Department of Civil Engineering
College of Engineering
King Saud University

GE 302 – Industry and the Environment

Air Pollution and Control

- Air is necessary for the survival of all higher forms of life on earth. On the average, a person needs at least 13 kg of air every day to live, but only about 1.4 kg of water and 0.7 kg of food.
- Scientific studies have demonstrated that over the long term, the standard of health for people living and working in **urban areas** is lower than that for populations in **rural areas**, where air pollution is much less severe.
- There is much scientific evidence of a distinct relationship between generally **dirty air** and a higher incidence of **respiratory diseases**, including lung cancer.
- There is also compelling evidence that air pollution has a significant and lasting worldwide (global) impact on the **Earth's climate**.

Atmospheric Layers

Atmospheric layers is divided into **5 layers,** based on increase or decrease of temperature with altitude.

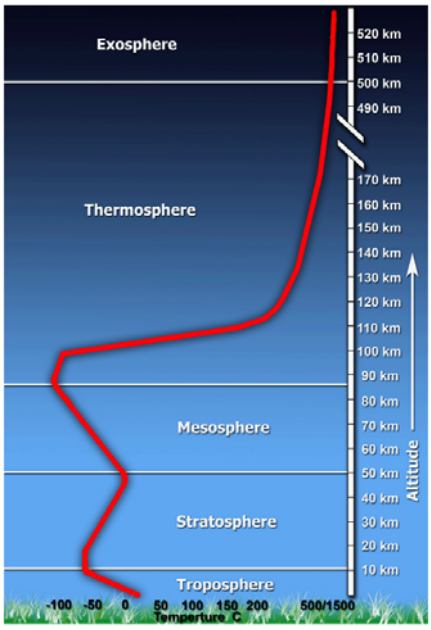
Exosphere

Thermosphere

Mesosphere

Stratosphere

Troposphere



Composition of the Atmosphere

- **Dry air in the troposphere** (the lowermost atmospheric layer) is a mixture of molecular of:
  - **78 % Nitrogen** by volume
  - **21 % Oxygen** by volume
  - **1 % Other gases**: argon(about 0.9 %), carbon dioxide, methane, and water vapor.
- The relative amount or concentrations of gases in air can be expressed in terms of **parts per million** (ppm) and in terms of **percentage**.
- For example, since **1 % = 10,000 ppm**, an oxygen level of 21 % in air can also be expressed as 210,000 ppm.
- The concentration of carbon dioxide (CO_2) in the atmosphere, now close to 0.04%, may be more conveniently expressed as 400 ppm.

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- The troposphere, contains about 80 % of the total air mass.
- It is in this relatively thin layer of air that oxygen-dependent life is sustained, clouds are formed, weather patterns develop, and most air pollution problems occur.
- The density of air (about 1.23 kg/m^3 at sea level) decreases significantly with an increase in altitude.
- **Troposphere** is about on average 12 km depth

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Effects of Weather

- Air pollutants are mixed, dispersed, and diluted within the troposphere by movement of air masses, both horizontally and vertically.
- Air movements and therefore air quality are very dependent on local and regional weather conditions.
- Knowledge of horizontal and vertical circulation patterns of air is of importance with regard to:
  - –site selection for new industrial plants.
  - –design of tall stacks or chimneys.

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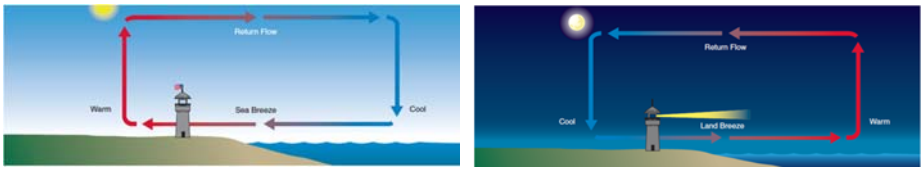
Horizontal Dispersion of Pollutants

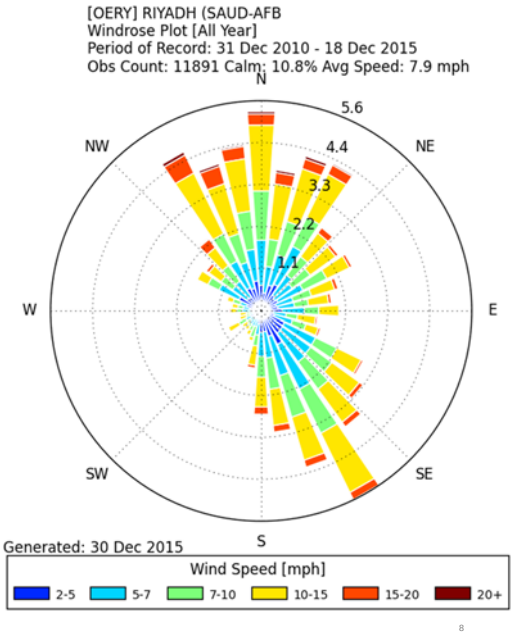
- Horizontal dispersion or spreading of air pollutants depends on wind speed and direction.
- Because soil and rock warm up and cool faster than water, winds near shorelines are directed toward the water at night and inland during the day.
- In an urban area, where steel, concrete, and masonry absorb and hold heat, a heat island cover the city at night, with a self-contained circulation pattern from which pollutants cannot readily escape.



Sea breeze and land breeze wind circulation pattern

Wind Rose of Riyadh

- The wind rose indicates the frequency with which the wind blows from a given direction (N - North, S - South, E - East, W - West).
- For example, a wedge directed straight up (N) and extending 3 rings means that the wind blows from the North 30% of the time



Vertical Dispersion of Pollutants

- Vertical mixing of air and dispersion of pollutants depends on the kind of atmospheric stability prevailing at any given time.
- The atmosphere is considered to be **stable** when there is **little or no vertical movement** of air masses and therefore little or no mixing and dispersion of pollutants in the vertical direction.
- An **unstable atmosphere**, on the other hand, is one in which the **air moves naturally in a vertical direction**, increasing mixing and dispersion of the pollutants.
- With regard to local or regional air quality, a condition of atmospheric instability is preferable to a stable condition.

Vertical Dispersion of Pollutants

- **Air stability** depends on the **rate of change of air temperature with altitude**, called the temperature gradient.
- The rate at which air temperature drops with increasing altitude in the troposphere is called the **environmental lapse rate**.
- The **dry adiabatic lapse rate** is the lapse rate of a dry mass of air which expands and cools as it rises. This rate is typically -10 °C per 1 km (or **-1 °C per 100 m**).
- Dry adiabatic lapse rate is independent of the prevailing atmospheric temperature gradient at any given time.

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Vertical Dispersion of Pollutants

- When the environmental lapse rate exceeds the adiabatic lapse rate, the atmosphere is unstable and vertical mixing of air masses will occur
- A lapse rate characterized by an increase in air temperature with increasing altitude, called a **temperature inversion**, results in an extremely stable condition.
  - This prevents the upward mixing of pollutants and a major cause of severe air pollution episodes.

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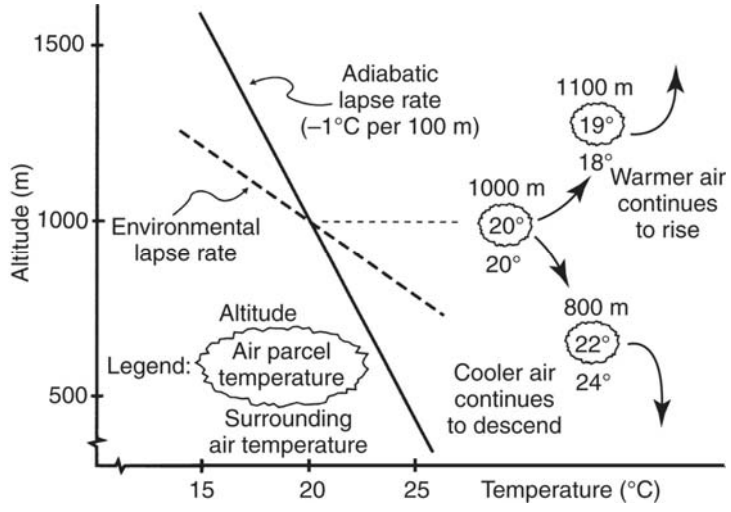

Illustration of unstable atmospheric conditions, when the environmental lapse rate (e.g., –2° per 100 m) exceeds the adiabatic lapse rate. In this example, buoyant forces keep the air parcels moving in a vertical direction.

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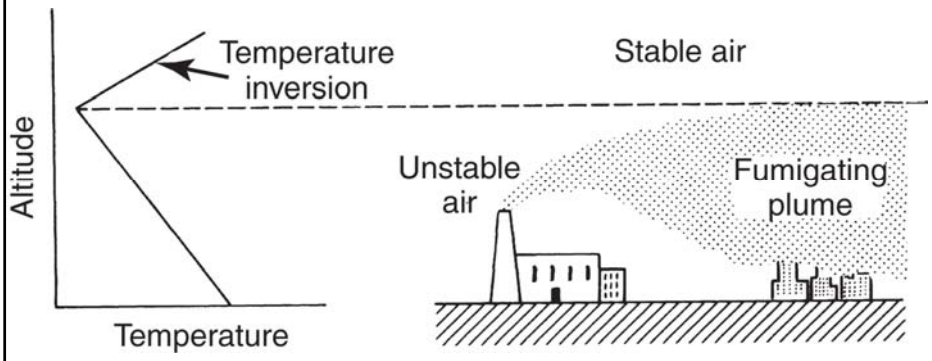

When a **temperature inversion** begins above the ground because of local weather conditions, **it acts as ceiling that prevents further vertical mixing and traps pollutants below it**

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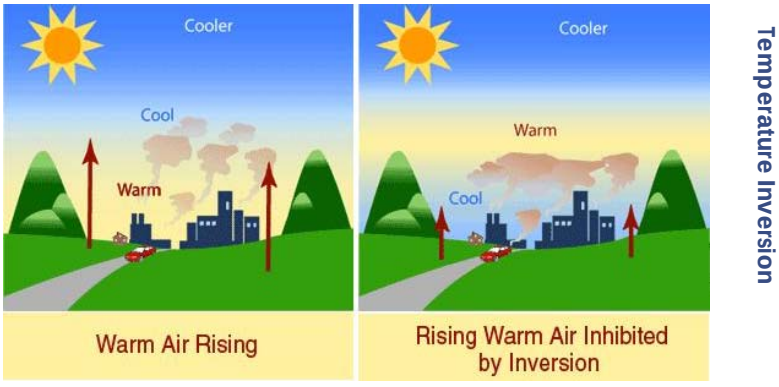

Temperature Inversion

- Trapping of pollutants below the inversion, allowing them to build up.
- If the sky is very hazy, or is sunsets are very red, there is likely an inversion somewhere in the lower atmosphere.
- This happens more frequently in high pressure zones, where the gradual sinking of air in the high pressure dome typically causes an inversion to form at the base of a sinking layer of air.

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Type of Air Pollution

- Air pollution may be simply defined as the presence of **certain substances** in the air in high enough concentrations and for long enough durations to cause undesirable effects.
  - "Certain substances" may be any gas, liquid, or solid
- Based on the sources, air pollutants involves:
  - **Primary pollutants**: are emitted directly into the air from a specific source, such as a power plant stack.
  - **Secondary pollutants**: are not emitted directly from a source but are formed in the atmosphere by complex chemical reactions involving the primary pollutants and sunlight (like ozone).

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- The sources of primary air pollutants are either **mobile** (e.g., automobiles) or **stationary** (e.g., coal-fired electric power generating stations).
- **Criteria air pollutants** that are regulated in many countries are:
  - **Sulfur dioxide (SO_2)**
  - **Nitrogen oxides (NO_x)**
  - **Carbon monoxide (CO)**
  - **Particulates matter (PM)**
  - **Lead (Pb)**
  - **Ozone (O_3)**
- All the criteria pollutants tend to harm human health, diminish environmental quality, and damage property.

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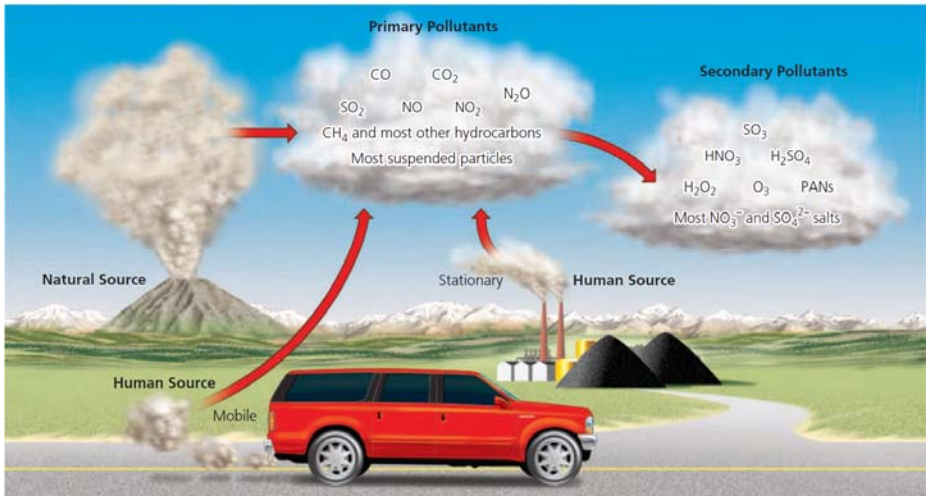

Human inputs of air pollutants come from **mobile sources** (such as cars) and **stationary sources** (such as industrial, power, and cement plants). Some **primary air pollutants** react with one another and with other chemicals in the air to form **secondary air pollutants**.

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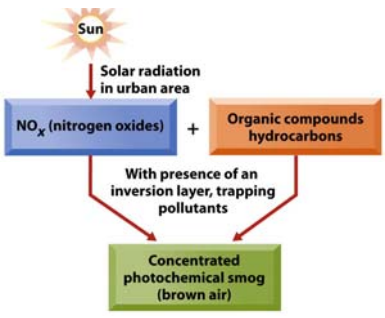
- **Sulfur dioxide**, a colorless gas with a sharp, choking odor,
  - comes primarily from fossil fuel combustion at electric power plants.
  - It is one of the causes of acid rain.
- **Nitrogen dioxide**, a pungent irritating gas
  - it is also caused by combustion of fossil fuels
  - can react in sunlight with hydrocarbons to form **photochemical smog**.

Photochemical smog, Santiago, Chile



- **Carbon monoxide** is a colorless and odorless gas
  - **CO** is a product of incomplete combustion, is the most abundant of the criteria pollutants
  - it comes largely from **highway vehicle emissions and residential heating systems**.
  - It reduces the ability of blood to transfer oxygen to body cells, and at high concentrations, it can be acutely toxic.

- **Particulates** are extremely small fragments of solid or liquid droplets suspended in air.
  - Major sources of particulates include industrial materials handling processes, coal- and oil-burning power plants, residential heating systems, and highway vehicles.
  - Particulates that penetrate deep into the lungs are harmful, and certain particulates can be toxic or carcinogenic (cause cancer)

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- **Particulates**
  - consider that the average human hair is about 65 µm in diameter
  - PM smaller than 1 µm tend to remain suspended in the atmosphere indefinitely, whereas those larger than 1 µm can eventually settle out.
  - The particulate materials of most concern with regard to adverse effects on human health are **equal to or less than 10 µm** in size and are referred to as **PM10**
  - Fine particles, those with diameters **equal to or smaller than 2.5 µm** (**PM2.5**) are of special concern because they are more likely to penetrate deep into the lungs when inhaled.

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- **Lead** fumes, emitted primarily by petroleum refining and smelting operations, are also toxic.

- **Ozone**, a secondary pollutant (i.e., not emitted directly but formed in the atmosphere), is an irritating gas and also a key component of photochemical smog

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Hazardous Air Pollutants

- Air pollutants associated with **certain specific sources**, and that pose an **immediate threat to human health**, are called **air toxics** or **hazardous air pollutants** (HAPs) examples are:
  - **Asbestos**
  - **Benzene**
  - **Beryllium**
  - **Mercury**
  - **Vinyl chloride**
  - **Radionuclides** (radioactive air pollutants)

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Gases Concentration Measurement

- Concentration of air gaseous pollutants in air are mostly expressed in volumetric terms

$$\frac{1 \text{ volume of gaseous pollutant}}{10^6 \text{ volume of air}} = \mathbf{1\ ppm}\ (\text{by volume})$$

- Sometimes concentrations are expressed as mass per unit volume, such as **µg/m3** or **mg/m3**.
- The relationship between ppm and mg/m3 depends on the **pressure, temperature,** and **molecular weight** (MW) of the pollutant.
- The ideal gas law helps us establish that relationship

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Conversion between ppm and mg/m³

In general, the conversion from ppm to mg/m³ is given by:

$$\mathbf{mg/m^3} = \frac{\mathbf{ppm \times MW}}{\mathbf{22.4}} \times \frac{\mathbf{273.15\ K}}{\mathbf{T\ (K)}} \times \frac{\mathbf{P\ (atm)}}{\mathbf{1\ atm}}$$

Where:

MW = molecular weight of the compound (g/mol)

T = absolute temperature (K) = °C + 273.15

P = absolute pressure (atm) = mmHg/760

$$\mathbf{mg/m^3} = \frac{\mathbf{ppm \times MW}}{\mathbf{22.414}}\ \ \mathbf{(at\ 0\ ℃\ and\ 1\ atm)}$$

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Example_1: The Air Quality Standard for carbon monoxide is 9.0 ppm. Express this standard as a percent by volume and in mg/m^3 at 1 atm and 25 °C.

Solution:

- Within a million volumes of this air there are 9.0 volumes of **CO,** no matter what the temperature or pressure (advantage of the ppm units)

$$\%\ \mathrm{CO} = \frac{9}{10^6} \times 100\ \% = 0.0009\ \%$$

- To find the concentration in mg/m^3, we need the molecular weight of **CO**, which is = 12 +16 = 28

$$\mathrm{mg/m^3} = \frac{\mathrm{ppm} \times \mathrm{MW}}{24.465} \quad (\text{at } 25\ ℃ \text{ and } 1\ \mathrm{atm})$$

$$\mathrm{CO} = \frac{9 \times 28}{24.465} = 10.3\ \mathrm{mg/m^3}$$

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Example_2: Suppose the exhaust gas from an automobile contains 0.75% by volume of sulfur dioxides (SO_2). Express this concentration in mg/m^3 at 29 °C and 1.0 atm pressure.

Solution:

Homework

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Primary and secondary National Ambient Air Quality Standards (NAAQS)

Pollutant	Averaging time	Allowable concentration
$PM_{2.5}$	Annual arithmetic mean	35 $\mu g/m^3$ (primary and secondary)
	24 h	12 $\mu g/m^3$ (primary and secondary)
PM_{10}	24 h	150 $\mu g/m^3$ (primary and secondary)
SO_2	1 h	75 ppb (primary)
	3 h	0.5 ppm (secondary)
CO	8 h	9 ppm (primary)
	1 h	35 ppm (primary)
NO_2	Annual arithmetic mean	53 ppb (primary and secondary)
	1 h	100 ppb (primary)
O_3	8 h	75 ppb (primary and secondary)
Pb	3 mo	0.15 $\mu g/m^3$ (primary and secondary)

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Effects of Ambient Air Pollution

- Air pollution is known to have many adverse effects, including those on:
  - –Human health
  - –Building facades and other exposed materials
  - –Vegetation and agricultural crops
  - –Animals and aquatic habitat
  - –The climate of Earth as a whole
- Generally, air pollution is most harmful to the elderly and to the baby.

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- Major health effects are categorized as being either:
  - **Acute**
    short-lasting, but severe, and may even result in death
  - **Chronic**
    long-term effects usually include respiratory illnesses such as asthma and perhaps lung cancer
  - **Temporary**
    effects include intermittent periods of eye or throat irritation, coughing, chest pain, ...
- Typical effects of sulfur dioxide, oxides of nitrogen, and ozone include eye and throat irritation, coughing, and chest pain.
- A **threshold level** for a given pollutant is a minimum level below which there will be no health effects.

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Worldwide Air Quality Issues

- Air pollution problems are not necessarily confined to a local or regional scale. Atmospheric circulation can transport certain pollutants far away from their point of origin, expanding air pollution to continental or global scales
- **Worldwide air quality issues**:
  - **Acid rain**
  - **Global warming**
  - **Ozone layer depletion**

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Acid Rain

- acid rain, for example, occurs largely on a regional and a continental scale. It has killed fish and plant life in thousands of lakes in Europe, China, Canada, and the northeast United States.
- It also causes deterioration of metals, concrete, painted surfaces, and other exposed objects.
- Acid rain is caused by emission of sulfur and nitrogen oxides, mostly from electric power plants.

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Global Warming

- The current trend of increasing average temperatures is believed by most scientists to be caused by the accumulation of **carbon dioxide** and other greenhouse gases emitted as a result of human activities.
- Global warming may lead to melting of glaciers and a rise in sea levels, as well as adversely affecting ecosystems in some parts of the world

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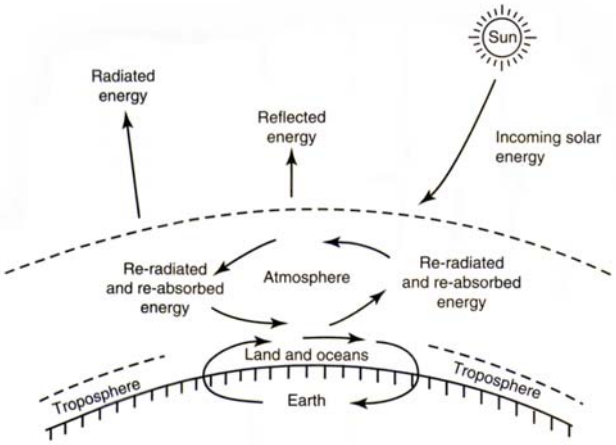
Global Warming



The amount of incoming energy from the sun is in equilibrium with the energy radiated and reflected back into space. The atmosphere acts as a "blanket" that regulates average temperatures at the Earth's surface. The "thicker" the blanket (i.e., the more "greenhouse gases" in the atmosphere), the warmer is the temperature in the lower atmosphere and Earth's surface.

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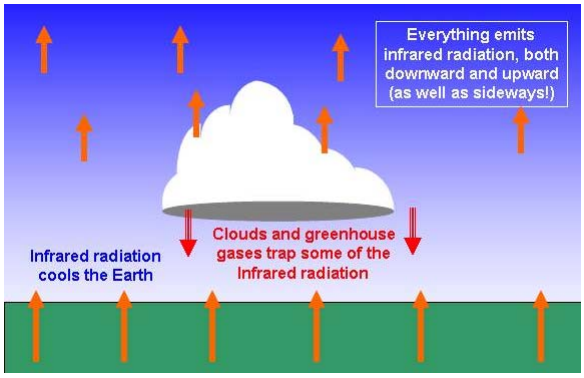
Infrared Radiation (Heat Radiation)



- Infrared (IR) radiation is just as important to the Earth's weather and climate as sunlight is.
- This is because, for all of the sunlight that the Earth absorbs, an equal amount of IR radiation must travel from the Earth back to outer space.
- If this was not the case, there would be global warming or global cooling.

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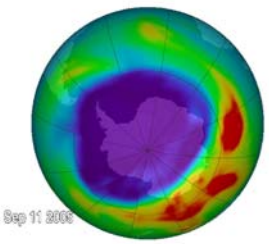
Ozone Layer Depletion

- **Stratospheric ozone** is important because it blocks harmful UV rays from the sun.
- But those ozone levels have been dropping, largely due to the presence of **non biodegradable organic chemicals** such as **chlorofluorocarbons (CFC)** from aerosol cans, refrigerants, and industrial solvents.
- CFC production and use is now banned in many counties.



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Air Quality Index

- To be able to provide the public with timely, easy-to-understand information about outdoor air quality and to evaluate national air quality trends, the Environmental Protection Agency (EPA) publishes a daily Air Quality Index or **AQI**
- EPA uses 5 Major air pollutants to define AQI.
  - Ground level ozone
  - Particulate matter
  - CO
  - SO_2
  - NO_2

Air Quality Index (AQI) Values	Levels of Health Concern
0 to 50	Good
51-100	Moderate
101-150	Unhealthy for Sensitive Groups
151-200	Unhealthy
201-300	Very Unhealthy
301 to 500	Hazardous

Air Quality Index (AQI)

Category and Range

Category	AQI	8-hr O_3 (ppm)	1-hr O_3 (ppm)	24-hr $PM_{2.5}$ (µg/m³)	24-hr PM_{10} (µg/m³)	8-hr CO (ppm)	24-hr SO_2 (ppm)
Good	0 – 50	0.000 – 0.064	—	0 – 15.4	0 – 54	0 – 4.4	0.000 – 0.034
Moderate	51 - **100**	0.065 – 0.084	—	15.5 – 40.4	55 – 154	4.5 – 9.4	0.035 – 0.144
Unhealthy for sensitive	101 - 150	0.085 – 0.104	0.125 – 0.164	40.5 – 65.4	155 – 254	9.5 – 12.4	0.145 – 0.224
Unhealthy	151 - 200	0.105 – 0.124	0.165 – 0.204	65.5 – 150.4	255 – 354	12.5 – 15.4	0.225 – 0.304
Very unhealthy	201 - 300	0.125 – 0.374	0.205 – 0.404	150.5 – 250.4	355 – 424	15.5 – 30.4	0.305 – 0.604
hazardous	301 - 400	Use 1-hr	0.405 – 0.504	250.5 – 350.4	425 – 504	30.5 – 40.4	0.605 – 0.804
hazardous	401 - 500	Use 1-hr	0.505 – 0.604	350.5 – 500.4	505 – 604	40.5 – 50.4	0.805 – 1.004

The **most significant number on the AQI scale is 100**, since this number corresponds to the standards established under the Clean Air Act for each pollutant.

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Example_3:

What AQI descriptor (good, moderate, etc.) should be reported for air quality on the following day?

Pollutant	Concentration
O_3, 1-hr (ppm)	0.15
CO, 8-hr (ppm)	12
$PM_{2.5}$, 24-hr (µg/m3)	130
PM_{10}, 24-hr (µg/m3)	180
SO_2, 24-hr (ppm)	0.12

Solution:

From AQI table:

AQI 151-200 triggered by PM2.5, **Unhealthy**

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Indoor Air Quality

- Indoor air quality (IAQ) is important because people generally spend most of their time indoors.
- Indoor air contaminants include:
  - **combustion products** (especially tobacco smoke)
  - radon
  - asbestos
  - formaldehyde
  - lead
  - biological substances
- **Environmental tobacco smoke** (**ETS**), which contains more than 40 carcinogenic compounds, causes thousands of lung cancer deaths each year in nonsmoking adults

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Indoor Air Quality

- **Radon**, a naturally occurring colorless, odorless, radioactive gas, can enter buildings through porous soil and rock fissures at basement walls and floors.
  - It can be a cause of lung cancer if inhaled for long periods
- **Asbestos**, a mineral fiber used as insulation and as a fire retardant in buildings. It has been banned from Saudi Arabia.
  - It can cause lung cancer if very small airborne asbestos fibers are inhaled.
- **Formaldehyde**, a colorless gas that comes from certain building materials and household products.
  - can cause eye and throat irritation (and maybe cancer)

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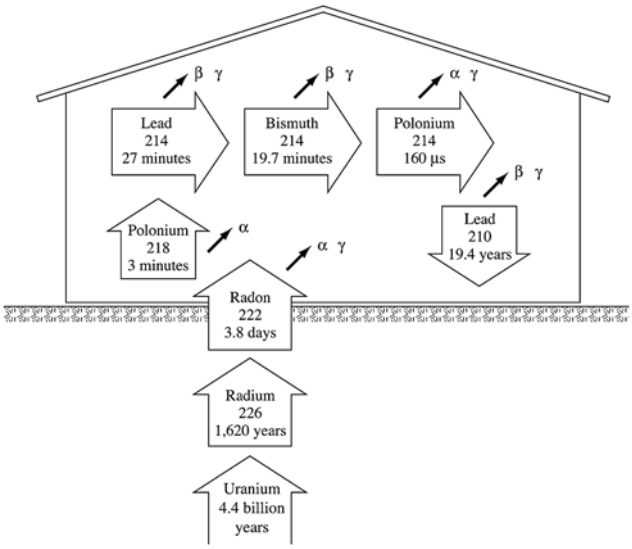

Simplified Uranium decay series, with half-lives and emissions. Radon gas that seeps out of soils can decay inside the buildings

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Indoor Air Quality

- Proper infiltration and ventilation (air exchange) is necessary to minimize levels of indoor air pollutants.
- Indoor Air Quality (IAQ) is a component of the LEED green building certification credits related to indoor environmental quality.

Leadership in **E**nergy and **E**nvironmental **D**esign (LEED)

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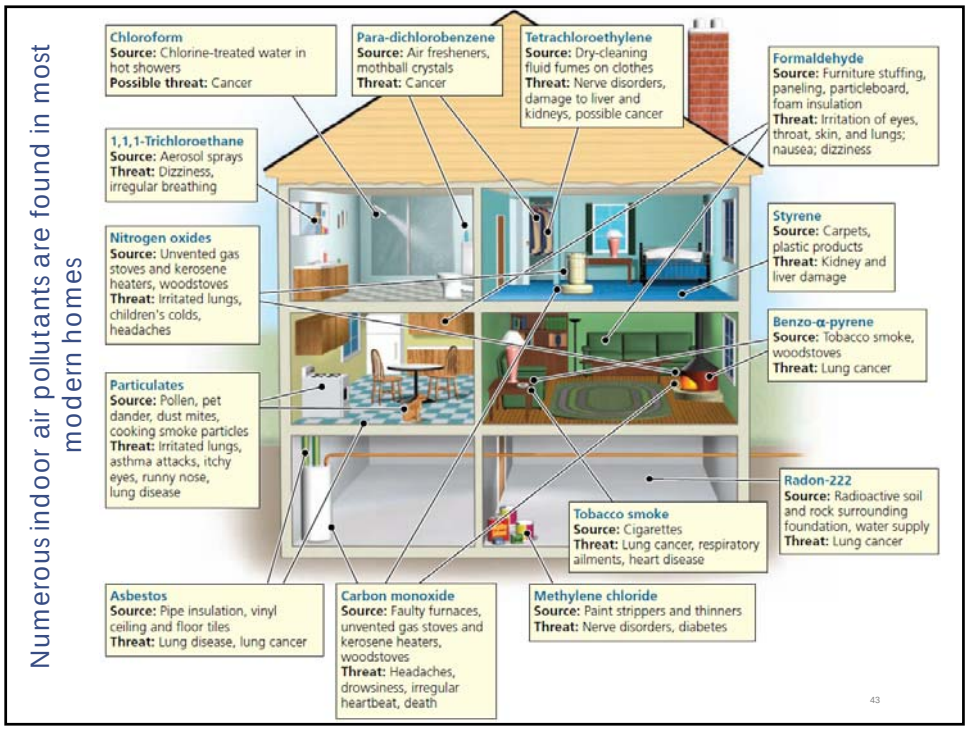

Air Pollution Control

- Air pollution control strategies include:
  - –Complete source shutdown
  - –Source location (or air zoning)
  - –Fuel substitution
  - –Process changes
  - –Enforcement of emission standards for specific sources
- Several types of air cleaning devices can trap air pollutants before they are emitted into the atmosphere.

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Air Pollution Control

- **Particulate matter control equipment** includes:
  - –Gravity settlers
  - –Cyclones
  - –Electrostatic precipitators
  - –Fabric filters
  - –Wet scrubbers
- The selection of control equipment depends on the range of particulate sizes, flow rates, temperatures of the carrier gas, costs, and other factors.
- One of the most efficient of these devices for **removing suspended particulates is the fabric filter** (or **baghouse**)

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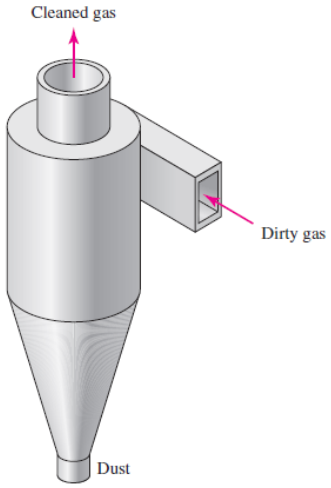
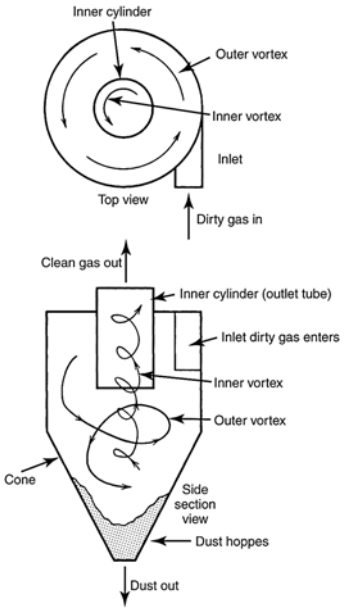
Particulate matter control equipment





Cyclones

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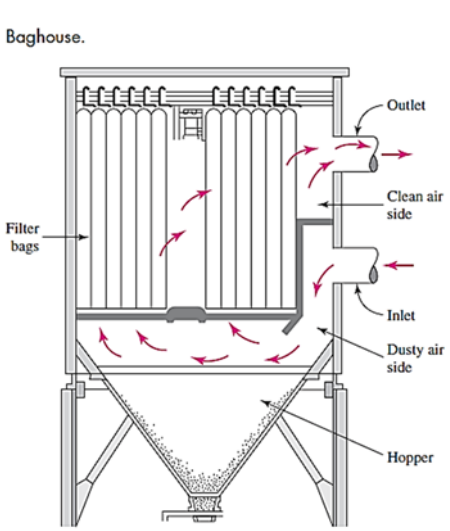
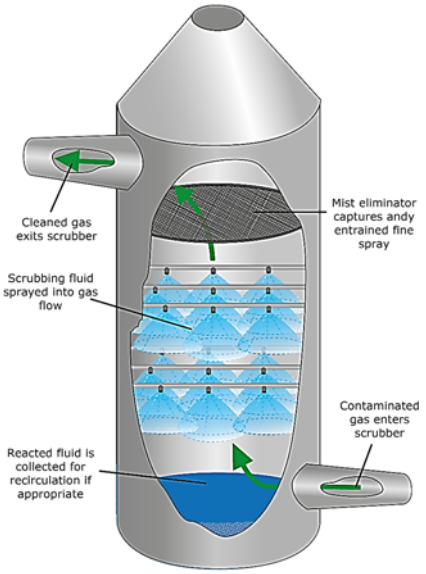
Particulate matter control equipment



Baghouse (Fabric filters)



Wet scrubbers

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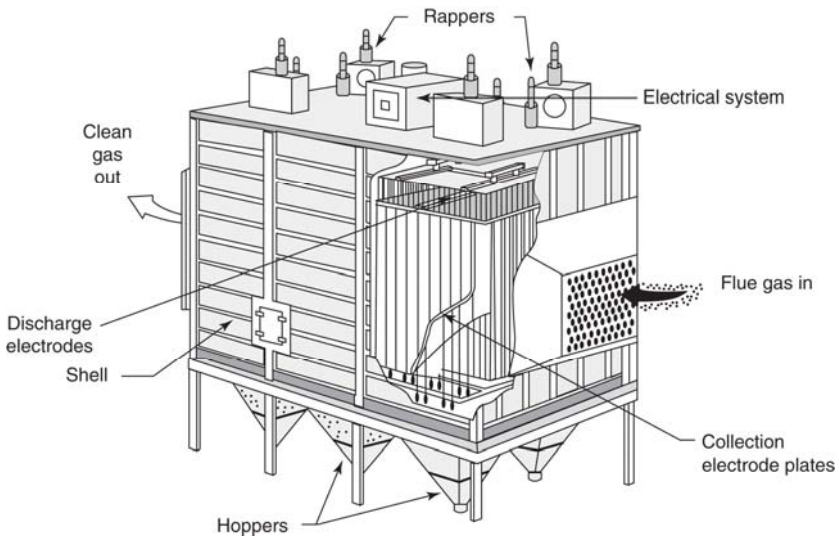
Particulate matter control equipment



Electrostatic precipitators

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Gaseous air pollutants

- Gaseous air pollutants can be controlled using either absorption or adsorption processes.
- **Absorption** involves the transfer of a gaseous pollutant into a contacting liquid.
- **Adsorption** involves attracting and trapping gas molecules onto the surface of a solid (e.g., activated carbon)
- **Wet scrubbers can be used for gas absorption**, as well as packed scrubber towers.
- Emissions from the internal combustion engine, which is a major mobile source of air pollutants, are controlled by positive crankcase ventilation systems and **catalytic converters**.

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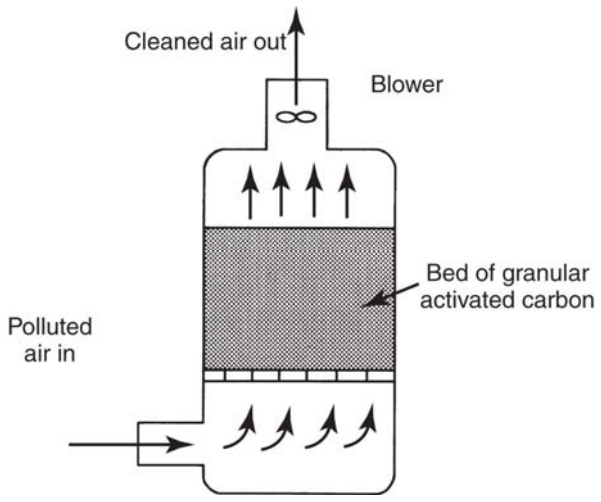

Activated carbon can be used to adsorb certain gaseous air pollutants

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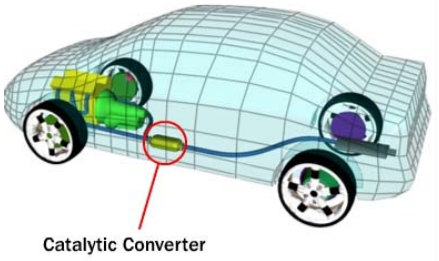
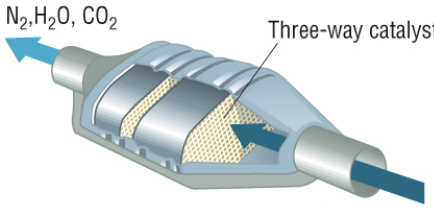
catalytic converters





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