CE 435: Environmental Pollution Management

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Level-4, Term II

CN-6

Department of Civil Engineering

Bangladesh University of Engineering and Technology (BUET)

Air Pollution

Air Pollution Control

Natural Atmospheric Cleansing Processes

The atmosphere has self-cleansing processes like rivers and streams. Major processes at work in the atmosphere are:

(1) Dispersion: by this process pollutants are mixed with air and their concentration is reduced (this is not actually removal mechanism).

(2) Dry Deposition: involves settling and impaction of particulates/ aerosols on surfaces. Processes involved include:
- **Gravitational settling;**
- **Flocculation and subsequent settling; and**
- **Adsorption.**

(3) Wet Deposition: Removal of pollutants/ particulates by the action of rain, snow, fog and mist.

Close to ground, "dry deposition" is the principal removal mechanism; whereas at altitudes above 100 m, "wet deposition" is the predominant removal mechanism.

Engineering Control of Air Pollution

(1) Control for receptors:

e.g., gas masks

(2) Control directed to atmosphere:

e.g., use of tall stacks to emit pollutants above inversion layer, to reduce ground level concentration

(3) Control at the source of emission:

usually the most effective means of control

Control at the Source of Emission

Broadly classified into three groups:

(1) Substituting fossil fuel by less polluting energy sources (e.g., solar energy, hydropower).

(2) Proper use and maintenance of existing plant/ machinery/ equipment/ vehicle (e.g., a properly maintained automobile can reduce HC and CO emissions by 20 to 50%).

(3) Installing control equipment at the source of emission (most widely used method of controlling emission at source).

Industrial Emission:
Control Devices for Particulate Contaminant

Can be divided into 5 major groups:

(1) Gravitational Settling Chambers

(2) Centrifugal Collectors:
- **(a) Cyclones**
- **(b) Dynamic precipitators**

(3) Wet Collectors:
- **(a) Spray towers**
- **(b) Wet cyclone scrubbers**
- **(c) Venturi scrubbers**

(4) Electrostatic Precipitators

(5) Fabric Filters

(1) Gravitational Settling Chamber

- Provide enlarged areas to minimize horizontal velocities and allow particulates to settle out.
- Usually velocity through chamber is between 0.3 to 2.5 m/s.
- Usually effective for removal of particles > 50 μm in size.
- Simple in design and operation, but require relatively large space for installation and have relatively low efficiency, especially for removal of smaller particles.

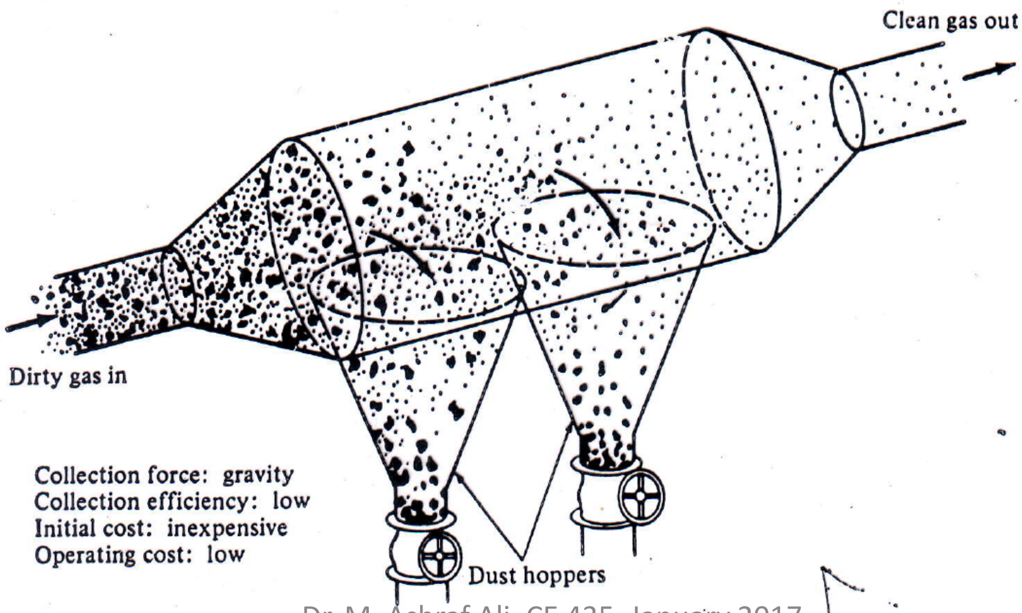


Figure 9-1 Gravitational settling chamber. (*From U.S. EPA* [9-15].)

(1) Gravitational Settling Chamber (contd.)

<u>Calculation of minimum diameter of a particle that would be collected/removed at 100% theoretical efficiency in a chamber of length L and height H:</u>

Terminal settling velocity (v_t) of a particle can be described by Stoke's Law as follows:

$$v_t = \frac{g(\rho_p - \rho_a) d_p^2}{18\mu} \quad \text{.....................} (1)$$

where,

v_t = terminal settling velocity (m/s)

g = acceleration due to gravity (m/s^2)

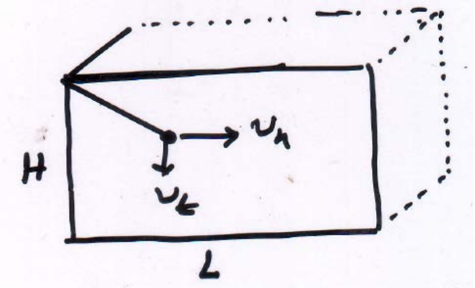
ρ_p = density of particle (kg/m^3)

ρ_a = density of air (kg/m^3) (= 1.2 kg/m^3, at sea level)

dp = diameter of particle (m)

μ = viscosity of air ($N.s/m^2$; kg/m.s)

(1) Gravitational Settling Chamber (contd.)



v_h = horizontal velocity (assumed to be same everywhere in the chamber)

Assume that if a particle settles to the bottom of the chamber, it stays there.

For a particle to settle within the Chamber,

$$L/v_h = H/v_t$$

$$\therefore\ v_t = (H.\ v_h)/L$$

$$\therefore\ (H.\ v_h)/L = [g\ (\rho_p - \rho_a)dp_*^2]\ /\ [18\mu]$$

Since, $\rho_p >> \rho_a$, $(\rho_p - \rho_a) = \rho_p$

$$\therefore\ dp_* = \left(\frac{18\mu\, v_h . H}{g\, \rho_p\, L}\right)^{1/2} \quad \cdots\cdots\cdots (2)$$

All particles with a settling velocity larger than dp_* in Eq. 2 will be removed at 100% efficiency, while removal efficiency of smaller particles will be equal to the ratio of their settling velocities to the settling velocity of dp_*.

Eq. 2 is valid for quiescent conditions, which cannot be maintained in a flow-through chamber. Hence, a correction factor (usually 2) is often used.

(1) Gravitational Settling Chamber (contd.)

Fractional collection/ removal efficiency of particle of diameter dp (where, dp < dp$_*$) can be written as follows:

$$\eta = \frac{L \cdot g \cdot dp^2 \cdot \rho_p}{H \cdot v_x \cdot 18\mu} \quad \ldots\ldots\ldots\ldots (3)$$

(1) Gravitational Settling Chamber (contd.)

Example 1. **Calculate the minimum size of particle that will be removed with 100% theoretical efficiency in a settling chamber under the following conditions:**

Air: **Horizontal velocity = 0.3 m/s**
Temperature = 77 °F
Particle: **Specific gravity = 2.0**
Chamber: **Length = 7.5 m; Height = 1.5 m**

At 77 °F, viscosity of air $\mu = 2.1 \times 10^{-5}$ kg/m.s

(1) Gravitational Settling Chamber (contd.)

Example 2. **Calculate the fractional removal efficiency (theoretical) of 20 μm particles in the above chamber.**

(2) Centrifugal Collectors

- Employ centrifugal force instead of gravity to separate particles from the gas stream.
- Particles ranging from 5 to 20 μm can be removed.
- Two general types of centrifugal collectors are used – Cyclones and Dynamic precipitators.

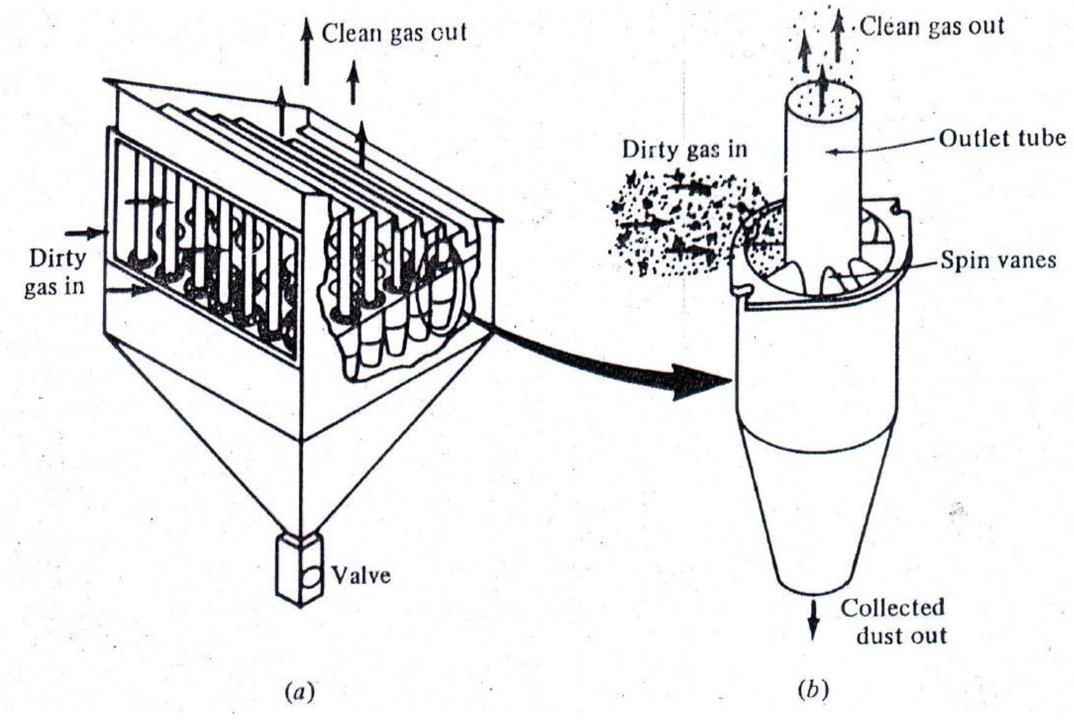


Fig. Cyclones arranged in parallel: (a) multiple cyclone; (b) collector element

(3) Wet Collectors

Wet collectors, or scrubbers, remove particulate matter from gas streams by incorporating the particles into liquid droplets directly on contact.

(4) Electrostatic Precipitators

Particulates moving through a region of high electrostatic potential tend to become charged and are then attracted to an oppositely charged area where they can be collected.

(5) Fabric Filter

Particulate laden gas stream passes through a woven or felted fabric that filters out the particulate matter and allows the gas to pass through.

Typical simple “fabric filter” baghouse

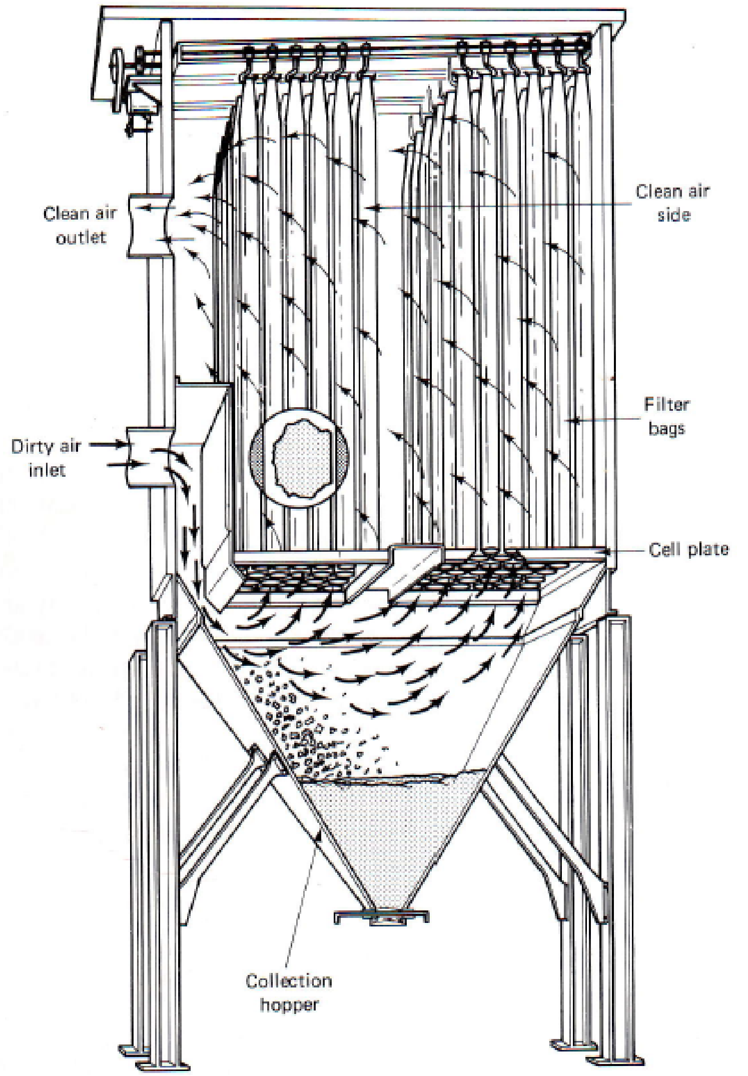


Figure 7.42 Typical simple fabric filter baghouse. (*Source:* Courtesy Wheelabrator Air Pollution Control.)

Industrial Emission: Control of Gaseous Pollutants

Two processes are commonly employed:

(1) Adsorption: passing a stream of effluent gas through a porous solid material (the adsorbent) contained in an adsorption bed. Types of adsorbent include: Activated carbon; Alumina; Silica gel, etc.

(2) Absorption: involves bringing pollutant gas in contact with a liquid absorbent (solvent) so that one or more constituents of the pollutant gas are removed, treated or modified. Types of absorbents include: Aqueous solutions of alkalis and alkaline earth metals (Ca and Mg)

Control of Vehicular Emission

Vehicle engine types:

The 4-stroke internal combustion (IC) engine has been the power source for over 99% of autos and small trucks ever built.

Other common engines:

- **Two-stroke engine**
- **Diesel engine**

Schematic of 4-stroke IC Engine

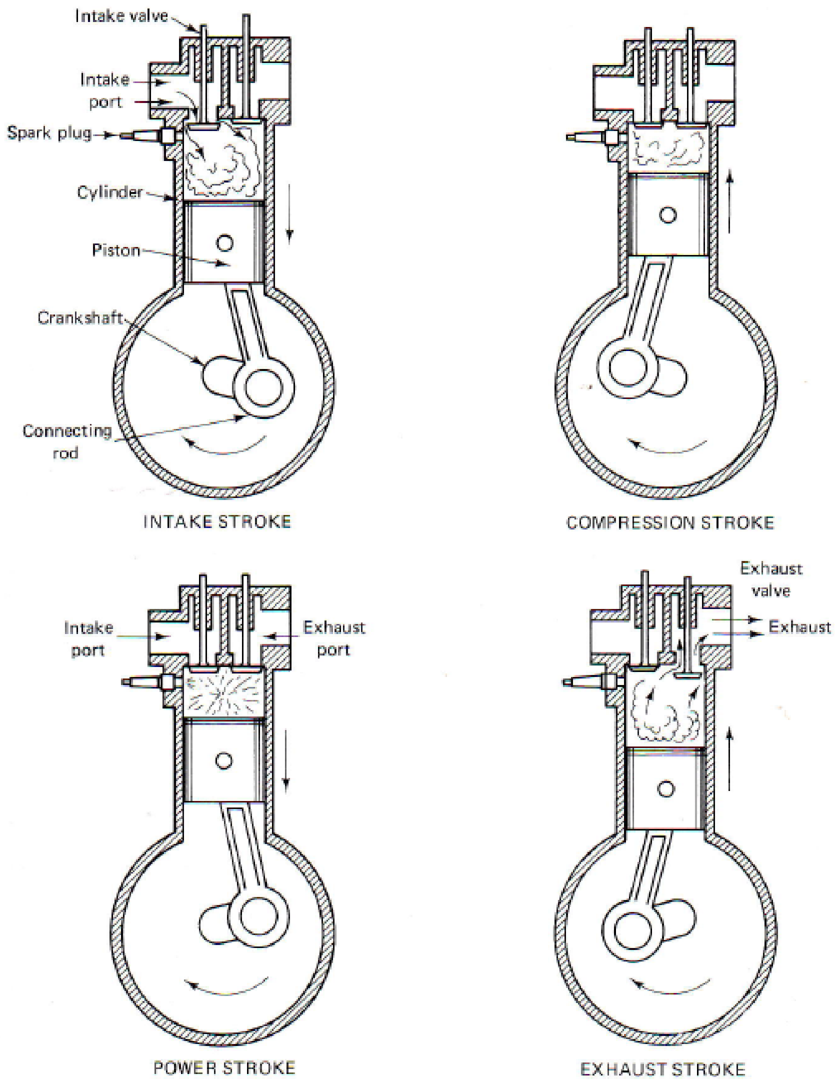


Figure 7.43 Schematic of a four-stroke, spark-ignited internal combustion engine. *Intake:* Intake valve open, piston motion sucks in fresh air/fuel charge. *Compression:* Both valves closed, air/fuel mixture is compressed by rising piston, spark ignites mixture near end of stroke. *Power:* Air fuel mixture burns, increasing temperature and pressure, expansion of combustion gases drives pistons down. *Exhaust:* Exhaust valve open, spent gases are pushed out of cylinder by rising piston. (Powell and Brennan, 1988.)

Factors Affecting Emission from 4-stroke IC Engines

The single most important factor in determining emissions from an internal combustion (IC) engine is the "ratio of air to fuel" or "A/F ratio".

Consider average composition of fuel to be: C_7H_{13}
For complete combustion, 1 mole of the fuel requires 10.25 moles of O_2, which is taken from air.
Molar ratio of "O" and "N" in air = 3.76
Ignoring other gases in air, we can write:

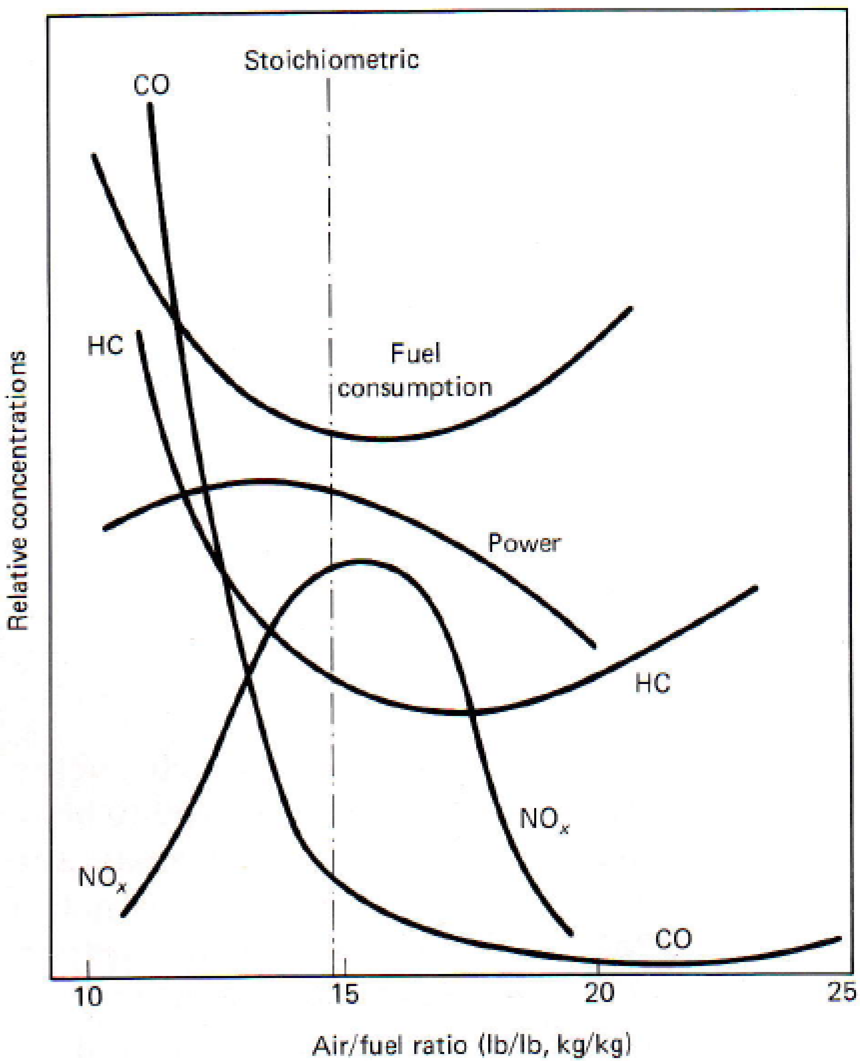
$$C_7H_{13} + 10.25\ O_2 + 38.54\ N_2 \rightarrow 7\ CO_2 + 6.5\ H_2O + 38.54\ N_2$$

Considering air to be made up of only O_2 and N_2, the air fuel ratio needed for complete oxidation of fuel:

$$\text{A/F Ratio} = (10.25\ O_2 + 38.54N_2\})/\ (C_7H_{13})$$
$$= (10.25x16x2 + 38.54x14x2)\ /\ (7x12 + 13X1) = 14.5$$

This A/F ratio (i.e. air to fuel ratio) for complete combustion is known as the "Stoichiometric ratio" for the fuel.
If actual air-fuel mixture has less air than what the "stoichiometric ratio" indicates, the mixture is said to be "rich" (i.e., rich in fuel).
If more air is provided than necessary, the mixture is said to be "lean" (i.e., lean in fuel).

Effect of A/F Ratio on Emission



- **A "rich" mixture encourages production of CO and unburned HC, since there is not enough O_2 for complete combustion.**
- **For "rich" mixtures, lack of O_2 lowers combustion temperature, reducing NO_x emissions. In the other direction, beyond a certain point, "lean" mixtures may have enough excess air that the dilution lowers combustion temperature and reduces NO_x emission.**
- **Also, maximum power is obtained for a slightly "rich" mixture, while maximum fuel economy occurs with slightly "lean" mixtures.**

Emission Control from IC Engines:
Combustion Emission

(A) Combustion Process Control:

(A.1) Controlling A/F ratio: Lean burn:

To reduce CO and HC emissions, the engine should be operated at a "lean" A/F mixture (i.e. high A/F ratio); this also promotes fuel economy.

However, this kind of operation normally puts the engine near the NO_x peak (see Fig.).

Because of the apparent opposite effect of A/F ratio on the 3 pollutants (CO, HC, NO_x), it is not possible to reduce all three pollutants solely through modification in A/F ratio.

(A.2) Exhaust Gas Recirculation (EGR):

In this process, the incoming combustion air is diluted with up to 20% of "exhaust gas".

EGR reduces the peak flame temperature and the O_2 content of burned gas by simple dilution with a gas (i.e. "exhaust" gas) that is mostly nitrogen, CO_2 and water. Both these effects lower the NO_x formation.

Emission Control from IC Engines:
Combustion Emission

B. Post Engine Control:

(B.1) Thermal Reactor:

A "thermal reactor" is basically an after-burner that encourages the continued oxidation of CO and HC after these gases have left the combustion chamber.

Exhaust gases are kept hot enough and enough O_2 is provided to allow combustion to continue outside the engine itself, thus reducing CO and HC emissions.

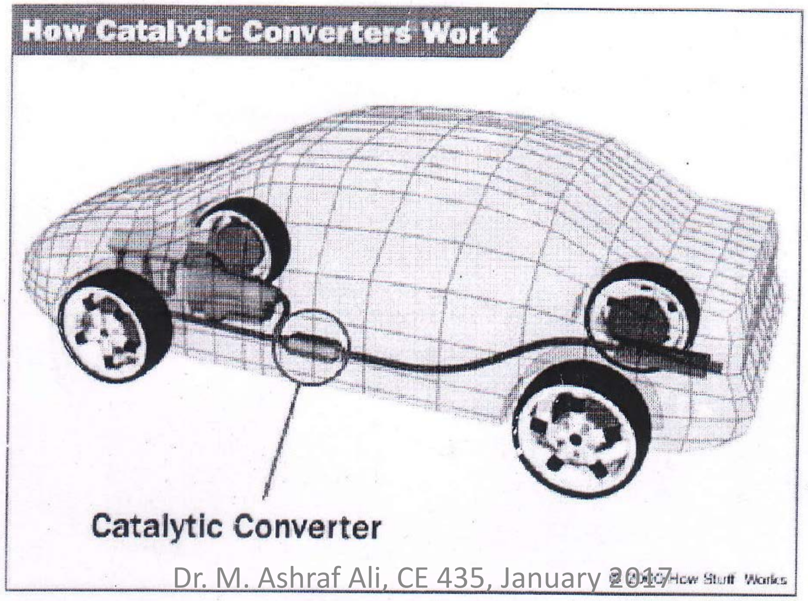
Usually the system is designed to cause the engine to run "rich" in order to provide sufficient unburned fuel in the reactor to allow combustion to take place. This has the secondary effect of modestly reducing NO_x emissions, although it increases fuel consumption (due to use of "rich" mixture).

(B.2) Catalytic Converters:

Most auto manufacturers have concluded that they cannot meet emission standards by engine modification alone. The approach most favored by auto manufacturers has been the "catalytic converter".

Catalytic converters are connected to a car's exhaust system (see Fig.).

Catalysts used include: Platinum (Pt), Rhodium (Rd), and Palladium (Pd) [about 4 – 5 g/converter].



(B.2) Catalytic Converters (contd.):

<u>Two way catalytic converter (catalysts: Pt, Pd):</u>

Oxidizes HC and CO to CO_2

$$CO + O_2 \rightarrow CO_2$$

$$HC + O_2 \rightarrow CO_2 + H_2O$$

<u>Three way catalytic converter (catalysts: Pt, Pd, Rd):</u>

Oxidizes HC and CO to CO_2; reduces NO_x to N_2

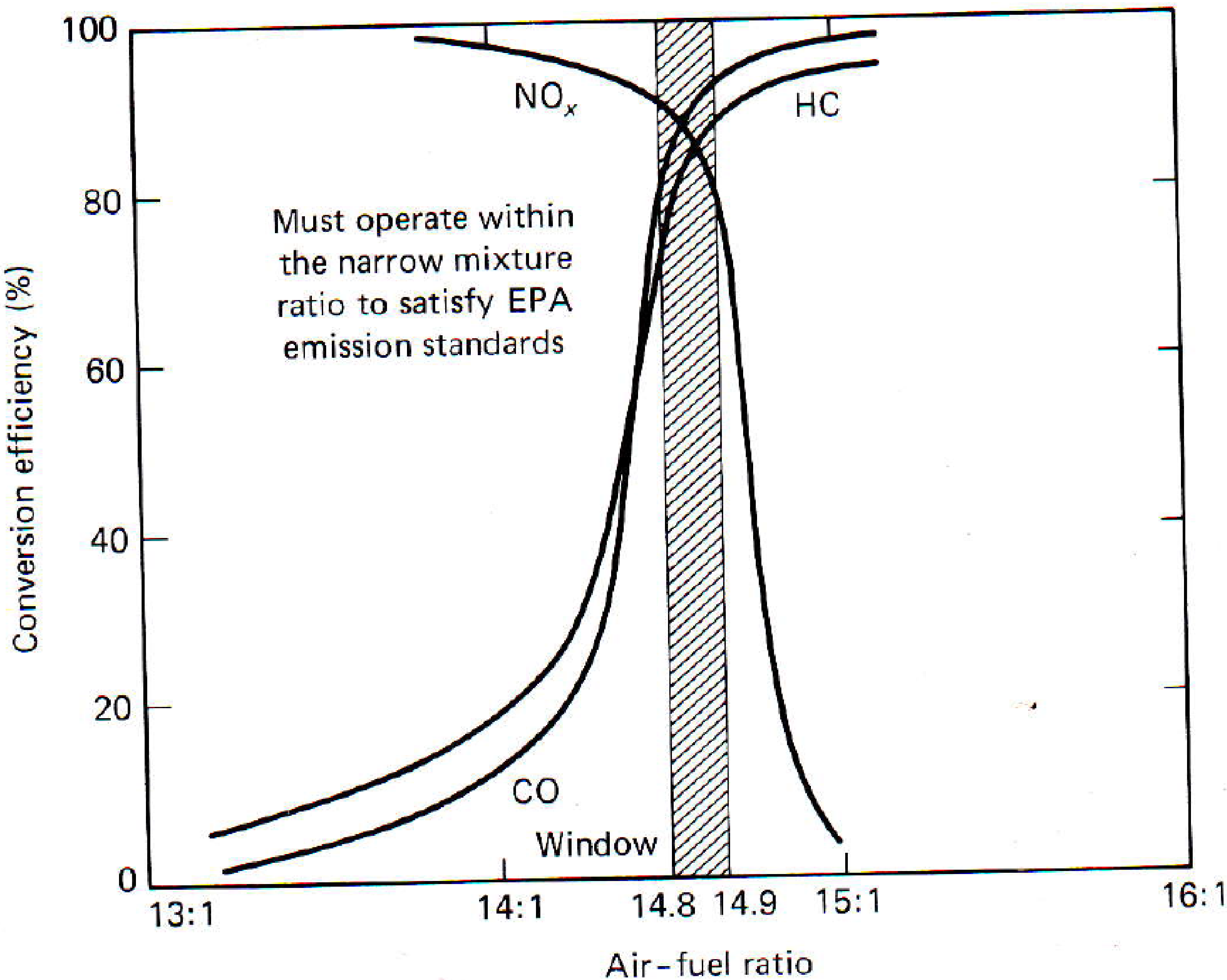
$$NO_x \rightarrow N_2 + O_2$$

(B.2) Catalytic Converters – Not a "magic box"

- **Catalytic converters start working effectively s they get warm above 250 – 300 °C. The reactions are exothermic. Converter material should be able to withstand up to 1000 °C. Generally heat-shields are used to protect other parts of vehicle body.**
- **Unleaded (Pb-free) fuel is essential to prevent "fouling" of catalytic converters.**
- **Catalytic converters must operate within a narrow band of A/F ratio:**
  - **If A/F ratio is > 14.9, conversion of NOx to N2 is reduced significantly (see Fig.).**
  - **If A/F ratio is < 14.8, conversion of HC and CO to CO2 is reduced significantly (see Fig.).**

This requires precise electronic control systems that monitor and control air-fuel mixture in the engine.

(B.2) Effect of A/F ration on conversion efficiency of a Converter



Emission Control from IC Engines:
Combustion Emission

(C) Alternative Vehicle Technology:

- Fuel cell vehicle
- Electric vehicle
- Hydrogen fuelled vehicle
- Hybrid vehicle
- Battery powered vehicle

Emission Control from IC Engines:
Combustion Emission

(D) Alternative Fuel:

- **Compressed natural gas (CNG)**
- **Liquefied petroleum gas (LPG)**
- **Methanol (CH_3OH)**
- **Ethanol (C_2H_5OH) – produced from fermentation of crops**
- **Propane**
- **Hydrogen**