Indoor and Outdoor Air Pollution

Jonathan M. Links, PhD
Johns Hopkins University
Section A

Introduction and Background
What Are the Problems?

- A person inhales approximately 30 m³ (or 35 pounds) of air per day
  - Roughly 6 times more than the food and drink consumed per day
- Exposure to air pollutants is continuous (and, usually, involuntary)
- Lung disease is the third leading cause of death in the U.S. (~335,000 deaths per year)
- Asthma is the most common chronic illness in children
  - Leading cause of hospital admissions of children
Types of Air Pollutants

- Natural
- Particulate matter
  - Volcanic ash
  - Radioactivity
  - Pollen dust
  - Smoke from fires
- Man-made
- Gaseous
  - Derived from combustion processes
  - Hydrocarbons
  - Oxides of sulfur and nitrogen compounds
Types of Air Pollutants

- Particulate matter
  - Solid or aqueous particles
    - 0.01 μm to 100 μm
  - Smallest particles (aerosols) can remain suspended
  - Below ~ 2.5 are capable of penetrating all sites of the respiratory tract
    - Carbonaceous dust, metallic oxides, salts, or acids
    - Porosity such that they absorb or adsorb other gases, liquids, and solids
Some Common Types of Particulate Matter

- Aerosols
  - Any tiny solid or liquid particle
- Dusts
  - Solid particles from grinding or crushing
- Fumes
  - Solid particles occurring when vapors condense
- Mist, fog
  - Liquid particles
- Smoke, soot, ash
  - Solid particles, mostly carbon, from combustion
- Smog
  - Any air pollutant; originally meant smoke plus fog
The Clean Air Act (CAA): Underlying Philosophy

- Everybody should have the same degree of protection
  - Establish uniform national standards
- Most susceptible subgroups of individuals (e.g., asthmatics, children) are to be protected
  - Element that drives much of the biomedical research
CAA Classification of Air Pollutants

- “Criteria” pollutants
  - Ubiquitous (wide-spread)
  - Not very toxic
  - PM, SO$_2$, NO$_2$, O$_3$, CO, Pb
Hazardous air pollutants (HAPs)
  - Sources may be limited and industry specific
  - More toxic and even carcinogenic
  - ~188 chemicals
  - For example, benzene, formaldehyde, cadmium, vinyl chloride

Separate strategies exist for regulating criteria and hazardous pollutants
Criteria Pollutants

- Emitted from many large diverse sources, including mobile and stationary sources
- Omnipresent and, therefore, pose the greatest overall threat to human health
- Assumption: the adverse health effects are not cancerous, and their dose-response relationship exhibits a threshold
National Air Pollution Emissions, 1998

Source: EPA.
Hazardous Air Pollutants (HAPs)

- 1990 CAA amendment specified 188 pollutants or chemical groups
- HAPs are more toxic than criteria pollutants; they “... may reasonably be expected to result in serious irreversible ... disease, including cancer”
- Examples
  - Heavy metals (chromium, mercury)
  - Organics (benzene, perchloroethylene)
HAP Sources

Area sources (non-point sources)
- Dry cleaning operations
- Solvent cleaning
- Secondary lead smelters and chrome plating
- Commercial sterilizers

Point sources
- Large industrial complexes
- Chemical plants
- Oil refineries
- Steel mills
- Aerospace manufacturers
- Marine tank vessel loading
Transformation and Long-Range Transport of HAPs

**Sources**
- Mobile
- Stationary
- Natural

Man-made

**Primary Pollutants**
- $SO_2$, $NO_2$, $CO$, PM

Chemical transformation in atmosphere

**Secondarily Formed Pollutants**
- $O_3$, acid aerosols
Sources and Emissions of Primary Air Pollutants

**Sources**

- Industrial processes: 16%
- Fuel combustion (stationary sources): 29%
- Transportation: 46%
- Miscellaneous: 7%
- Solid waste disposal: 2%

**Emissions**

- Particulates: 5%
- CO: 48%
- NO\(_x\): 16%
- SO\(_2\): 16%
- VOCs: 15%
Transformation of Air Pollutants

- Ozone formation
  
  Hydrocarbons (VOCs) + NO₂ → Sunlight → O₃

- Fine particle formation (droplet aerosols)
  
  SO₂ (gas) → Atmospheric oxidation → H₂SO₄ (particle)
Gases in Photo-Chemical Smog as a Function of Time

- Source: Adapted from Manahan, S. E.
Accumulation of Pollutants

- As air moves across the continent from west to east, each population area adds to the total pollution in the atmosphere.

Source: Adapted by CTLT from Boyce, A.
Normal Pattern

Source: Adapted by CTLT from Mackenzie, F.T.
Inversion Layer

Pattern developed during a temperature inversion

Solar radiation

Cool air

Warm inversion layer

Pollution trapped

Cool air

Source: Adapted by CTLT from Mackenzie, F.T.
Aerosol Formation

- $\text{H}_2\text{SO}_4$ (sulfates) and $\text{O}_3$ cross state and national jurisdictions
- Acid sulfates and $\text{O}_3$ are often together, temporally and spatially

Source: Adapted by CTLT from Boyce, A.
Dry and Wet Deposition of Air Pollutants

Photochemical action

Oxidation

SO₂ + H₂O → H₂SO₄
NOₓ + H₂O → HNO₃

Prevailing winds

Atmospheric moisture

Dissolution

2H⁺ + SO₄⁻⁻
H⁺ + NO₃⁻

Wet deposition

Dry deposition

NOₓ → SO₂

Limestone buffers acidity

Granite produces acid-sensitive soils and lakes

pH 7.0

pH 4.6

Source: Adapted by CTLT from Kemp, D. D.
Section B

Health Effects
Aerodynamic Behavior of Aerosols

- Solid particle origin, size distribution, composition, and airborne residence time
Subdivisions of the Conducting Airways

Schematic representation for the subdivisions of the conducting airways and terminal respiratory units

Source: Adapted by CTLT from Murray.
Particle sizes for common air pollutants and the sites of their deposition within the respiratory tract (assuming a respiratory rate of 15/min and a tidal volume of 750 ml)

Source: Adapted by CTLT from Blumenthal, D. S.
Three Mechanisms of Aerosol Particle Deposition

- Schematic representation of the three main mechanisms of aerosol particle deposition

A. Sedimentation

B. Inertia

C. Diffusion
# Particle Deposition in the Lung

<table>
<thead>
<tr>
<th>Particle size</th>
<th>Respiratory rate</th>
<th>Deposition process</th>
<th>Deposition site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>High</td>
<td>Impaction</td>
<td>Large airways</td>
</tr>
<tr>
<td>Coarse</td>
<td>Low</td>
<td>Sedimentation</td>
<td>Large and smaller airways</td>
</tr>
<tr>
<td>Fine</td>
<td>High</td>
<td>Diffusion</td>
<td>Large and smaller airways</td>
</tr>
<tr>
<td>Fine</td>
<td>Low</td>
<td>Diffusion</td>
<td>Alveoli</td>
</tr>
</tbody>
</table>
Numbers and surface areas of monodispersed particles of unit density of different sizes at a mass concentration of 10 g/m³

<table>
<thead>
<tr>
<th>Particle Diameter (µ)</th>
<th>Particle Number per m³ [x10⁶]</th>
<th>Particle Surface Area (m²/ m³ air) [x10⁶]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>2,400,000</td>
<td>3,016</td>
</tr>
<tr>
<td>0.1</td>
<td>19,100</td>
<td>600</td>
</tr>
<tr>
<td>0.5</td>
<td>153</td>
<td>120</td>
</tr>
<tr>
<td>1.0</td>
<td>19</td>
<td>60</td>
</tr>
<tr>
<td>2.0</td>
<td>1</td>
<td>24</td>
</tr>
</tbody>
</table>
Health Effects Associated with Air Pollution

- **Acute**
  - Loss of lung function (FEV$_1$ by spirometry)
  - Disability (absenteeism, increased need for medication, increased emergency room visits, hospitalization)
  - Increased mortality rate (respiratory and cardiovascular deaths)
  - Symptoms of irritation (cough)

- **Chronic**
  - Impaired lung growth (spirometry)
  - Accelerated lung aging (spirometry)
  - Damage to other organ systems

- **Cancer**
Criteria Pollutants: Method of Control

- National ambient air quality standards (NAAQS)
- Level of protection
  - “…adequate margin of safety”
    - To protect against effects that have not yet been uncovered by research, and effects whose medical significance is a matter of controversy
    - To be set low enough to protect the health of all susceptible groups within the population
Susceptibility

Percentage of Population Responding

Dose

Threshold Dose

susceptible

resistant
Criteria Pollutants and Susceptible Subpopulations

- **SO$_2$**
  - Persons with increased airway reactivity (asthmatics)

- **CO**
  - Persons with arteriosclerotic disease affecting coronary vessels (angina patients)

- **Pb**
  - Fetuses and children
Criteria Pollutants and Susceptible Subpopulations

- **PM$_{10}$**
  - Mortality—the elderly with cardiovascular and pulmonary disease
  - Morbidity—children

- **NO$_2$**
  - Children (respiratory illness)

- **O$_3$**
  - Active people
Because they may exhibit no threshold, air quality standards would be inappropriate; instead, site-specific emission standards are established.

The emission standards must provide an *ample* (not simply *adequate*—as with the criteria pollutants) margin of safety.

- Note: *Ample* is also ambiguous, but more demanding than *adequate*. 
Has the CAA Been Effective?

![Bar chart showing changes in emissions from 1970 to 1995. CO has decreased by 28%, NOx has increased by 6%, VOC has decreased by 25%, PM-10 has decreased by 79%, and SO2 has decreased by 41%. Lead has decreased by 98%.

Notes Available

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Section C

Indoor Air
Indoor Air Pollution: Reasons for Special Concern

- ~75–90% of time spent indoors
  - Time depends on season, age, gender, health status
- Many air pollutants known to be hazardous to health are emitted indoors
- Indoor environments trap pollutants
  - Levels may be 2 to 5 times higher than outside
Air Inside a Building Can Be Polluted as a Result of

- Energy conservation measures
  - “Air tightening” of buildings
  - Ventilation standards lowered
- Building occupancy
- Human activities inside the structure
- Gas-off from synthetic building materials
- Reliance on forced air ventilation systems
Air Inside a Building Can Be Polluted as a Result of

- Biogenic pollutants
  - Aeropathogens
  - Aeroallergens
- Infiltration from outdoors
  - Molds and fungi, combustion sources, animal dander, outdoor air pollution
- Reactivity of pollutants
- Poor housing conditions
  - Vermin and pests
## Sources of Indoor Air Pollutants

<table>
<thead>
<tr>
<th>Sources</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil and groundwater</td>
<td>Radon and radioactive progeny</td>
</tr>
<tr>
<td>Building materials and furnishings (carpeting, paint, varnish, adhesives)</td>
<td>Formaldehyde, asbestos, vinyl chloride, organic fumes</td>
</tr>
<tr>
<td>Personal activities and hobbies</td>
<td>Cigarette smoking, fireplace smoke, solvent and glue fumes</td>
</tr>
<tr>
<td>Appliances, cooking, and heating</td>
<td>Carbon monoxide, natural gas, cooking odors, boiler and heater fumes</td>
</tr>
</tbody>
</table>
## More Sources of Indoor Air Pollutants

<table>
<thead>
<tr>
<th>Sources</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household chemicals (bleach, oven cleaner, insect sprays, nail polish, hair spray)</td>
<td>Ammonia, hydrogen chloride, pesticides, organic fumes, aerosols</td>
</tr>
<tr>
<td>Electronic equipment and wiring</td>
<td>Organic fumes, electromagnetic radiation</td>
</tr>
<tr>
<td>Pets</td>
<td>Hair, feces, proteins, dust</td>
</tr>
<tr>
<td>Plants</td>
<td>Pollen, hydrocarbons</td>
</tr>
</tbody>
</table>
The Stack Effect
Air Pollution in the Home

Adapted by CTLT from Boyce, A.
Air Exchange Rate

- Rate at which air is replaced in the structure by external air
  - Average for American home: 0.7 to 1.0 air changes per hour
  - Tightly sealed homes without provisions for and exchange: ~0.2 air changes per hour

- Make-up air (from outside)
  - Before 1973: 15 cubic feet per minute (cfm) per person
  - After 1973: 5.0 cfm per person
Environmental Tobacco Smoke (ETS)
### Selected Toxins and Carcinogens in Cigarette Smoke

- Ratio of selected toxic [T] and carcinogenic [C] agents in side-stream (SS) smoke and mainstream (MS) smoke

<table>
<thead>
<tr>
<th>Chemical</th>
<th>~ Ratio of SS/MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide [T]</td>
<td>3–15</td>
</tr>
<tr>
<td>Benzene [C]</td>
<td>8–10</td>
</tr>
<tr>
<td>Formaldehyde [C]</td>
<td>50</td>
</tr>
<tr>
<td>Hydrazine [C]</td>
<td>3</td>
</tr>
<tr>
<td>Ammonia [T]</td>
<td>46</td>
</tr>
<tr>
<td>Tar [C]</td>
<td>1–16</td>
</tr>
<tr>
<td>Nicotine [T]</td>
<td>1–21</td>
</tr>
<tr>
<td>Benzo[a]pyrene [C]</td>
<td>3–20</td>
</tr>
<tr>
<td>Cadmium [C]</td>
<td>7</td>
</tr>
<tr>
<td>Nickel [C]</td>
<td>13–20</td>
</tr>
</tbody>
</table>

Source: Samet, J.
Lung cancer in women according to the presence of direct and involuntary smoking.
Field Survey of Indoor RSP

Field survey of indoor respirable suspended particulates (RSP)

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of occupants</th>
<th>Number of smokers</th>
<th>Indoor RSP (μg/m³)</th>
<th>Outdoor RSP (μg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cocktail party</td>
<td>14</td>
<td>2</td>
<td>350</td>
<td>–</td>
</tr>
<tr>
<td>Lodge hall</td>
<td>350</td>
<td>40</td>
<td>700</td>
<td>60</td>
</tr>
<tr>
<td>Bar and grill</td>
<td>75</td>
<td>9</td>
<td>590</td>
<td>63</td>
</tr>
<tr>
<td>Pizzeria</td>
<td>50</td>
<td>5</td>
<td>415</td>
<td>40</td>
</tr>
<tr>
<td>Church Bingo game Services</td>
<td>150  300</td>
<td>20  0</td>
<td>280  30</td>
<td>–  –</td>
</tr>
<tr>
<td>Bowling alley</td>
<td>128</td>
<td>14</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Hospital waiting room</td>
<td>19</td>
<td>2</td>
<td>190</td>
<td>58</td>
</tr>
</tbody>
</table>

Comparison of air pollutant emissions from energy equivalent fuels (kg)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>PM</th>
<th>SO\textsubscript{x}</th>
<th>NO\textsubscript{x}</th>
<th>HCO</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>2,170</td>
<td>86</td>
<td>110</td>
<td>1,450</td>
<td>18,790</td>
</tr>
<tr>
<td>Coal</td>
<td>520</td>
<td>1,200</td>
<td>270</td>
<td>430</td>
<td>2,380</td>
</tr>
<tr>
<td>Oil</td>
<td>11</td>
<td>1,170</td>
<td>71</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Gas</td>
<td>7</td>
<td>Neg.</td>
<td>38</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>
Role of Biofuels in Cooking and Heating

Source: Smith, K. R.
Emissions of TSP in Small Stoves for Various Biofuels

- Emission of total suspended particulates (TSP) in small open cook stoves for various biofuels

Source: Smith, K. R.
## Indoor Air Pollution from Biomass Combustion

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement period</th>
<th>Concentration of TSP as multiple of WHO peak guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Cooking</td>
<td>11</td>
</tr>
<tr>
<td>Gambia</td>
<td>Average over day</td>
<td>4–11</td>
</tr>
<tr>
<td>India</td>
<td>Cooking</td>
<td>16–91</td>
</tr>
<tr>
<td>Kenya</td>
<td>Space heating (o.n.)</td>
<td>12–34</td>
</tr>
<tr>
<td>Nepal</td>
<td>Cooking</td>
<td>9–38</td>
</tr>
<tr>
<td>Papua</td>
<td>Space heating (o.n.)</td>
<td>5–39</td>
</tr>
</tbody>
</table>

Source: Smith, K. R.
# Sources of VOCs in Indoor Air

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction materials</td>
<td>Foam insulation, carpet glue, paint</td>
<td>Methyl chloroform, formaldehyde, styrene, xylene, tetrachloroethylene, benzene, 1,1,1-trichloroethane</td>
</tr>
<tr>
<td>Structural components</td>
<td>Particle board, vinyl tile, sheetrock</td>
<td>Formaldehyde, xylene, acetone, benzene, n-decane, benzyl chloride</td>
</tr>
<tr>
<td>Furnishings</td>
<td>Foam, textured carpet, drapery, upholstery fabric</td>
<td>Formaldehyde, methyl chloroform, benzene, tetrachloroethylene, 1,1,1-trichloroethane</td>
</tr>
<tr>
<td>Cleaners and solvents</td>
<td>Liquid detergent, chlorine bleach, scouring powder, furniture wax</td>
<td>Xylene, n-dodecane, benzene, chloroform, n-undecane, n-decane, 1,1,1-trichloroethane</td>
</tr>
<tr>
<td>Personal care products</td>
<td>Eyeliner pencil, deodorant, skin lotion</td>
<td>Methyl chloroform, styrene, tetrachloroethylene, benzene, isoprene</td>
</tr>
<tr>
<td>Combustion</td>
<td>Wood, kerosene</td>
<td>Acrolein, formaldehyde, 1-nitropyrene, 1-nitronapthalene</td>
</tr>
</tbody>
</table>

Source: Samet, J.
Selected VOCs in Indoor and Outdoor Air

Source: Data from (February 1998). Scientific American.
Selected Indoor Aeroallergens and Aeropathogens

- **Bacteria**
  - *Staphylococcus aureus*
  - *Legionella*
  - *Escherichia coli*
  - *Salmonella spp.*
  - *Pseudomonas aeruginosa*
  - *Mycobacterium tuberculosis*
  - *Klebsiella pneumoniae*

Source: Samet, J.
More Indoor Aeroallergens and Aeropathogens

- Yeasts
  - *Candida albicans*
  - *Saccharomyces cerevisiae*
- Viruses
- Fungi
  - *Aspergillus niger*
  - *Penicillium funicolosum*
  - *Trichophyton spp.*
- Amoeba
- Arthropods
  - Mites, cockroaches
- Dander
  - Cat, dog, hamster
Regulatory Jurisdictions

- Outdoor air: EPA, clean air act (CAA)
- Occupational air: OSHA
- Indoor air (apart from occupational air)
  - No specific federal laws
  - State and local jurisdictions regulate air quality in public buildings
    - Standards in ventilation and air exchange rates
    - Controlling activities (e.g., smoking)
    - Limit use of products that affect air quality
- Private residence
  - Must rely on education
Strategies to Control Indoor Air Pollution

- Ventilation
- Source removal
- Source modification
- Air cleaning (pollutant removal)
- Education
Building-Related Illness

- Discrete, identifiable disease or illness
- Can be traced to a specific pollutant or sources within a building
- Cough, chest tightness, fever, chills, muscle aches, or more serious outcomes
- Legionnaires’ disease, hypersensitivity pneumonitis, humidifier fever
Sick-Building Syndrome (SBS)

- Set of symptoms associated with time spent in building
  - Respiratory tract irritation, skin irritation, headache, dizziness, nausea, fatigue, concentration problems
- Symptoms diminish or cease when occupants leave the building
- Cannot be traced to specific pollutants or sources within the building
- Related to multiple chemical sensitivity (MCS)
Key Points: Outdoor Air Pollutants and Health Effects

- Major outdoor air pollutants are $O_3$, $SO_2$, $NO_2$, Pb, CO, PM
- They are either directly emitted into outdoor air (primary pollutants) or formed in the air via chemical reactions (secondary pollutants)
- Adverse health effects include acute reduction of lung function, respiratory or cardiovascular deaths, and cancer
Key Points: Criteria

Setting of criteria includes pollutants that:

- “May reasonably be expected to endanger public health and welfare”
- Must reflect the latest scientific information
- Must allow for an adequate margin of safety
- But cannot consider cost
Key Points: Indoors

- We spend up to 90% of our lives indoors
- The indoor environment contains many toxicants, either because they’re emitted indoors (e.g., VOCs or ETS) or because they’re trapped due to energy conservation measures (e.g., respirable particles or radon)
Key Points (Continued)

- ETS is a major source of toxic and carcinogenic agents that are less completely combusted in SS than in MS smoke.
- Building-related illness has traceable etiology, whereas sick-building syndrome and multiple chemical sensitivity do not.