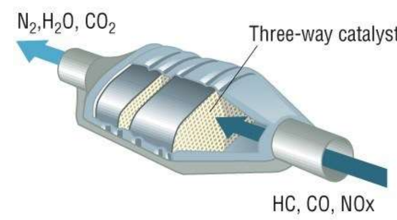
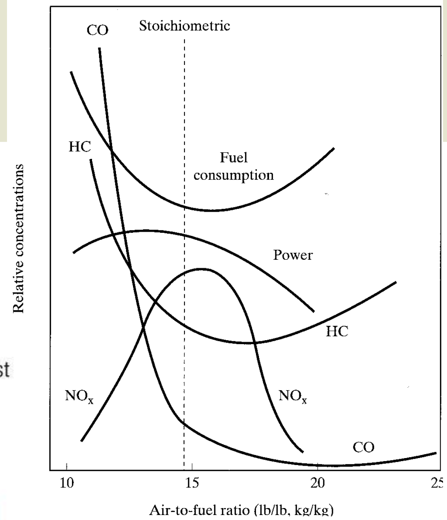
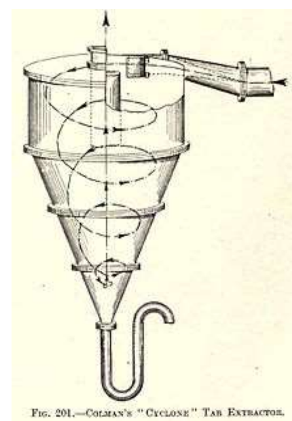




Lecture 7

Air Quality:

Air Pollution Control



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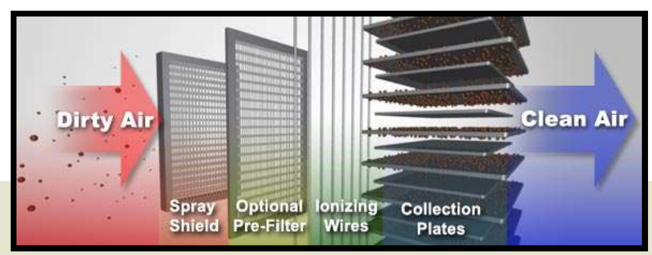


Recap

- Similar to urban airshed, an indoor box model can be built
- e.g. a basic mass balance for pollution in the building/ room, assuming well-mixed conditions:

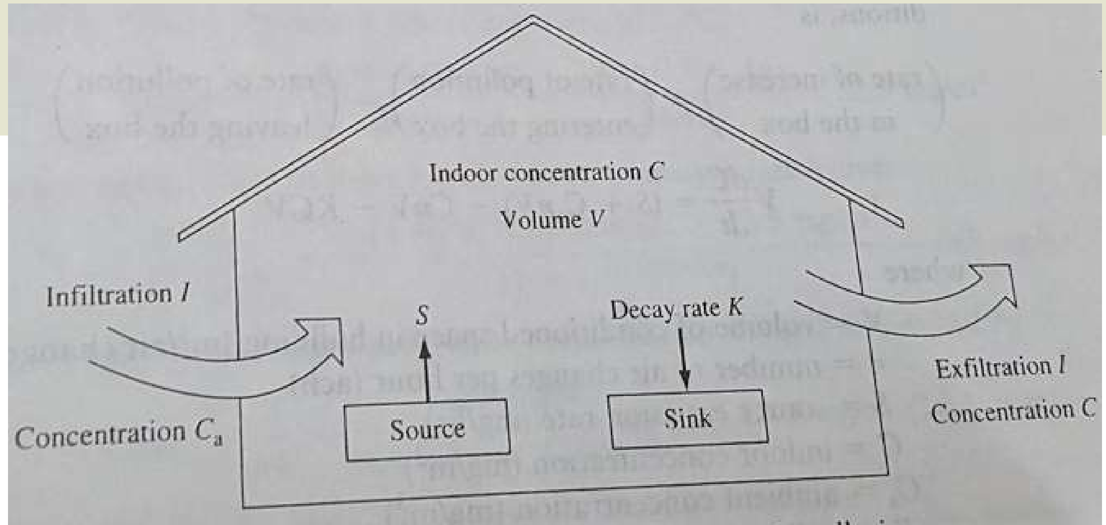


FIGURE 7.65 Box model for indoor air pollution.

$$\begin{pmatrix}\text{rate of increase}\\ \text{in the box}\end{pmatrix} = \begin{pmatrix}\text{rate of pollution}\\ \text{entering the box}\end{pmatrix} - \begin{pmatrix}\text{rate of pollution}\\ \text{leaving the box}\end{pmatrix} - \begin{pmatrix}\text{rate of decay}\\ \text{in the box}\end{pmatrix}$$

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

where, n is number of air changes per hour

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

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

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

Today's Learning Objectives !

- To learn about air pollution control methods from mobile and stationary sources

Indoor Box Model: Example !

An outdoor airflow of 0.047 m^3/s enters a 3 m high room having a 100 m^2 of new wall-to-wall carpet. If one square meter carpet gives off formaldehyde (HCHO) at a rate of 0.1 $\mu g/s$, assuming outdoor air is formaldehyde free and formaldehyde is conservative:

1. What is the outdoor air change rate for the room?
2. What is the formaldehyde conc. under steady state?
3. If the carpet is removed very quickly from the room, how long would it take for the formaldehyde to reach 5% of its initial conc.?

1. Air change rate, n = Q/V

$$n = \frac{0.047 m^3 / s}{(3m \times 100 m^2)} \times 3600 s / hr$$

$$= 0.56 / hr$$ = *0.56 ACH*

Indoor Box Model: Example !

An outdoor airflow of 0.047 m^3/s enters a 3 m high room having a 100 m^2 of new wall-to-wall carpet. If one square meter carpet gives off formaldehyde (HCHO) at a rate of 0.1 $\mu g/s$, assuming outdoor air is formaldehyde free and formaldehyde is conservative:

2. What is the formaldehyde conc. under steady state?

2. Formaldehyde conc. under steady state,

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

$$C(\infty) = \frac{S/V}{n} = \frac{S}{Q}$$

$$= \frac{0.1\mu g/(s.m^2) \times 100 m^2}{0.0476 m^3/s} = 213 \mu g/m^3$$

Indoor Box Model: Example !

An outdoor airflow of 0.047 m^3/s enters a 3 m high room having a 100 m^2 of new wall-to-wall carpet. If one square meter carpet gives off formaldehyde (HCHO) at a rate of 0.1 μg/s, assuming outdoor air is formaldehyde free and formaldehyde is conservative:

3. If the carpet is removed very quickly from the room, how long would it take for the formaldehyde to reach 5% of its initial conc.?

3. Time for HCHO to reach its 5% value,

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

$$C(t) = C(0)e^{-nt}$$ or $$C(t)/C(0) = e^{-nt}$$

=> $$0.05 = e^{-0.56t}$$

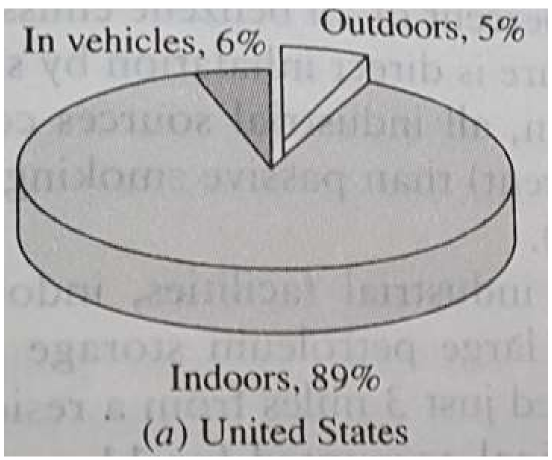
Therefore, *t = 5.3 hr*

Need for Indoor Models:
… so to estimate Indoor Exposures

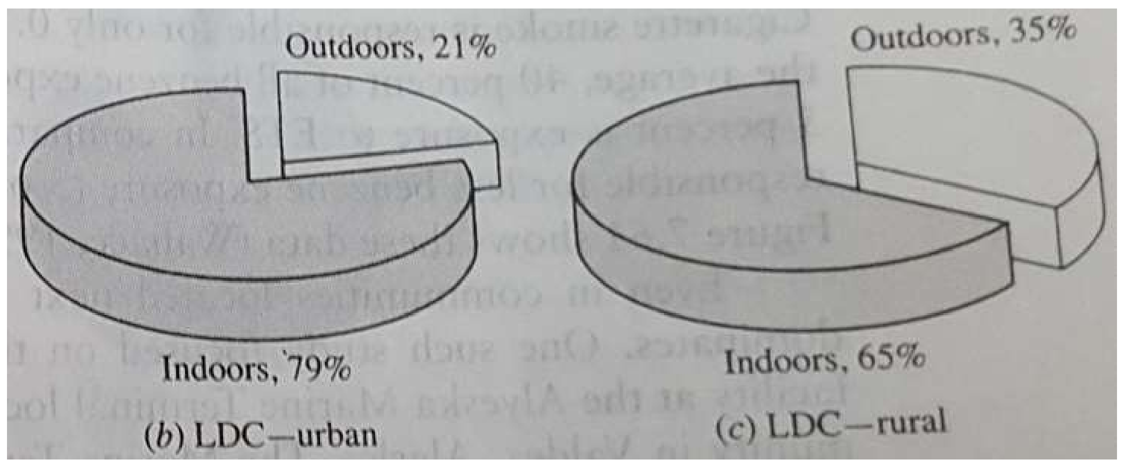
- Outdoor models needed so to manage air quality in ambient environments where no measurements are available
- But as far as human health effects are concerned, what matters is not the pollutants’ conc., but what humans get exposed to!

Exposure = concentration x duration of time in contact

- Contact duration depends on where people spend their time



(*a*) United States



(*b*) LDC—urban

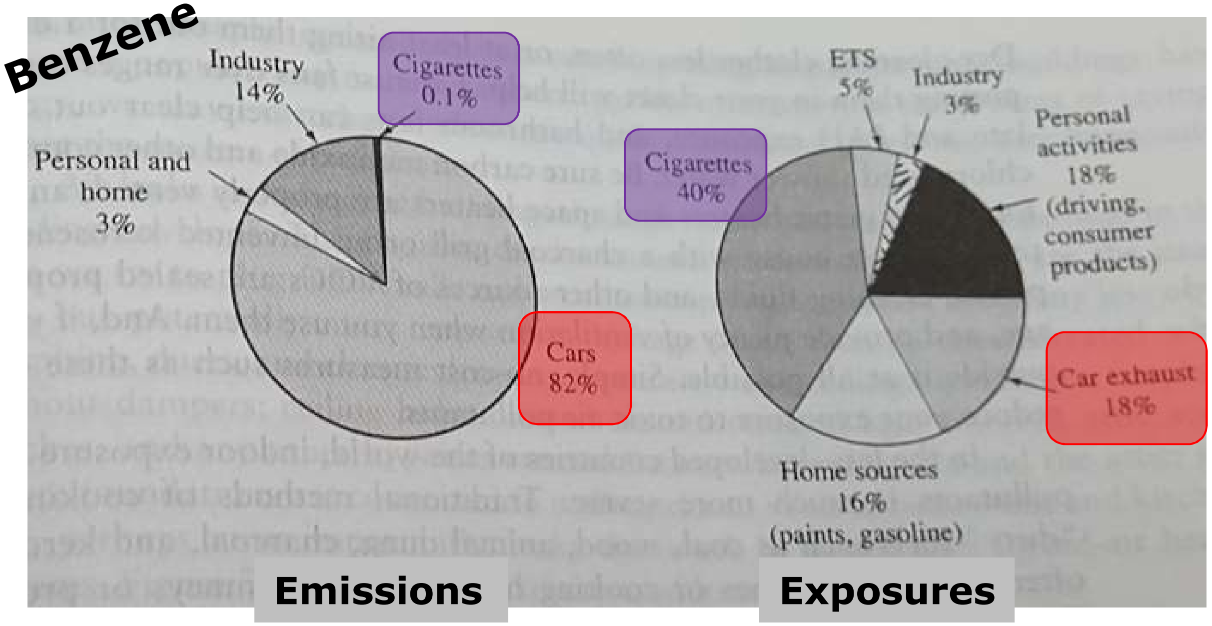
(*c*) LDC—rural

Master and Ela, 2008

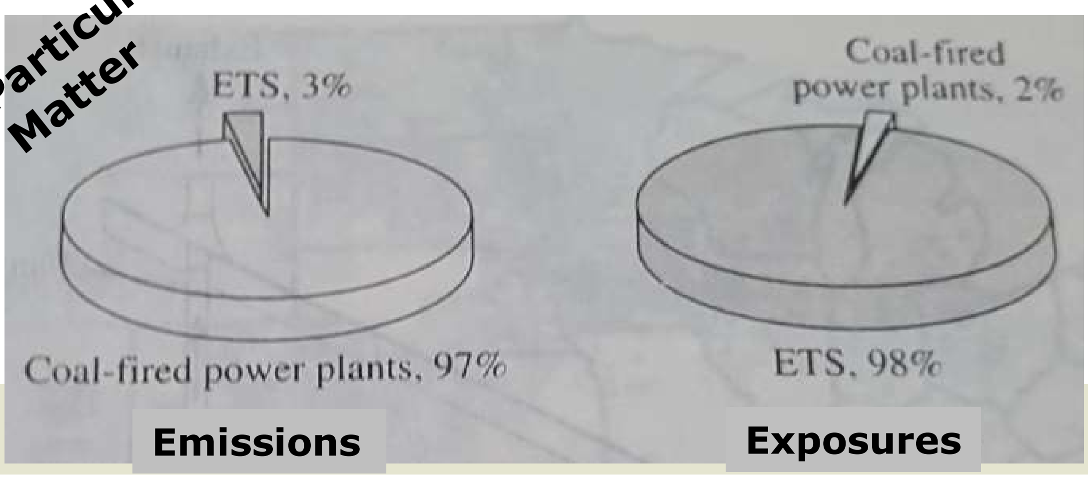
Air Pollution Exposures

- Some of the largest emissions may have lowest exposures and vice-versa

Benzene



Particulate Matter



Master and Ela, 2008

Air Pollution Control: Mobile Sources

India Emission Standards

Standard	Reference	Date	Region
India 2000	Euro 1	2000	Nationwide
Bharat Stage II	Euro 2	2001	NCR*, Mumbai, Kolkata, Chennai
		2003.04	NCR*, 11 cities†
		2005.04	Nationwide
Bharat Stage III	Euro 3	2005.04	NCR*, 11 cities†
		2010.04	Nationwide
Bharat Stage IV	Euro 4	2010.04	NCR*, 13 cities‡
		2015.07	Above plus 29 cities mainly in the states of Haryana, Uttar Pradesh, Rajasthan and Maharastra [3231]
		2015.10	North India plus bordering districts of Rajasthan (9 States) [3232]
		2016.04	Western India plus parts of South and East India (10 States and Territories) [3232]
		2017.04	Nationwide [3232]
Bharat Stage V	Euro 5	n/a [a]	
Bharat Stage VI	Euro 6	2020.04	Nationwide [3349]

* National Capital Region (Delhi)
† Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Secunderabad, Ahmedabad, Pune, Surat, Kanpur and Agra
‡ Above cities plus Solapur and Lucknow. The program was later expanded with the aim of including 50 additional cities by March 2015
[a] Initially proposed in 2015.11 [3297][3298] but removed from a 2016.02 proposal [3349]

www.dieselnet.com/standards/in/

Emission control of IC engines

- Maintaining a stoichiometric air/fuel ratio

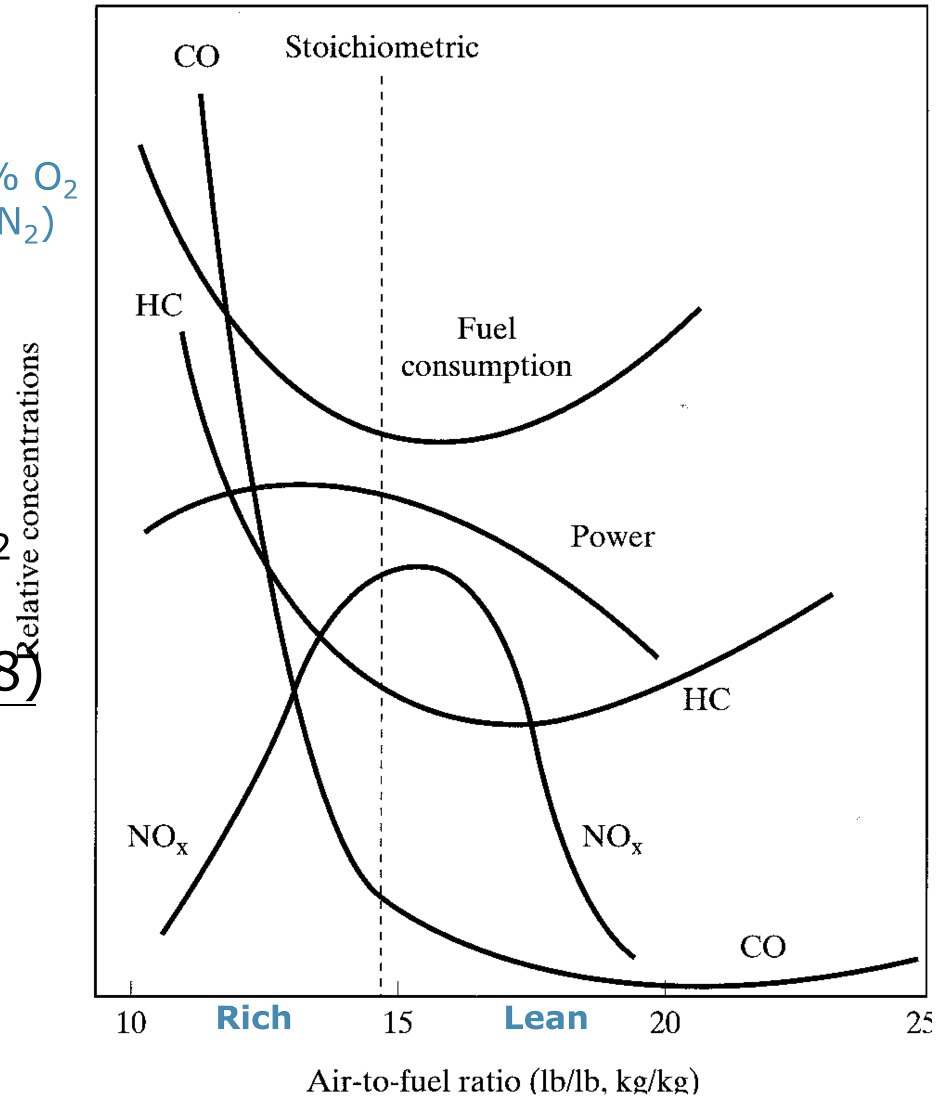
Air (20.9% O_2 + 78.1% N_2)

- $C_7H_{13} + 10.25O_2 \longrightarrow 7CO_2 + 6.5H_2O$

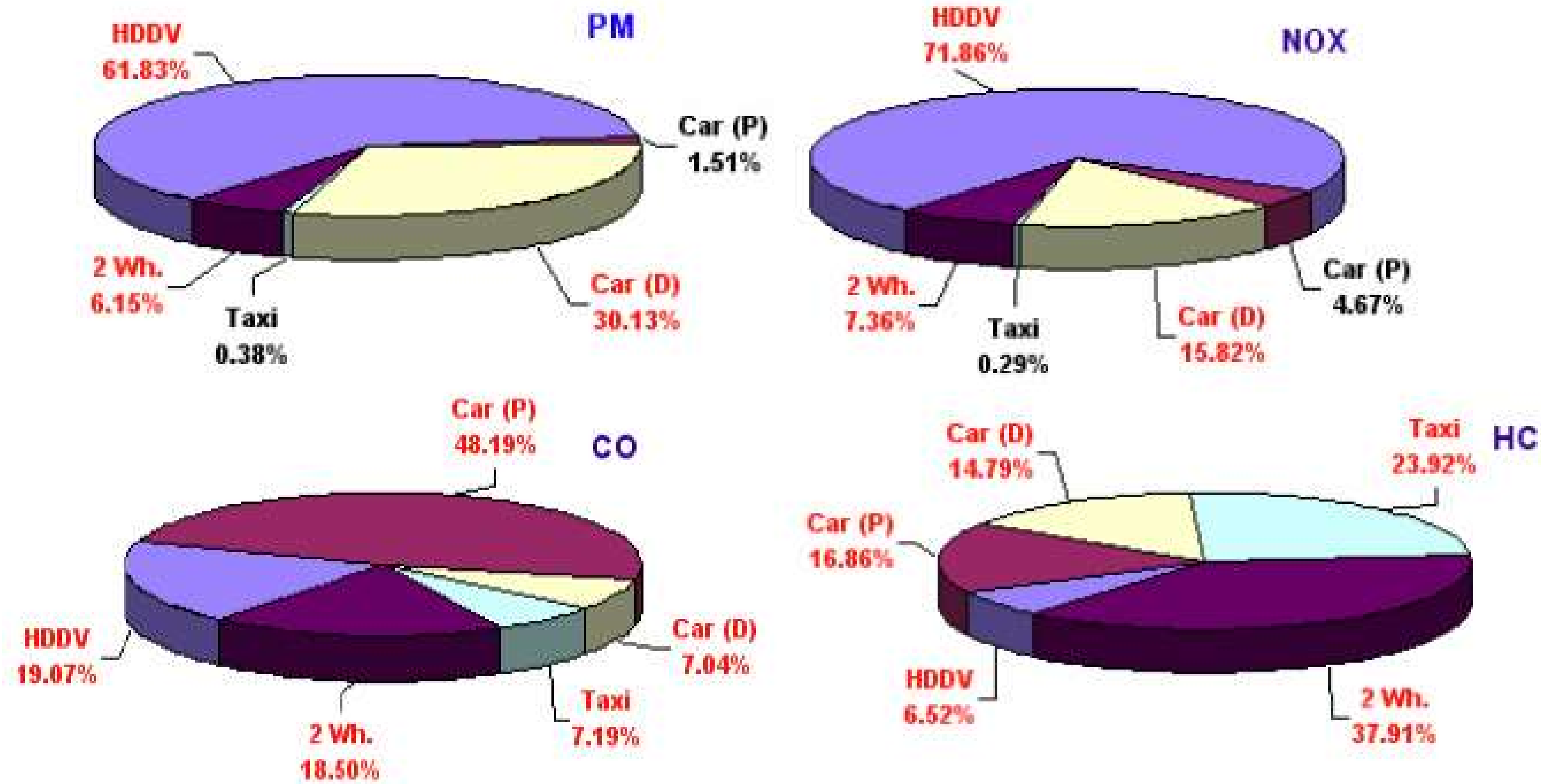
- $C_7H_{13} + 10.25O_2 + 38.5N_2 \longrightarrow 7CO_2 + 6.5H_2O + 38.5N_2$

- $$\text{Air/Fuel} = \frac{(10.25\text{x}32 + 38.5\text{x}28)}{(12\text{x}7+1\text{x}13)} = 14.5 \text{ kg/kg}$$

- Petrol vs. Diesel emissions

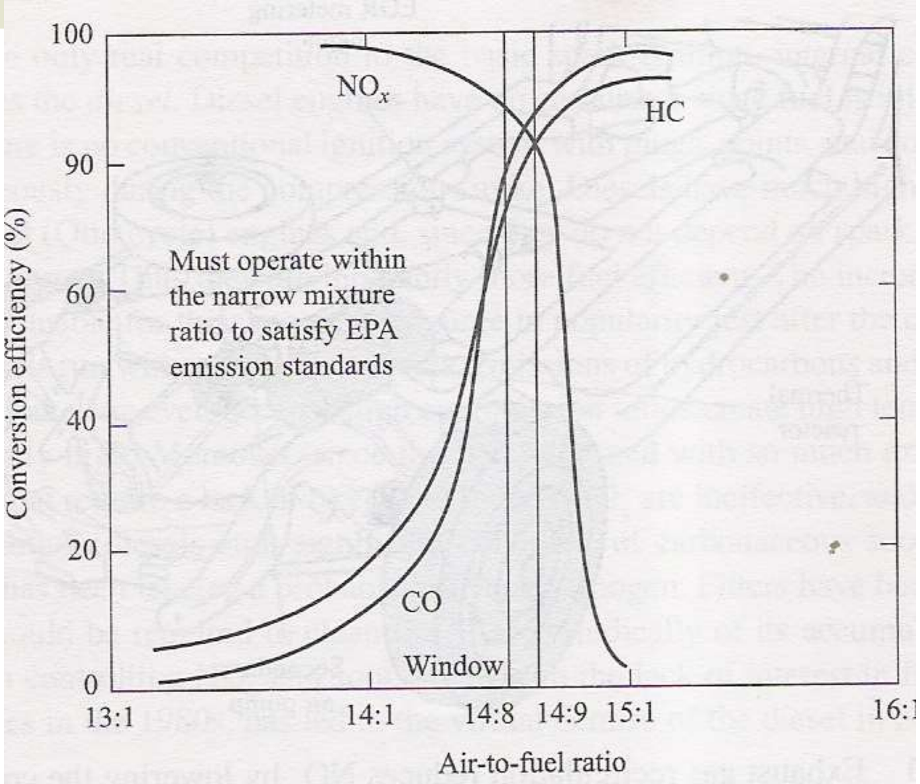


Total emissions from IC engines:
Petrol vs. Diesel



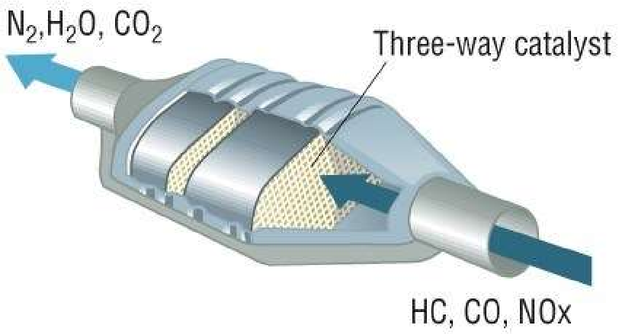
(CPCB report, 2011 & NEERI report, 2010)

Three-way Catalytic converter



A three-way catalytic converter has three simultaneous tasks:

- Reduction of nitrogen oxides to nitrogen and oxygen:
  $\mathbf{2NO_x \rightarrow xO_2 + N_2}$
- Oxidation of carbon monoxide to carbon dioxide:
  $\mathbf{2CO + O_2 \rightarrow 2CO_2}$
- Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water:
  $\mathbf{C_xH_{2x+2} + 2xO_2 \rightarrow xCO_2 + 2_xH_2O}$



Cleaner/Alternative fuel

- Vaporization of gasoline should be reduced
- Oxygen containing additives reduce air requirement., e.g. ethanol, MTBE (Hazardous)
  - Methanol: Less photochemically reactive VOC, but emits HCHO (eye irritant), difficult to start in winters: can be overcome by M85 (85% methanol, 15% gasoline)
  - Ethanol: E10 (10% ethanol & 90% gasoline; used as an oxygenate to reduce CO emissions
  - Biodiesel: produced from animal fats, vegetable oils; generally blended with diesel e.g. B2, B5 and B20 are common
  - CNG: Low HC, high NO_x, inconvenient refueling, leakage hazard
  - LPG: Propane, high NO_x
  - Electric /hybrid vehicles

Landmarks dates in Delhi NCR clean up !

- April 1995: Mandatory fitting of catalytic convertors
- April 1996: Low sulphur diesel introduced
- April 1998: Introduction of CNG buses in Delhi
- Sept 1998: Complete removal of lead in petrol
- Dec 1998: Restrict plying of goods vehicles during the day
- Sept 1999: Amendment of Motor Vehicles Act to include CNG
- April 2000: Private vehicles to be registered only if they conform to Euro II standards
- April 2000: Eight-year-old commercial vehicles phased out
- Nov 2002: Conversion of all public transport buses to CNG

Air Pollution Control: Stationary Sources

- Pre-combustion Control
  - Switching to less S and less N fuel
- Combustion Control
  - Improving the combustion process
  - New burners to reduce NO_x
  - Integrated Gasification combined cycle
- Post-Combustion Control
  - Particulate collection devices
  - Flue gas desulfurization

Air Pollution Control: PM

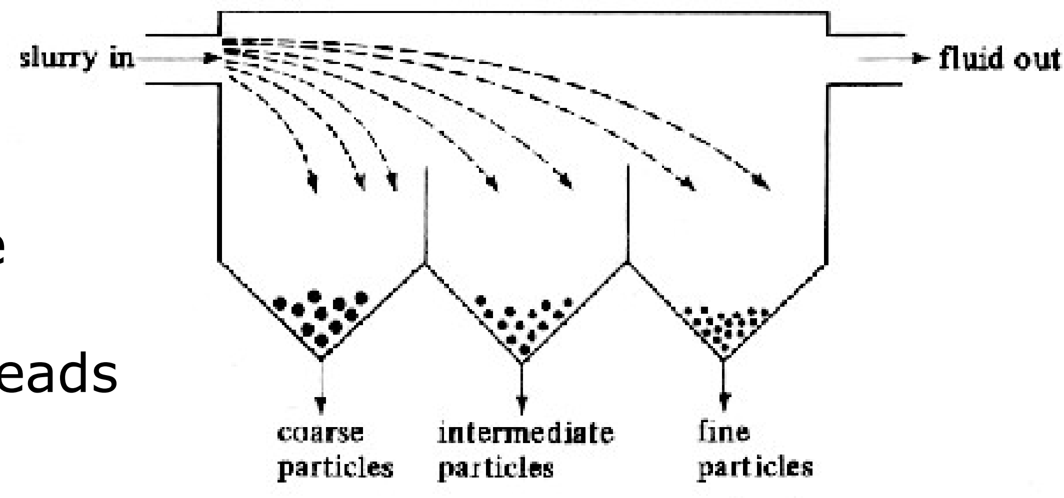
- Device selection depends on
  - Particle size
  - Concentration
  - Corrosivity
  - Volumetric flow rate
  - Required collection efficiency
  - Cost

- Mechanical
  - Gravity based: Settling Chambers $> 20\ \mu m$
  - Inertia based: Cyclones $> 10\ \mu m$
  - Diffusion based: Filters $> 0.1\ \mu m$

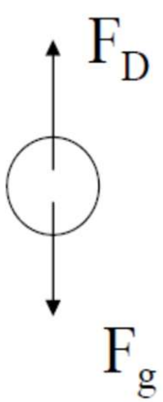
- Electrical
  - Electrostatic Precipitators $> 0.1\ \mu m$

Mechanical - Gravity

Gravitational Settlers



- Particle settling:
  Gravitational forces are balanced by drag and buoyancy forces. This leads to Stokes law - settling velocity of particles.



$$m_p \, g = \rho_p \frac{\pi}{6} d^3 g$$
$$F_d = 3 \pi \mu d v$$

When $F_d = F_g$, settling velocity is given by

$$v_t = g \, d^2 \frac{\rho_p}{18 \mu}$$

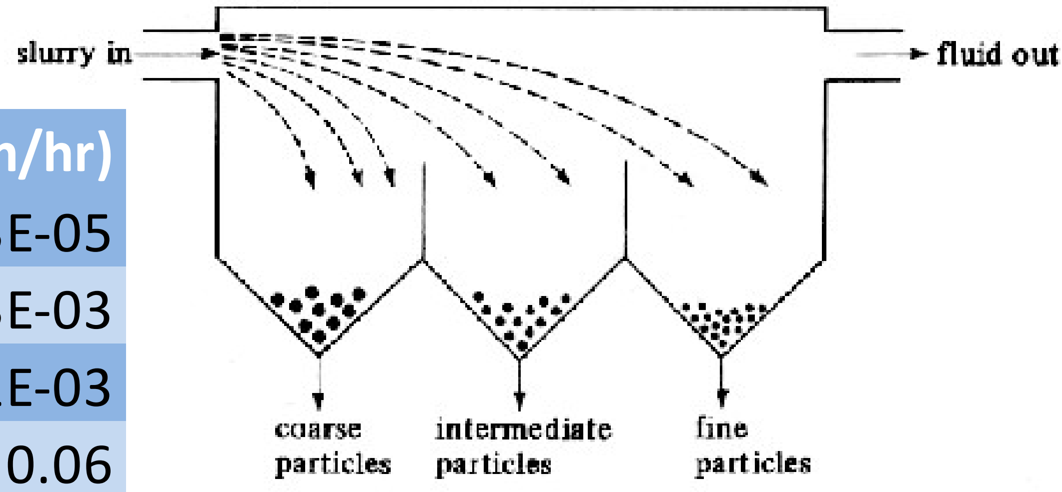
V_t (1μm particle) = 0.006 cm/s

where,
g – gravity acceleration 9.8 m/s^2
d – particle diameter (m)
r_p – particle density (g/m^3)= 2 x 10^6 g/m^3
μ - air viscosity = 0.0172 g/m.s

Mechanical - Gravity

Gravitational Settlers

D_p (μm)	V_t (m/s)	V_t (m/hr)
0.01	6.3E-09	2.3E-05
0.1	6.3E-07	2.3E-03
0.2	2.5E-06	9.1E-03
0.5	1.6E-05	0.06
1	6.3E-05	0.23
2	2.5E-04	0.91
5	0.0016	5.70
10	0.0063	22.79
20	0.0253	91.16
50	0.1583	569.77
100	0.6331	2279.07
200	2.5323	9116.28
500	15.8269	56976.74
1000	63.3075	227906.98



V_t (1μm particle) = 0.006 cm/s

$$v_t = g\, d^2 \frac{\rho_p}{18\,\mu}$$

Mechanical - Inertia

Cyclones

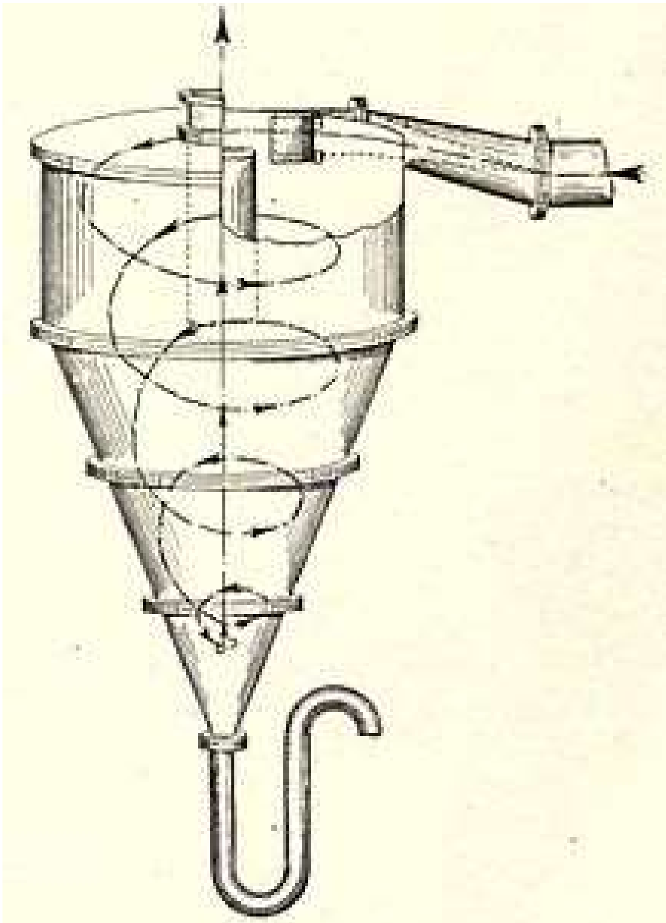
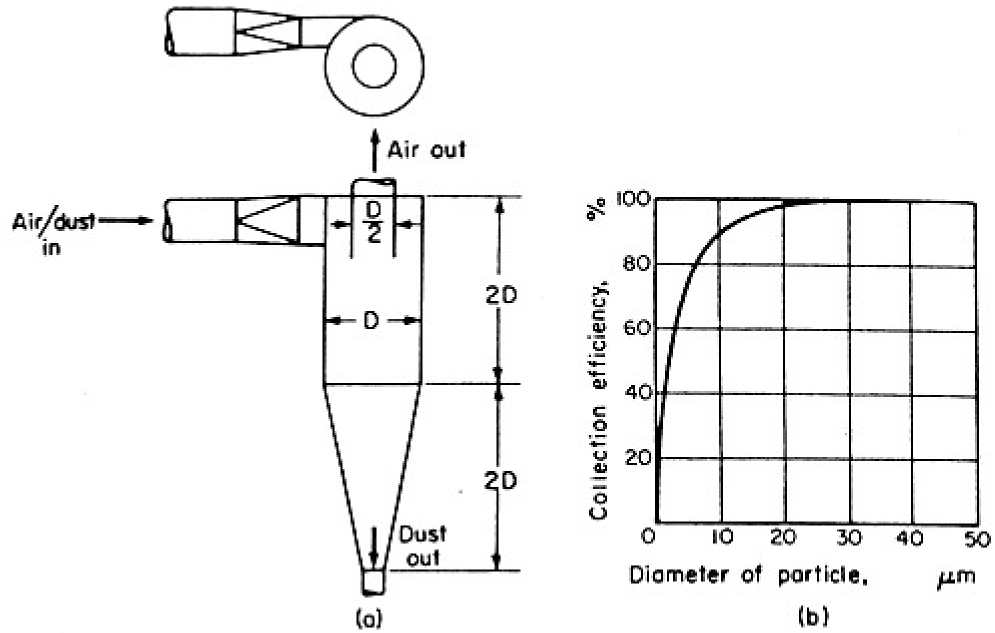


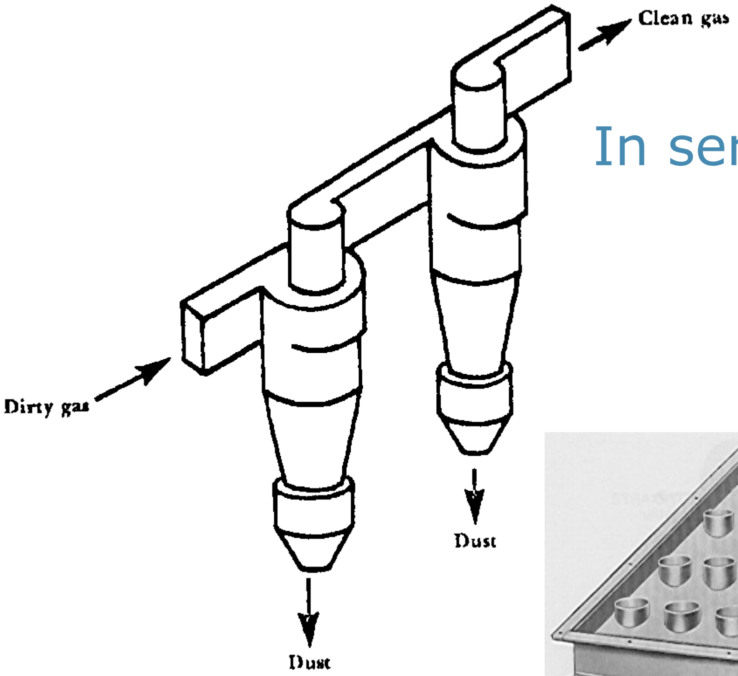
Fig. 201.—Colman's "Cyclone" Tar Extractor.



- For PM > 5 μm
- Efficiency > 90%
- Maintenance-free
- Low-cost

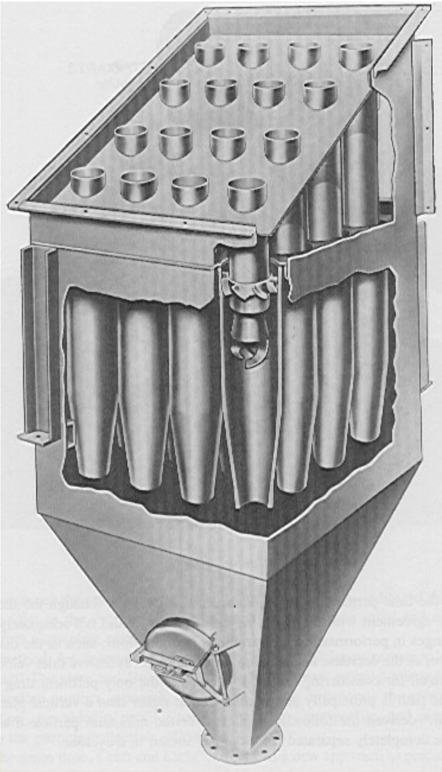
Mechanical - Inertia

Cyclones



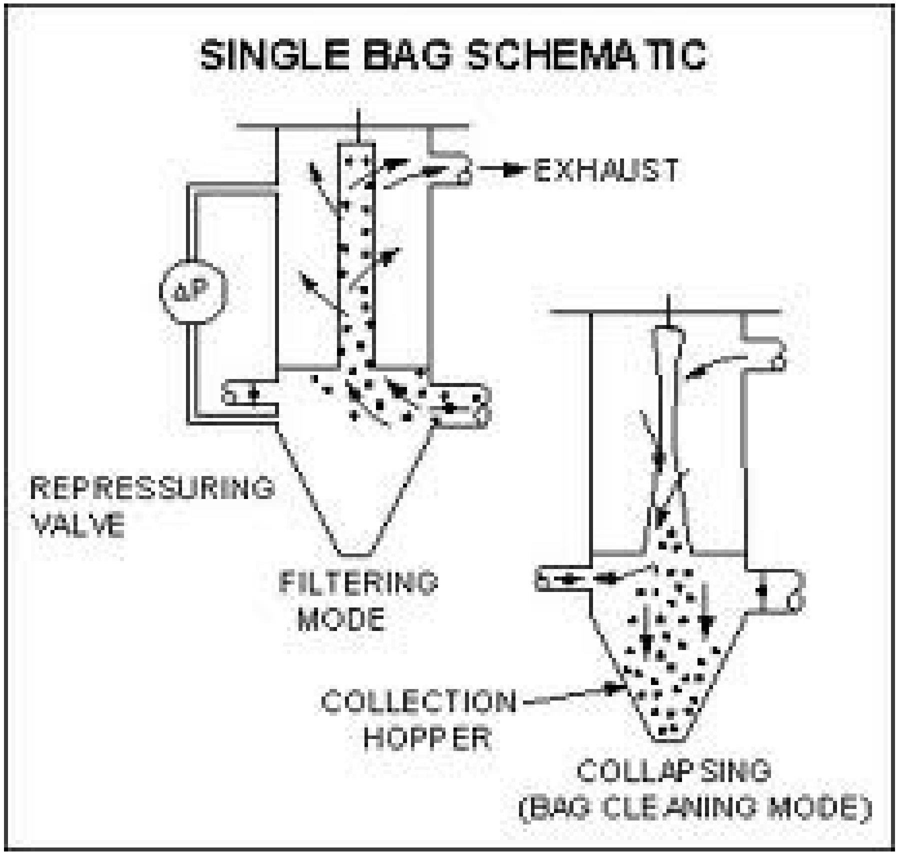
In series

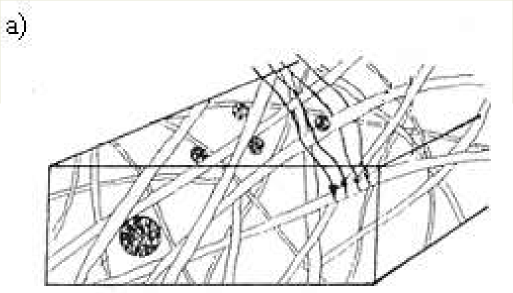
In parallel

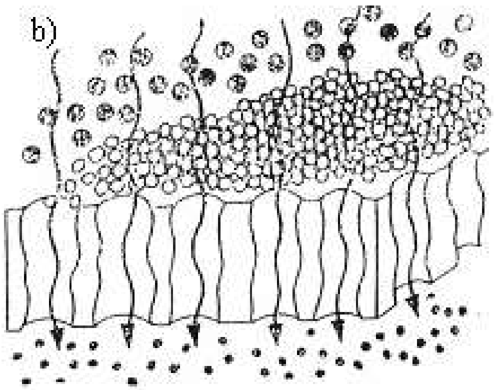


Mechanical - Filtration

Bag filters





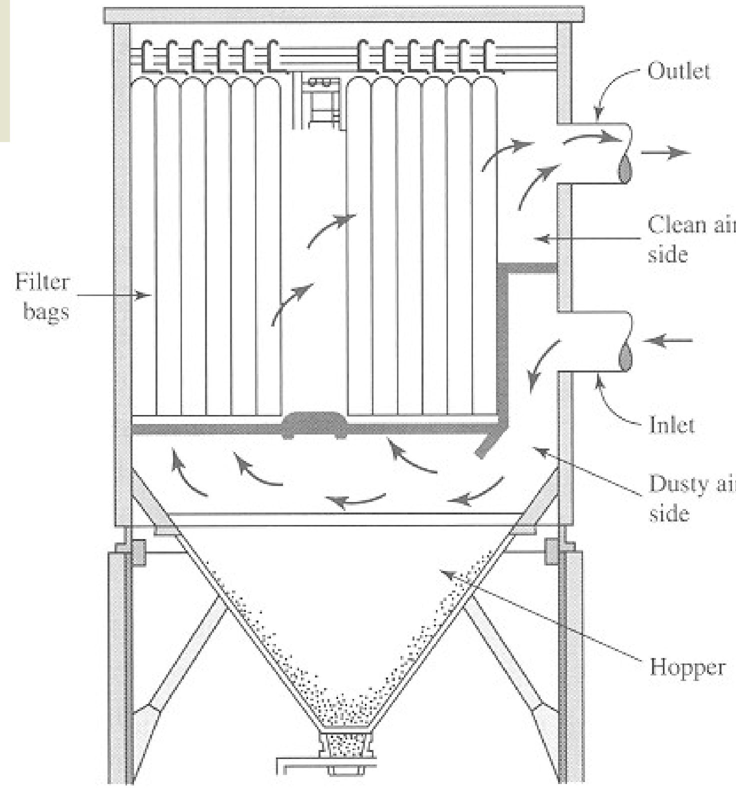


Filtration through fibrous material via:

- Diffusion
- Impaction
- Interception
- (NOT SIEVING)

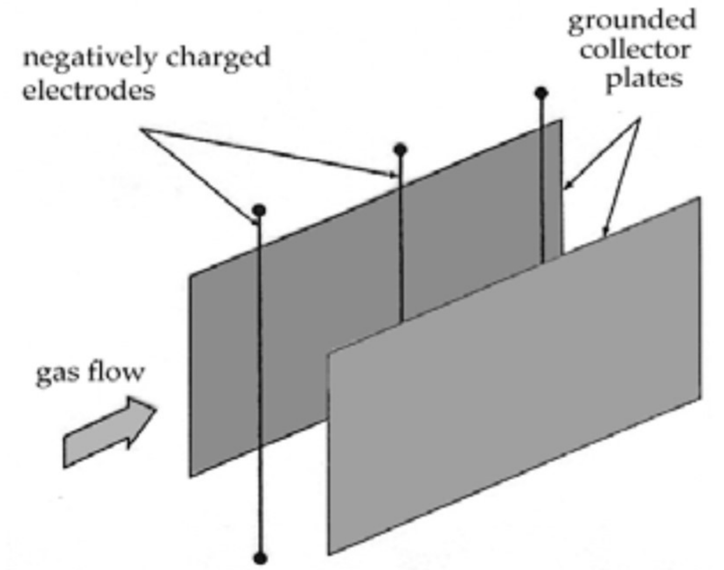
Mechanical - Filtration

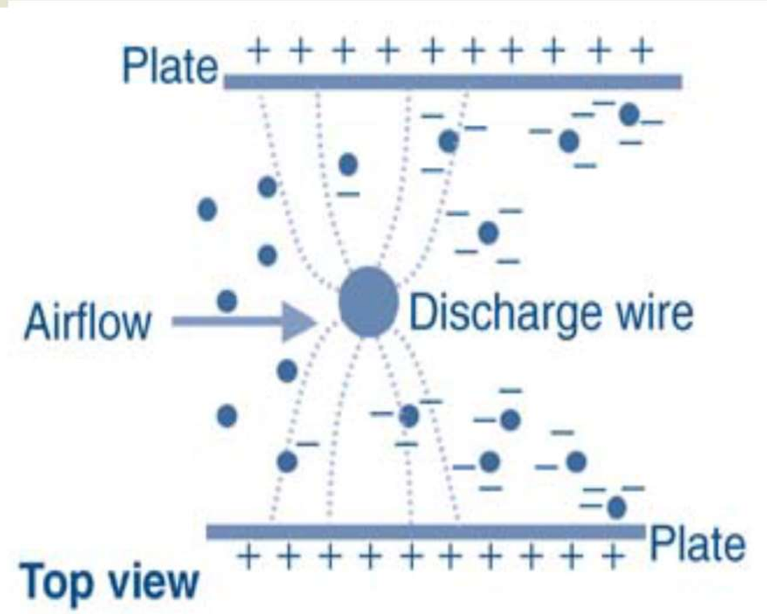
Bag filters



- Efficiency – 100% for particles >0.01-1 μm
- Cannot operate in moist environment
- Large & expensive
- Competitive with ESP

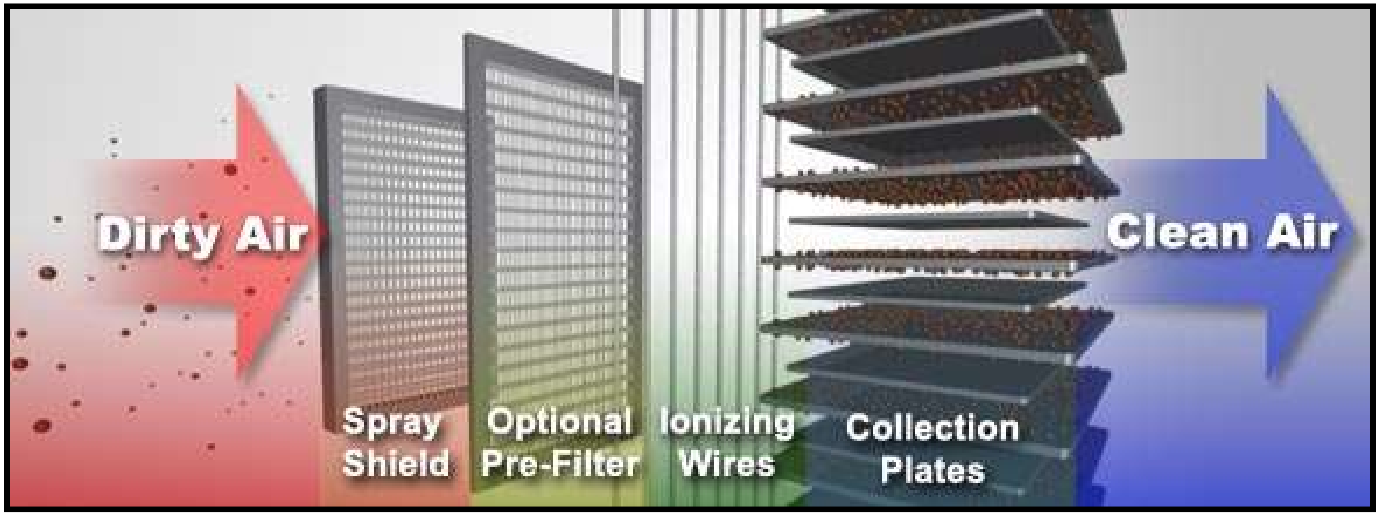
Electrostatic Precipitators (ESP)

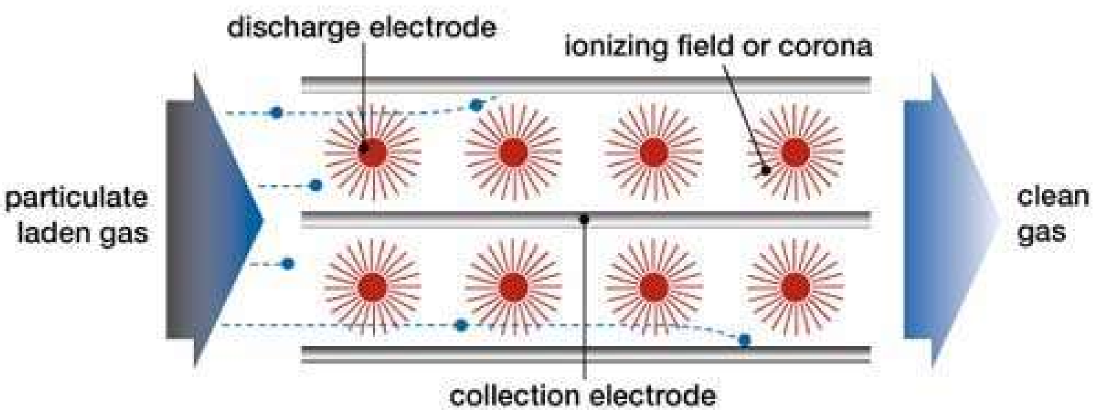




- *Principle*: Electrodes at high voltage create a corona effect (ionized atmosphere) surrounding them
- This charges the passing particles
- Once charged, particles are subject to a transverse electrostatic force that pulls them toward the collecting plates
- Plates are periodically “rapped” (vibrated) to make the collected particles fall down into a receiver basket

Electrostatic Precipitators (ESP)





- Removal>98%, all sizes
- Little pressure drop, low O&M cost, but expensive
- Occupy large space
- Plate area requirement depends on required efficiency

Air Pollution Control - Gases

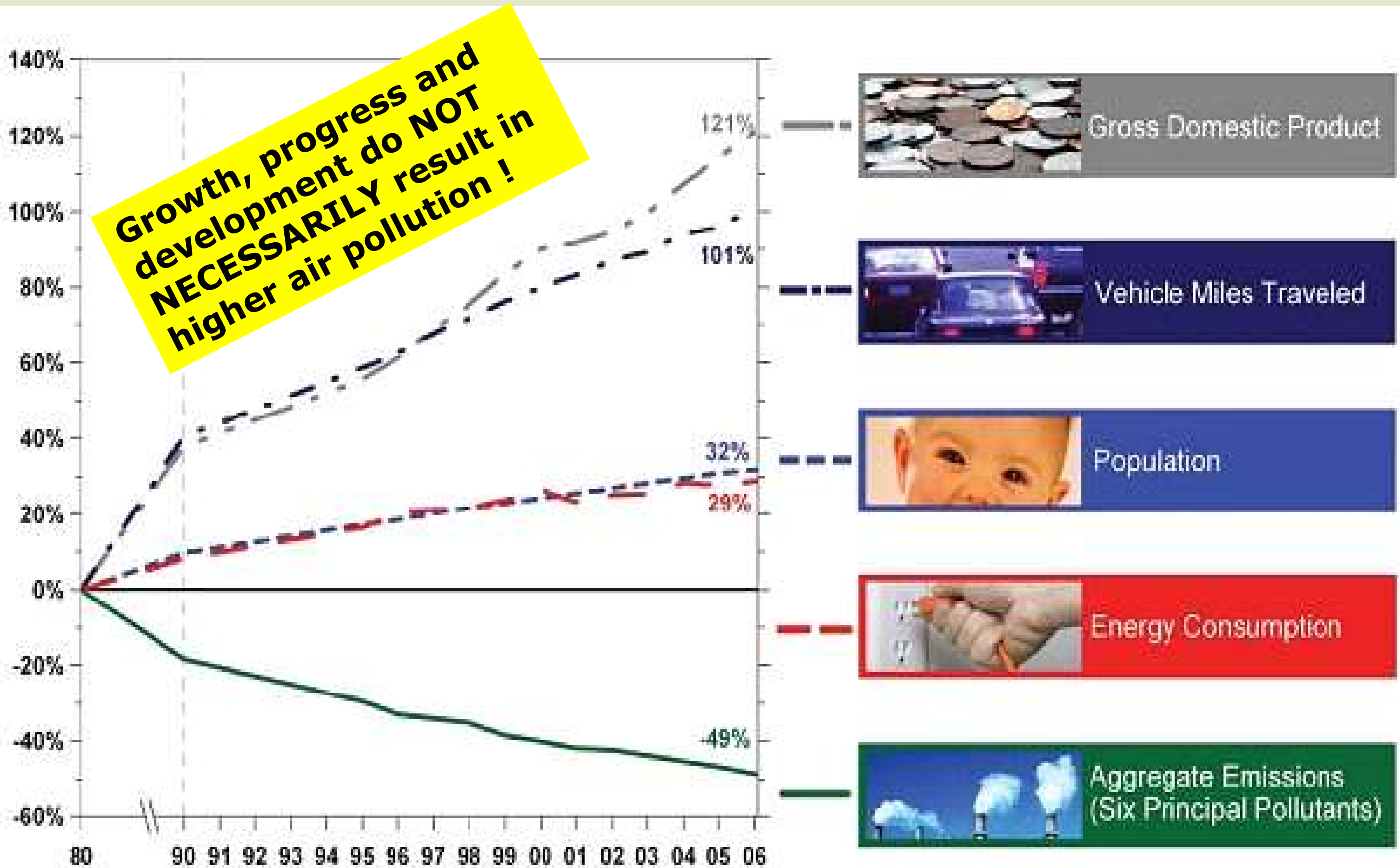
- Absorption/ Adsorption
- Incineration
- Chemical Reactions
  - Catalysts: e.g. selective catalytic reduction (SCR) for NO_x control; NH_3 is injected into boiler flue gas and the mix is passed through a catalyst bed where NO_x is reduced to N_2:

    $$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6H_2O$$

  - Flue gas desulfurisation: Finely pulverized limestone ($CaCO_3$) is mixed with water to create a slurry that is sprayed into the flue gas; about 90% SO_2 can be captured:

    $$CaCO_3 + SO_2 + 2H_2O \longrightarrow CaSO_3.2H_2O + CO_2$$

Air quality policies do matter !



From Lecture slides, Prof. Nino Künzli, SwissTPH, Basel, 2012
Adapted from Masters and Ela, 2008

Good luck for the ES 200 end-sem exam !!!

Mon, 11.Sep, 17:30-20:30