Air Pollution
Meteorology
Air Pollution Meteorology

- Air Pollution Transport by Convection
  - Adiabatic Lapse Rate
  - Atmospheric Stability
  - Air Parcel Buoyancy

- Chimney Plumes
  - Plume Shape vs. Atmospheric Stability
  - Plume Spread

- Temperature Inversions
Air Pollution Meteorology

• To discuss air pollution we need to understand the physical state of the atmosphere.
  → Are there strong winds?
  → Is the air moving vertically?
  → Is there a lot of sunlight?
  → When was the last precipitation event?
Vertical Air Movement

• Does hot air sink or rise?
• What is the change in temperature with elevation?
• How can we show this mathematically?
  → Start with the 1st law of thermodynamics and the ideal gas law

\[ dQ = C_p \, dt - V \, dP \]

- \( dQ \): heat added to air parcel (J/kg)
- \( C_p \): specific heat
- \( dT \): temperature change
- \( V \): volume per unit mass
- \( dP \): incremental pressure in parcel
Assume change in parcel is *adiabatic*  
→ no heat is transferred across boundary  
\((dQ = 0)\)

\[
\frac{dT}{dP} = \frac{V}{C_p}
\]

Need to relate temperature change to elevation, not pressure

A “slice” of air that is \(dz\) thick and has area \(A\) and weight of \(g \rho A dz\)  
\(g = \) acceleration due to gravity  
\(\rho = \) density of air
Relating the pressure above and below this parcel:

\[ P(z) = P(z + dz) + \frac{g \rho A dz}{A} \]

\[ dP \approx P(z + dz) - P(z) \]

\[ = -g \rho dz \]

\[ \Rightarrow \frac{dP}{dz} = -g \rho \]

Take the earlier equation \( \frac{dT}{dP} = \frac{V}{C_p} \)

We need to find \( \frac{dT}{dz} \)

\[ \frac{dT}{dz} = \frac{dT}{dP} \frac{dP}{dz} = \frac{V}{C_p} (-g \rho) \]
Volume per unit mass and density per unit volume cancel each other:

\[
\frac{dT}{dz} = -\frac{g}{C_p}
\]

This is defined as the Dry Adiabatic Lapse Rate

\[
\Gamma_d = -\frac{g}{C_p} = 9.8\text{K/km} \approx 10\text{K/km}
\]

This is the rate of temperature change that would be experienced by a “dry” parcel of air moving up or down in ideal conditions.
In English units = 5.4 °F/ 1000 ft)

Example
At 30,000 ft (~ 9 km), air is ~ –40°F. Does an airplane that uses it for fresh air have to heat it or cool it after compressing it to sea level pressure?
The adiabatic lapse rate for saturated air is (smaller? larger?) than the lapse rate for dry air.

The $C_p$ for water undergoing a phase change is much larger than that of air.

If air is saturated, any cooling will result in condensation.

Condensation heat raises temperature inside the air parcel, offsetting some loss of temperature from adiabatic expansion.

**FIGURE 7.39** The dry adiabatic lapse rate $\Gamma_d$ is a constant $10^\circ C/km$, but the saturated adiabatic lapse rate $\Gamma_s$ varies with temperature. In the troposphere, $\Gamma_s$ is approximately $6^\circ C/km$. 

*Saturated Adiabatic Lapse Rate*
• The actual rate of temperature change with elevation is the ambient lapse rate or environmental lapse rate

→ Depends on the effects of wind, sunlight, water vapor, and clouds on temperatures near the ground and aloft

→ Global average environmental lapse rate near the ground is about 6.5°C/km
Relating the Ambient Lapse Rate to Stability

- To determine the stability of an air parcel, we compare the ambient lapse rate $\gamma$ to the adiabatic lapse rate $\Gamma$.

- Imagine a parcel of air that starts out at the same temperature and pressure of air around it.

  $\rightarrow$ If the parcel is forced upward, it will expand adiabatically

  $\rightarrow$ This will decrease the internal energy and hence the temperature of the air parcel.
→ If the air parcel is now cooler than the air around it, the parcel will have the tendency to sink back downward

→ If the air parcel is warmer than the air around it, it will continue moving upward

**FIGURE 7.40** Demonstrating atmospheric stability in a dry atmosphere. When a 20°C parcel of air at 1 km (position 1) moves up to 2 km (position 2), its temperature drops to 10°C (following the dry adiabatic lapse rate). In (a) the parcel of air raised to 2 km is warmer than the surrounding ambient air so the parcel keeps rising (unstable). In (b) the parcel at 2 km is colder than ambient, so it sinks back down (stable).
• Since the (adiabatic) lapse rate for the air parcel is fixed and the ambient lapse rate is variable, the tendency for a lifted air parcel to be warmer or colder than the surrounding air will depend on the value of the ambient lapse rate.

\[ \gamma < \Gamma \]

\[ \gamma > \Gamma \]
Equilibrium States of Stability

Stable Equilibrium

Stable equilibrium states resist perturbations

An atmosphere with a sub-adiabatic ambient lapse rate will tend not to mix vertically
Equilibrium States of Stability

Unstable Equilibrium

Unstable equilibrium states easily accelerate away

An atmosphere with a super-adiabatic ambient lapse rate will mix vertically
Neutral Equilibrium

Neutral equilibrium states neither suppress nor encourage changes.

An atmosphere with an adiabatic ambient lapse rate will mix vertically.

\[ \gamma = \Gamma \]
Chimney Plumes vs. Atmospheric Stability

Chimney plume dispersion depends on atmospheric stability—the less stable the atmosphere, the quicker the plume disperses.

However, this has the opposite effect on air quality at the ground, since the plume starts above ground and must disperse downward to reach people.

FIGURE 7.47 Effect of atmospheric lapse rates and stack heights on plume behavior. The dashed line is the dry adiabatic lapse rate for reference.
While we preferred unstable atmospheres to help disperse pollutants away from the ground, we need a stable atmosphere to keep elevated plumes away from the ground!
The atmosphere is heated from below, but still it can have layers that are thermally stratified.

- **a)** Cool marine air undercuts warm air over land
- **b)** Flow of air from a high plateau descends and warms by adiabatic compression, creating a cap above a cooler air mass in a basin below the highlands.
- **c)** Sinking air adiabatically compresses and warms aloft
- **d)** Ground cools at night, creating cool layer of air at the ground
The atmosphere undergoes a temperature inversion at ~12km. Below this is the troposphere. Above this is the stratosphere. Large thunderstorms often “bump” into this region.
A Smoggy Day in L.A.

- Primary pollutants emitted in the morning over the city
- Ocean breeze sweeps primary pollutants toward foothills
- Inversion layer keeps pollution trapped in valleys, sunlight helps photochemical buildup of ozone
• **Secondary pollutants peak in afternoon (what time?) near foothills**

• **Nighttime land breeze sweeps pollution out to sea**
Indoor Air Pollution
Indoor Air Pollution

- Background, sources, definitions
- Indoor air pollution concentration calculations
- Radon gas
  - Background and health effects
  - Sources
  - Mitigation
- Combustion sources
Indoor Air Pollution Fundamentals

• Indoor pollutants may create largest portion of health risks from air pollution.
  → We spend a lot of time indoors
  → We are not far from the sources
  → The biggest of these (on average) is from smoking and radon
    — Yet health effects correlate strongly with outdoor pollutant concentrations.
## Indoor Air Quality

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asbestos</td>
<td>fireproofing, insulation, vinyl floors</td>
</tr>
<tr>
<td>CO</td>
<td>combustion</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>particle board, carpet, foam insulation</td>
</tr>
<tr>
<td>Particles</td>
<td>wood stoves, “pig pen” effect</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>space heaters, stoves</td>
</tr>
<tr>
<td>O\textsubscript{3}</td>
<td>electrostatic cleaners, dog brushes</td>
</tr>
<tr>
<td>Radon</td>
<td>diffusion from soils, groundwater</td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>kerosene space heaters</td>
</tr>
<tr>
<td>VOCs</td>
<td>cooking, cleaning products, showers</td>
</tr>
</tbody>
</table>

Most Americans spend the majority of their time indoors.
More Fundamentals

- How does the exchange of indoor air and outside air happen?
  → Infiltration—air exchange when doors and windows are closed:
    - Air moves through cracks around doors and windows, through gaps around where plumbing and wires enter house, and through the foundation-wall connection.
    - The average house has ~ 1 m² of holes... presumably more in Southern California!
• How does the exchange of indoor air and outside air happen?

→ Natural ventilation: open the doors and windows to let fresh air in.

→ Forced ventilation: mechanical air handling systems brings in outside air.
Definitions

• Air changes per hour (ach): a number that tells how many times per hour a volume equal to the house’s volume gets exchanged.

• If all of the air is replaced each hour, the exchange rate is 1 ach.

• A high ach is 3 or 4; typical value 0.5 to 1

• New, energy efficient construction can be 0.1 ach.
Modelling Indoor Air Quality

Use a material balance “box model” to get indoor concentration

accumulation rate = input rate + sources – output rate – decay

\[ V \frac{dC}{dt} = S + C_a I V - C I V - KCV \]

- C = indoor concentration (mg/m³)
- V = volume of conditioned space in building (m³/air change)
- I = Q/V = ach = infiltration rate
- S = pollutant source strength (mg/hr)
- C_a = ambient (=outside) concentration of pollutant (mg/m³)
- K = decay rate or reaction rate of pollutant (hr⁻¹)
The steady-state solution can be found by setting

$$\frac{dC}{dt} = 0$$

$$\Rightarrow C(\infty) = \frac{S}{V} + \frac{C_aI}{I + K}$$

and the general solution is:

$$C(t) = \frac{S}{V} + \frac{C_aI}{I + K} \left(1 - e^{-(I+K)t}\right) + C(0)e^{-(I+K)t}$$

where $C(0)$ is the initial concentration of the pollutant in the building.
Example

Carbon monoxide is emitted from your gas oven at 2000 mg/hr. You plan to cook your turkey for 7 hours. Assume you live in a small apartment (65 m²) with 3 meter ceilings. COᵢ = 0 when you started cooking. Your CO detector went off after 5 hours. Its alarm is set at 10.0 mg/m³, the 8-hr ambient standard.

Find the air exchange rate in your apartment.

Assume that the outside [CO] = 0 as a first approximation; CO is fairly unreactive (K = 0)
\[ C(t) = \frac{S}{I/V} \left(1 - e^{lt}\right) \]

Cannot solve for the infiltration rate since I is not separable in this equation, so we will have to guess and do it iteratively.

Know \( C(t) = 10 \)

Evaluate right hand side with \( I = 0.5 \) ach

\[
C(t) = \frac{S}{I/V} \left(1 - e^{-lt}\right) = \frac{2000}{0.5 \times 65 \times 3} \left(1 - e^{0.5 \times 5}\right) = 18.8 \text{ mg/m}^3
\]

The air exchange rate must be higher if the actual concentration is 10 mg/m\(^3\).
OR, notice that the exponential term is small and first evaluate without it:

\[ I = \frac{S}{CV} = \frac{2000}{10 \times 65 \times 3} = 1.03 \text{ ach} \]

So try 1.0 ach

\[ C = 10.2 \text{ mg/m}^3 (\text{good enough})! \]
Radon ($^{222}\text{Rn}$)

- Radon is an indoor air pollutant that has received a lot of attention recently
  - Radon gas and its radioactive daughters are known carcinogens
  - It is estimated that this is the second leading cause of lung cancer, after smoking.
## Lung Cancer Deaths, 1986

<table>
<thead>
<tr>
<th>Smoking history</th>
<th>Population (million)</th>
<th>All Causes</th>
<th>Radon Attributable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never smoked</td>
<td>145</td>
<td>5000</td>
<td>500</td>
</tr>
<tr>
<td>Former smoker</td>
<td>43</td>
<td>57,000</td>
<td>6,400</td>
</tr>
<tr>
<td>Light smoker*</td>
<td>38</td>
<td>37,600</td>
<td>4,500</td>
</tr>
<tr>
<td>Heavy smoker</td>
<td>14</td>
<td>30,800</td>
<td>4,200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>241</strong></td>
<td><strong>130,400</strong></td>
<td><strong>15,700</strong></td>
</tr>
</tbody>
</table>

* less than 25 cig/day
Radon forms in soil from decay of radioisotopes

\[ ^{238}\text{U} \rightarrow ^{226}\text{Ra} \rightarrow ^{222}\text{Rn} \]
then it seeps upward and is sucked into the house

**FIGURE 7.54** Simplified uranium decay series, with half-lives and emissions. Radon gas that seeps out of soils can decay inside of buildings.

**TABLE 7.12** Radon measurement units

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curie</td>
<td>1 Ci = $3.7 \times 10^{10}$ radioactive decays per second (1 g radium)</td>
</tr>
<tr>
<td>Picocurie</td>
<td>1 pCi = 2.2 radioactive decays per minute</td>
</tr>
<tr>
<td>Becquerel</td>
<td>1 Bq = 1 radioactive decay per second</td>
</tr>
<tr>
<td>Picocurie per liter</td>
<td>1 pCi/L = 37 Bq/m³</td>
</tr>
<tr>
<td>EPA criterion</td>
<td>4 pCi/L = 150 Bq/m³ (0.0000028 parts per trillion of radon)</td>
</tr>
<tr>
<td>Working level(^*)</td>
<td>1 WL = 200 pCi/L = 7400 Bq/m³ of radon</td>
</tr>
<tr>
<td>Working-level month</td>
<td>1 WLM = 1 working-level of exposure for 173 hours</td>
</tr>
</tbody>
</table>

\(^*\) One WL is defined as 100 pCi/L of radon in equilibrium with its progeny.
Other Radon Sources

- Radon can also be captured on groundwater, which is released during aeration (showering, cleaning).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Transfer Coefficient (% released of total radon content)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dishwashing</td>
<td>0.98–0.90</td>
</tr>
<tr>
<td>Laundry</td>
<td>0.95–0.90</td>
</tr>
<tr>
<td>Shower</td>
<td>0.71–0.63</td>
</tr>
<tr>
<td>Bath</td>
<td>0.50–0.47</td>
</tr>
<tr>
<td>Toilet</td>
<td>0.29–0.30</td>
</tr>
<tr>
<td>Cleaning</td>
<td>0.28–0.45</td>
</tr>
</tbody>
</table>

The radon potential is a function of soil and rock types.

Figure 8.3  Geologic radon potential of the United States. (Source: IAR, 1992.)
These geographic differences are reflected in radon concentrations in groundwater supplies.

Figure 8.7  Geometric average Rn concentration in pCi/L for public ground-water supplies in the United States. (Source: Hess et al., 1985.)
Mitigation

Radon mitigation techniques have been developed for airborne radon. Most of these focus on ventilating basements or sub-slab regions of houses in areas that are radon-rich.
Combustion and Indoor Air Quality

- Heating and cooking appliances are sources of indoor air pollutants such as CO, NOx and VOC's.

- This figure nicely illustrates a step function input and the decay that followed.

- Most experiments have shown that emission levels are very variable with equipment type, maintenance, and operation.

Figure 4.2. Concentration of combustion products during the operation of an unvented space heater. (Source: Girman et al., 1982.)
Add the complications of air exchange rates and decay mechanisms, and indoor problems might look like this!

Figure 4.5  Interrelated factors that determine indoor pollutant concentration from combustion appliances. (Source: CPSC, 1983.)