

ENVE 576

Indoor Air Pollution

Fall 2015

Week 1: August 25, 2015
Course introduction

Built
Environment
Research

@ IIT



*Advancing energy, environmental, and
sustainability research within the built environment*

www.built-envi.com

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Dr. Brent Stephens, Ph.D.

Civil, Architectural and Environmental Engineering

Illinois Institute of Technology

brent@iit.edu

Today's objectives

- Introduce the course
- Introduce myself
- Introduce yourselves
- Discuss syllabus
 - Course information, outline, schedule, ground rules
 - Why are we all here?
- Introduce the course, topics, and field of indoor air
 - Time activity and human exposure
 - Indoor and outdoor atmospheres
 - Fundamental air principles

About me

- B.S.E., Civil Engineering
 - Tennessee Technological University, 2007
- M.S.E., Environmental and Water Resources Engineering
 - The University of Texas at Austin, 2009
 - Thesis: “Energy implications of filtration in residential and light-commercial buildings”
- Ph.D. Civil Engineering
 - The University of Texas at Austin, 2012
 - Dissertation: “Characterizing the impacts of air-conditioning systems, filters, and building envelopes on exposures to indoor pollutants and energy consumption in residential and light-commercial buildings”
- Entering my 4th year at IIT
- 3rd time teaching this course
 - Learning experience for everyone

Course information

ENVE 576: Indoor Air Pollution

Course Unique Number(s)

- Section 1: 17688 (in class)
- Section 2: 17689 (online)

Classroom and Meeting Time

- Engineering 1 Room 241
- Tuesday nights, 5:00 PM – 7:40 PM

Prerequisites

- None

Course information

Course Catalog Official Description

- Indoor air pollution sources, indoor pollutant levels, monitoring instruments and designs; indoor pollution control strategies: source control, control equipment and ventilation; energy conservation and indoor air pollution; exposure studies and population time budgets; effects of indoor air pollution; risk analysis; models for predicting source emission rates and their impact on indoor air environments.

Course objectives (in my own words)

To introduce students to important concepts of indoor airborne pollutants, including their physical and chemical properties, emission sources, and removal mechanisms. By taking this course students will be able to:

1. Describe particle-phase, gas-phase, and biological pollutants found in indoor environments
2. Model indoor pollutant emission, transport, and control
3. Manipulate and perform calculations with aerosol distributions and gas-phase compounds
4. Analyze indoor pollutant control technologies and determine their effectiveness
5. Read and critically analyze articles in the technical literature on indoor air pollution
6. Prepare and review written and oral technical communication

Textbook and reading materials

- There is **no textbook** for this course
- I rely on a mixture of notes from various textbooks and technical papers and publications
 - As well as notes from my previous courses

I will draw from several reference texts, in case you are interested:

- Hinds, W. C., *Aerosol technology: Properties, behavior, and measurement of airborne particles*, Wiley (1999)
- Morawska, L. and Salthammer, T., *Indoor environment: airborne particles and settled dust*, Wiley-VCH (2003)
- Salthammer, T. and Uhde, E., *Organic Indoor Air Pollutants: occurrence, measurement, evaluation*, Wiley-VCH (2009)
- Seinfeld, J. H. and Pandis, S. N., *Atmospheric chemistry and physics: from air pollution to climate change*, Wiley (2006)
- Spengler, J., McCarthy, J., and Samet, J. *Indoor air quality handbook*, McGraw-Hill Professional (2001)

Textbook and reading materials

- In our syllabus I've also listed almost 50 research articles and other documents that I will utilize in class
 - These are all labeled “suggested readings”
 - That means you **do not** have to read them
 - They mostly provide references for those interested in learning more
- I use these articles to inform the core of each lecture
 - But also rely on many others that aren't listed
- Every once in a while I will ask that you do read a particular article
 - I'll let you know

Course topics

- Introduction: Human exposure, indoor and outdoor atmospheres
- Reactor models, ventilation, and human exposure patterns
- Pollutant types and sources
- Gaseous pollutants (VOCs and others)
 - Sources, adsorption/desorption, emission models, reactive deposition, homogeneous chemistry, byproduct formation
- Particulate matter
 - Single particle physics, particle size distributions, respiratory deposition, sources, surface deposition and resuspension, filtration and air cleaners
- Biological matter
 - Dust, pollen, mold, microbes generally
- Semi-volatile organic compounds (SVOCs)
 - Pesticides, flame retardants, etc.
- Measurement techniques and sampling campaigns
- Health effects: epidemiology and physiological responses
- IAQ in developing countries
- Applications: standards and manufacturer ratings
- Infectious disease transmission and risk

About you

- Who are you?
 - First and last name
 - Where are you from?
- What is your primary degree emphasis?
 - Undergraduate or graduate?
 - Engineering or other?
 - If graduate, masters or PhD?
 - Doing research? If so, what is your research topic?
- Why are you taking this course?
- Any relevant work and/or research experiences?

Course expectations

Graduate course: Focus on research & peer-reviewed literature

Grading:

- Homework/Blog Posts
 - 4 HW assignments and 3 blog posts throughout semester
- Exam(s)
 - One take-home exam will be given in early November
 - No final exam scheduled
- Final Project
 - A major deliverable in this course will be one final project
 - Research report on indoor air pollution
 - Will involve measurement and/or modeling of some pollutant in some indoor environment
 - Very flexible, and you will have a few weeks to decide

Course grading

Grading scale

A $\geq 90\%$

B 80-89.9%

C 70-79.9%

D or below $<69.9\%$

A note on research project expectations

- Your research project will be very much like a conference paper or journal article
 - For those already doing research, this gives you a chance to get something more out of your coursework
 - Alternatively, it gives you a chance to get away from your thesis work!
- The purpose is to introduce a topic, survey the peer reviewed literature, describe your methods of calculation and/or measurement, show your results, discuss them, and conclude
 - Sometimes a student will have something strong enough for a publication (e.g., Stephens et al. 2013 *Atmos Environ* 79:334-339)
- More on this later today and throughout the course

Course website

- I will post lecture notes and updated syllabus on our course website:
 - <http://built-envi.com/courses/enve-576-indoor-air-pollution-fall-2015/>
 - I will do so always just before class (within ~1 hour usually)
- I will also use Blackboard (BB) for:
 - Updated syllabus/schedule/suggested reading assignments
 - Lecture notes
 - Reading materials
 - Should be about 50 articles already uploaded now and available for download
 - **Is that true?**
 - Assignments
 - Grades
- I generally communicate with the class via email
 - Don't let me go into your spam folder
 - **Do you have a different email address that you prefer?**
 - If so, email me at brent@iit.edu

Blog posts

IIT IAQ Blog

Student blog posts for ENVE 576: Indoor Air Pollution, a graduate course at Illinois Institute of Technology taught by Prof. Brent Stephens

[Home](#)

[About](#)

Category Cloud

[Course information](#)

[IAQ](#)

Archives

[August 2015](#) (1)

[December 2014](#) (17)

[November 2014](#) (32)

[October 2014](#) (2)

[September 2014](#) (34)

Welcome to the Fall 2015 semester

All students in ENVE 576 will be required to write 3 blog posts throughout the Fall 2015 semester on topics related to indoor air pollution, indoor exposures, and environmental health. You may use posts from last year as a guide, but be careful not to duplicate anyone's work.

Posted on [August 14, 2015](#) by [profstephens](#). Posted in [IAQ](#) | [Leave a comment](#) | [Edit](#)

-
- You will receive an email invitation to become an author on our course blog
 - You will be expected to write **3 blog posts** throughout the semester on topics of your choice
 - Each post should be at least 500 words
 - Grading: 50% content/relevance; 50% grammar/writing effectiveness
 - Grade: 50 points per post

Tentative schedule (always check updated syllabus)

Course Topics and Tentative Schedule				
Week	Date	Lecture Topics	Reading*	Assignment:
1	Tues. Aug 25	Introduction to topic/field <ul style="list-style-type: none"> Indoor and outdoor atmospheres Fundamental air principles 	1-4	
2	Tues. Sep 1	Reactor models <ul style="list-style-type: none"> Steady-state and dynamic Ventilation and air exchange rates Human exposure patterns <ul style="list-style-type: none"> Inhalation and intake fractions 	5-7	
3	Tues. Sep 8	Overview of indoor pollutants/constituents <ul style="list-style-type: none"> Particulate matter Gas-phase compounds <ul style="list-style-type: none"> ⇒ Organic and inorganic Biological 	8	HW #1 due
4	Rescheduled: Thurs. Sep 17	Location T.B.D. Gaseous pollutants <ul style="list-style-type: none"> Sources and emissions models 	9-12	Blog #1 due
5	Tues. Sep 22	Gaseous pollutants and indoor chemistry <ul style="list-style-type: none"> Adsorption/desorption Reactive surface deposition Homogenous chemistry Reaction byproduct formation 	13-17	HW #2 due
6	Tues. Sep 29	Indoor aerosols <ul style="list-style-type: none"> Single particle physics and dynamics Particle size distributions Respiratory deposition 	18-20	
7	Tues. Oct 6	Indoor aerosols <ul style="list-style-type: none"> Particle sources (indoor and outdoor) Deposition and resuspension Penetration/infiltration 	21-26	HW #3 due
8	Tues. Oct 13	<i>Conference travel – Class cancelled</i>		Blog #2 due
9	Tues. Oct 20	<i>Conference travel – Guest lecture – Dr. Stephanie Kunkel, Indoor microbiology</i>	27-29	
10	Tues. Oct 27	Indoor aerosols <ul style="list-style-type: none"> Filtration and air cleaners 	30-33	HW #4 due
11	Tues. Nov 3	SVOCs and aerosol sampling techniques	34	Exam assigned
12	Tues. Nov 10	IAQ measurement techniques	35	Exam due
13	Tues. Nov 17	Health effects <ul style="list-style-type: none"> Epidemiology and physical responses IAQ in developing countries 	36-42	
14	Tues. Nov 24	Infectious disease transmission	43-45	Blog #3 due
15	Tues. Dec 1	Applications <ul style="list-style-type: none"> Standards and manufacturer ratings Modeling software 	46-49	
Final	Tues. Dec 8 5-7 PM	Final presentations (no final exam)		Final project report due

Any questions thus far?

Introduction to field and topic of indoor air

- Why do we study indoor air?
- We spend most of our time indoors
 - Nearly 90% of the time, on average in the developed world
 - Approximately 18 hours indoors for every 1 hour outdoors
- We bring materials, furnishings, appliances, and activities into buildings, most of which emit/release a variety of substances
 - Some harmful, some not
- Buildings also exchange air with the outdoors
 - Outdoor air pollution becomes indoor air pollution
 - Indoor pollution becomes outdoor pollution
- Indoor air is a dominant environmental exposure
 - More than half of the body's intake of air is done so inside homes
 - 80-90% inhaled in buildings generally

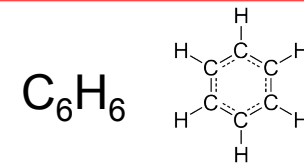
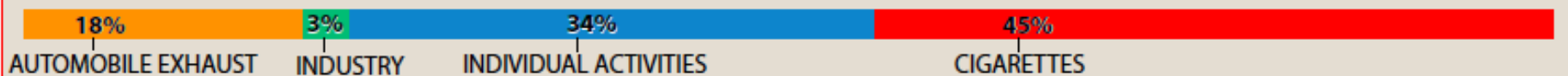
Why do we study indoor air?

- Indoor concentrations of most pollutants are higher than outside
 - Global average of ~3:1 indoor/outdoor ratio
 - Large variability between pollutants
- Increasing number of indoor exposure related diseases/health effects
- We keep sensitive equipment/precious artifacts inside buildings
- We regulate outdoor air based on emissions
 - No indoor air regulations
 - Other than smoking bans and product emission controls at manufacture stage
 - Canada just initiated residential NO₂ standard
 - Disconnect between emissions and exposure
 - Benzene example (outdoor sources include auto exhaust and industry):

SOURCES OF BENZENE EMISSIONS



SOURCES OF BENZENE EXPOSURE



History of indoor air

- Since there has been shelter, indoor air has been important
- Greeks and Romans (400 BC) knew of adverse effects of polluted air in crowded cities and mines
- The Bible mentions living in damp (moist) buildings was linked to leprosy
 - Bacterial infection
- Crowded cities and chimney sweeps in 1600s and 1700s highlighted the importance of air pollution indoors and outdoors
- In the 1800s, slaves and prisoners died in very small, poorly ventilated rooms
 - Providing evidence of the important of ventilation
- Also “bad air” blamed for the spread of disease
 - “deficient ventilation ... (is) more fatal than all other causes put together,” 1850
- Now, in developed regions of the world, buildings have vented cooking appliances with generally clean fuels, central heating and air-conditioning, new furnishings and materials, lower ventilation rates
 - And a relatively high prevalence of allergies, asthma, and other health issues
- In developing regions of the world we still have burning of biomass on inefficient and unvented stoves
 - And a high prevalence of respiratory disease and other health effects

Modern indoor environments

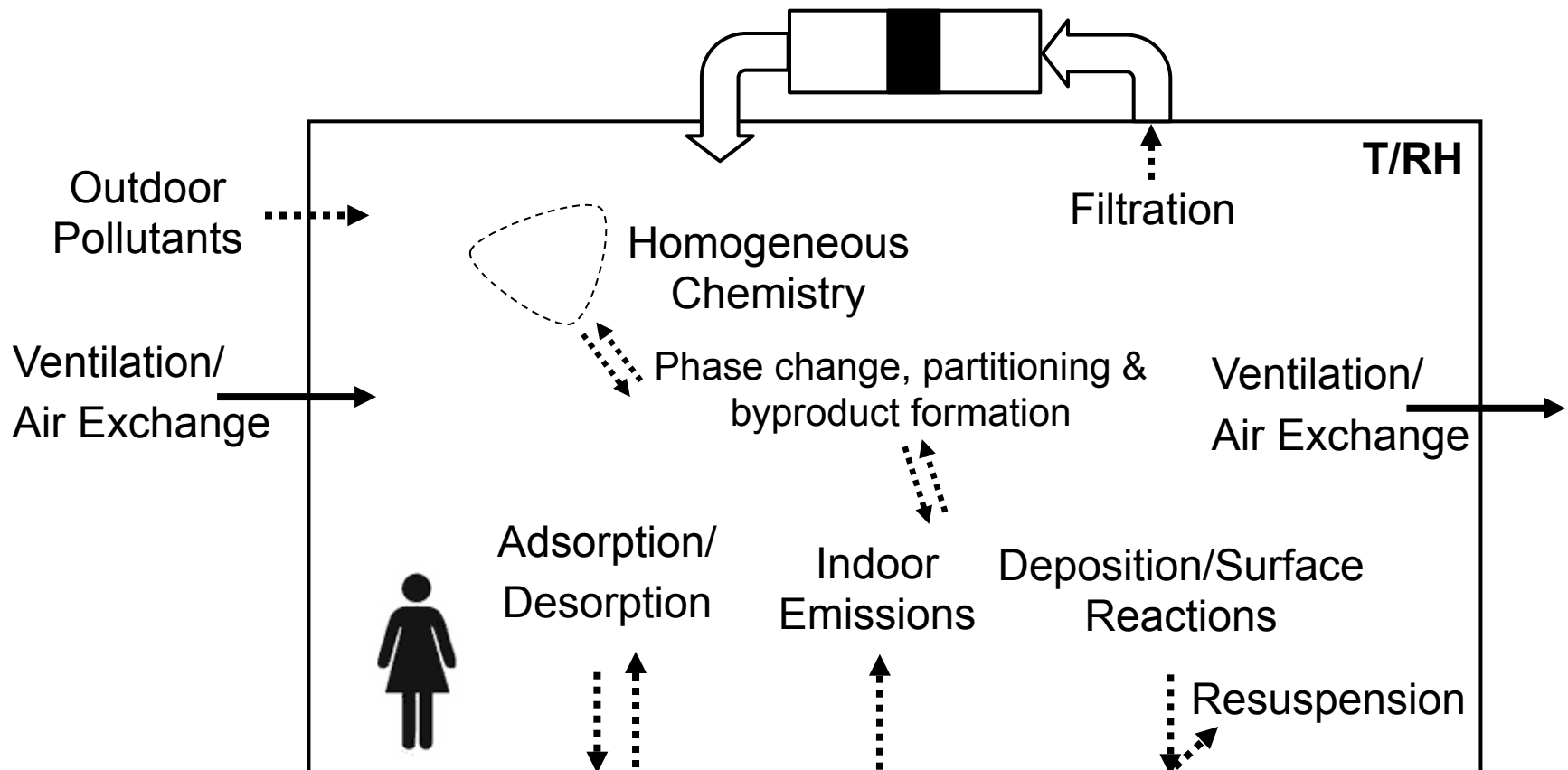


Types of indoor emission sources

- Building materials (VOC/SVOC)
 - Wood and composite wood
 - Gypsum wallboard
 - Concrete
 - Carpet
 - Vinyl flooring
- Furnishings (VOC/SVOC)
 - Bedding
 - Tables
 - Couches/chairs
 - Drapes
- Architectural coatings (VOC/SVOC)
 - Paints
 - Stains
 - Varnishes
- Consumer products (VOC/SVOC)
 - Cleaners
 - Fragrances
 - Personal care products
- Combustion (VOC/PM/SVOC/other)
 - Cigarettes, cigars, pipes
 - Gas stoves
 - Space heaters
 - Candles
 - Incense
- Electronics (PM/VOC/SVOC/other)
 - Laser printers
 - Computers
 - Photocopiers
- Volatilization from water (VOC)
- Soil vapor intrusion (VOC)
- People, pets, insects

Modern indoor environments

To understand the levels of airborne pollutants that we are exposed to, we need to understand the underlying physical, chemical, and biological mechanisms that drive pollutant emission, transport, and control



Some important classes of indoor pollutants

- Inorganic gases
 - CO, NO₂, O₃, NH₃, H₂S, SO₂
- Organic gases (may partition to solids, binding to particles)
 - Volatile organic compounds (hundreds of these)
 - Semi-volatile organic compounds (SVOCs)
 - Carbonyls
 - Acids
 - Radicals
- Particulate matter
 - Size, shape, mass, constituents (e.g., elemental, chemical, metals)
- Radioactive gases and particles
- Microbiological
 - Bacteria, viruses, fungi, allergens

Indoor air physics and chemistry

- Indoor air physics and chemistry is much like outdoor air physics and chemistry
 - With a few important exceptions
- Indoor atmospheres constitute a very small fraction of the planetary atmosphere
 - However, most of that air is breathed by humans on a daily basis

Table 1

Some attributes of the global, urban, and indoor atmospheres^a

Environment	Mass (kg)	Flow, F (kg d ⁻¹)	Mass breathed, Q^b (kg d ⁻¹)	Ratio, $Q : F$
Global atmosphere	5×10^{18}	—	$\sim 10^{11}$	—
Urban atmospheres	$\sim 10^{15}$	$\sim 3 \times 10^{15}$	$\sim 4 \times 10^{10}$	$\sim 10^{-5}$
Indoor atmospheres	$\sim 10^{12}$	$\sim 10^{13}$	$\sim 8 \times 10^{10}$	$\sim 10^{-2}$

^aFor the urban and indoor atmospheres, attributes are summed over all environments on earth.

^bFor the global and urban atmospheres, the mass breathed includes air inside and outside of buildings.

Indoor air physics and chemistry

Table 2
Some attributes of urban and indoor atmospheres

Parameter	Urban atmosphere	Indoor atmosphere
Residence time	~ 10 h	~ 1 h
Light-energy flux	~ 1000 W m ⁻² (daytime)	~ 1 W m ⁻²
Surface-volume ratio	~ 0.01 m ² m ⁻³	~ 3 m ² m ⁻³
Precipitation	~ 10–150 cm year ⁻¹	Absent

- Residence times are lower indoors than outdoors
- Sunlight is much much lower indoors than outdoors
- Surface-to-volume ratios are much much higher indoors
- There is no precipitation indoors (hopefully)

Exposure science

- A closely related field is “exposure science”
 - Bridge between physical sciences/engineering and health sciences
 - How much of which pollutants are humans exposed to?
 - How and where do they come in contact with the body?



Exposure science

- Exposure pathways
 - Ingestion, inhalation, dermal uptake, ocular (eyes), hands
- Inhalation exposure
 - Adults inhale 15-20 m³ of air per day
 - Adults ingest 1.2 L per day of water, or 0.0012 m³/day
 - Adults ingest about ~16000 times as much air as water per day!
 - Water is about 800 times as dense as air, so humans ingest about 18 times more mass of air than water per day
 - The point is that we put large amounts of air into our bodies every day by inhalation!
 - So what pollutants are contained in air are important!

What are the risks of indoor air pollution?

- In 1987, the US Environmental Protection Agency (EPA) published a report on the population-wide impacts of environmental problems
 - Health effects in humans (cancer and non-cancer)
 - Ecological impacts
 - Impacts on human welfare

United States
Environmental Protection
Agency

Office of Policy Analysis
Office of Policy, Planning
and Evaluation

February, 1987



Unfinished Business: A Comparative Assessment of Environmental Problems Overview Report

US EPA population **cancer** risks, 1987

1. (tie) Worker exposure to chemicals
1. (tie) **Indoor radon**
3. Pesticide residue on foods
4. (tie) **Indoor air pollutants** (non-radon)
4. (tie) **Consumer exposure to chemicals**
(includes cleaning fluids, particleboard, asbestos products)
6. Hazardous/toxic outdoor air pollutants (from industry)
7. Depletion of stratospheric ozone
8. Hazardous waste sites (inactive)
9. Drinking water (radon and THMs)
10. Application of pesticides
11. Radiation other than indoor radon
- 12-29. Others, including groundwater contamination at 21 and criteria air pollutants at 22

US EPA population **non-cancer** risks, 1987

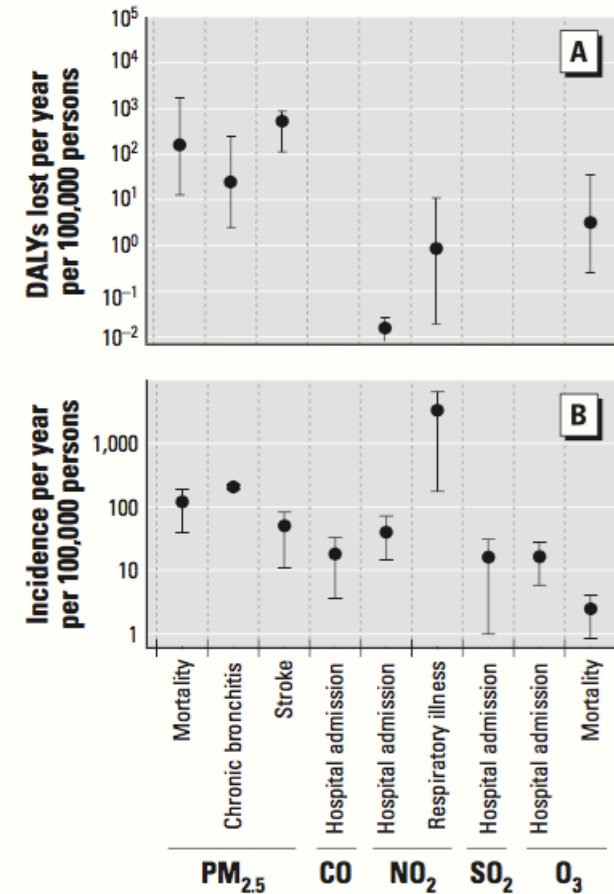
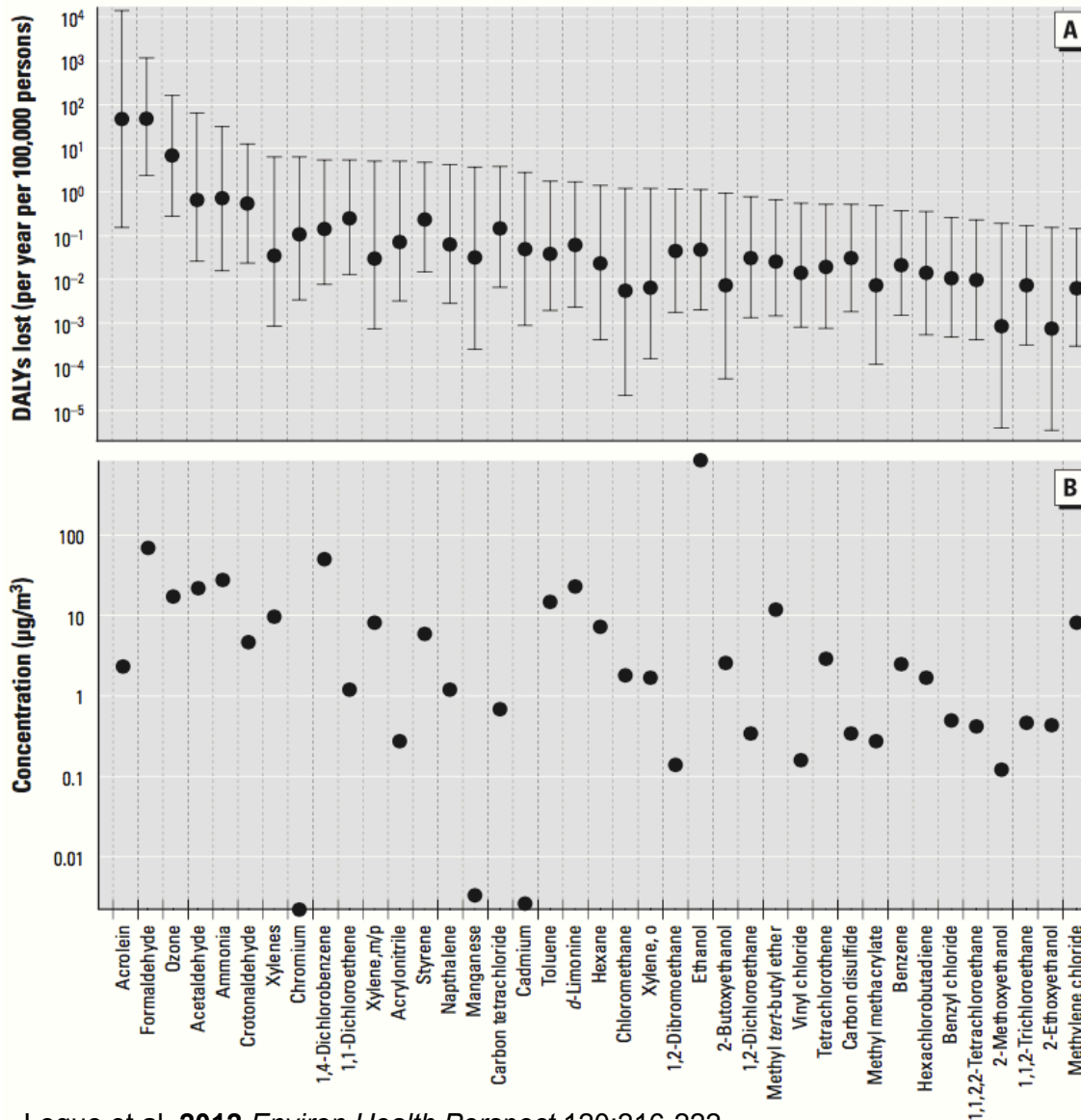
- “High” non-cancer risks
 - Criteria air pollutants (e.g., PM_{2.5}, O₃, NO₂, Pb)
 - Hazardous air pollutants
 - **Indoor air pollutants (not radon)**
 - Drinking water
 - Accidental toxic releases
 - Pesticides on food and application of pesticides

Indoor Air Pollution Other Than Radon

Comments

Important health problem, although not generally recognized as such by the public. For a variety of reasons (statutory, multitude of sources, difficulty of control, etc.), this has not been a major EPA priority.

Chronic health impacts of residential indoor air pollutants



The cumulative chronic health impacts from inhalation of indoor pollutants, excluding radon and secondhand smoke, are estimated to result in between 400 and 1,100 disability-adjusted life-years (DALYs) lost per 100,000 persons per year, representing **5-14% of the annual non-communicable, non-psychiatric disease burden in the U.S.**

Costs of poor IAQ/ventilation

- Health and productivity gains from better indoor environments in the U.S.
 - Fisk (2000) *Annual Reviews of Energy and Environment*
 - \$6-14 billion from reduced respiratory disease
 - \$1-4 billion from reduced allergies and asthma
 - \$10-30 billion from reduced sick building syndrome
 - \$20-160 billion from direct improvements in worker performance
- \$37-208 billion annual savings possible
 - Fisk (2002) *ASHRAE Journal*
- Improved ventilation in a manufacturing facility led to reduced sick days
 - Milton et al. (2000) *Indoor Air*
- Increased ventilation led to slight increase (5%) in productivity
 - Wargocki et al. (2000) *Indoor Air*

Methods of studying indoor air pollution

- Indoor air quality (IAQ) isn't really a standalone discipline
 - Involves engineers, public health professionals, analytical chemists, building scientists, architects, contractors, medical professionals, epidemiologists, academics, biologists, psychologists, economists, etc.
 - Many different approaches
- The big picture is that:
 - We are interested in concentrations of pollutants and human exposures
 - Worker productivity/safety
 - Health effects
 - Material degradation
 - Biological growth/disinfection
 - So we need to use and convert concentrations and conduct mass balances to get concentrations, exposures, and doses
 - And to determine what affects those

Who studies indoor air?

- National/state institutions

- US EPA <http://www.epa.gov/iaq/>
- NIOSH/CDC <http://www.cdc.gov/niosh/topics/indoorenv/>
- NIST <http://www.nist.gov/indoor-air-quality.cfm>
- NRC-Canada
http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/indoor_environment.html
- CARB <http://www.arb.ca.gov/research/indoor/indoor.htm>
- LBNL <http://energy.lbl.gov/ie/>

- Universities

- Drexel, Harvard, Berkeley, Penn State, Rutgers, University of Texas at Austin, Tulsa, Clarkson, Purdue, Syracuse ... IIT!
- University of Toronto, Danish Technical University, Tsinghua, National University of Singapore, Hong Kong University
 - Many others

Who studies indoor air?

- Standards organizations and professional societies
 - ISIAQ (International Society of Indoor Air Quality and Climate)
 - ISES (International Society of Exposure Science)
 - AAAR (American Association for Aerosol Research)
 - ASHRAE (American Soc. of Heating, Refrigerating, and Air-Conditioning Eng.)
 - IAQA (Indoor Air Quality Association)
 - AIHA (American Industrial Hygiene Association)
- Important journals
 - *Indoor Air*
 - *Building and Environment*
 - *Atmospheric Environment*
 - *Environmental Health Perspectives*
 - *Environmental Science and Technology*
 - *Journal of Exposure Science and Environmental Epidemiology*
 - *HVAC&R Research*
 - *Environmental Pollution*
 - *Aerosol Science and Technology*

FUNDAMENTAL AIR PRINCIPLES

What is “air”?

- What chemical species are in “clean” air?

– Species	MW (g/mol)	%
– Nitrogen (N ₂)	28	78.1%
– Oxygen (O ₂)	32	20.9%
– Argon (Ar)	40	0.9%
– Water (H ₂ O)	18	0.1-3% (highly variable)
– Carbon dioxide (CO ₂)	44	0.04% (400 ppm)*
– Neon (Ne)	20	0.0018% (18 ppm)
– Helium (He)	4	0.0005% (5 ppm)
– Methane (CH ₄)	16	0.0002% (2 ppm)
– Krypton (Kr)	84	0.0001% (1 ppm)
– Hydrogen (H ₂)	2	0.00006% (0.6 ppm)

* Can reach 5000 ppm (0.5%) or more indoors

What is “air”?

- What chemical species are in “**polluted**” air?

– Species	MW (g/mol)	%
– Nitrogen (N ₂)	28	78.1%
– Oxygen (O ₂)	32	20.9%
– Argon (Ar)	40	0.9%
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– Hydrogen (H ₂)	2	0.00006% (0.6 ppm)
– xyz pollutant	depends	< 300 <u>ppb</u> (0.00003%)**

* Can reach 5000 ppm (0.5%) or more indoors

** Highly variable

Air as an ideal gas

- Every gas in air acts as an ideal gas

$$PV = nRT \quad \text{Ideal Gas Law (Boyle's law + Charles's law)}$$

- Air as a composition of ideal gases
 - A bunch of ideal gases acting as an ideal gas
- For individual gases (e.g., N₂, O₂, Ar, H₂O, CO₂, pollutant *i*):

$$P_i V = n_i RT$$

P_i = partial pressure exerted by gas *i*
 n_i = # of moles of gas *i*
 R, V, T = gas constant, volume, temperature

$$P_i = \frac{n_i}{V} RT$$

Rearrange so that n_i/V is the molar concentration

$$P_i = y_i P_{tot}$$

P_{tot} = total pressure of air (atm, Pa, etc.)
 y_i = mole fraction of gas *i* in air (moles *i* / moles air)

Air as an ideal gas

- Air as a composite mixture

$$P_i = y_i P_{tot}$$

$$P_{tot} = \sum P_i = \sum \frac{n_i}{V} RT = \frac{RT}{V} \sum n_i = \frac{RT}{V} n_{tot}$$

$$PV = nRT$$

Density of air (at sea level)

$$PV = nRT \quad \longrightarrow \quad \frac{n}{V} = \frac{P}{RT}$$

$$\frac{n}{V} = \frac{P}{RT} = \frac{1 \text{ atm}}{\left(82.05 \times 10^{-6} \frac{\text{atm} \cdot \text{m}^3}{\text{mol} \cdot \text{K}}\right) \times 293 \text{ K}}$$

20°C, 68°F

$$\frac{n}{V} = 41.6 \frac{\text{moles}}{\text{m}^3} = 0.0416 \frac{\text{moles}}{\text{L}}$$

$$\rho_{air} = MW_{air} \times 0.0416 \frac{\text{moles}}{\text{L}} \text{ @20 degrees C}$$

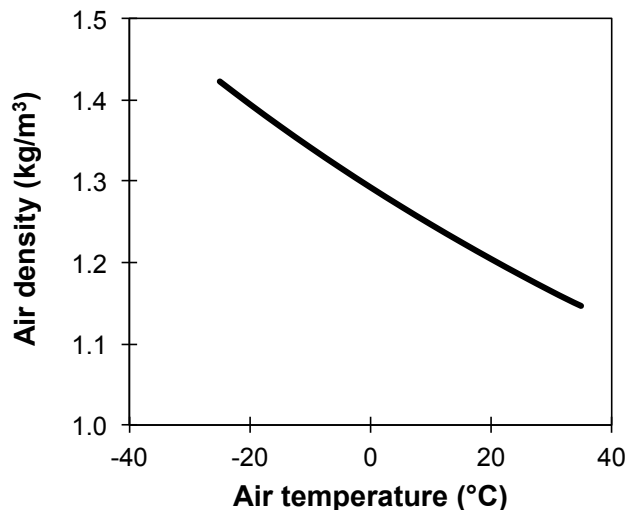
What is the molecular weight (MW) of air?

$$MW_{air} = \sum y_i MW_i = y_{N_2} MW_{N_2} + y_{O_2} MW_{O_2} + y_{H_2O} MW_{H_2O} + \dots$$

$$MW_{air} = 0.781(28 \text{ g/mol}) + 0.209(32 \text{ g/mol}) + \dots = 29 \text{ g/mol}$$

$$\rho_{air} = \left(29 \frac{\text{g}}{\text{mol}}\right) \times 0.0416 \frac{\text{mol}}{\text{L}} = 1.2 \frac{\text{g}}{\text{L}} = 1.2 \frac{\text{kg}}{\text{m}^3} \text{ @20 degrees C}$$

Hang on to this number: density of air is $\sim 1.2 \text{ kg/m}^3$ at 20°C
at sea level



$$\rho_{air} \approx 1.3 - 0.0046(T_{air}) \text{ where } T_{air} \text{ is in degrees C}$$

Units of measurement for air pollutants

- **Number concentrations** (# per volume of air, #/m³)
 - # of molecules per m³ (highly reactive species, e.g., OH radical)
 - # of particles per m³ (particulate matter)
 - # of cells or colony forming units per m³ (biological)
- **Mass concentrations** (mass per volume of air)
 - ng/m³ typical for metals and for SVOCs
 - μg/m³ typical for indoor VOCs and particulate matter
 - mg/m³ big sources, e.g., ETS, cooking, industrial hygiene
- **Molar concentrations** (variations on $y_i = \text{mol}_i / \text{mol}_{\text{air}}$)
 - Mole fraction (y_i) = mol/mol
 - % concentration = moles per 100 moles = 100 * y_i
 - Parts per million by volume (ppm_v) (or just ppm in this course)

$$1 \text{ ppm} = \frac{1 \text{ mol of } i}{10^6 \text{ moles of air}} = 10^{-6} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-6} * y_i$$

- Parts per billion by volume (ppb_v) (or just ppb in this course)

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-9} * y_i$$

Units of measurement

- Conversion between mass and volume concentrations

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}}$$

- If we multiply y_i by MW of pollutant, moles/L of air, and conversion factors:

$$10^{-9} \frac{\text{moles of } i}{\text{moles of air}} * MW_i \left(\frac{\text{g of } i}{\text{moles of } i} \right) * \left(\frac{\text{moles of air}}{24 \text{ L}} \right) * 10^6 \frac{\mu\text{g}}{\text{g}} * 10^3 \frac{\text{L}}{\text{m}^3}$$

$$\underbrace{\left(\frac{V}{n} = \left(\frac{n}{V} \right)^{-1} = \left(0.0416 \frac{\text{moles}}{\text{L}} \right)^{-1} = 24 \frac{\text{L}}{\text{mole}} @20 \text{ degrees C} \right.}_{}$$

- Then:

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = \# \text{ of ppb} * \frac{MW_i}{24} = \# \text{ of ppb} * \frac{MW_i P}{RT}$$

$$\# \text{ of } \frac{\text{mg}}{\text{m}^3} = \# \text{ of ppm} * \frac{MW_i}{24} = \# \text{ of ppm} * \frac{MW_i P}{RT}$$

Unit conversion example

- What mass concentration for ozone corresponds to 120 ppb?
 - At 20 degrees C (68 degrees F)

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = \# \text{ of ppb} * \frac{MW_i}{24} = \# \text{ of ppb} * \frac{MW_i P}{RT}$$

$$MW_{\text{ozone}} = 48 \text{ g/mol}$$

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = 120 \text{ ppb} * \frac{48}{24} = 240 \frac{\mu\text{g}}{\text{m}^3}$$

Unit conversion example

- What mass concentration for ozone corresponds to 120 ppb?

$$MW_{\text{ozone}} = 48 \text{ g/mol} \quad \# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = 120 \text{ ppb} * \frac{48}{24} = 240 \frac{\mu\text{g}}{\text{m}^3} \quad @ 20^\circ\text{C}$$

– What if T rises to 100 degrees F (38 °C)?

- 311 K

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = \# \text{ of ppb} * \frac{MW_i P}{RT} = \frac{120 \text{ mol}}{10^9 \text{ mol}} * \frac{(48 \frac{\text{g}}{\text{mol}}) * 1 \text{ atm}}{8.205 \times 10^{-5} \frac{\text{m}^3 \cdot \text{atm}}{\text{mol} \cdot \text{K}} * 311 \text{ K}} * \frac{10^6 \mu\text{g}}{\text{g}} = 225 \frac{\mu\text{g}}{\text{m}^3}$$

- Effects of temperature:
 - When using ppm and ppb (mol/mol), T doesn't affect concentration
 - When using mass concentrations, if T ↑ RT ↑ mass concentration (m/V) ↓

Unit conversions summary

- Indoors we can usually use simple assumptions:

- Air density = 1.2 kg/m³

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = \# \text{ of ppb} * \frac{MW_i}{24}$$

$$\# \text{ of } \frac{\text{mg}}{\text{m}^3} = \# \text{ of ppm} * \frac{MW_i}{24}$$

- Temperatures rarely deviate from 60-80°F (15-27°C)
 - 288-300 K

Role of water vapor in air

- Relative humidity

$$RH = \frac{P_w}{P_{w,sat}}(T)$$

- Where can you get $P_{w,s}$?

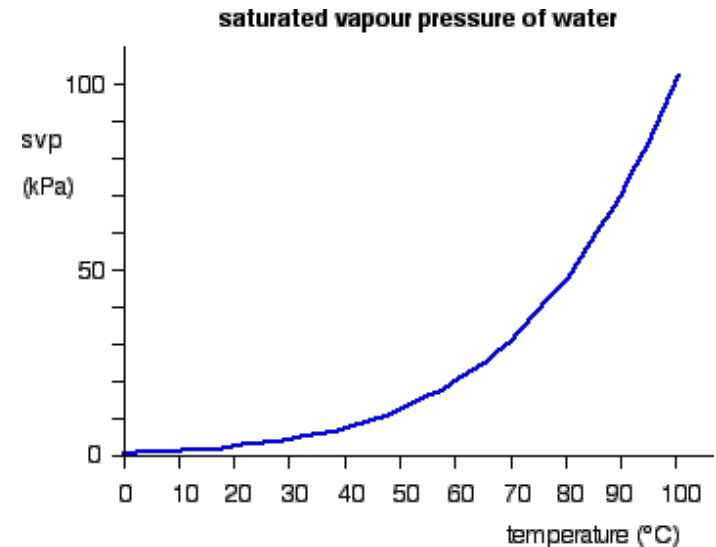
$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13} \ln T$$

where

$$\begin{aligned} C_8 &= -5.800\ 220\ 6\ E+03 \\ C_9 &= 1.391\ 499\ 3\ E+00 \\ C_{10} &= -4.864\ 023\ 9\ E-02 \\ C_{11} &= 4.176\ 476\ 8\ E-05 \\ C_{12} &= -1.445\ 209\ 3\ E-08 \\ C_{13} &= 6.545\ 967\ 3\ E+00 \end{aligned}$$

$$\begin{aligned} p_{ws} &= \text{saturation pressure, Pa} \\ T &= \text{absolute temperature, K} = \text{°C} + 273.15 \end{aligned}$$

ASHRAE Handbook of Fundamentals
Equation or chart





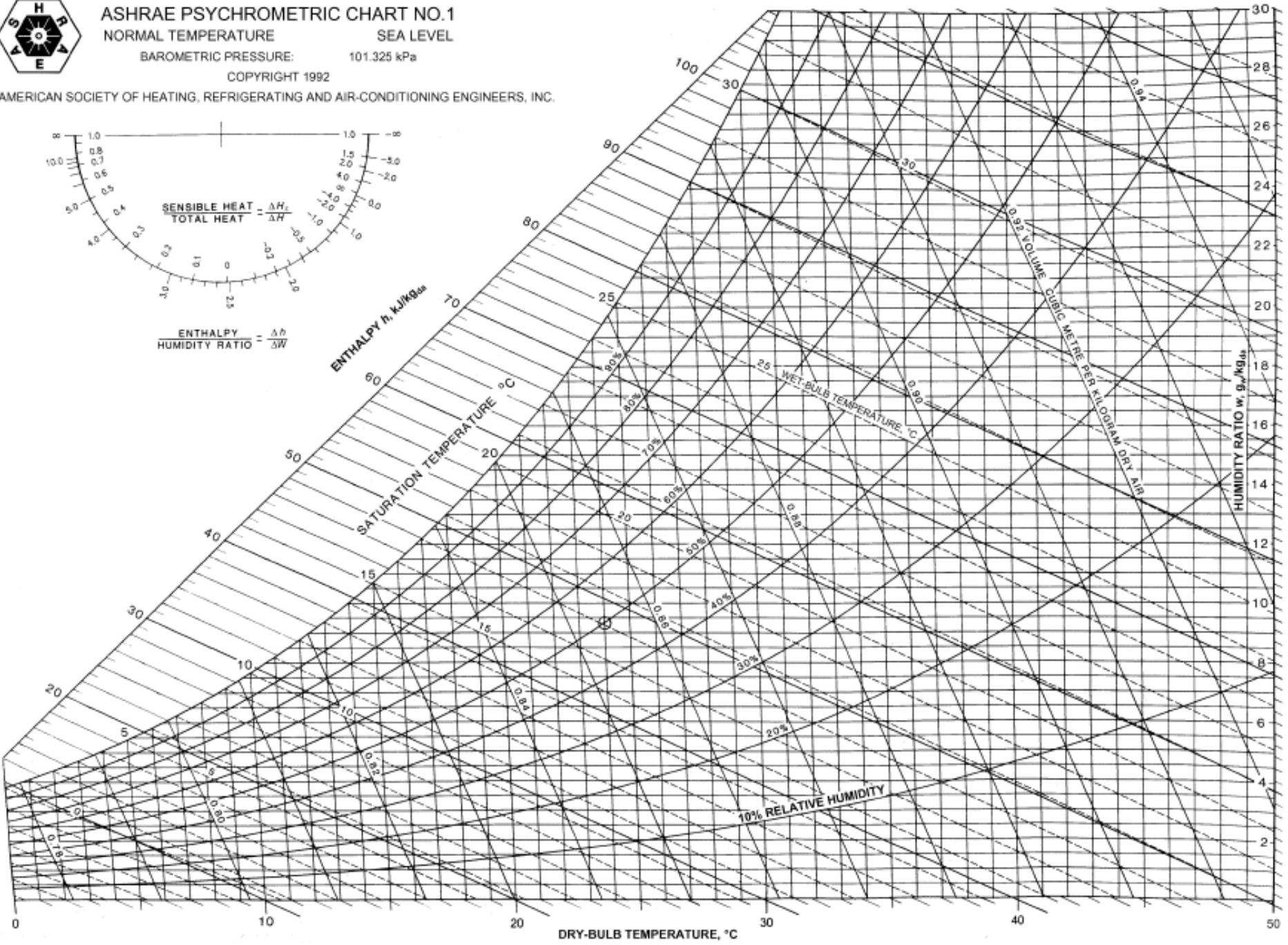
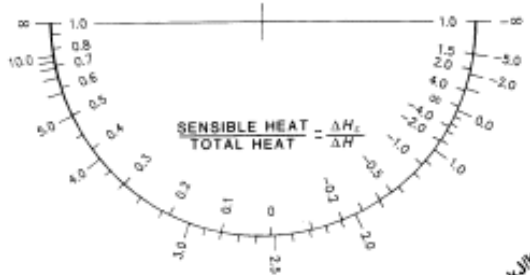
ASHRAE PSYCHROMETRIC CHART NO. 1

NORMAL TEMPERATURE SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

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AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.



Psychrometric chart: Moist air properties

- Need two quantities for a state point
 - Can get all other quantities from a state point
- Can do all calculations without a chart
 - Often require iteration
 - Many “digital” psychrometric charts available
 - Can make your own
 - Best source is *ASHRAE Handbook of Fundamentals*

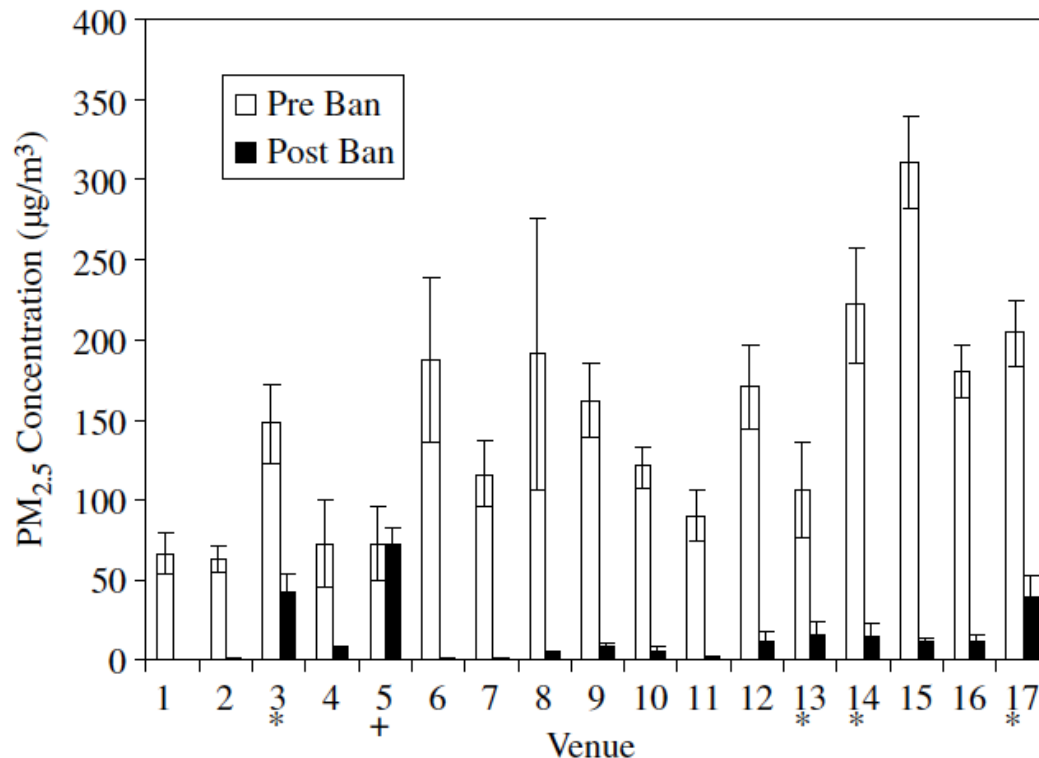
INDOOR AIR RESEARCH

Example class research projects

- Environmental tobacco smoke in hospitality venues before and after a smoking ban in Austin, Texas
 - By a colleague of mine: measurements in bars
 - Became a journal article in *J Expo Sci Environ Epidem*
- Contribution of wall cavity insulation to indoor contaminant levels
 - Modeling using previous literature, turned into conference paper
- Investigation of Chinese drywall in U.S. homes
 - Modeling using previous literature
- Particle exposure in a fire station in Austin, Texas
 - Measurement in a fire station

Project example: ETS in bars

- Measured occupancy and IAQ in 17 bars before and after a city-wide smoking ban in Austin, TX

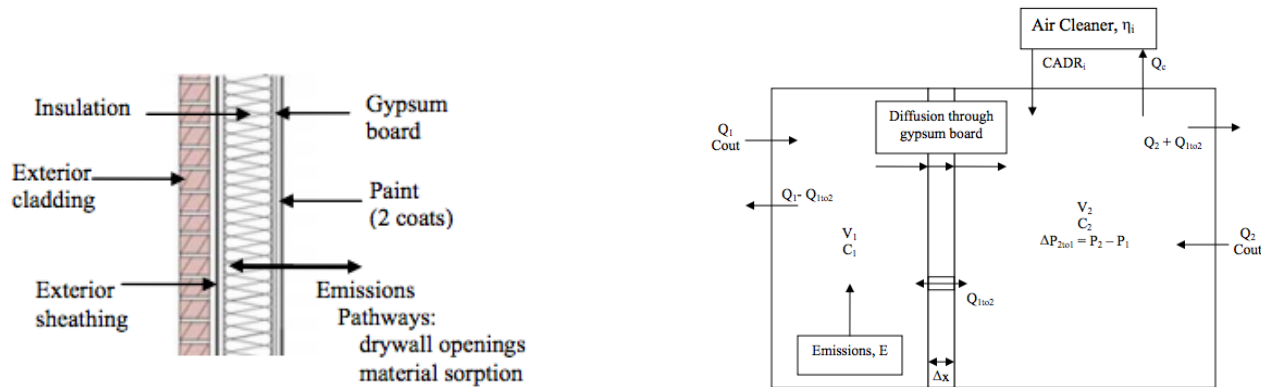


PM_{2.5}
concentrations
decreased
71-99% in all
venues

Figure 1. Best estimate pre- and post-ban PM_{2.5} concentrations for all venues: *indicates occupant non-compliance and + indicates venues exempt from the ordinance.

Project example: Emissions from insulation

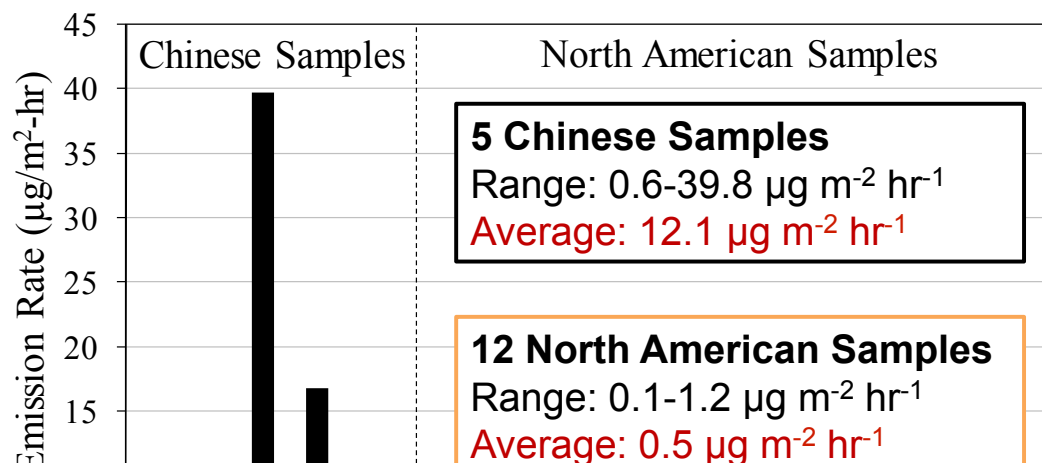
- Modeled pollutant emission from insulation materials
 - Polyurethane foam, cellulose, fiberglass, cementitious foam



Polyurethane Spray-Foam			Blown-in Cellulose		
	C_1 ($\mu\text{g}/\text{m}^3$)	C_2 ($\mu\text{g}/\text{m}^3$)		C_1 ($\mu\text{g}/\text{m}^3$)	C_2 ($\mu\text{g}/\text{m}^3$)
Pentamethyl dipropylenetriamine	435	212	Nonanal	6	3
Butylated Hydroxytoluene (BHT)	88	43	Acetone	13	6
Fiberglass Batt			Formaldehyde	3	1
	C_1 ($\mu\text{g}/\text{m}^3$)	C_2 ($\mu\text{g}/\text{m}^3$)	Hexanal	8	4
Nonanal	2	<1	Toluene	1	1
Formaldehyde	22	11	Cementitious Foam		
Base Case Model Inputs				C_1 ($\mu\text{g}/\text{m}^3$)	C_2 ($\mu\text{g}/\text{m}^3$)
$\Delta P = -1 \text{ Pa}$, $\lambda_1 = 1 \text{ hr}^{-1}$, $\lambda_2 = 0.5 \text{ hr}^{-1}$, wall opening = $0.0002 \text{ m}^2/\text{m}^2$, $T=25^\circ\text{C}$			Glyoxal (ethanedial)	63	31

Project example: Corrosive drywall emissions

- In 2009, tainted drywall (gypsum wallboard) materials were imported into the U.S. from China
 - Emitted pollutants into the indoor air, made people sick (nausea, headaches), smelled like rotten eggs, and corroded metals all around the homes
- At the time, lab and field samples were still being collected and the reports were still forthcoming
 - So I tried to model what the likely corrosive compound emission were



Hydrogen sulfide. Steady-state indoor concentrations of hydrogen sulfide exceed odor thresholds and recommended exposure levels in seven of the nine hypothetical conditions. Visible corrosion could likely occur within the period of one year in six of the hypothetical conditions. Even at low emission rates, hydrogen sulfide remains a potential culprit, especially in newly constructed tighter homes with low natural air exchange rates. Predicted hydrogen sulfide concentrations are likely to corrode copper, establish a sulfurous odor, and cause health effects include cough, nausea, and headache.

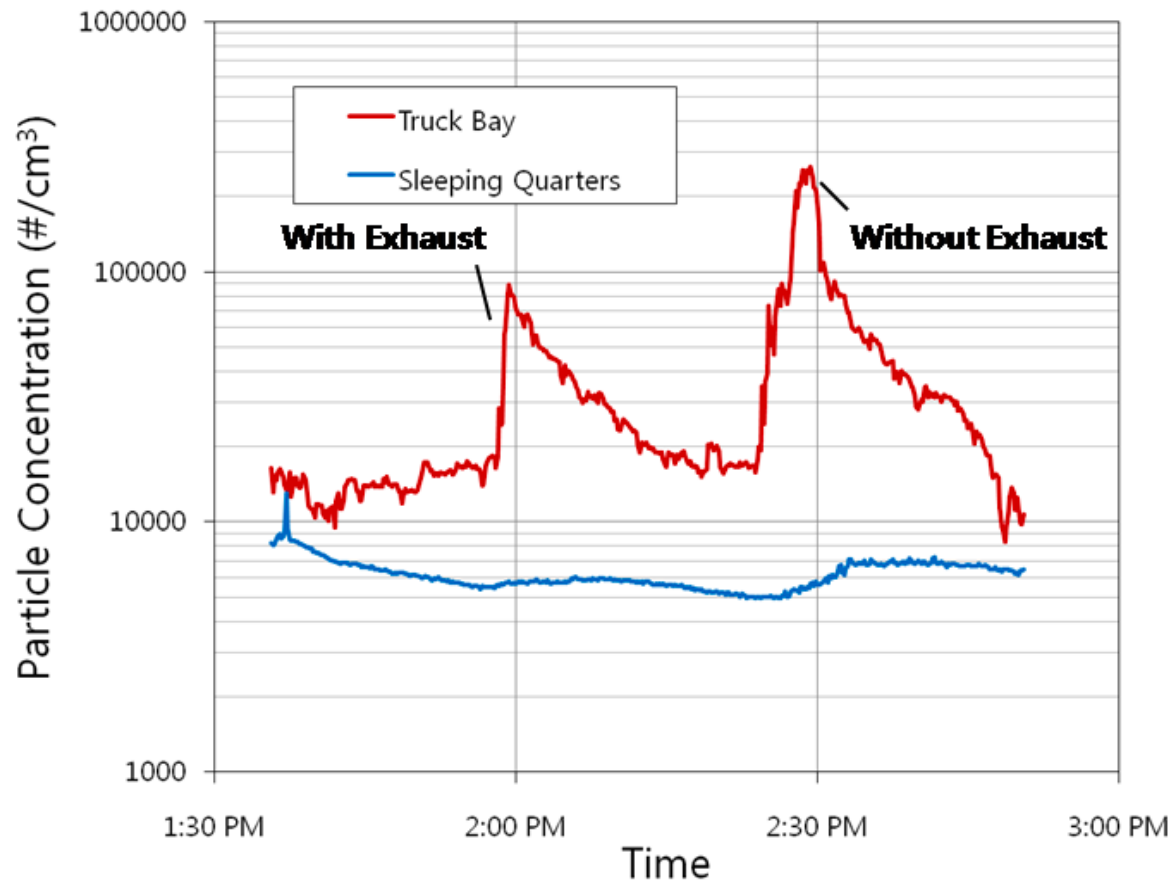
Project example: PM in fire stations

- Firefighters work, eat, sleep, and exercise during their 24 hour shifts
 - Right next to the diesel trucks that come in and out of the garage
 - Vents were installed a few years ago to expel diesel exhaust from garage
 - Do they work?

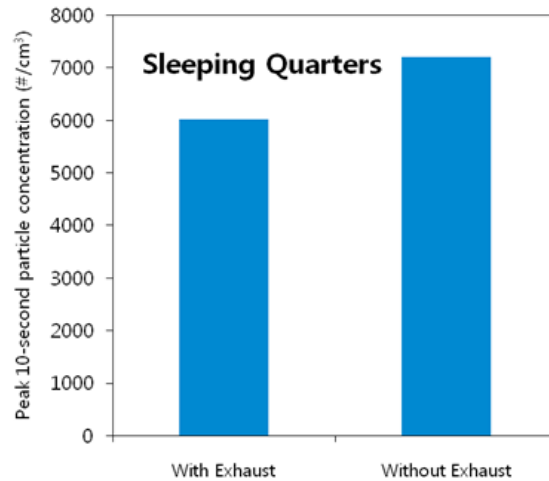
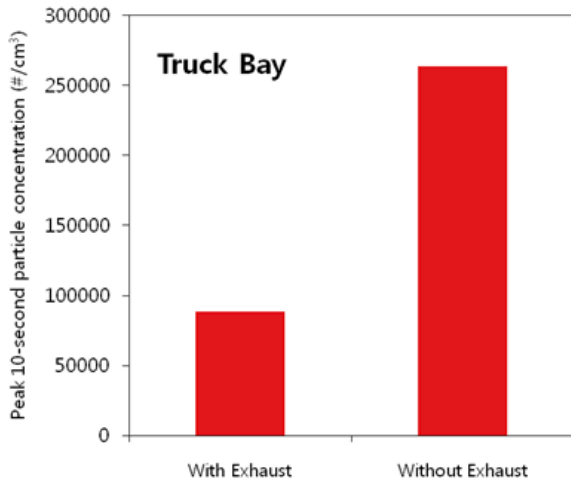


Project example: PM in fire stations

- Time-varying particle concentrations in the truck bay and upstairs sleeping quarters for one afternoon in 2012
 - With and without exhaust system installed

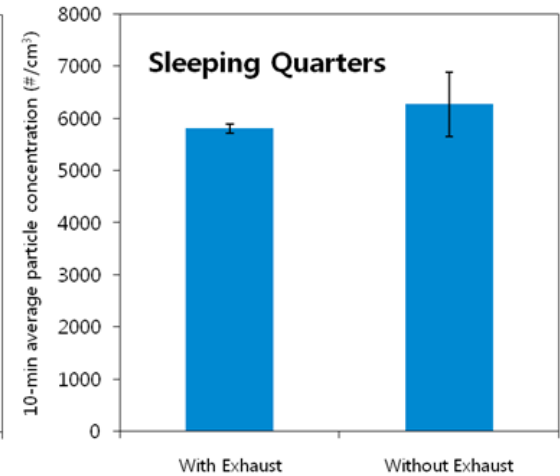
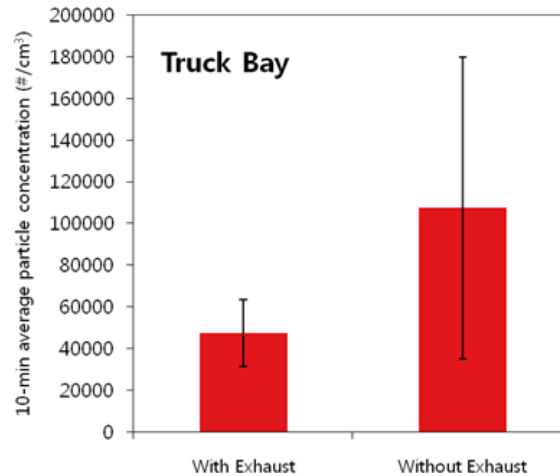


Project example: PM in fire stations



- 10-second peak concentrations in bay and sleeping quarters
 - w/ and w/out exhaust

- 10-minute average (+/- s.d.) concentrations in bay and sleeping quarters
 - w/ and w/out exhaust



Introduction to research

- Web of Science, Google Scholar, and others
 - <http://library.iit.edu/databases/>
- Accessing from off-campus
 - Example: <http://scholar.google.com.ezproxy.gl.iit.edu/>
- My own research publications
 - www.built-envi.com

Reference management: HUGE time saver

- One of the biggest time savers you can utilize is to use a citation/reference manager
- I use Zotero and keep all of my papers in PDF form downloaded into a single 'articles' folder
 - Saved as: *Author et al 2013 – Journal – Title.pdf*
 - You can download CSL files that govern the citation format used by the journal you are targeting (swappable)
- Others use Mendeley, Endnote, and others

The logo for Zotero, featuring the word "zotero" in a lowercase, sans-serif font. The letter "z" is red, and the remaining letters "otero" are black. The logo is set against a light gray rectangular background.

Information for next lecture

- Topics
 - Human exposure patterns
 - Reactor models
 - Ventilation and air exchange rates