University of Jordan

Department of Chemical Engineering

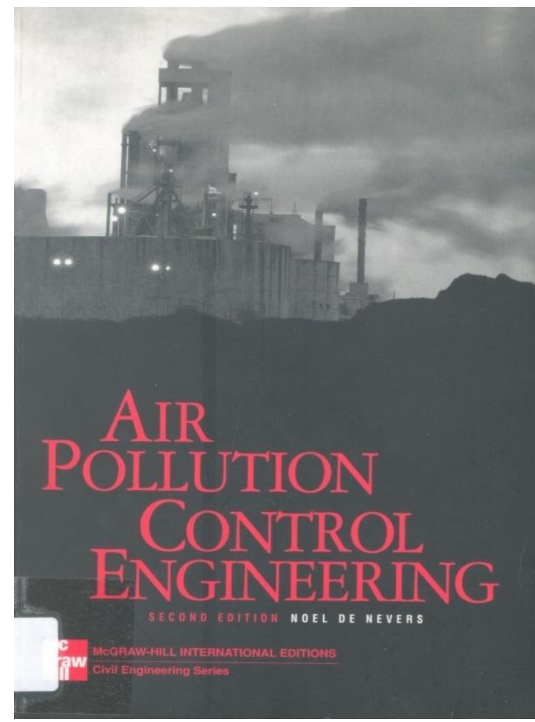
0905475 Air Pollution

Second Semester

2010/2011

Main Reference:

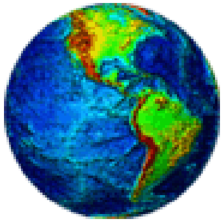
De Nevers, Noel (1995), Air Pollution Control Engineering, McGraw-Hill, New York.

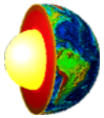


INTRODUCTION

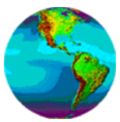
Sept., 28, 2015

The Earth’s Great Spheres

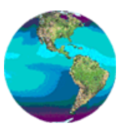




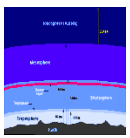
- Lithosphere- The lithosphere contains all of the cold, hard solid land of the planet's crust (surface), the semi-solid land underneath the crust, and the liquid land near the center of the planet



- Hydrosphere- The hydrosphere contains all the solid, liquid, and gaseous water of the planet



- Biosphere- The biosphere contains all the planet's living things. This sphere includes all of the microorganisms, plants, and animals of Earth



- Atmosphere- The atmosphere contains all the air in Earth's system

THE AIR

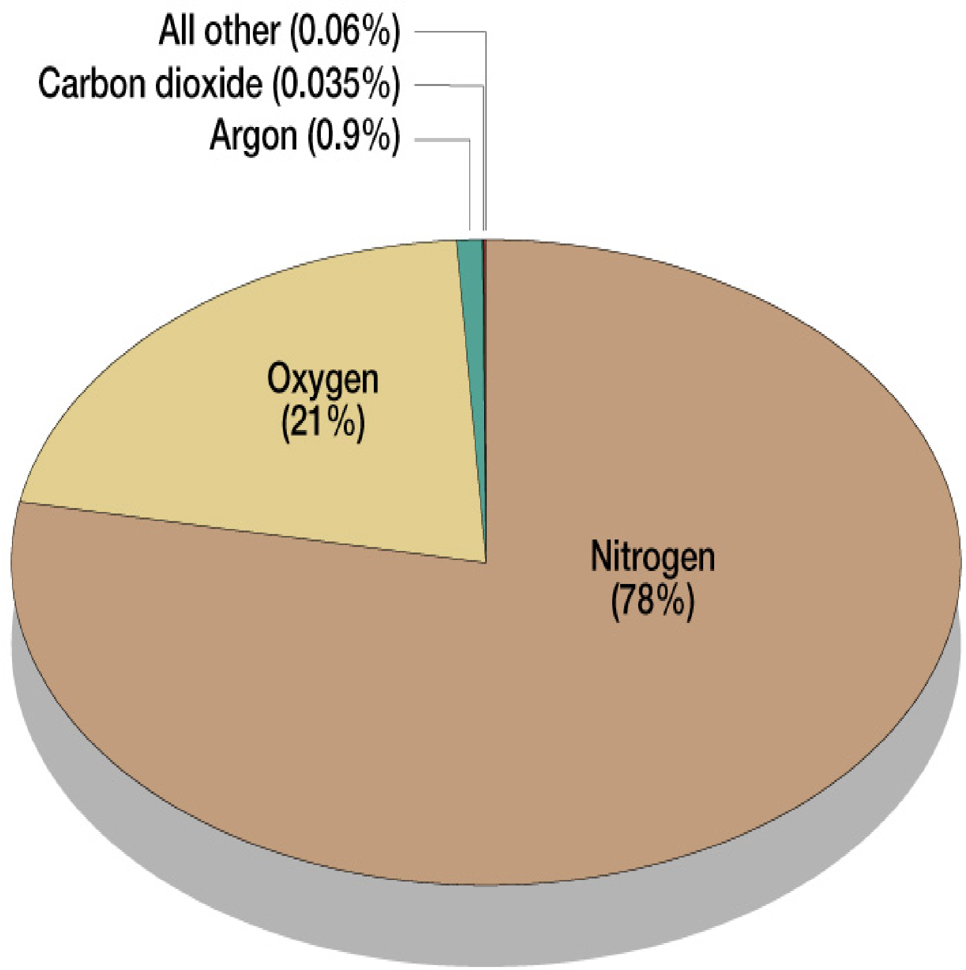
- The air composition in the lower atmosphere is shown next.

- Natural, absorbed air pollution:
  - When forest fires occur, or when natural decomposition takes place, the gaseous by-products, mainly CO_2, are also released to the air.

- Nutrient recycling:
  - Green plants rapidly turns CO_2 into plant mass through photosynthesis so the air's carrying capacity is not permanently reduced by the release of these combustion products.

Composition

- Nitrogen
  - Inert, harmless
- Oxygen
  - Reactive
  - Essential
- CO_2 (greenhouse)
  - Varies slowly
- H_2O
  - Varies constantly



Composition of dry atmosphere, by volume

ppmv: parts per million by volume

Gas	Volume
Nitrogen (N_2)	780,840 ppmv (78.084%)
Oxygen (O_2)	209,460 ppmv (20.946%)
Argon (Ar)	9,340 ppmv (0.9340%)
Carbon dioxide (CO_2)	375 ppmv
Neon (Ne)	18.18 ppmv
Helium (He)	5.24 ppmv
Methane (CH_4)	1.745 ppmv
Krypton (Kr)	1.14 ppmv
Hydrogen (H_2)	0.55 ppmv
Not included in above dry atmosphere:	
Water vapor (highly variable)	typically 1%

Minor components of air not listed above include:

Gas	Volume
nitrous oxide	0.5 ppmv
xenon	0.09 ppmv
ozone	0.0 to 0.07 ppmv
nitrogen dioxide	0.02 ppmv
iodine	0.01 ppmv
carbon monoxide	Trace
ammonia	Trace

- The mean molecular mass of air is 28.97 g/mol.

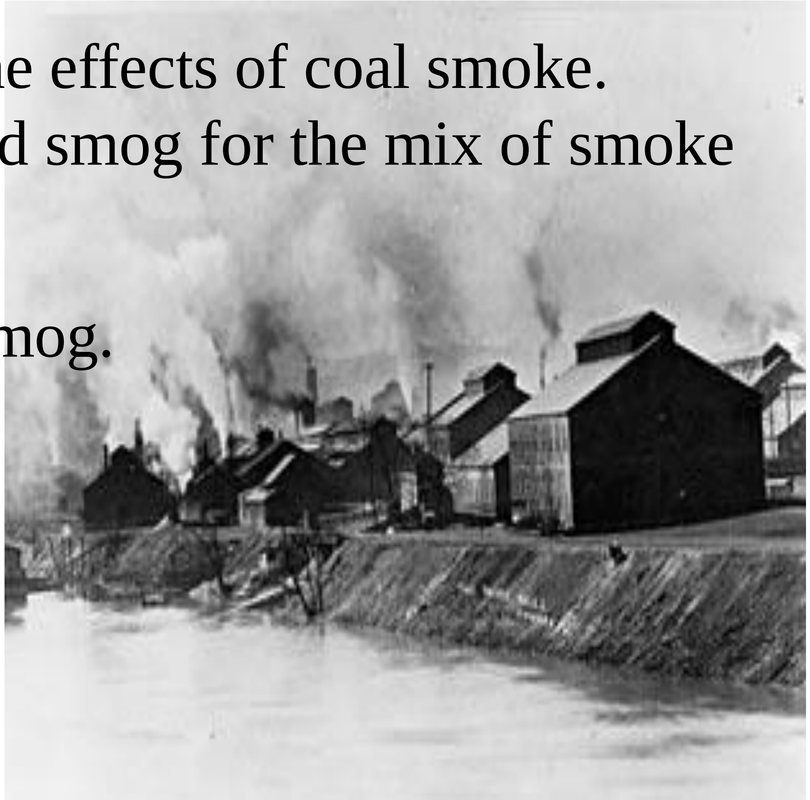
Definition & Causes of AP

1. Air pollution is the presence of undesirable material in air, in quantities large enough to produce harmful effects. This definition does not restrict air pollution to human causes, although we normally only talk about these.
2. The undesirable materials may damage human health, vegetation, human property, or the global environment as well as create aesthetic insults in the form of brown or hazy air or unpleasant smells.
3. Main Causes Air Pollution:
   - High rate of growth in human populations, worldwide industrialization, Widespread use of automobiles, Chemical revolution of the mid-twentieth century, and Expansion and development of non-renewable energy sources.

Examples of Catastrophic Air Pollution

- 1911 in London - 1150 died from the effects of coal smoke. Author of the report coined the word smog for the mix of smoke and fog that hung over London.

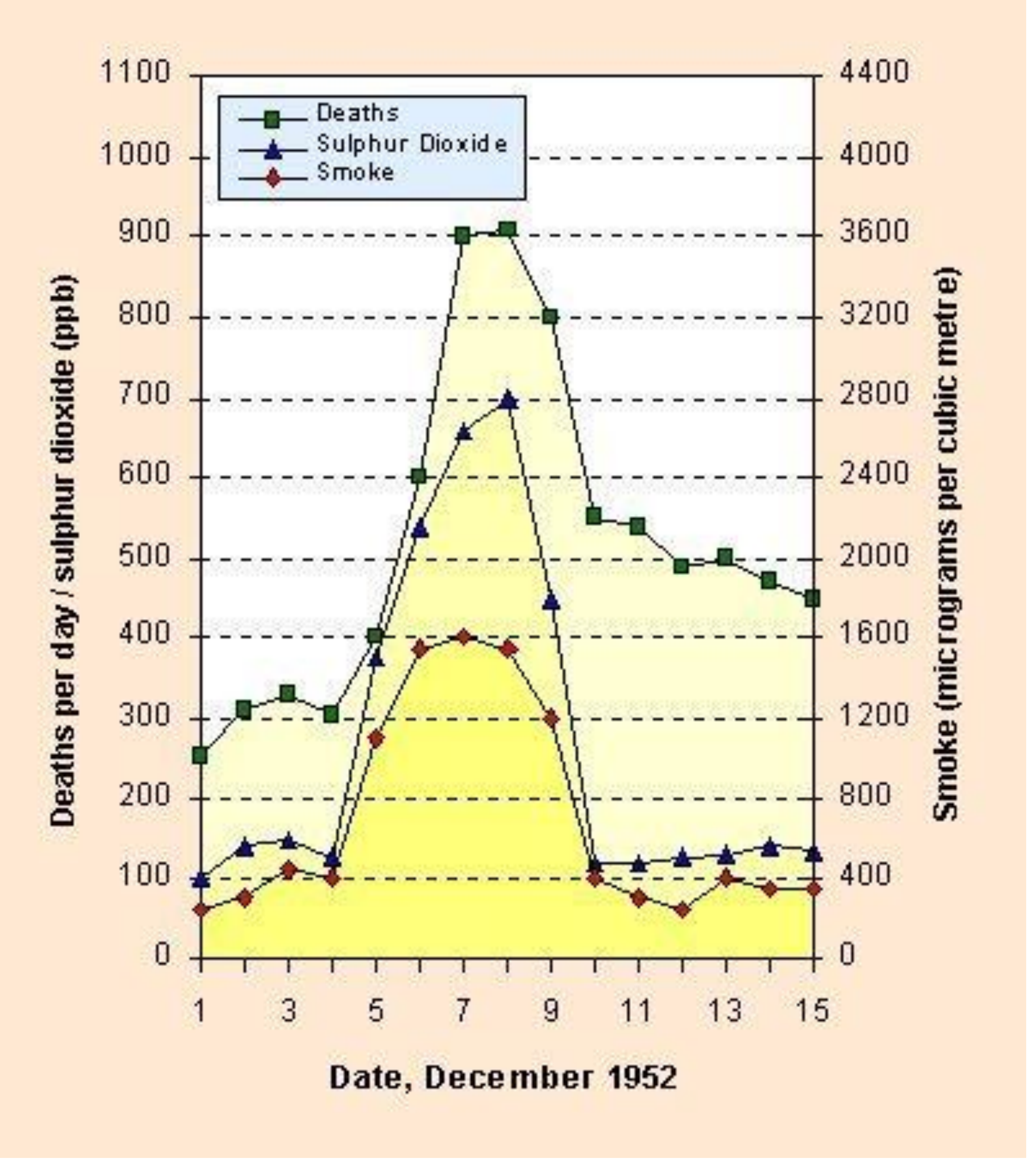
- 1952 in London - 4000 died from smog.



- 1948 in Donora, Penn. Town of 14,000 people - 20 died and 6000 were ill from smog from the community's steel mill, zinc smelter, and sulfuric acid plant.

- 1963 in New York City - 300 people died from air pollution.

London Smog 1952



Types of Air Pollution

1. Personal air exposure
   – It refers to exposure to dust, fumes and gases to which an individual exposes himself when he indulge himself in smoking.
2. Occupational air exposure
   – It represents the type of exposure of individuals to potentially harmful concentration of aerosols, vapors, and gases in their working environment.
3. Community air exposure
   – This is most serious, complex, consists of varieties of assortment of pollution sources, meteorological factors, and wide variety of adverse social, economical, and health effects.

Air Pollution Sources

1. Natural Sources – Volcano, forest fire, dust storms, oceans, plants and trees
2. Anthropogenic Sources – created by human beings
   - Stationary sources
     - Point sources (Industrial processing, power plants, fuels combustion etc.)
     - Area sources (Residential heating coal gas oil, on site incineration, open burning etc.)
   - Mobile sources
     - Line sources (Highway vehicles, railroad locomotives, channel vessels etc.)

AIR POLLUTANTS

Gases: CO, NOx, SOx, VOCs

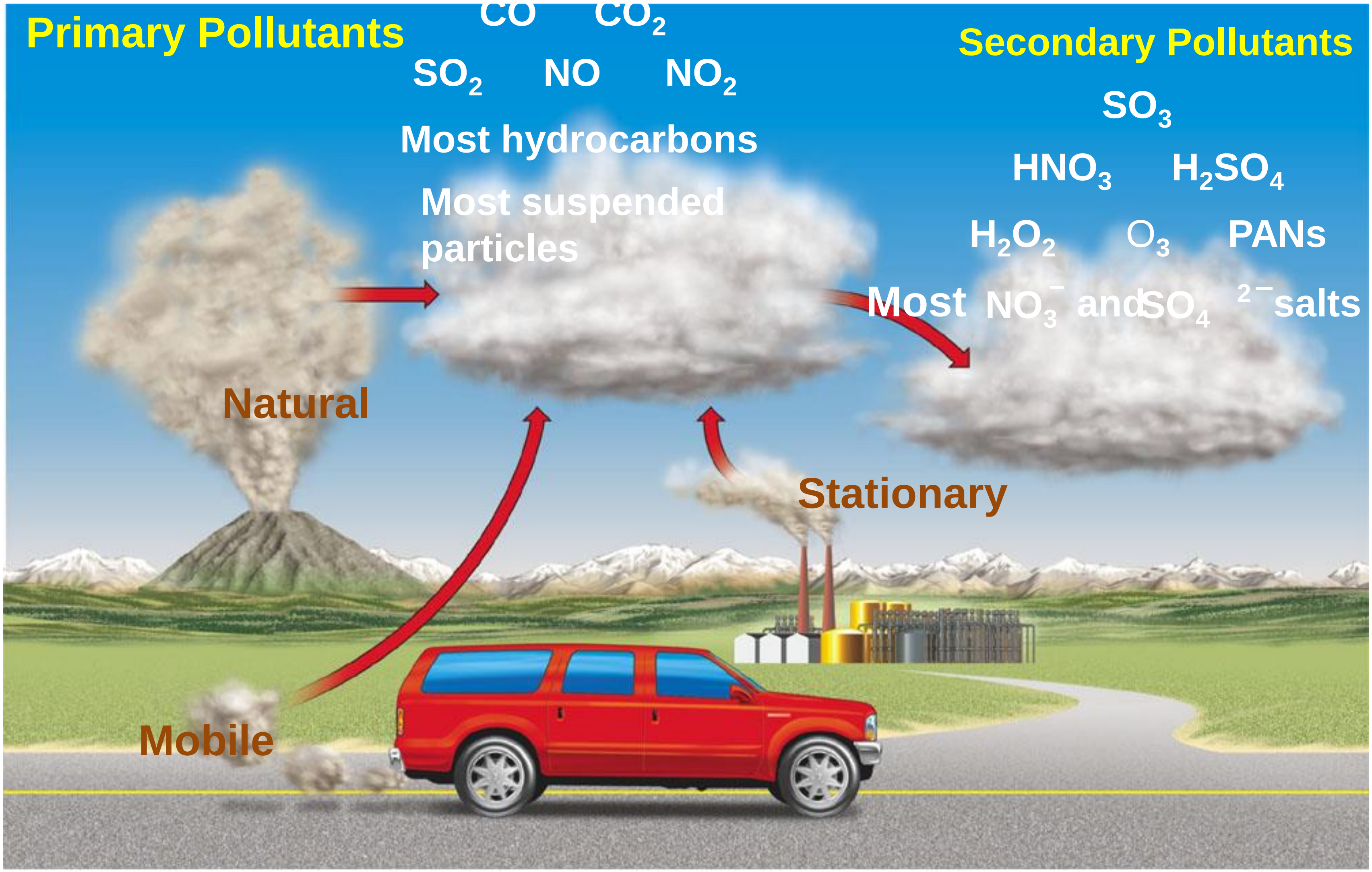
Particulate Matter: PM, PM10, PM2.5, TSP, Pb
ash, dust, smoke, mist

Primary : found in the atmosphere in the same chemical/ physical form as when it was emitted from its source (CO, SO2, some VOCs, some PM)

Secondary : Formed in the air as a result of physical/ chemical transformations of primary pollutants (ground-level ozone, some PM, some VOCs)

Special Category: HAZAP. Control of HAZAP is not based on health criteria, but on Maximum Achievable Control Technology

Air Pollution Sources

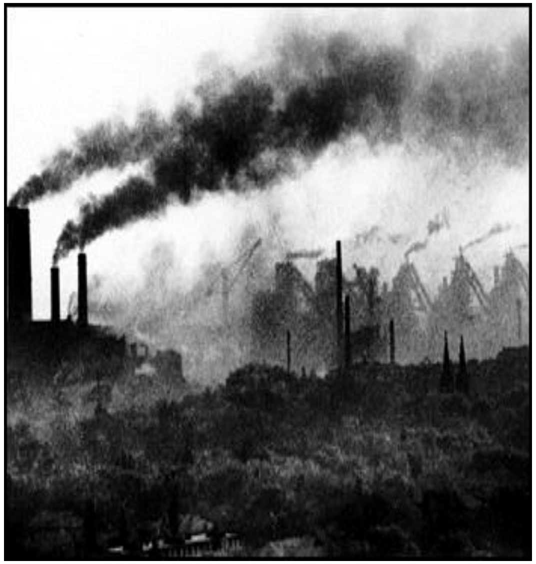


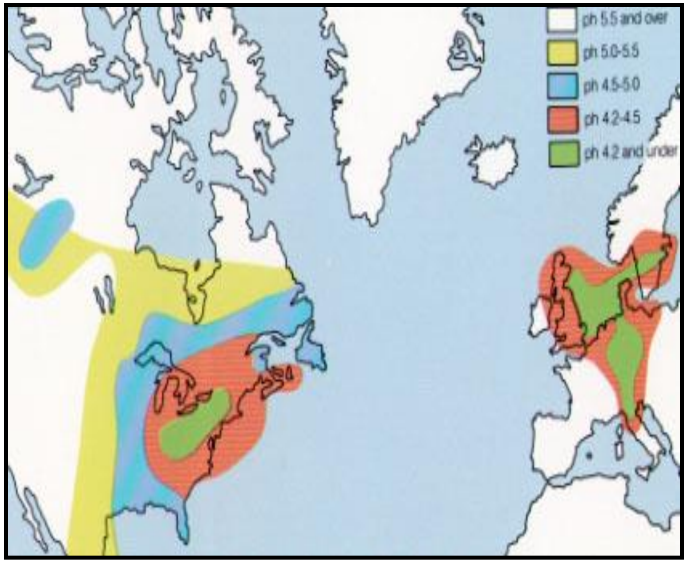
Scales of Air Pollution

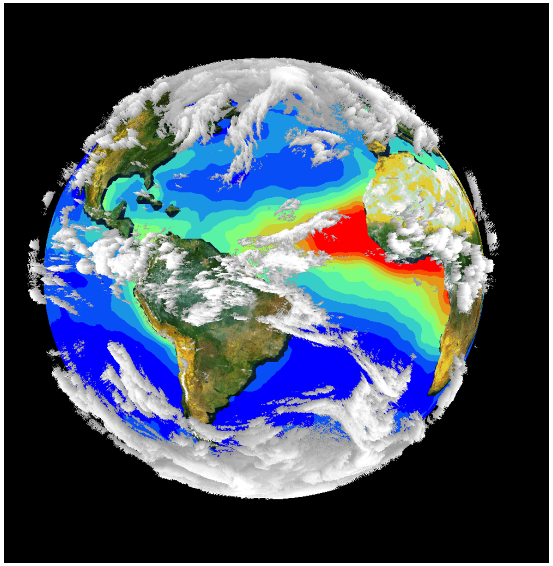
Before 1950s:
Local
Smoke, Fly ash

1970s-1990s:
Regional
Acid Rain, Haze

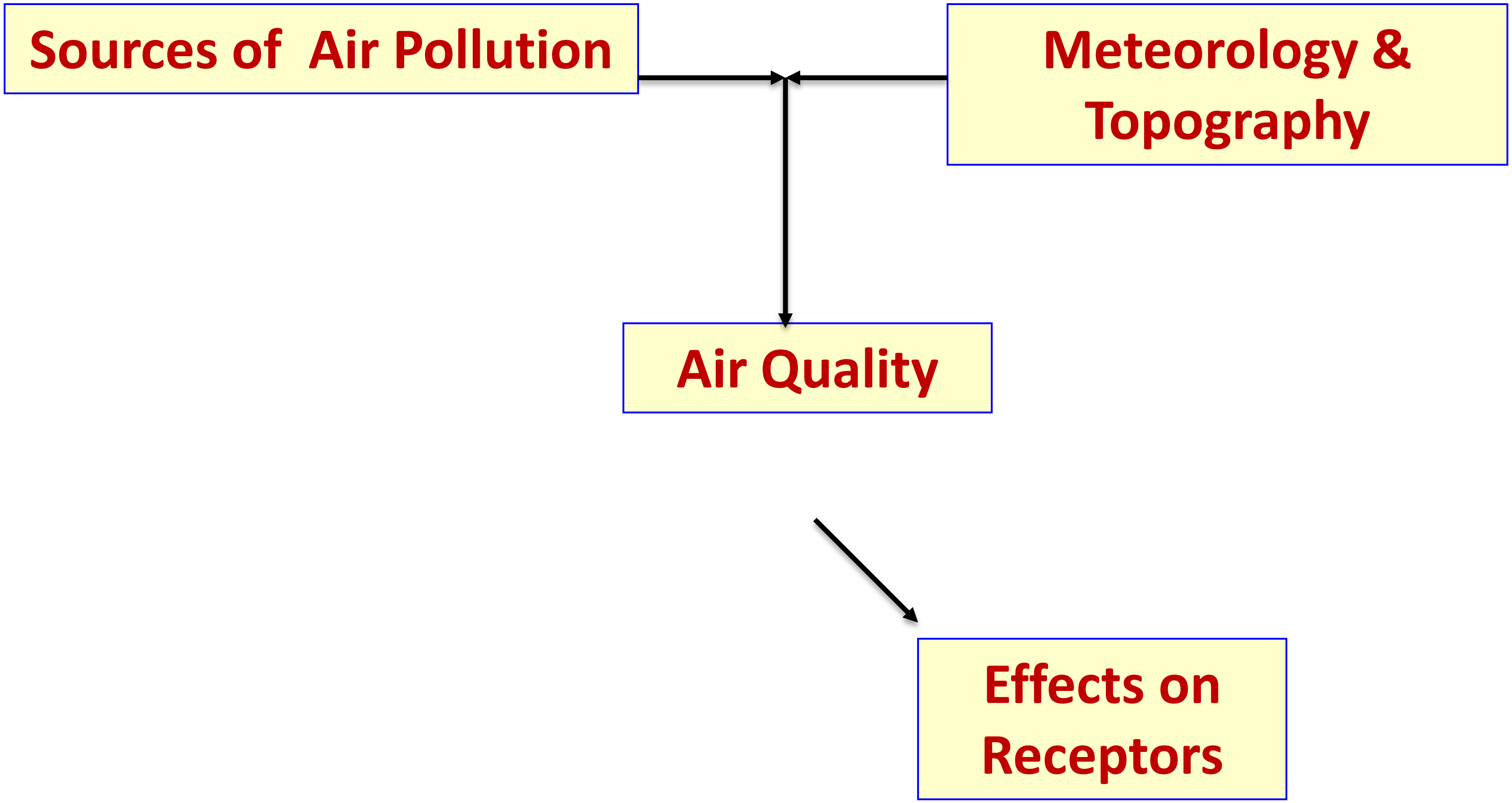
Post- 2000s:
Global
Global Warming







Air Pollution Problem
Based on System Approach



1.1 History of Air Pollution Control

- Although air pollution control actions go back at least as far as the thirteenth century, most of the major effort in the world has taken place since 1945.
- In the 1930s and 1940s, a factory smoke stack issuing a thick plume of smoke was considered a sign of prosperity!
- Before 1945, industrial air pollution control efforts were directed at controlling large-factory emissions of pollutants that had led to conflict with neighbors of the factories and much of this did not involve governmental actions.

1.1 History of Air Pollution Control

- In 1969 and 1970, the United States experienced a great environmental awakening.
- Environmental matters were scarcely mentioned in newspapers in 1968, but the same newspapers had an environmental story every day in 1970.
- This period saw the passage of the National Environmental Policy Act and the Clean Air Act of 1970, both of which have had sweeping effects and have greatly changed American way of dealing with air pollution.
- Similar changes took place throughout the industrial world at about the same time, with similar effects.

1.1 History of Air Pollution Control

- At first the leaders of the older “smokestack” industries (steel, copper, some electric power) fought the new regulations, in the courts, in the press, and in congress.
- Twenty-five years later their successors mostly have decided that the air pollution regulations are here to stay and that their goals should be to influence the regulatory process to make the regulations as clear and practical as possible and then to comply with the regulations in as efficient and economical a way as possible.

1.1 History of Air Pollution Control

- In the late 1980s, a new theme entered the air pollution arena: global air pollution.
- In the 1980s, three problems emerged involving longer-lived pollutants and pollutants that are transported a long way before they do their damage:
  1. acid rain
  2. destruction of ozone layer by chlorofluorocarbons and
  3. buildup of carbon dioxide in the atmosphere.

1.1 History of Air Pollution Control

- The legal and administrative structure developed in the 1970s to deal with local air pollution problems seems useless to deal with these international or global problems.

- The developing countries responded later than the US, and used a mixture of the ideas combined from the US and the World Health Organization, which seek similar goals by somewhat different means.

1.3 DIRTY AIR REMOVAL OR POLLUTION CONTROL?

Example 1.1.

The area of the Los Angeles basin is 4083 square miles. The heavily polluted air layer is assumed to be 2000 ft thick on average.

One solution to Los Angeles' problems would be to pump this contaminated air away. Suppose that we wish to pump out the Los Angeles basin every day and that the air must be pumped 50 miles to the desert near Palm Springs.

Assume also that the average velocity in the pipe is 40 ft/s.

Estimate the required pipe diameter.

Solution

The flow rate required is

$$Q = \frac{AH}{\Delta t} = \frac{4083\ \text{mi}^2 \cdot 2000\ \text{ft}}{24\ \text{h}} \cdot \frac{(5280\ \text{ft/mi})^2}{3600\ \text{s/h}} = 2.63 \times 10^9\ \frac{\text{ft}^3}{\text{s}}$$

$$= 7.47 \times 10^7\ \frac{\text{m}^3}{\text{s}}$$

and the required pipe diameter is

$$D = \sqrt{\frac{4Q}{\pi V}} = \sqrt{\frac{4 \times 2.63 \times 10^9\ \text{ft}^3/\text{s}}{\pi \times 40\ \text{ft/s}}} = 9158\ \text{ft} = 2791\ \text{m}$$

Solution (Cont'd)

- This is about six times the height of the tallest man-made structure, and far beyond our current structural engineering capabilities.
- Similar calculations (Problem 1.1) show that the power required to drive the flow exceeds the amount of electrical power generated in the Los Angeles basin.
- We are unlikely to solve our air pollution problems by pumping away the polluted air, although this solution is still frequently proposed.
- Instead, we must deal with those problems by reducing emissions, the principal subject of the rest of this book.

1.4 ONE PROBLEM OR A FAMILY OF PROBLEMS?

1. In **Table 1 .1** we see emissions estimates for the major man-made pollutants for the United States in 1997.

   From this table, we see the following:

   – There are six individual pollutants listed, which are the major regulated pollutants in the United States.

   – There is a much longer list of other pollutants, emitted in much lesser quantities and regulated in a different way in the United.

2. Some of the pollutants come mostly from transportation (motor vehicles) and others come mostly from industrial sources.

3. There is no entry for "General air pollution."

TABLE 1.1

National emissions estimates for 1997 (Values in millions of short tons/yr)

Source category	PM_{10}	SO_2	CO	NO_X	VOC	Pb
Transportation	0.7	1.4	67.0	11.6	7.7	0.00052
Fuel combustion	1.1	17.3	4.8	10.7	0.9	0.00050
Industrial processes	1.3	1.7	6.1	0.9	9.8	0.0029
Miscellaneous	–	0.0	9.6	0.3	0.8	–
Total	3.1	20.4	87.5	23.5	19.2	0.0039
Percentage of 1970 total	–	65%	78%	116%	70%	1.7%

Increase or Decrease?

- From 1970 to 1997, the US has made significant progress in reducing emissions of lead (mostly by taking lead out of gasoline) and modest progress in reducing emissions of the other major pollutants.
- The air pollutant emissions situation can be roughly approximated by the formula:

$$\begin{pmatrix} \text{Air pollutant} \\ \text{emissions} \end{pmatrix} = (\text{population}) \begin{pmatrix} \text{economic activity} \\ \text{per person} \end{pmatrix} \begin{pmatrix} \text{pollutant emissions} \\ \text{per unit of economic activity} \end{pmatrix}$$

Increase or Decrease?

- Since the environmental awakening of 19 the population of the US has increased b 30%, the economic activity per person by 80%, and the motor vehicle usage by abo factor of 4.

- However, the *pollutant emissions per uni economic activity have declined steadily* of

1.5 EMISSIONS, TRANSPORT, RECEPTORS

- **Figure 1.1** is a schematic of the air pollution process. Some source emits pollutants to the atmosphere.

- The pollutants are:
  - transported, diluted, and modified chemically or physically in the atmosphere; and
  - finally they reach some receptor, where they damage health, property, or some other part of the environment.

- Some of the pollutants are removed from the atmosphere by natural processes, so that they never find a receptor.

- Air pollution problem is complex due to wide variations in sources, pollutants, atmospheric conditions, technology and other means of control.

Sources - Atmospheric phenomena - Receptor Effects

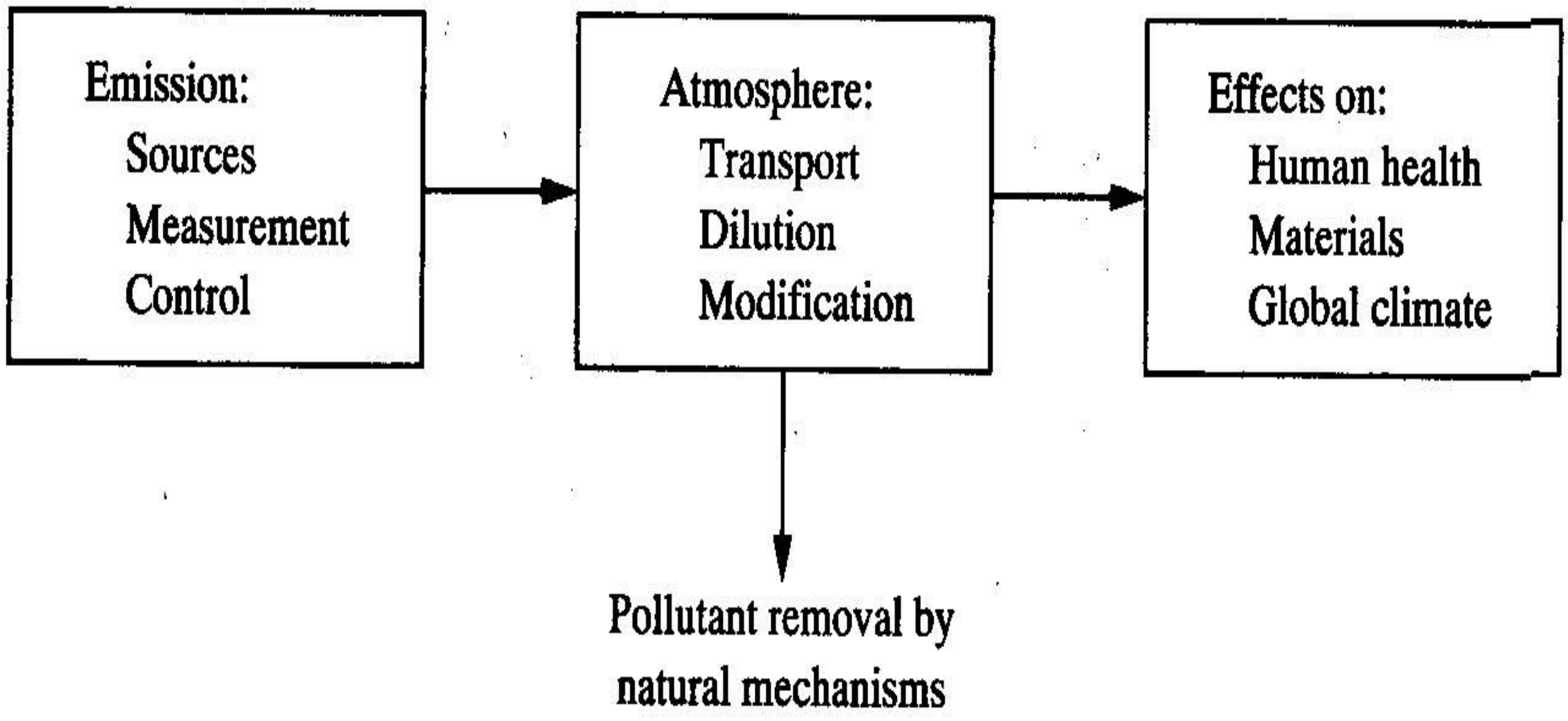


FIGURE 1.1
Air pollution schematic, showing the interrelations among emissions, transport, dilution, modification, and effects.

Ret. de Nevers

1.5 EMISSIONS, TRANSPORT, RECEPTORS

- In **Fig. 1.1** we also see a major reason why air pollution is different from water pollution.
  - Water pollution transport mechanisms are complex, but not as complex as atmospheric transport.
  - We would also see that the chemical or biological form in which most water pollutants are emitted is the one that causes harmful effects.
  - The same is not true of air pollution: many of the major pollutants are **formed in the atmosphere** and are called secondary pollutants to distinguish them from their precursors, the primary pollutants.

1.5 EMISSIONS, TRANSPORT, RECEPTORS

- Several of these ideas are illustrated in **Fig. 1.2**, where we see smoothed average concentrations of *four air pollutants for one day in Los Angeles.*
  - CO and NO are primary pollutants, emitted mostly by automobiles. The peak concentrations of CO and NO occur during the morning commute period.
  - NO2 and O3 are secondary pollutants formed in the atmosphere by complex reactions, summarized as:

$$NO + HC + O_2 + \text{sunlight} \rightarrow NO_2 + O_3$$

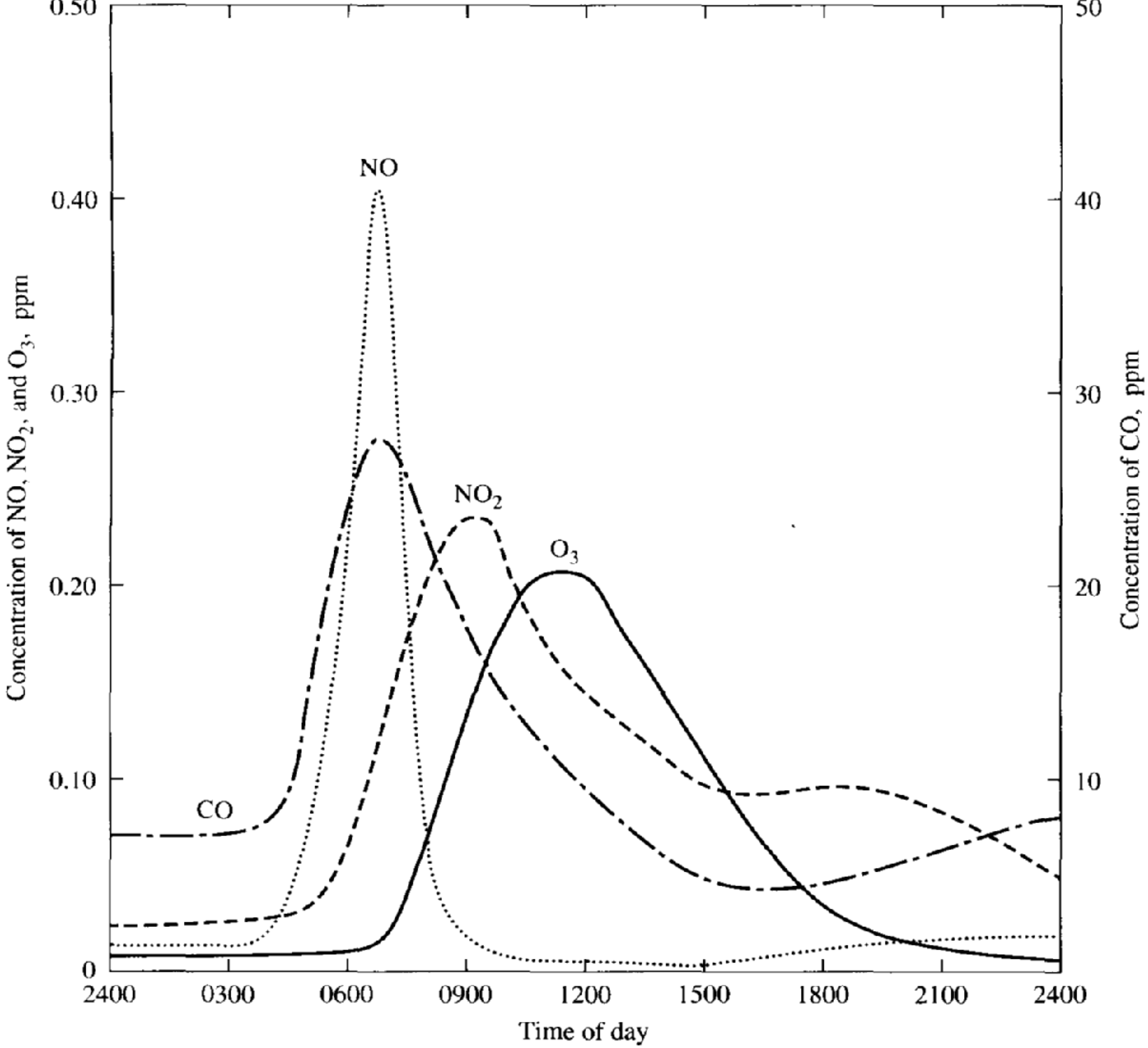


FIGURE 1.2

Smoothed average daily concentrations of selected pollutants in Los Angeles, California, July 19, 1965 [3, 4]. Observe the progression $NO \rightarrow NO_2 \rightarrow O_3$ and the different behavior of CO, which does not undergo rapid chemical reactions in the atmosphere.

1.5 EMISSIONS, TRANSPORT, RECEPTORS

- The peak concentration of NO_2 occurs before the peak for O_3 because the reaction sequence forms NO_2 first, then O_3.

- The CO concentration peak does not decline as rapidly as the NO peak because the CO concentration is reduced only by atmospheric mixing and dilution whereas the NO concentration is reduced by dilution and mixing *and by the chemical reaction (see previous equation).*

- The *afternoon commute* also produces increases in NO and CO, but the measured concentrations are not as large as the morning peaks because the *average wind speed is higher and the atmospheric mixing is stronger in the afternoon than in the morning.*

1.5 EMISSIONS, TRANSPORT, RECEPTORS

- It has also been observed that the highest peak O_3 concentration normally occurs about 30 to 60 miles downwind of the place that had the maximum morning emission of NO and HC because the polluted air mass can ride the wind that far in a day.

- Thus, any regulatory scheme for these pollutants must account for the fact that the *worst pollutant exposure may occur in a different city, country or region* from the major emission source.

- The two pollutants of greatest current health concern are both secondary: ozone, as described above, and fine particles.

- The very small particles that enter most deeply into out lungs and that are believed to be most harmful are largely formed in the atmosphere by reactions that can be summarized as:

$$HC + SO_X + NO_X \rightarrow \text{fine particles}$$

1.6 UNITS AND STANDARDS

- Both English and **SI units** are used.
  - As much as possible, we use the units most commonly used in the United States in that particular part of the air pollution control field.
  - Historically, scientists have used metric or SI (often the cgs version of metric) whereas engineers have used the English engineering system.
  - The regulators have used mixed systems.

1.6 UNITS AND STANDARDS

- The permitted emissions from automobiles are stated in **g/mile**, a mixed metric/English unit.
  - This seems like an illogical unit, but it is not.
  - The emission data are used in mathematical models that express emissions in **g/s.**
  - The available data on automobile usage are all in vehicle miles driven/hour, and the federal automobile fuel efficiency standards, which are tested by the air pollution branch of the U.S. EPA, are in miles/gallon.
- The prudent engineer will accept the units in use, clearly state the units on any quantity, and always check the units in every calculation.

Ideal Gas Law

- $PV = nRT$, ρ = mass/vol,   so $PM = \rho RT$
- $R = 0.08206$ L-atm-mol^{-1}-K^{-1}
- At STP (P=1 atm, T=25^{o}C=298K), this gives
  <u>molar volume</u> of any ideal gas as

$$V/n = RT/1 \approx 24.466 \text{ L/mol}$$

Ideal Gas Law

- To treat "air" as an ideal gas, we need its molecular weight

- Air is approximately 78% N_2, 21% O_2, 1% Ar

- Assuming N_2, O_2, and Ar are ideal gases, MW of air = 0.78(28) + 0.21(32) + 0.01(40) = 28.964 ≈ 29 (g/mol, kg/kmol, lb/lbmol)

Unit Conversions Using Ideal Gas Law

- Common units for gases: ppm, ppb, $\mu g/m^3$
- Common units for particulates: $\mu g/m^3$, mg/m^3
- Gaseous concentrations in ppm and ppb are on a *volume basis*, not a mass basis

Unit Conversions Using Ideal Gas Law

- Concentration in ppm = (mole fraction, volume fraction, or partial pressure) x 10^6
- Concentration in ppb = (mole fraction, volume fraction, or partial pressure) x 10^9

Note: I prefer to use the notations "ppm_v" and "ppb_v" to clearly indicate that these are volume/volume measurements. However, this is invariably the case when dealing with airborne substances.

- How to convert between ppm and $\mu g/m^3$?

Units for AP & WP

- When expressing the concentration of SO_2 in the air , 1ppm SO_2 means $1m^3$ SO_2 in 10^6 m^3 air .

- When expressing the concentration of Hg in the polluted water , 1ppm Hg means 1mg Hg in 1L waste water .

Units of Air Pollutants

For perfect gases at 1 atm and 25° C, (1x 10-6 m3 = 1ppm):

Number of moles (n) $= \frac{PV}{RT} = \frac{1.013 \times 10^{5} \times 10^{-6}}{8.314.(273.5 + 25)}$

$= 40.87 \times 10^{-6} mol$

For perfect gases at 1 atm and 25° C, (1 m3):

Number of moles (n) $= \frac{PV}{RT} = \frac{1.013 \times 10^{5} \times 1}{8.314.(273.5 + 25)}$

$= 40.87 mol$

Conversion between ppm and $\mu g/m^3$

At 1 atm and 25° C:

1m^3 of any perfect gas contains 40.87 moles .

C ($\mu g/m^3$)= ppm × (40.87 mol/m3) × (molecular weight, g/mol)

OR

C ($\mu g/m^3$)= 10-6 m3 × (40.87 mol/m3) × (molecular weight, g/mol) x 106 µg/g

Note: 1 ppm = 10-6 m3 in SI units

Example: For SO_2 = 0.03ppm

C = 0.03 × 40.87 × 64

=78.5 $\mu g/m^3$

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