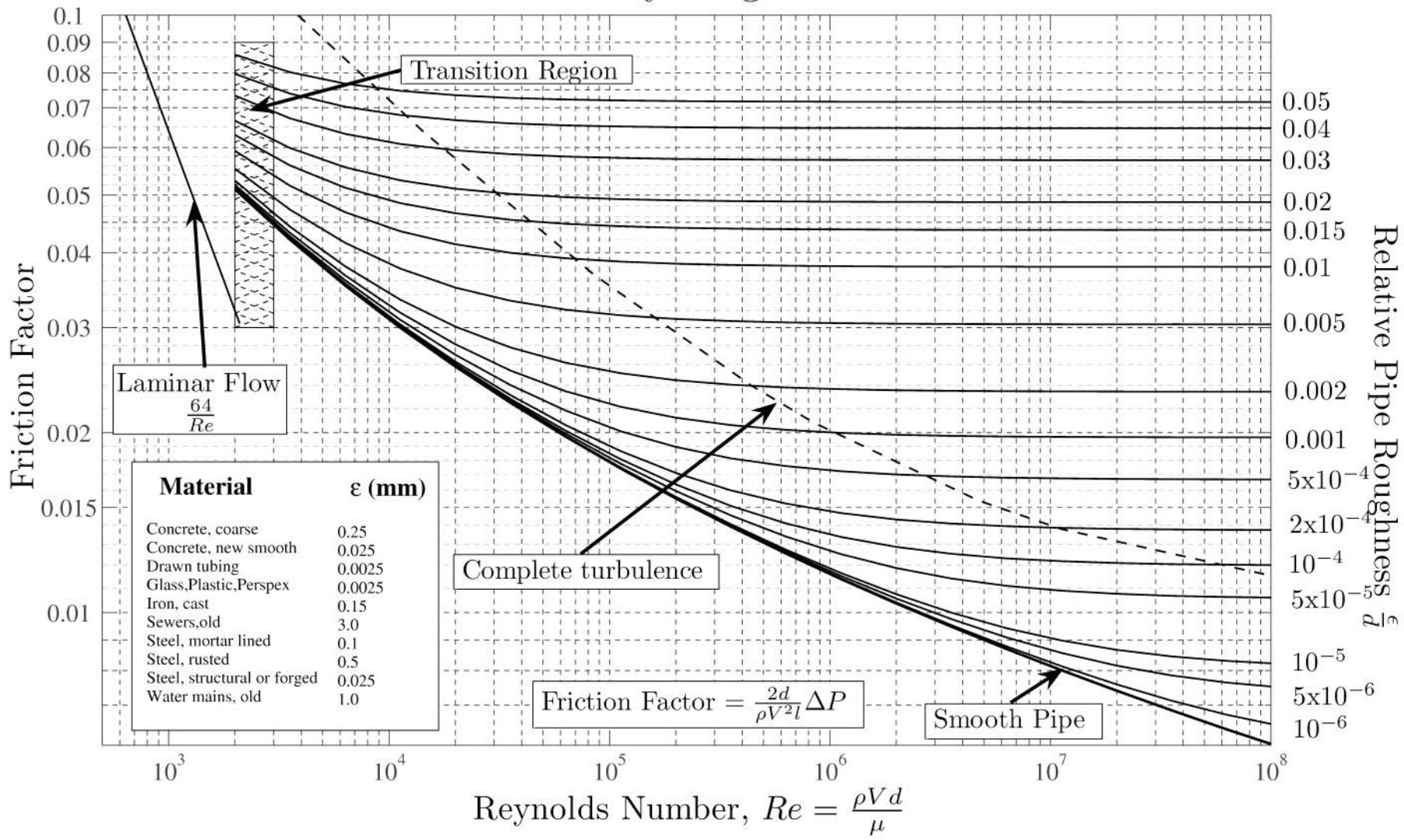
Apply Bernoullis Equation

$$\Delta P = \frac{\rho V^2}{2} \left(\frac{4fL}{D} + K_{entrance} + K_{exit} \right)$$

Use Moody's Chart to find 'f'

And Power, P ? Q x delp P

Moody Diagram




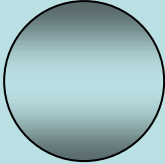




Background Information

Particulate matter (PM)

Aerodynamic Diameter

Decrease in Size – Increase in Toxicity



	SPM	-	$\leq 100 \mu\text{m}$
	TSPM	-	$\leq 40 \mu\text{m}$
	PM ₁₀	-	$\leq 10 \mu\text{m}$
	PM _{2.5} (Fine particles)	-	$\leq 2.5 \mu\text{m}$
	PM _{0.1} (Ultrafine particles)	-	$\leq 0.1 \mu\text{m}$

USEPA (1996)