Energy and air quality in the built environment

Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering

ILLINOIS INSTITUTE OF TECHNOLOGY

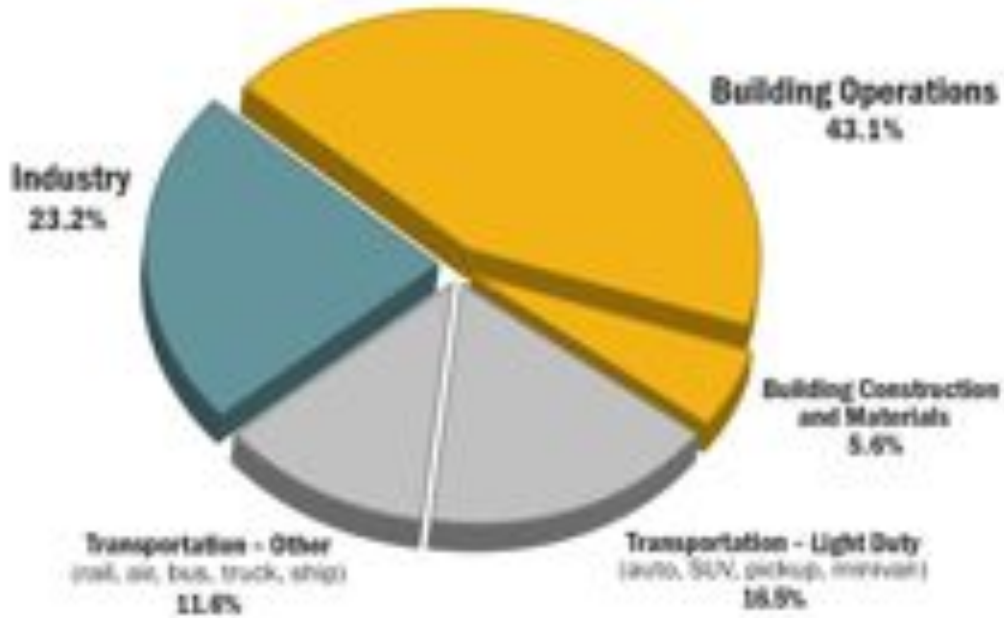
The Built Environment Research Group

advancing energy, environmental, and sustainability research within the built environment at Illinois Institute of Technology

web www.built-envi.com **email** brent@iit.edu **twitter** @built_envi

What do you think of when you hear "energy"?

What do I think of when I hear “energy”?

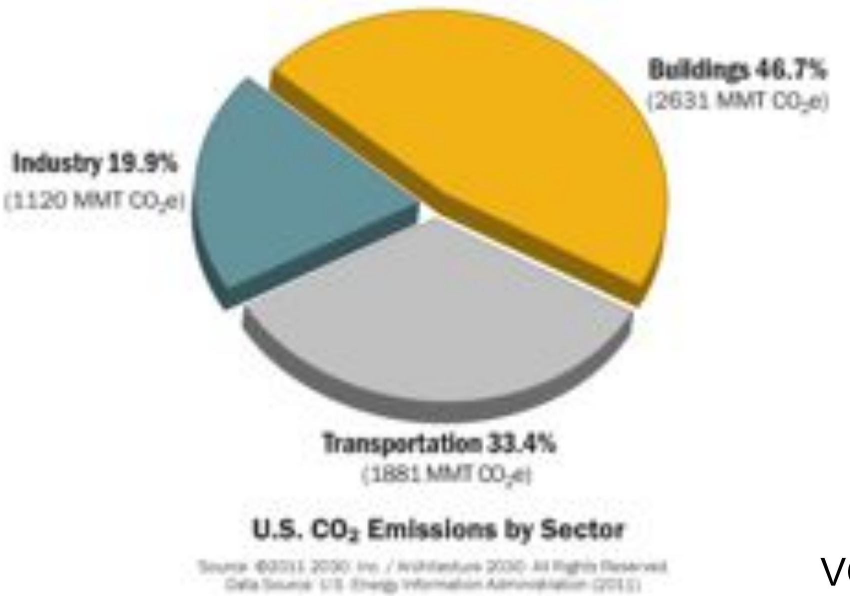


Buildings account for ~43-48% of total U.S. energy consumption

Buildings in the U.S. account for **~7%** of the total amount of energy used in the **world**

Buildings account for *a lot* of GHG and pollutant emissions

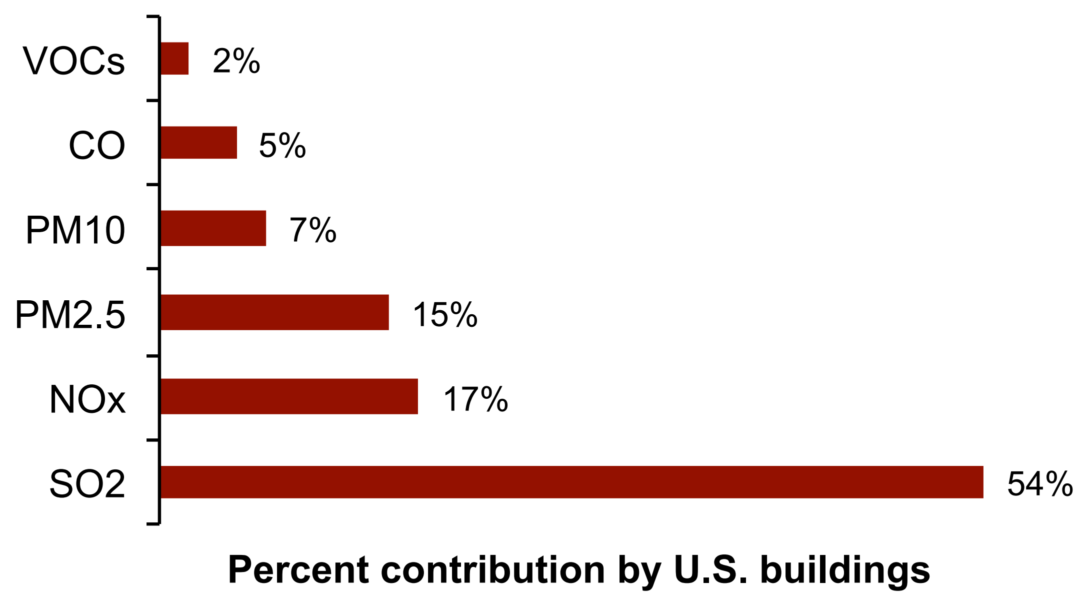
Contribution to GHGs



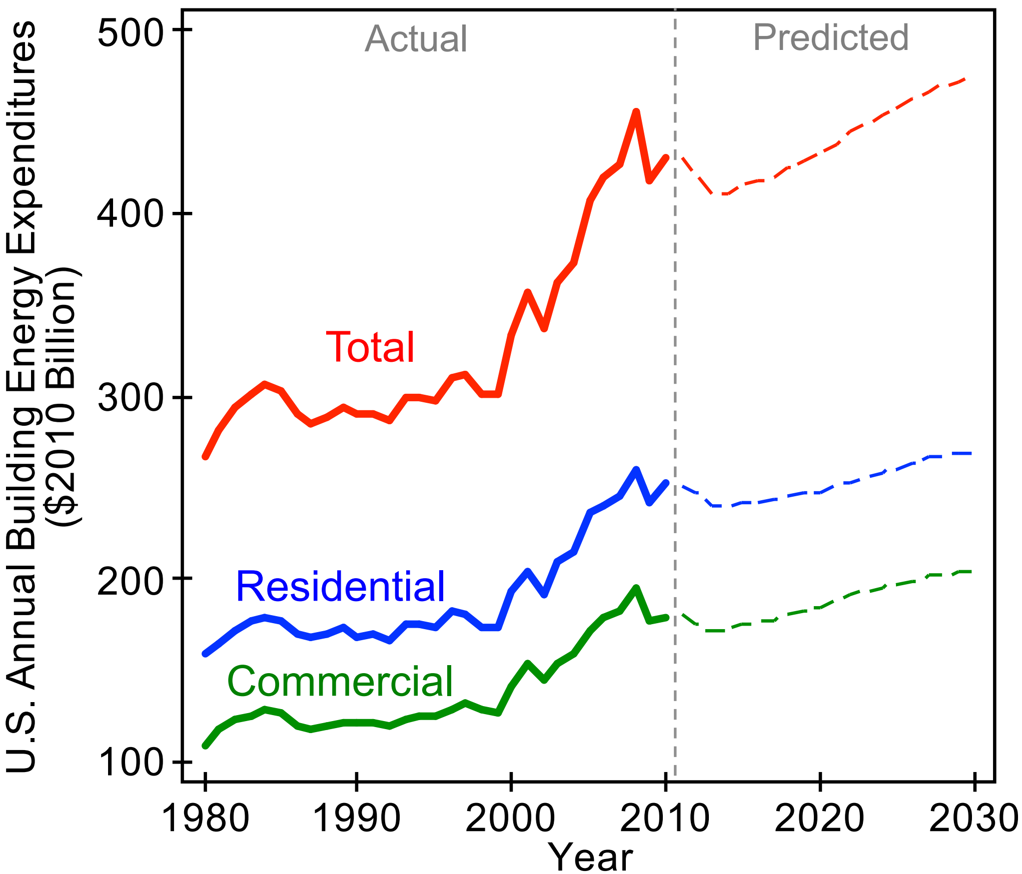
Major uses

- Heating
- Cooling
- Lighting
- Water heating

Contribution to outdoor air pollution

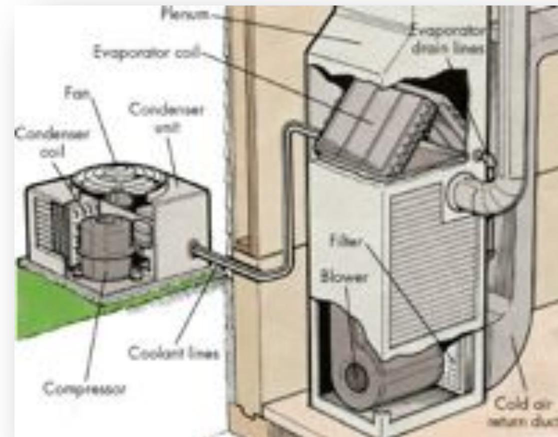


Building energy use costs ***a lot*** of money



U.S. building energy expenditures totaled ~$430 billion in 2010

Approximately 3% of our GDP



Approximately 1/3 of building energy use is for space conditioning

~1% of our GDP is spent on heating and cooling buildings

What do you think of when you hear "air pollution"?

What do I think of when I hear "air pollution"?

Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units

Maddalena et al., *Environ. Sci. Technol.* **2009**, 43, 5626-5632

Formaldehyde in the Indoor Environment

Salthammer et al., *Chem. Rev.* **2010**, 110, 2536-2572

Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes

Kelly et al., *Environ. Sci. Technol.* **1999**, 33, 81-88

What do I think of when I hear "air pollution"?

Association between gas cooking and respiratory disease in children

Melia et al., *British Medical Journal* **1977**, 2, 149-152

Indoor Air Pollution and Asthma

Ostro et al., *Am. J. Respir. Crit. Care. Med.* **1994**, 149, 1400-1406

Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves

Garrett et al., *Am. J. Respir. Crit. Care. Med.* **1998**, 158, 891-895

Pollutant Exposures from Natural Gas Cooking Burners

Logue et al., *Environ Health Perspect.* **2014**, 122, 43-50

Association of domestic exposure to volatile organic compounds with asthma in young children

Rumchev et al., *Thorax* **2004**, 59, 746-751

What do I think of when I hear "air pollution"?

Cleaning products and air fresheners: exposure to primary and secondary air pollutants

Nazaroff and Weschler, *Atmos Environ.* **2004**, 38, 2841-2865

Frequent use of chemical household products is associated with persistent wheezing in pre-school age children

Sherriff et al., *Thorax* **2005**, 60, 45-49

The Use of Household Cleaning Sprays and Adult Asthma

Zock et al., *Am. J. Respir. Crit. Care. Med.* **2007**, 176, 735-741

What do I think of when I hear "air pollution"?




The Association between Asthma and Allergic Symptoms in Children and Phthalates in House Dust: A Nested Case–Control Study

Bornehag et al., *Environ. Health Perspect.* **2004**, 112, 1393-1397

Intellectual Impairment in Children with Blood Lead Concentrations below 10 µg per Deciliter

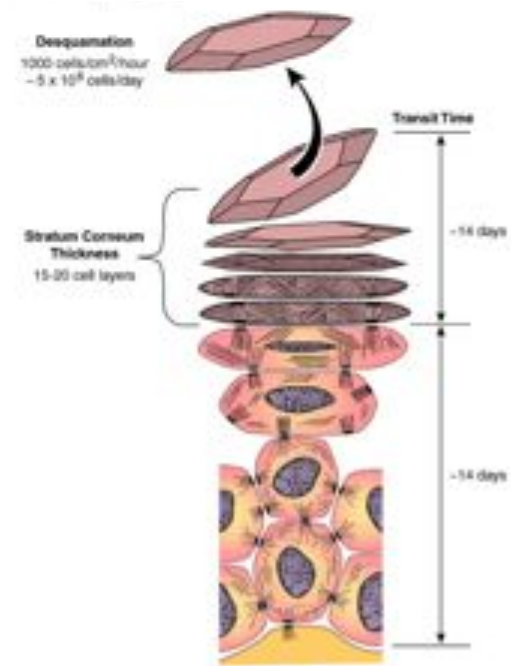
Canfield et al., *New Engl. J. Med.* **2003**, 348, 1517-1526

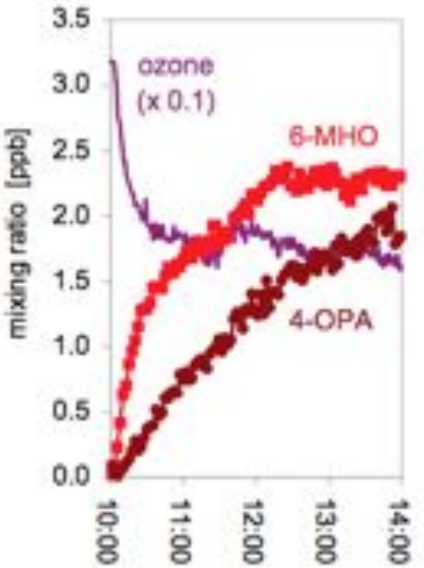
What do I think of when I hear "air pollution"?

Epidermal desquamation

Milstone, *J. Dermatol. Sci.* **2004**, 36, 131-140

We shed our entire outer layer of skin every 2-4 weeks





Reactions of ozone with human skin lipids: Sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air

Wisthaler and Weschler, *Proc Nat Acad Sci.* **2010**, 107, 6568-6575

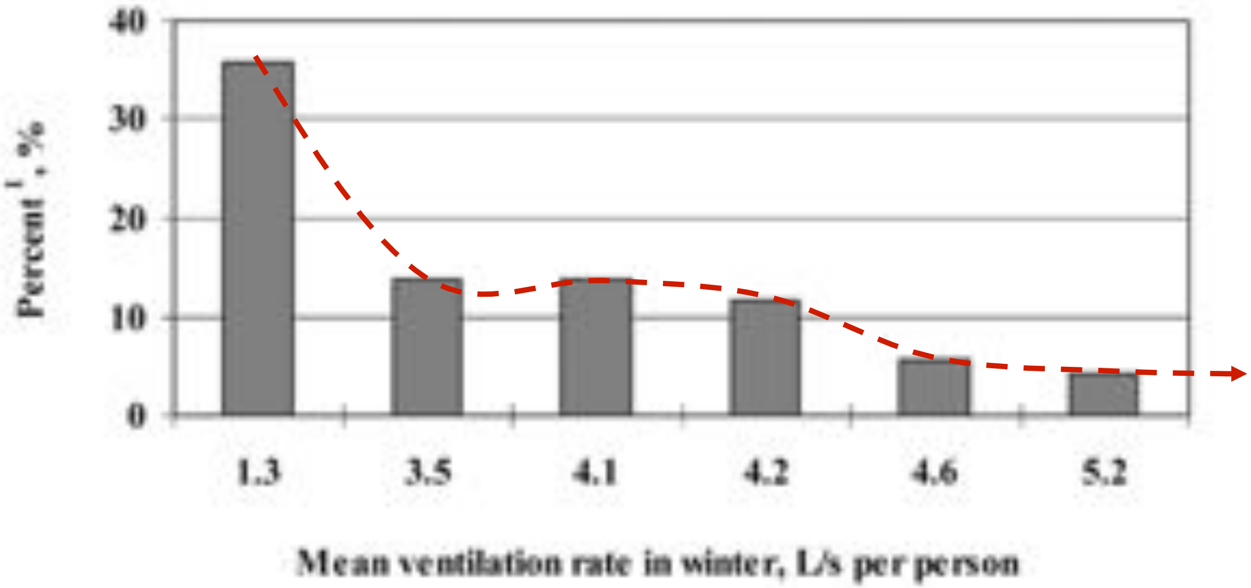
What do I think of when I hear "air pollution"?

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

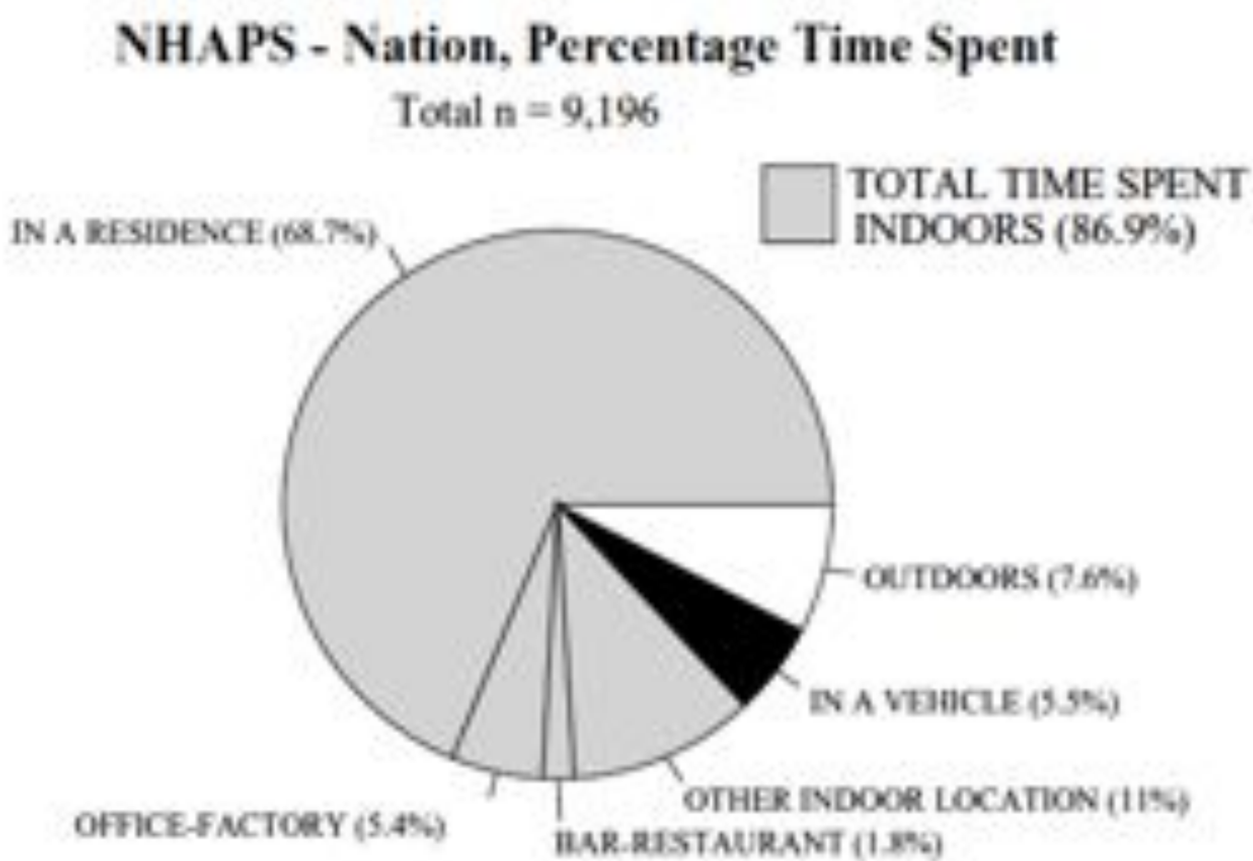
Yu et al., *New Engl. J. Med* **2004**, 350, 1731-1739

In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

Sun et al. **2011** *PLoS ONE* 6:e27140



We spend *a lot* of our time in buildings



- Americans spend almost 90% of their time indoors
  - 75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* **2001**, 11, 231-252

Buildings impact people, energy, and the environment

The design, construction, and operation of buildings, including their heating, ventilation, and air-conditioning (HVAC) systems and building envelopes, greatly affect their contribution to energy use, greenhouse gas emissions, financial expenditures, and human exposures to airborne pollutants in the indoor environment

The **Built Environment Research Group** at IIT is dedicated to investigating problems and solutions related to energy and air quality within the built environment

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

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Highlights of some recent research projects

1. Indoor exposures to outdoor pollutants
2. HVAC filters for reducing airborne infectious disease transmission indoors
3. Building science measurements in the Hospital Microbiome Project
4. Open source building science sensors (OSBSS)
5. Ultrafine particle emissions from desktop 3D printers

1. INDOOR EXPOSURES TO OUTDOOR AIR POLLUTION: PARTICULATE MATTER

Motivation: Health effects and outdoor PM

- Epidemiological studies show associations between elevated outdoor particulate matter (PM) and adverse health effects

  Pope et al., **2002** *J Am Med Assoc*; Peng et al., **2005** *Am J Epidem*; Pope and Dockery, **2006** *J Air Waste Manag Assoc*; Miller et al., **2007** *New Engl J Med*; Stölzel et al., **2007** *J Expo Sci Environ Epidem*; Andersen et al., **2010** *Eur Heart J;* Brook et al. **2010** *Circulation*; Ostro et al., **2010** *Environ Health Persp*

  – Effects ranging from respiratory symptoms to mortality

  – PM_{10}, $PM_{2.5}$, and ultrafine particles (UFP, < 100 nm)

    - Also specific constituents and seasonal differences

- But we spend most of our time indoors

  ~87% of the time on average (~69% at home) Klepeis et al., **2001** *J Expo Anal Env Epi*

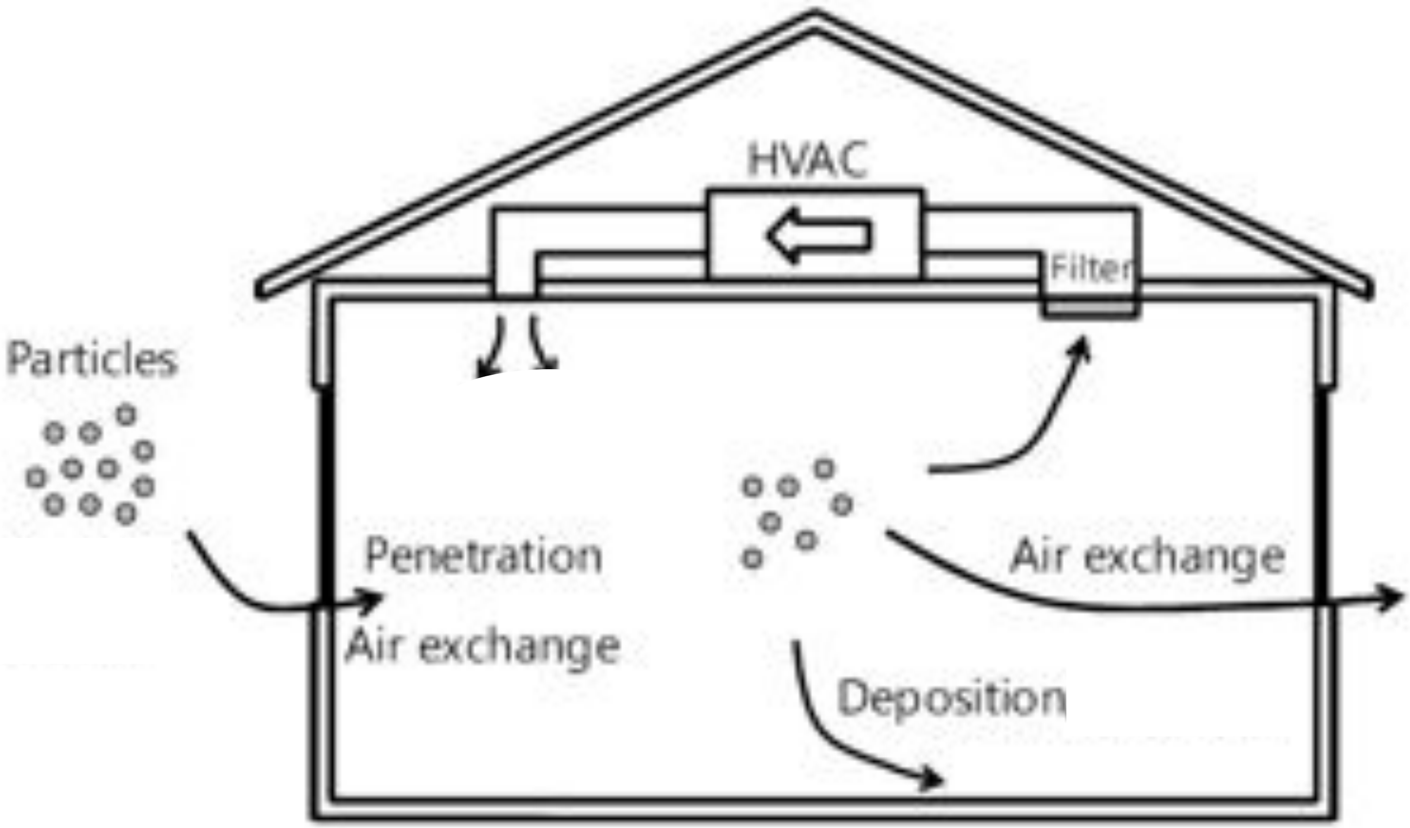
- Outdoor particles can infiltrate and persist in homes with varying efficiencies Chen and Zhao, **2011** *AE;* Williams et al., **2003** *AE;* Kearney et al., **2010** *AE*

- Much of our exposure to outdoor PM often occurs indoors

  – Often at home

  Meng et al., **2005** *J Expo Anal Environ Epidem;* Kearney et al., **2010** *Atmos Environ;* Wallace and Ott **2011** *J Expo Sci Environ Epidem;* MacNeill et al. **2012** *Atmos Environ*

Mechanisms that impact indoor exposures to outdoor PM



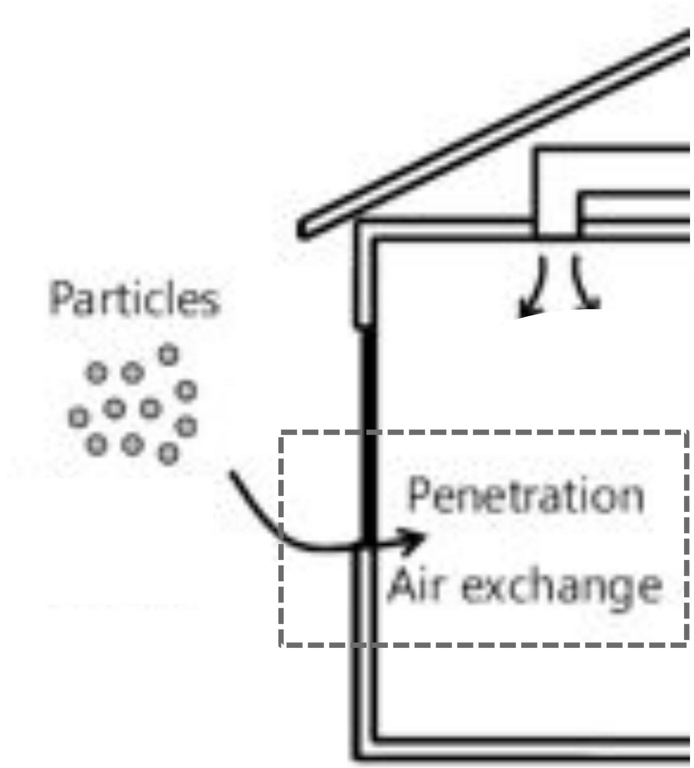
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\text{inf}} = \frac{P\lambda}{\lambda + k + f\dfrac{\eta Q}{V}}$$

Penetration from outdoors

Air exchange
Deposition
HVAC filter removal

Mechanisms that impact indoor exposures to outdoor PM



"Penetration Factor"
If *P* = 1:
The envelope offers no protection
If *P* = 0:
The envelope offers complete protection

C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
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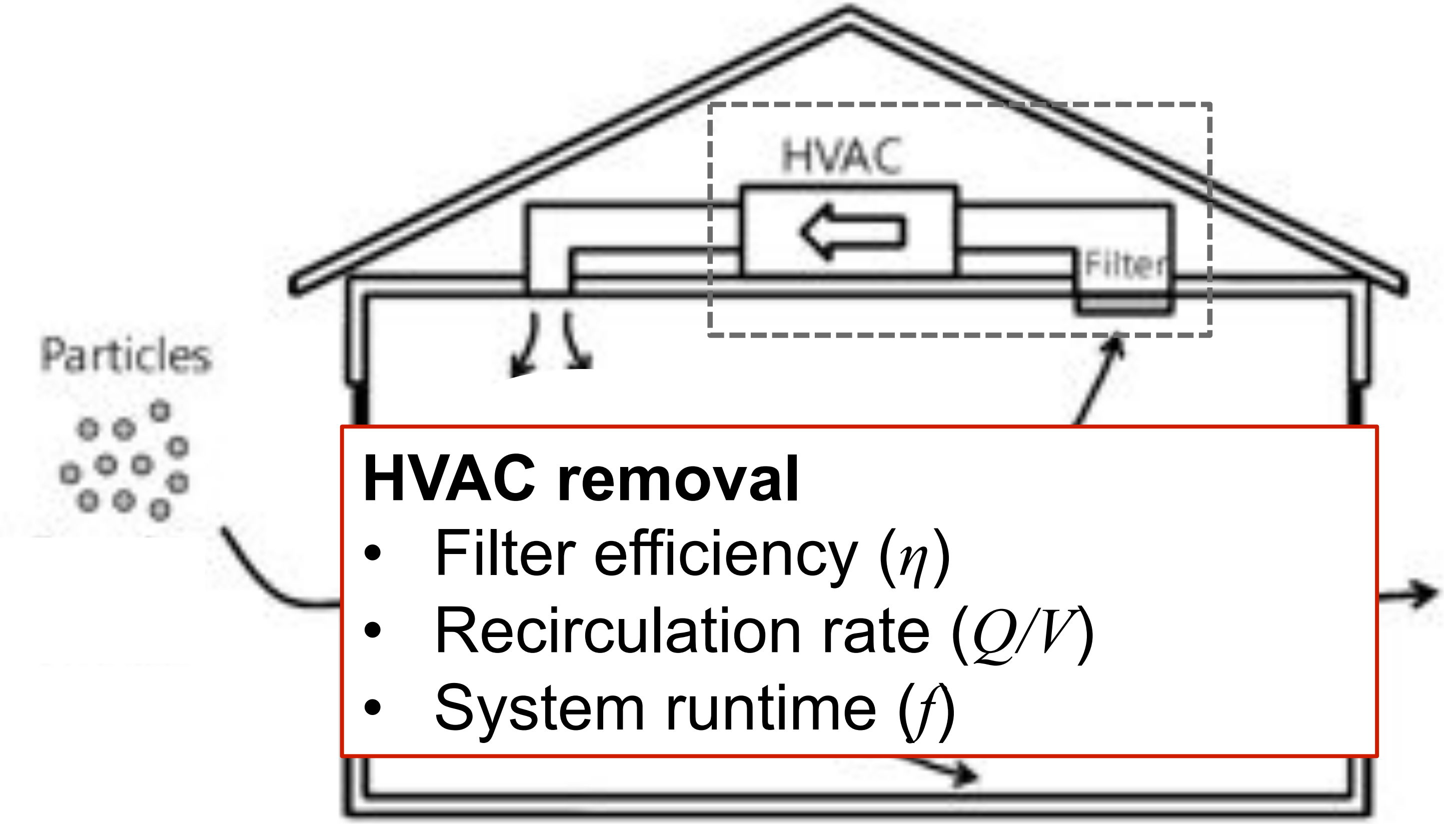
Penetration from outdoors

Mechanisms that impact indoor exposures to outdoor PM



HVAC removal
- Filter efficiency (η)
- Recirculation rate (Q/V)
- System runtime (f)

C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\inf} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

Filter removal
HVAC operation

Goals of this work

- Further explore the impacts of building design and operation – including **building envelopes** and **HVAC filters** – on indoor PM of outdoor origin

  Key parameters:
  - Particle penetration factor, P
  - Air exchange rate, λ
  - Particle removal by HVAC filter, $\eta Q/V$
  - HVAC system runtime, f

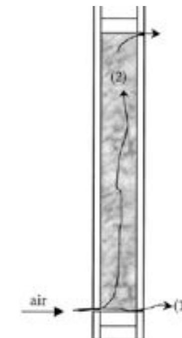
- Using recently measured data from recent studies on residential (and some small commercial) buildings

- Can we also **predict** these impacts?

Measuring particle infiltration

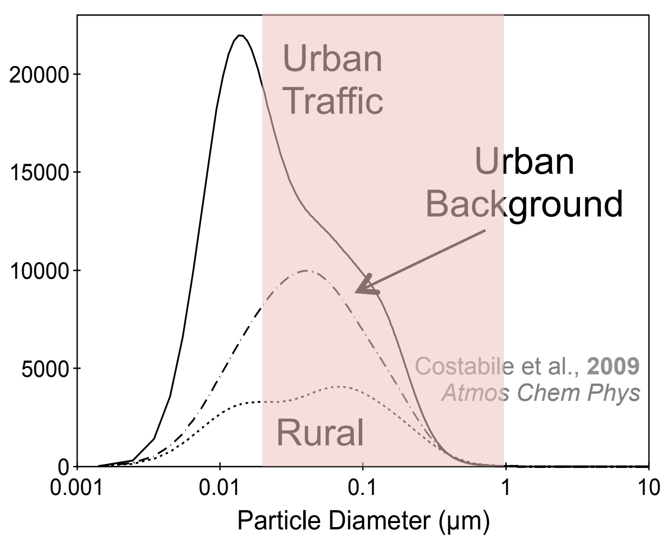
- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

Liu and Nazaroff, **2001** *Atmos Environ*



- Are building details and particle penetration factors correlated?
  - e.g., air leakage parameters or building age
  - Needed a test method for measuring *P* quickly
- Applied a particle penetration test method in 19 homes

Stephens and Siegel, **2012** *Indoor Air*

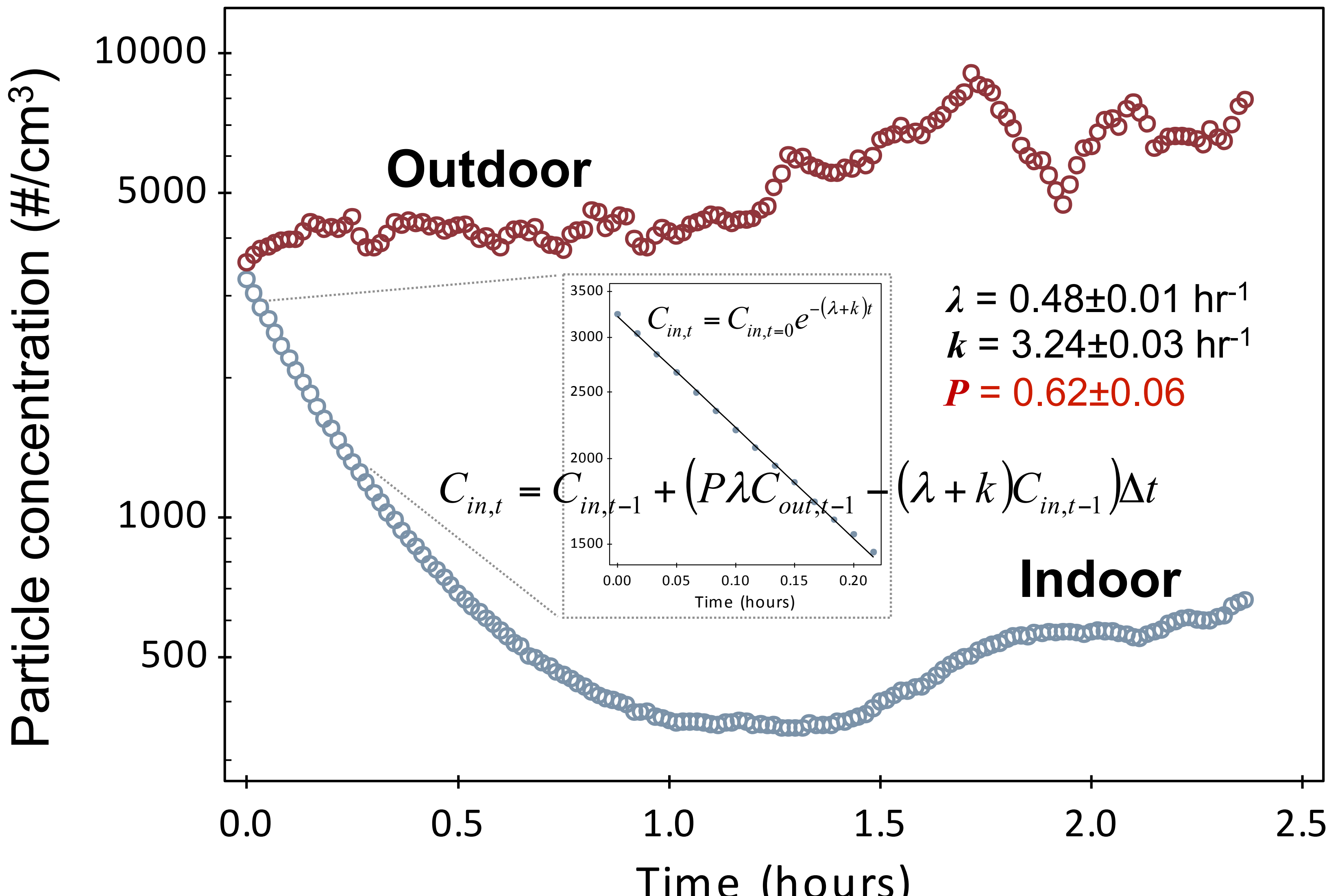


TSI P-Traks
20 – 1000 nm

PM infiltration: Test homes

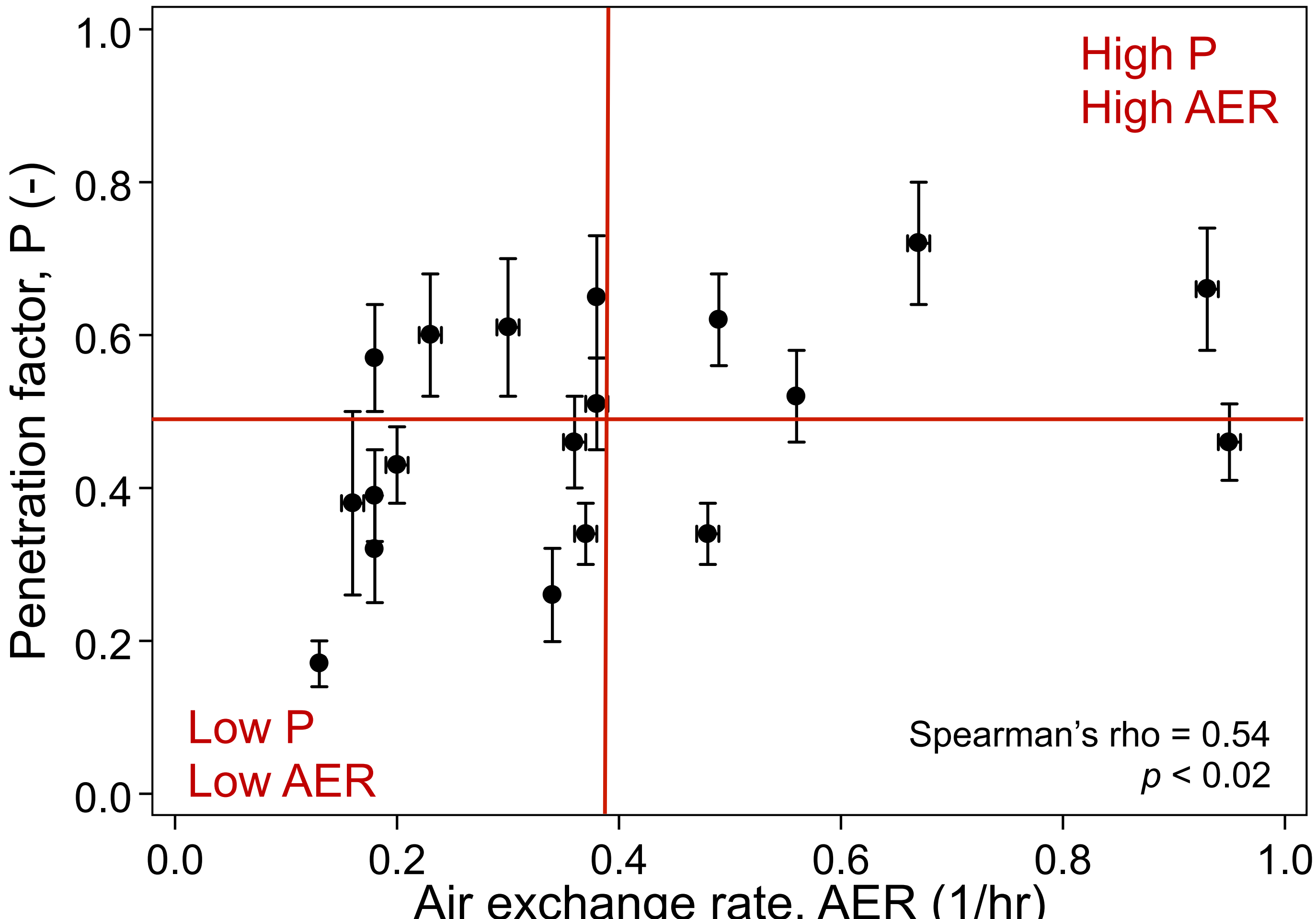
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Test method: Submicron particle infiltration (20-1000 nm)



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Particle infiltration results: P and AER



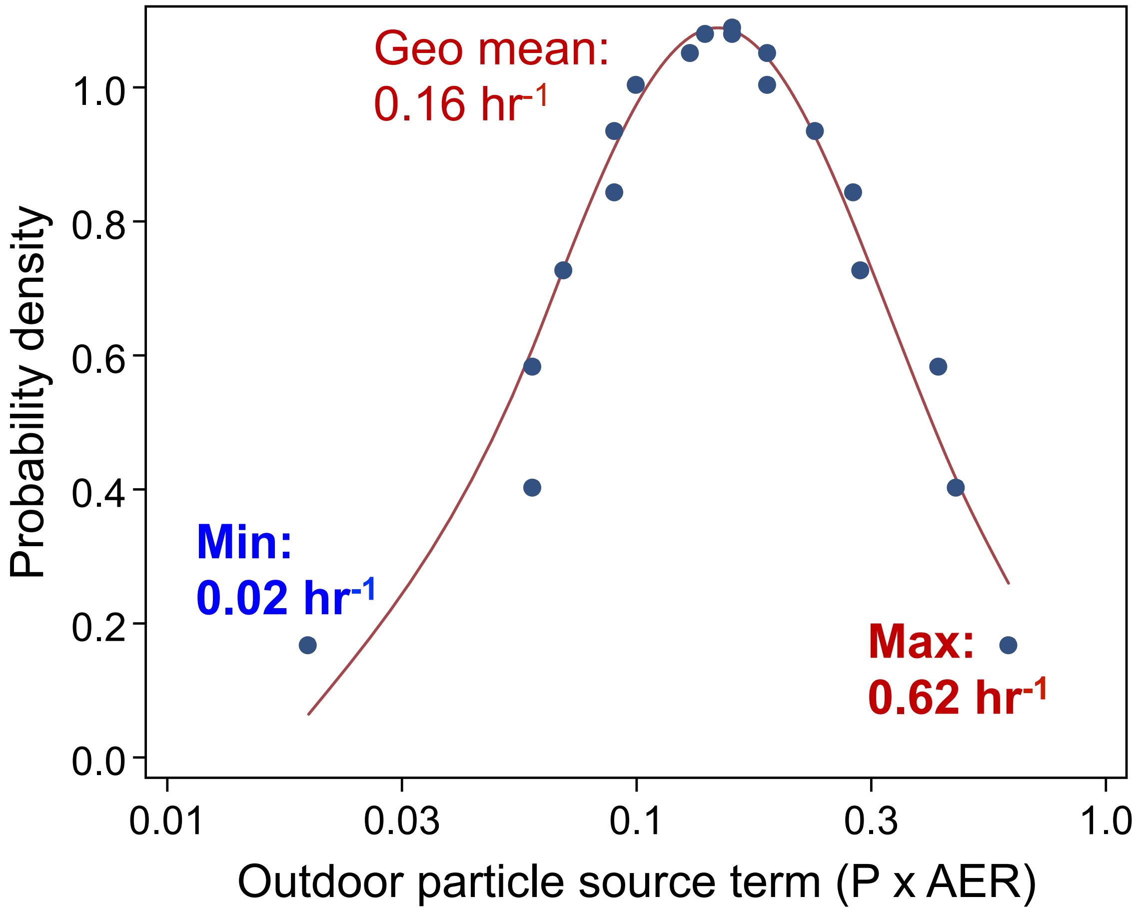
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

Air exchange rates: Mean = 0.39 hr^{-1} Range = 0.13 to 0.95 hr^{-1}

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

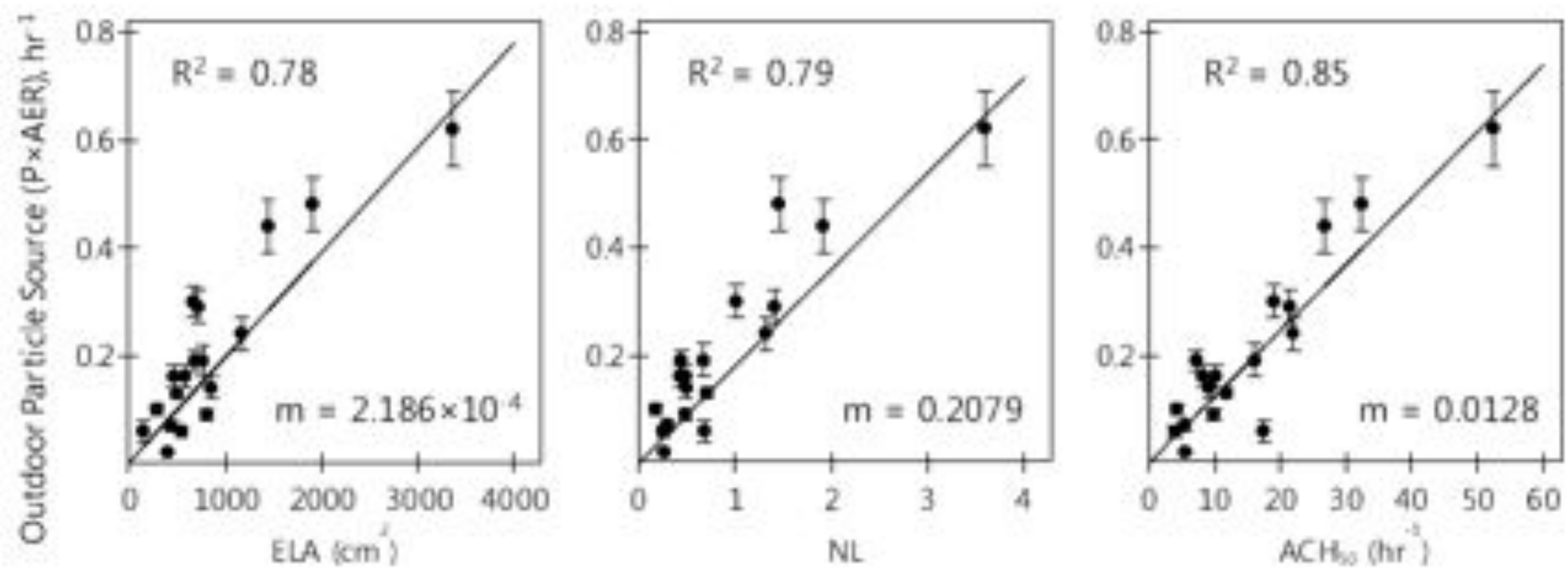
Outdoor particle source terms: P×AER

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



Outdoor particle sources and envelope air tightness

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$ vs. blower door test results



Leakier homes had much higher outdoor particle source rates

Older homes also had much higher outdoor particle source rates

- Potential socioeconomic implications: low-income homes are older/leakier

Chan et al., **2005** *Atmos Environ*

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

HVAC filter removal: Efficiency is not the whole story

$$Loss = k + f\frac{\eta Q}{V}$$

1-inch depth

MERV 4

MERV 6

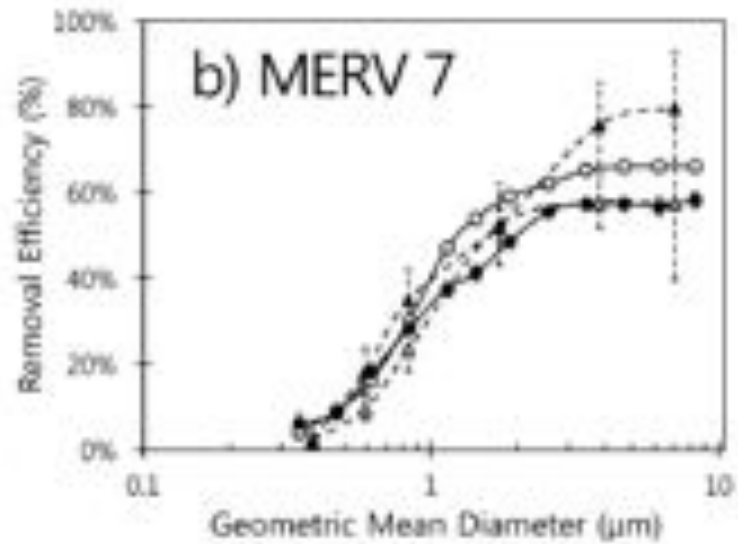
MERV 11

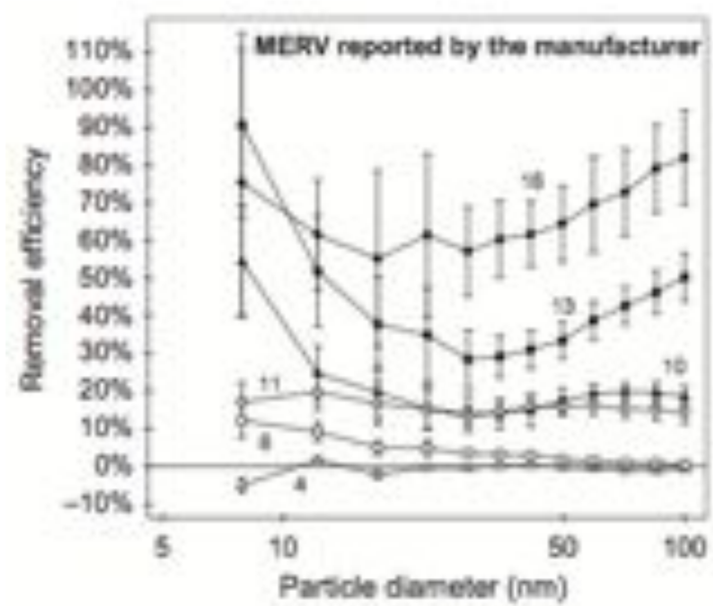
5-inch depth

MERV 10

MERV 13

MERV 16





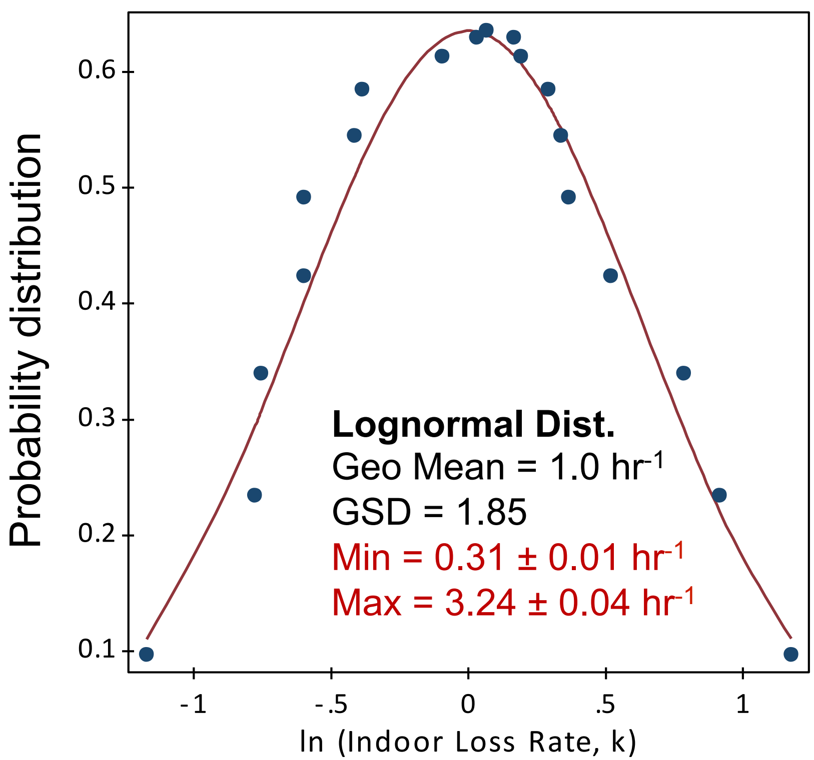
Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513
Stephens and Siegel, *Indoor Air* **2013**

Indoor particle removal rates

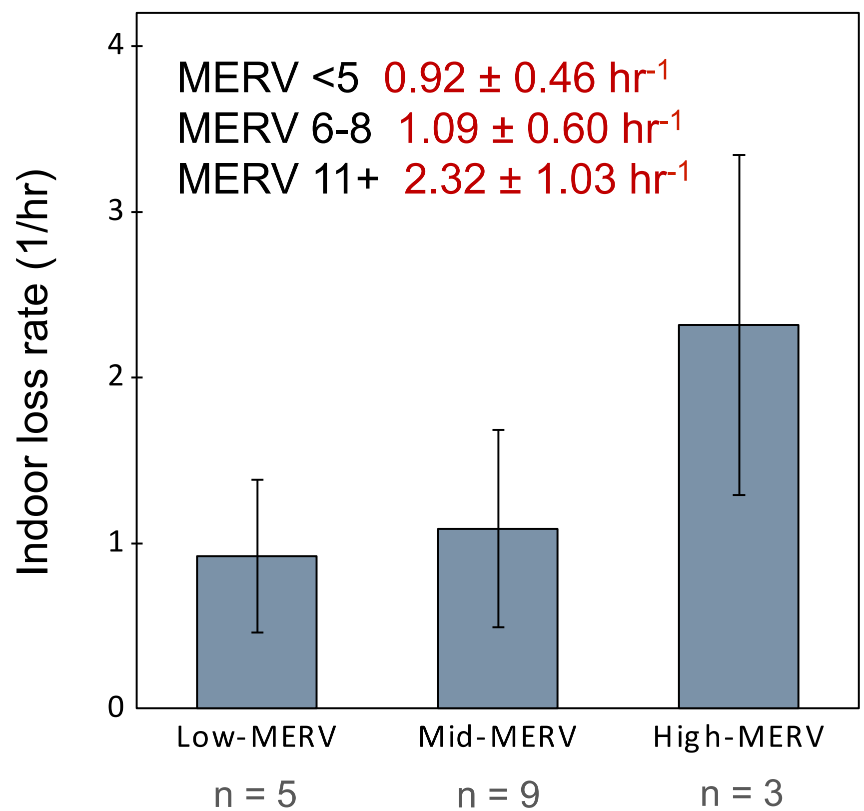
- Submicron particle loss with HVAC system operating 100%

$$Loss = k + f\frac{\eta Q}{V}$$

where $f = 1$



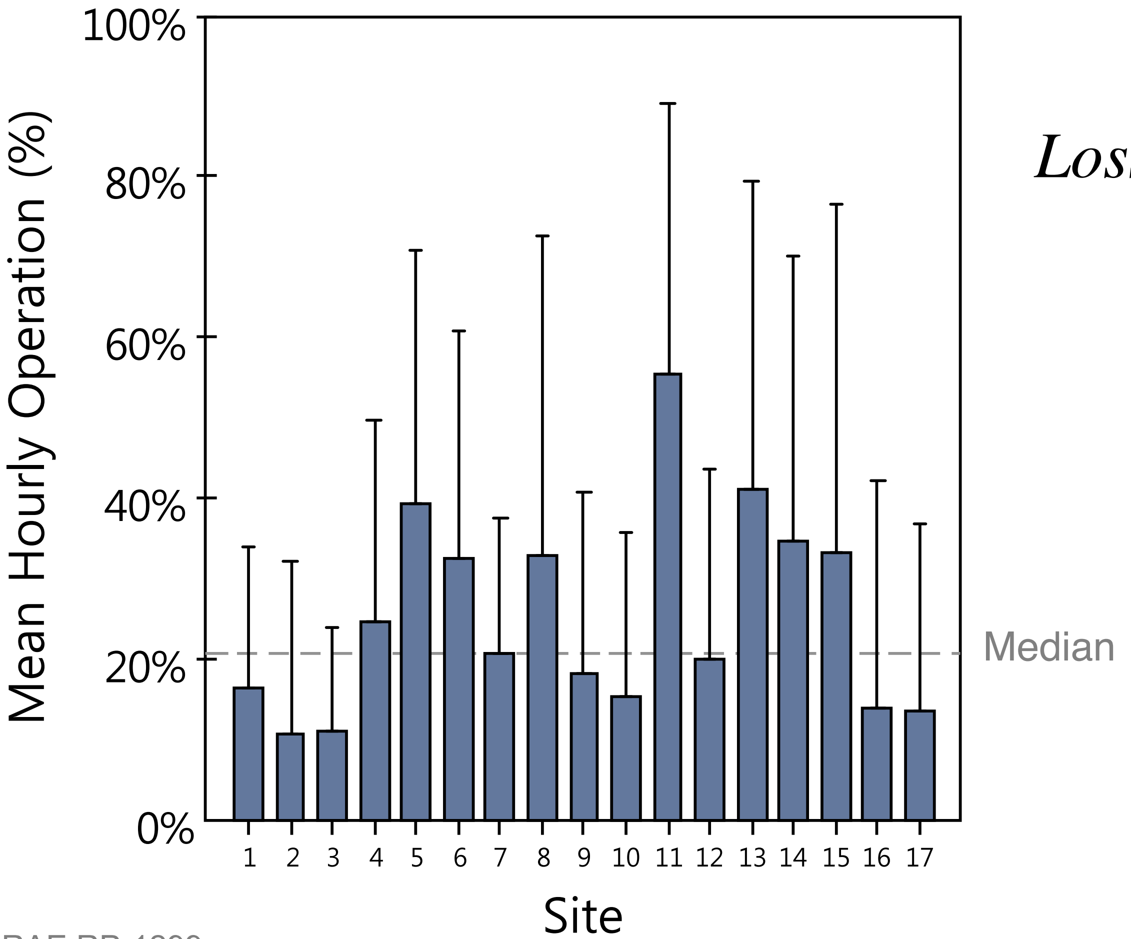
Split by filter type



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

HVAC system runtimes in other homes and small offices

- Mean HVAC runtimes in TX ranged 10.7% to 55.3%
  - Median $f \approx 21\%$ (influenced by climate and thermostat settings)



$$Loss = k + f\frac{\eta Q}{V}$$

Stephens et al., **2010** ASHRAE RP-1299
Stephens et al., **2011** *Building and Environment* 46(10):1972-1983

VARIATIONS IN PM EXPOSURES

Across observed range of envelope penetration, filter efficiency, and runtimes

Implications for submicron PM exposure

- Penetration factors ranged 0.17 to 0.72
- AER ranged 0.13 hr^{-1} to 0.95 hr^{-1}
- Outdoor particle source terms ranged 0.02 hr^{-1} to 0.62 hr^{-1}
  - Factor of **~30** difference from lowest to highest
  - Higher in older, leakier homes

- Indoor removal rates ranged 0.31 hr^{-1} to 3.24 hr^{-1}
  - Factor of **~10** difference from least efficient to most efficient filter
  - Varied with rated filter efficiency (particularly for high-efficiency)

- HVAC fractional operation ranged 10.7% to 55.3%
  - Factor of **~5** difference
  - Varied with thermostat settings, occupancy, and outdoor climate

Implications for submicron PM exposure

- Combined effects: $F_{\text{inf}} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + k + f\frac{\eta Q}{V}}$

	Lower bound	Upper bound
Penetration factor, *P*	0.17	0.72
Air exchange rate, *AER* (1/hr)	0.13	0.95
Outdoor source term, *P×AER* (1/hr)	0.02	0.62
Indoor loss rate, $k + \eta Q/V$ (1/hr)	3.24	0.31
Fractional HVAC operation, *f*	55.3%	10.7%
I/O submicron PM ratio (F_{inf})	**0.01**	**0.70**

Factor of **~70** difference in indoor proportion of outdoor particles between:

- A new airtight home with a very good filter and high HVAC operation, and
- A leaky old home with a poor filter and low HVAC operation

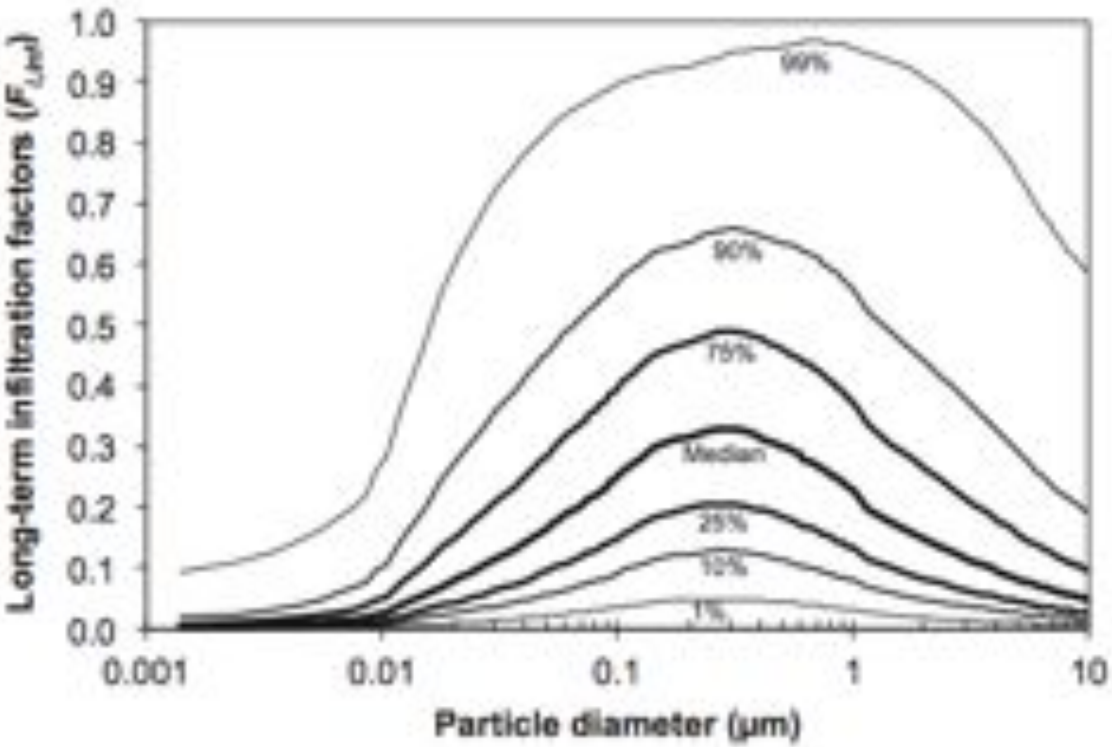
- Some potential for predictive ability using:
  - Age of home
  - Building airtightness test results
  - Knowledge of HVAC filter type
  - I/O climate conditions

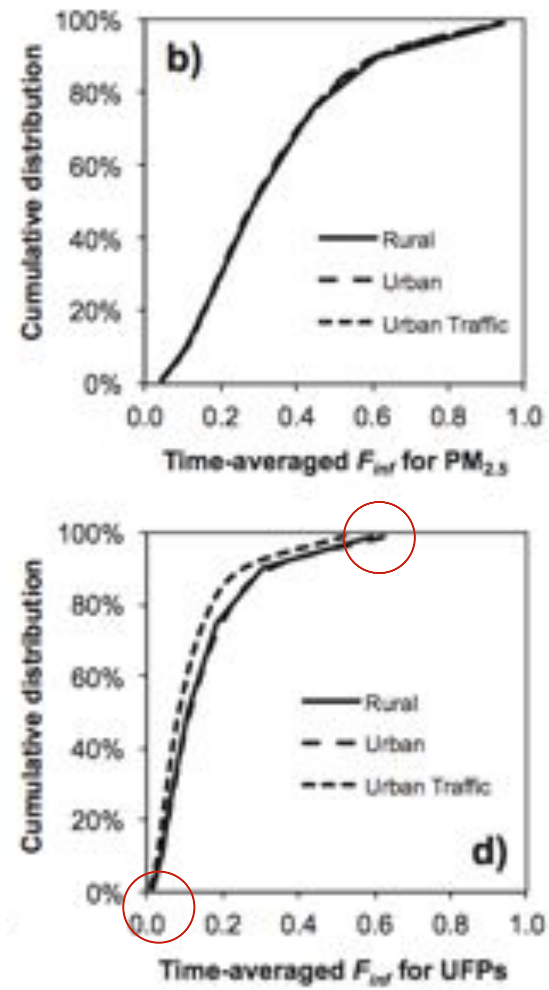
Modeling size-resolved indoor PM of outdoor origin

Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S.

Zeineb El Orch [a], Brent Stephens [a,*], Michael S. Waring [b]

[a] Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA
[b] Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA





El Orch et al., **2014** *Building and Environment* 74:106-118

2. FILTRATION OF INFECTIOUS AEROSOLS

Motivation

- Communicable respiratory illnesses have significant economic impacts in the U.S.
  - 43 common colds and 26 cases of influenza per 100 persons
  - Healthcare costs, absence from work, lost worker productivity
    - Total cost was ~$70 billion in 2000

Fisk **2000** *Ann Review Energy Environ* 25:537-566

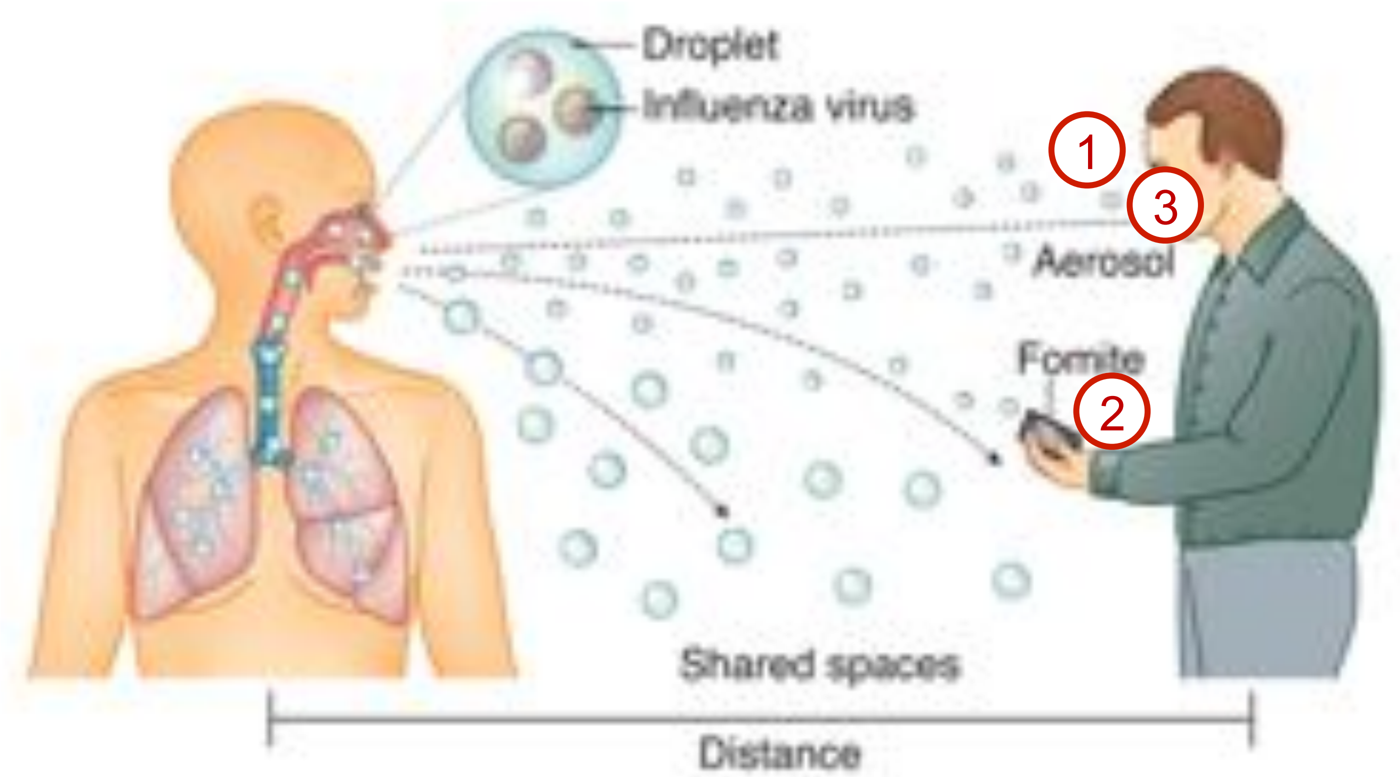
- Airborne transmission of respiratory pathogens is complex
  - Continuing debate about transmission modes

- Control of airborne infectious disease transmission
  - Studies suggest building characteristics, outdoor air ventilation rates, and lower occupant density can reduce respiratory illnesses 15-76%

Langmuir et al. **1948** *Am J Hyg*; Brundage et al. **1988** *JAMA*;
Drink a et al. **1996** *Am Geriatr Soc*; Fisk **2000**; Li et al. **2007** *Indoor Air*

- Others: UVGI, facemasks, isolation … HVAC filtration?

Primary modes of disease transmission

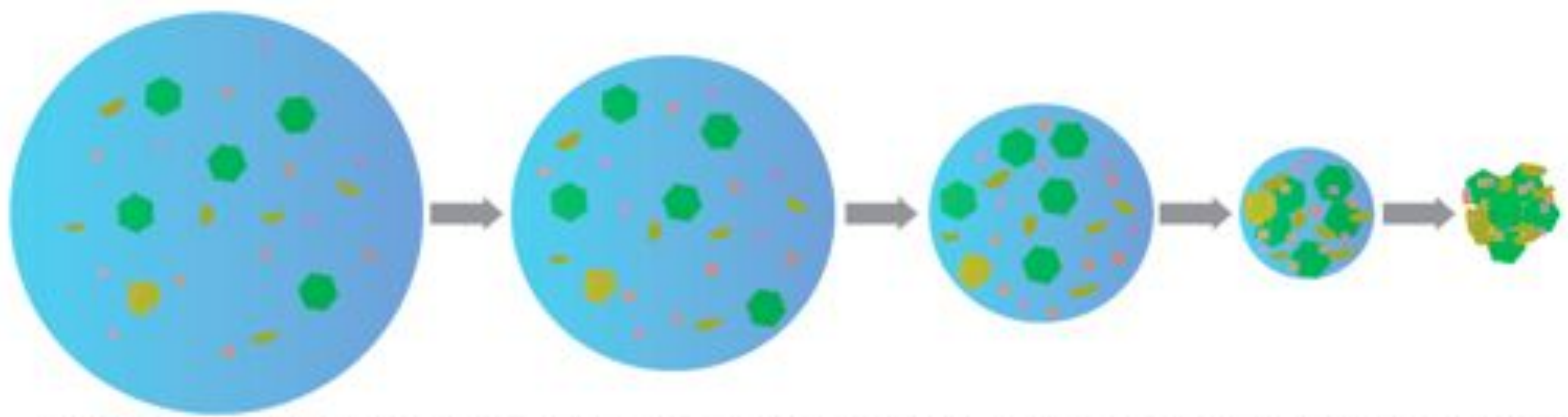


1. Direct contact with pathogen sources
2. Contact with contaminated object surfaces (“fomite”)
3. Inhalation of airborne infectious aerosols (often longer distances)

Lakdawala and Subbarao **2012** *Nature Medicine* 18:1468-1470

“Spreading”: Expulsion of droplets

- When a person coughs, sneezes, speaks or breaths:
  - Particles of liquid water, proteins, salts, and other matter are expelled
    - These are called droplets
    - These particles may contain smaller infectious organisms
  - Droplets rapidly deposit to surfaces and/or decrease in size as the surrounding liquid evaporates
    - Droplet nuclei remain after evaporation
    - Typically 40-50% smaller diameter (d_p) than original droplets
      - Still contain infectious organisms

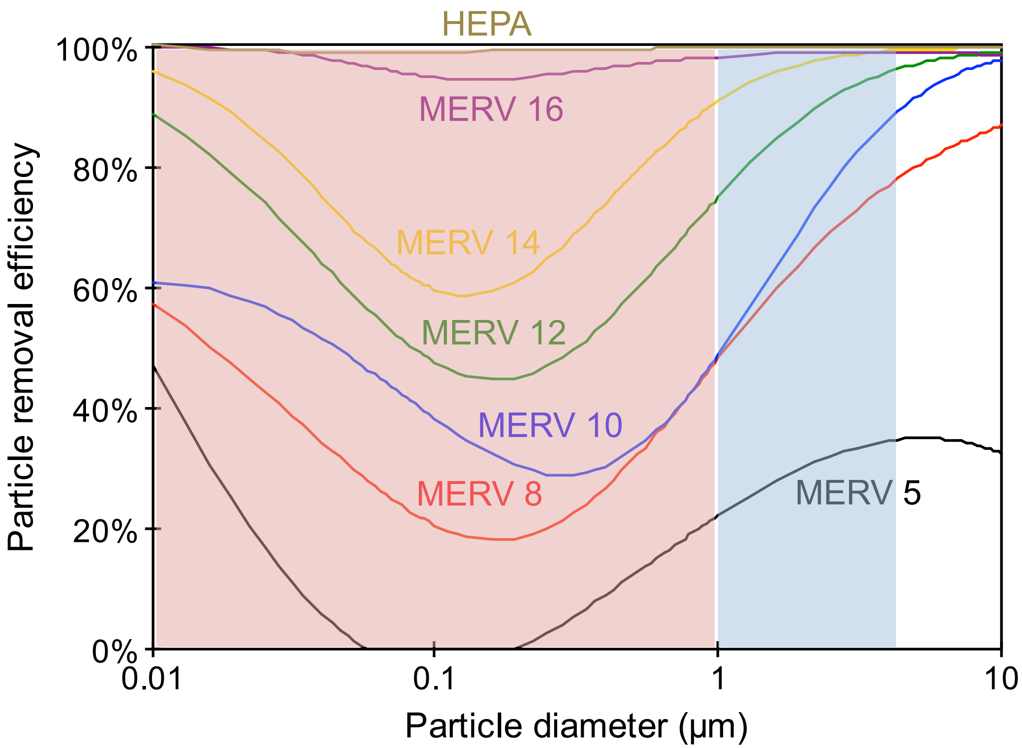


Verreault et al. **2008** *Microbiology and Molecular Biology Reviews* 72:413-444; Nicas et al. **2005** *J Occup Environ Hyg* 2:143-154; Chen and Zhao **2010** *Indoor Air* 20:95-111; Yang and Marr **2011** *PLoS ONE* 6:e21481

Rapid evaporation of droplets, *Mythbusters*

What particle sizes are actually emitted by humans?

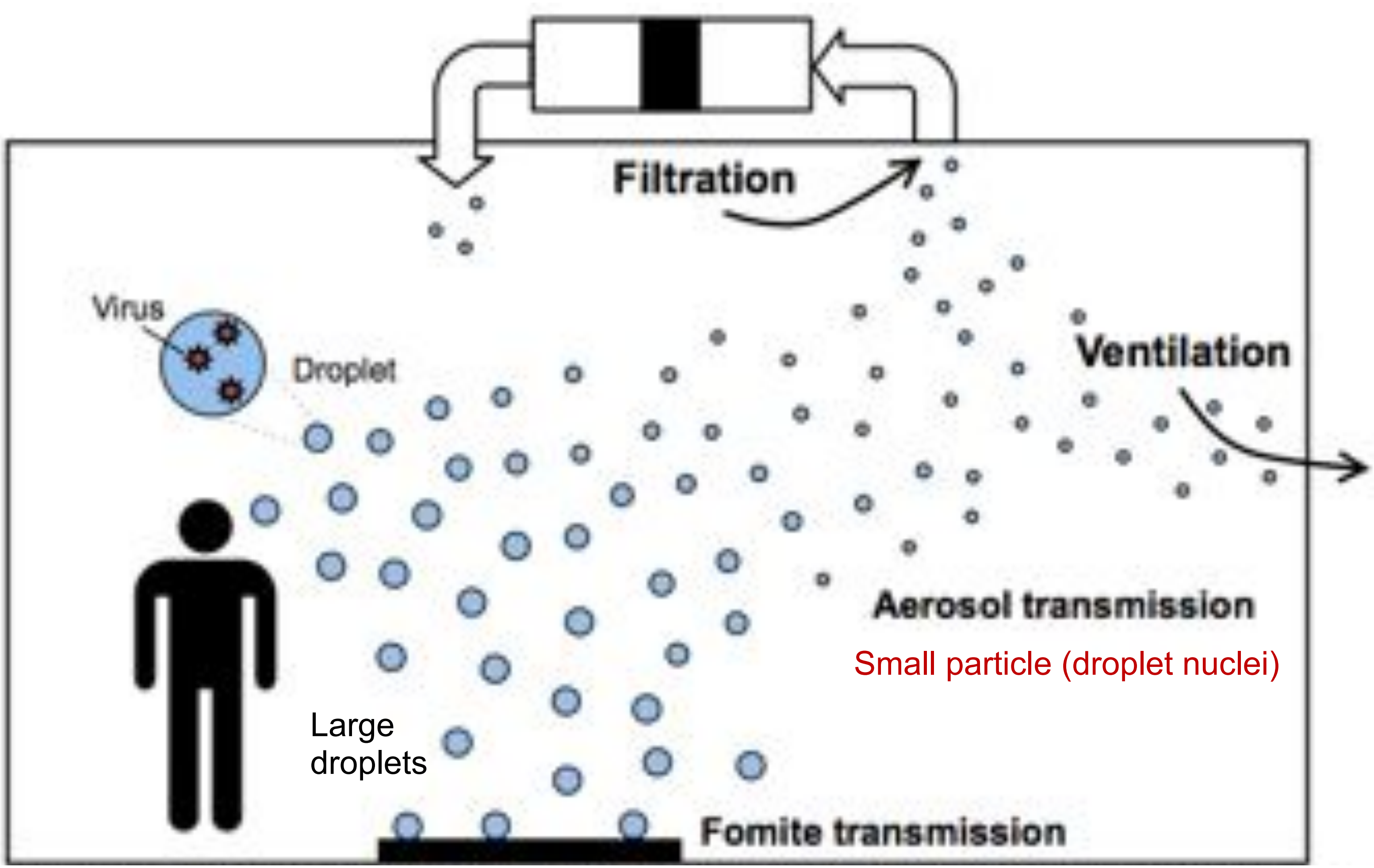
- When considering particle filtration of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols



- Commonly believed that droplet nuclei average 1-3 μm
  - Recent studies show that 80-90% of particles expelled during human activities are actually smaller than 1-2 μm

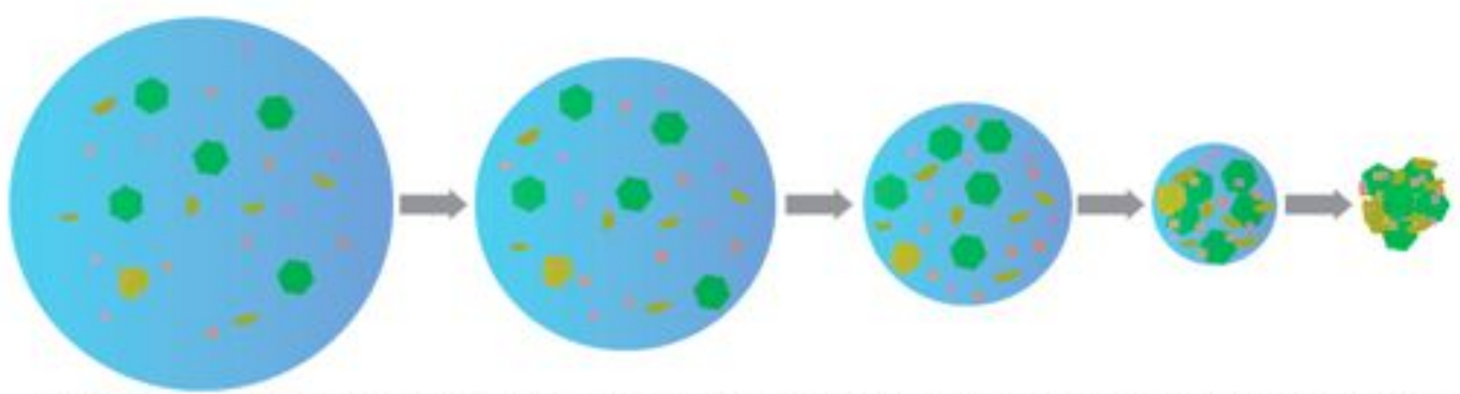
Papineni and Rosenthal **1997** *J Aerosol Medicine* 10:105-116; Yang et al., **2007** *J Aerosol Med* 20:484-494; Lindsley et al., **2012** *J Occup Environ Hygiene* 9:443-449; Fabian et al., **2008** *PLoS ONE* 3:e2691

Particle size is important for distribution and removal



What about infectious organisms within particles?

- Most particles emitted during human activities are smaller than 1-2 μm
  - But particle volume scales with d_p^3
  - Does the amount of viral or bacterial material contained in droplet nuclei scale similarly?

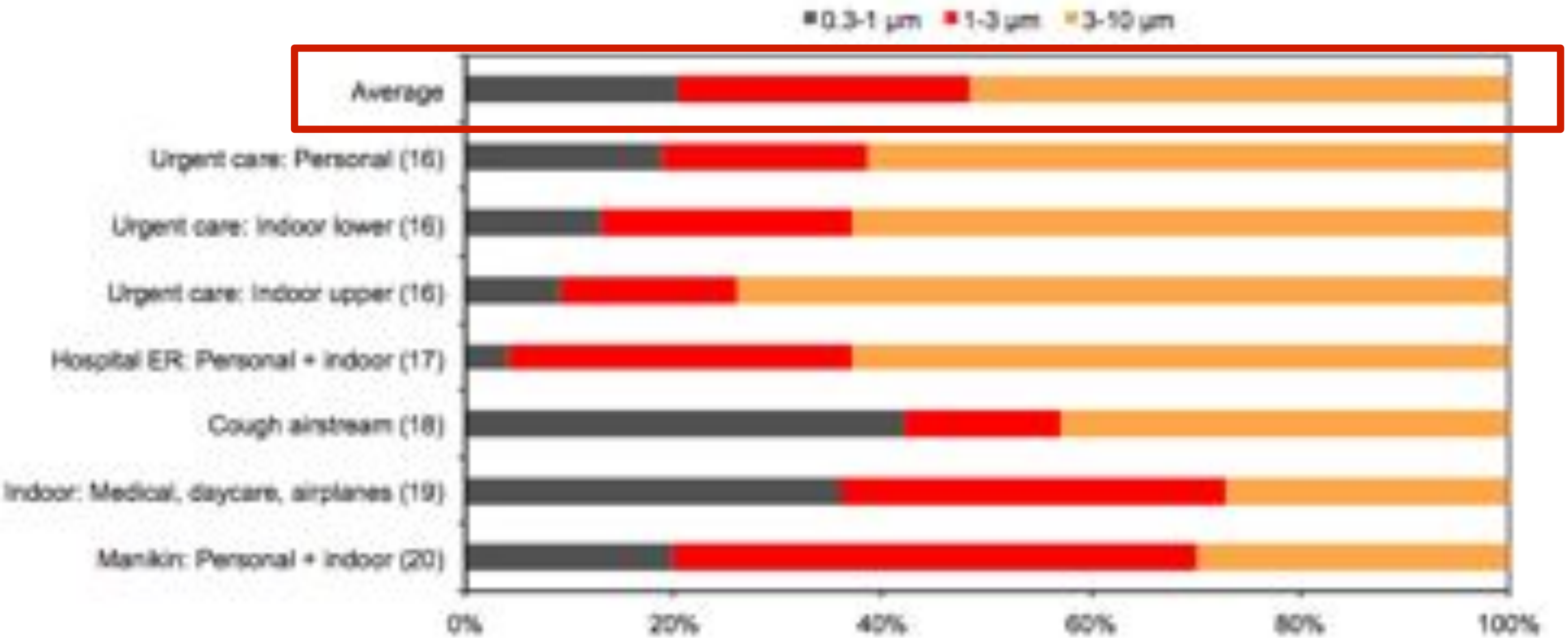


- Several recent studies have measured influenza virus content in size-fractioned indoor aerosols…

Size-resolved influenza virus indoors: Summary

Recent measurements of influenza viruses in size-fractioned indoor aerosols:

- Healthcare centers, ER, cough airstreams, daycare, airplanes, manikins
- Adjusted to fit into Standard 52.2 size bins



Average influenza size distribution:

20% <1 μm **29% 1-3 μm** **51% >3 μm**

[16] Lindsley et al., **2010** *Clin Infect Dis* 50:693-698; [17] Blachere et al., **2009** *Clin Infect Dis* 48(4):438-40
[18] Lindsley et al., **2010** *PLoS ONE* 5:e15100; [19] Yang et al., **2011** *J R Soc Interface* 8:1176-1184;
[20] Noti et al. **2012** *Clin Infect Dis* 54(11):1569–77

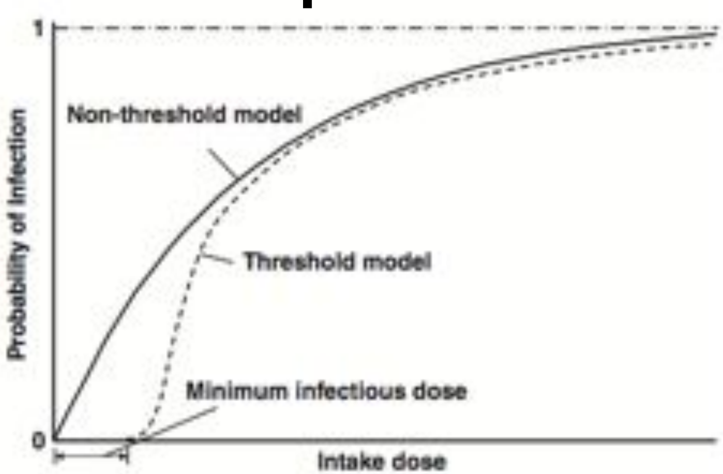
Methods of estimating infectious disease risks

Wells-Riley model

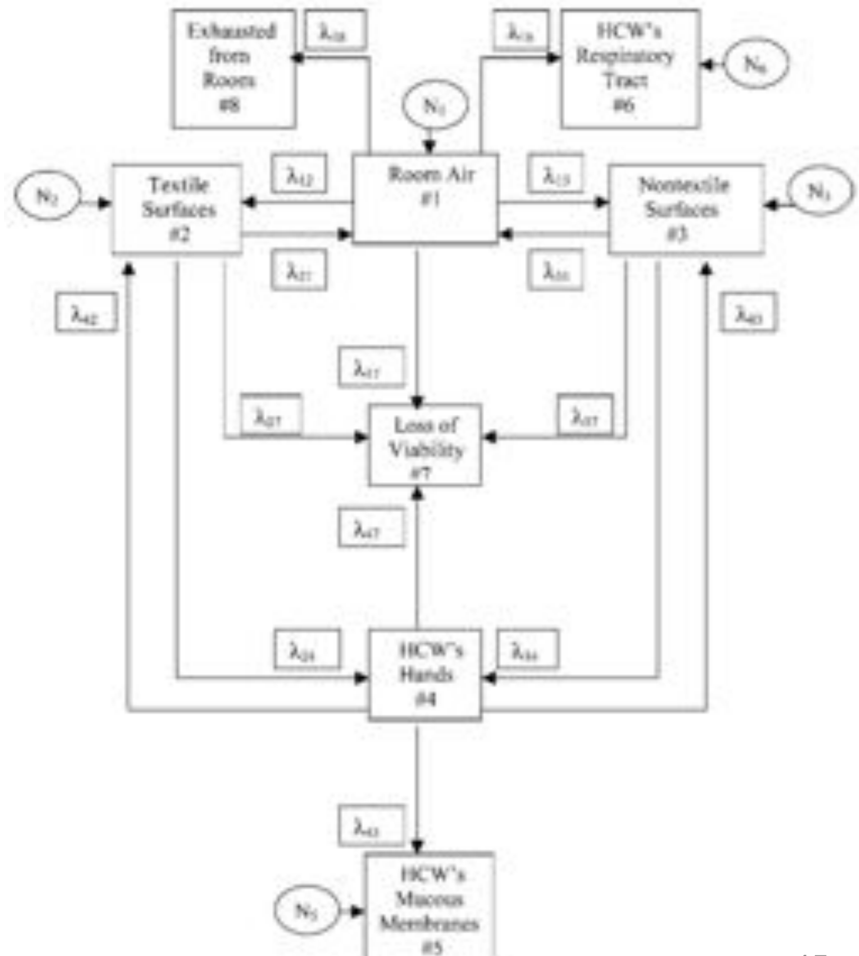
$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

$P_{\text{infection}}$ = the probability of infection
cases = the number of infection cases
susceptibles = number of susceptible individuals
I = number of infector individuals
p = pulmonary ventilation rate of a person (m^3/hour)
q = quanta generation rate (1/hr)
t = exposure time (hr)
Q_{oa} = room ventilation rate with clean air (m^3/hour)

Dose-response models

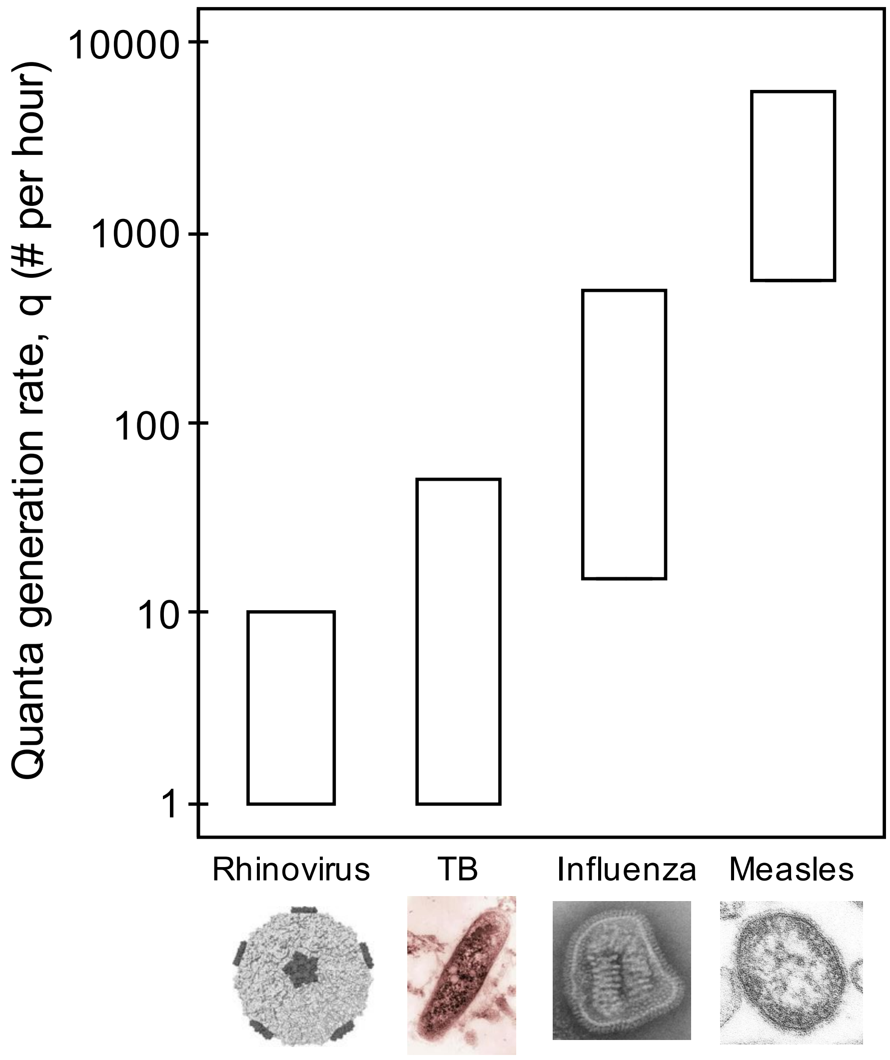


Markov chain models



Concept of quanta generation

- The unit *quantum of infection* is not an actual physical unit
- It is a hypothetical infectious dose
  - Back calculated from epidemiological studies
- Accounts for emissions, transport, inhalation, infectivity, and susceptibility all in one term



Riley et al., **1978** *Am J Epidemiology* 107:421-432 (and many others for quanta estimates)

Incorporating other loss terms into Wells-Riley model

$$P_{\text{infection}} = 1 - \exp\left[-\frac{Iqpt}{V} \Big/ \left(\lambda_{\text{ventilation}} + k_{\text{filtration}} + k_{\text{deposition}} \right) \right]$$

Loss by HVAC filtration (1/hr)

Loss by particle deposition (1/hr)

$$k_{\text{filtration}} = f_{\text{HVAC}} \frac{Q_{\text{filter}} \eta_{\text{filter}}}{V} = \lambda_{\text{recirculated}} \eta_{\text{filter}}$$

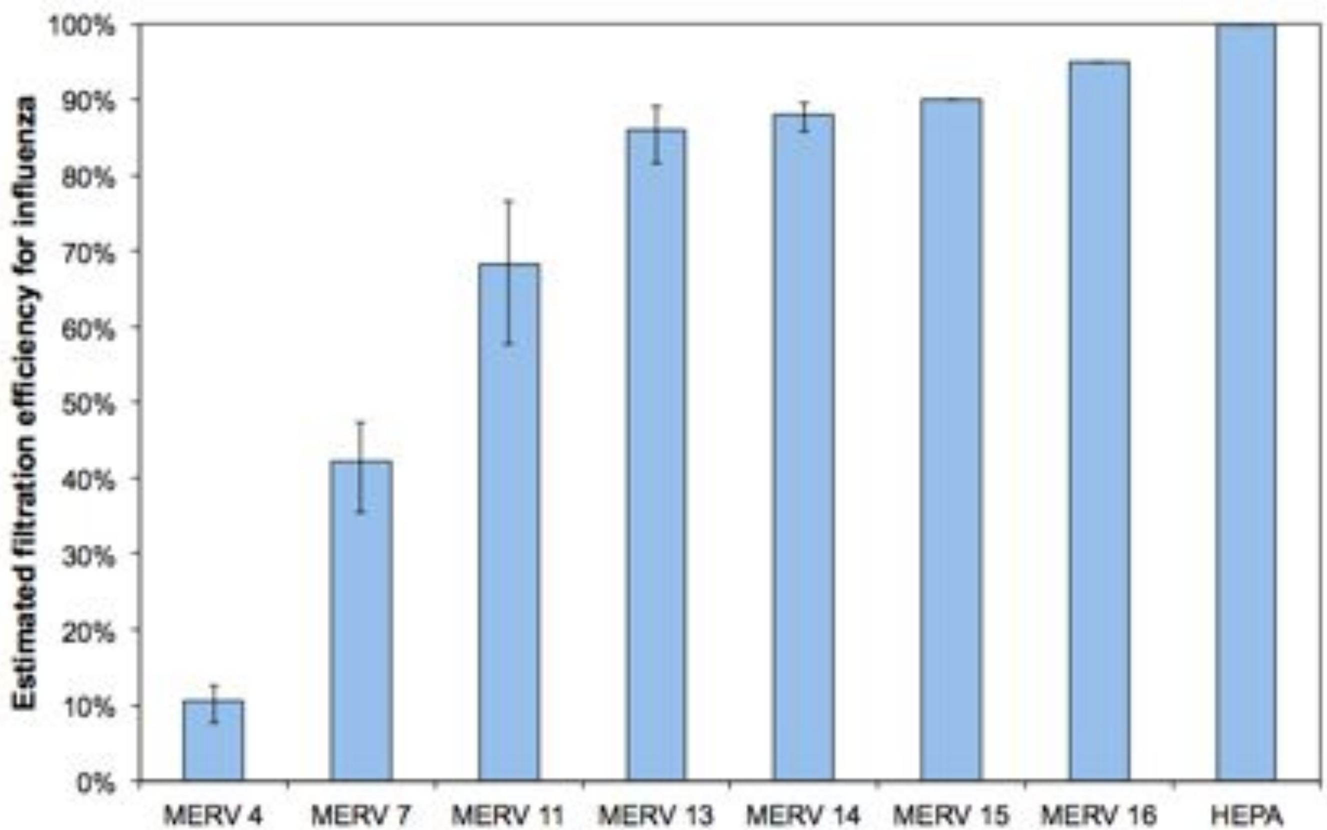
f_{HVAC} = fractional HVAC operation time (-)
Q_{filter} = airflow rate through filter (m^3/hr)
η_{filter} = particle removal efficiency of the filter (-)
$\lambda_{recirculated}$ = recirculation rate through the HVAC filter (1/hr)

To connect Wells-Riley with filtration, we need to know several specific building characteristics as well as:

- Size-resolved quanta generation rates
- Removal efficiency of HVAC filters for infectious aerosols

MERV and infectious aerosols: Removal efficiency

- Using previous data on influenza virus in size-resolved particle samples taken in real indoor environments, we can estimate the size-weighted average removal efficiency of a range of filters for infectious aerosols:



Case study: Influenza in an office environment

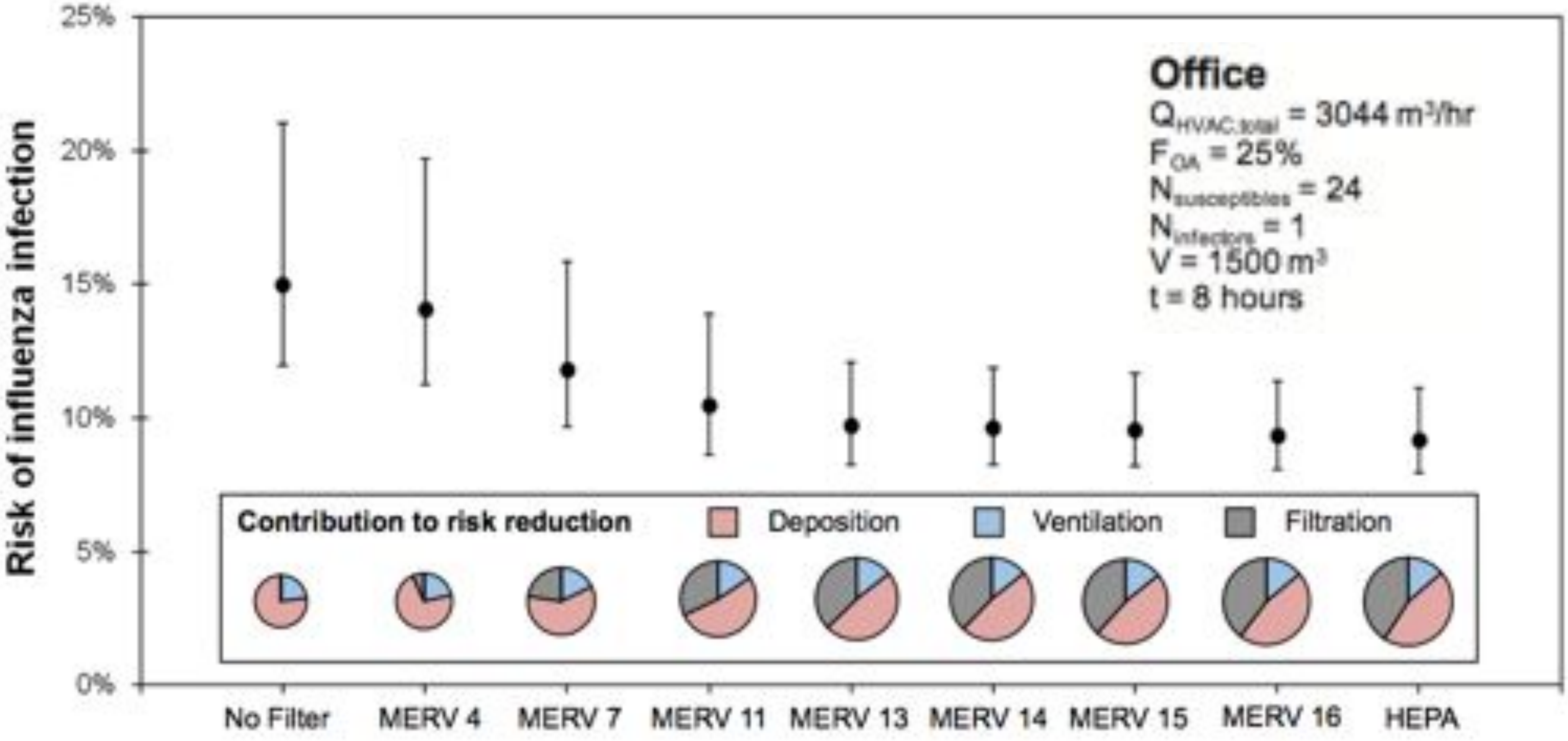
- Because the Wells-Riley model utilizes building volume, we must rely on case studies to explore possible impacts of filtration
  - Cannot generalize entirely because filtration effectiveness is a function of not only removal efficiency but recirculation rates through HVAC filters (flow vs. volume)

- We chose a hypothetical office environments with 1 infector:
  - 500 m^2
  - 25 adult occupants
  - ASHRAE 62.1 minimum ventilation rates
  - 25% OA
  - 8 hours of occupancy

- Used mean quanta generation rate from previous studies
  - Influenza (q = 100/hr)

Azimi and Stephens **2013** *Building and Environment* 70:150-160

Estimated risk of infection with HVAC filtration: Office

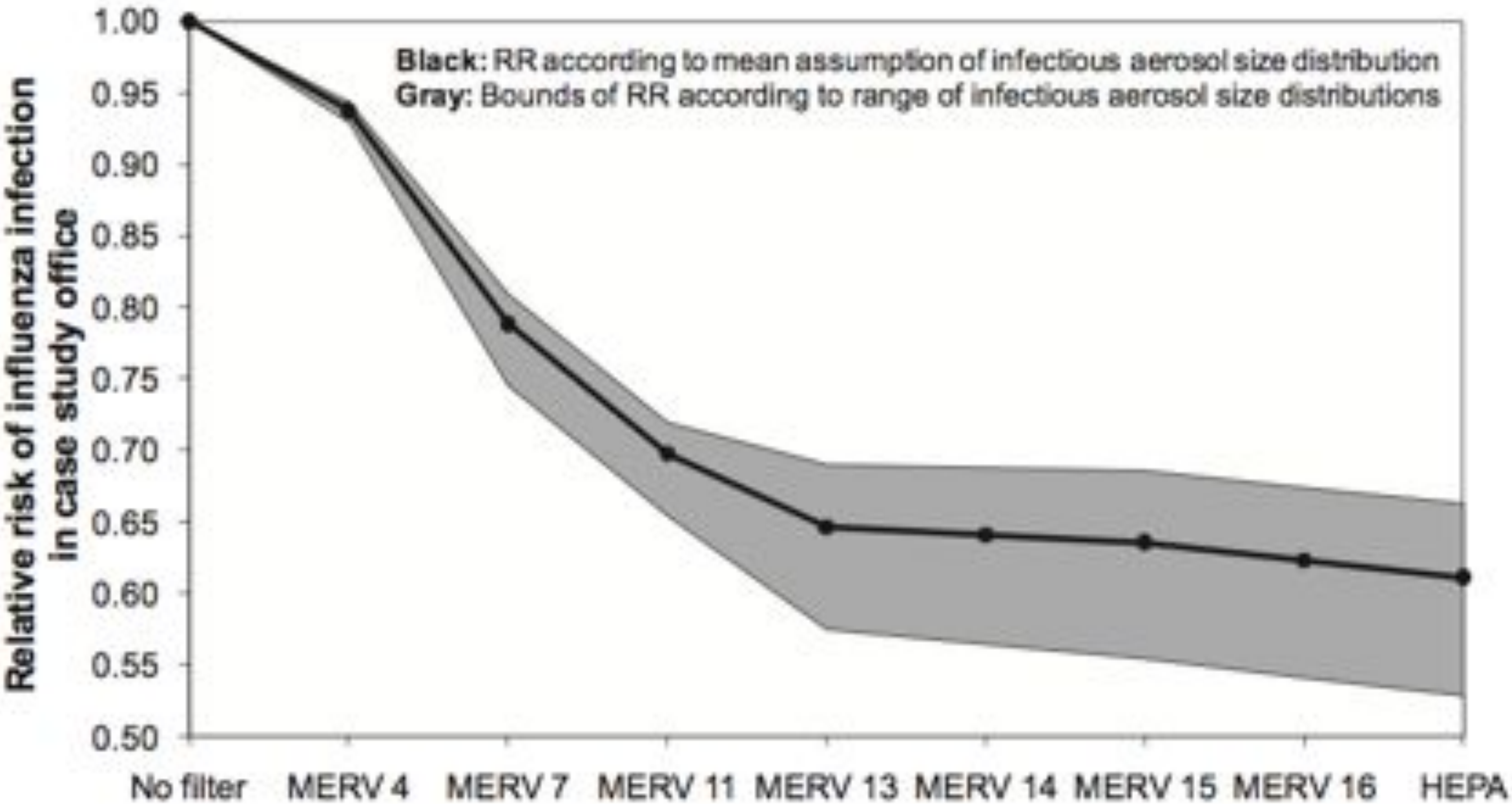


From no filter to MERV 13 or greater:
From 4 out of 24 occupants infected w/ flu to 2 out of 24

Azimi and Stephens **2013** *Building and Environment* 70:150-160

Generalizing results

- Using relative risks across all estimates of influenza aerosol size distributions and all HVAC filters allows us to identify trends and generalize results



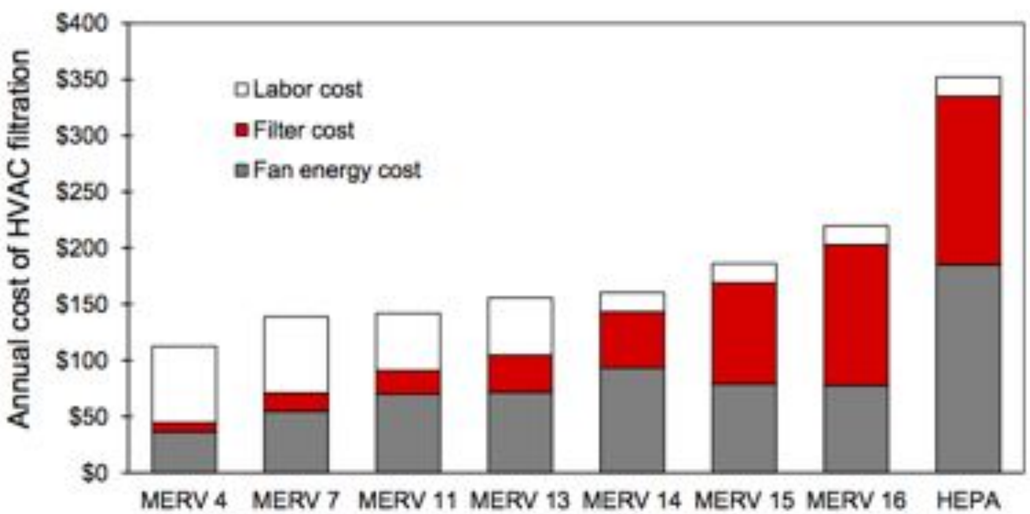
Azimi and Stephens **2013** *Building and Environment* 70:150-160

Estimating costs of outdoor air vs. filtration

- Making assumptions about operational periods in each building type, costs of natural gas and electricity, and HVAC equipment efficiency we estimate the cost of conditioning each unit of outdoor air ventilation rate delivered in each of four cities:
  - Chicago, Charlotte, Houston, and Phoenix

$$E_{\text{heating}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{\text{p,air}} HDD \frac{1}{\eta_{\text{heating}}} \alpha \qquad E_{\text{cooling}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{\text{p,air}} CDD \frac{1}{\eta_{\text{cooling}}} \beta$$

- We can also estimate the cost of filtration by combining filter costs, fan energy costs, and replacement costs (labor)



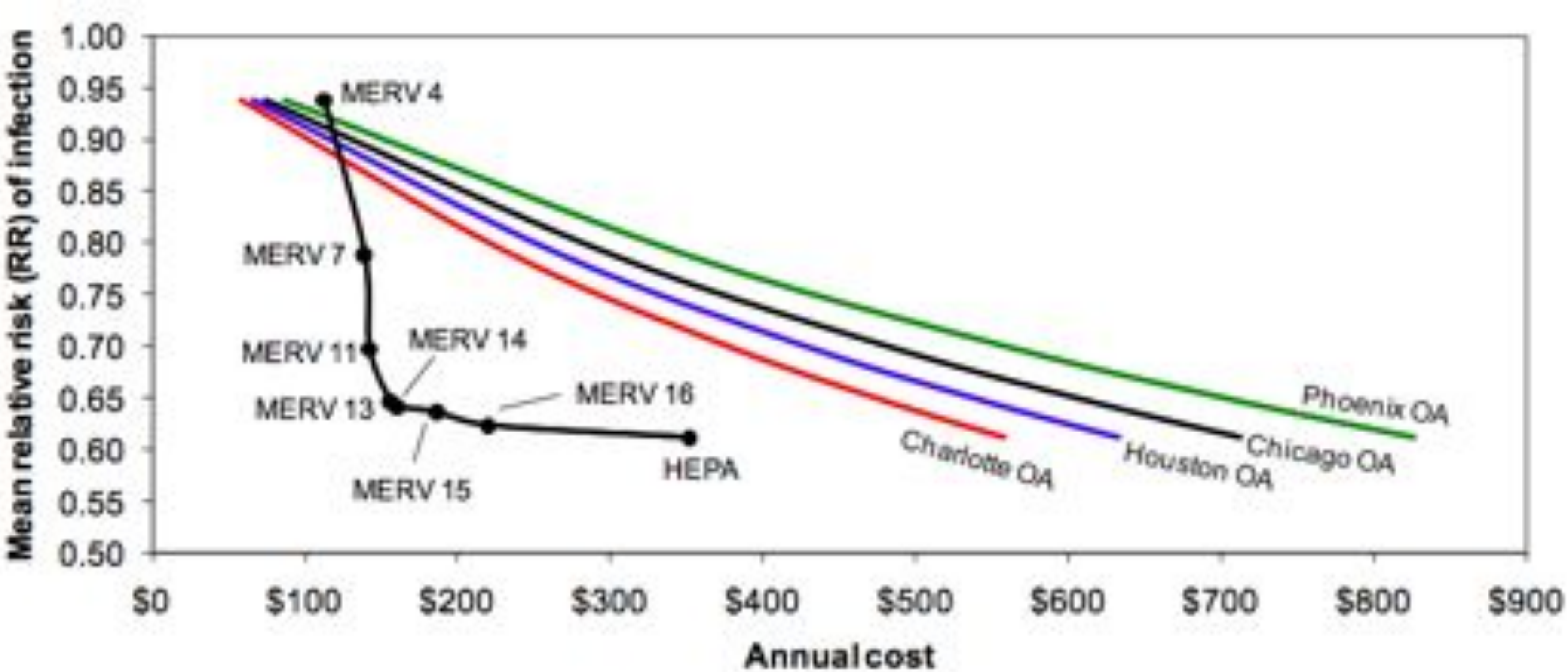
$$W_{\text{filtration}} = \frac{Q_{\text{recirculated}} \Delta P_{\text{avg}}}{\eta_{\text{fan}} \eta_{\text{motor}}}$$

$$C_{\text{filtration}} = W_{\text{filtration}} t_{\text{operating}} P_{\text{electric}}$$

Procedure similar to Bekö et al. **2008** *Building and Environment*

Azimi and Stephens **2013** *Building and Environment* 70:150-160

Relative risk vs. estimated annual cost: Filtration vs. OA



MERV 13-14 predicted to offer greatest risk reduction at lowest cost

Azimi and Stephens **2013** *Building and Environment* 70:150-160

3. BUILDING SCIENCE MEASUREMENTS FOR THE HOSPITAL MICROBIOME PROJECT

The Hospital Microbiome Project (HMP)

The Hospital Microbiome Project (HMP) is collecting microbial samples from surfaces, air, staff, and patients from the University of Chicago's new hospital pavilion in order to better understand the factors that influence bacterial population development in healthcare environments

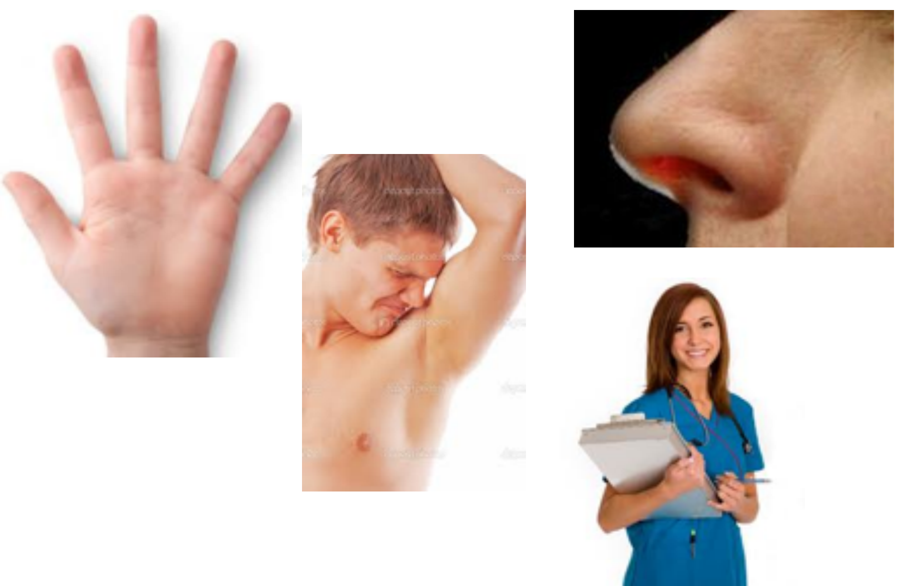
ALFRED P. SLOAN FOUNDATION

The HMP provides a unique opportunity to sample in a newly constructed hospital environment immediately prior to occupation and for nearly one year afterward

Biological sampling

- Both culture (agar plates for antibiotic resistant bacteria) and culture-independent methods (16S rRNA, 18S rRNA, and fungal ITS on Illumina HiSeq, as well as qPCR on a sub-section of samples) are being used to process over 12,000 microbial swab samples over the course of 1 year
  - 1 month prior to the hospital opening and 11 months after

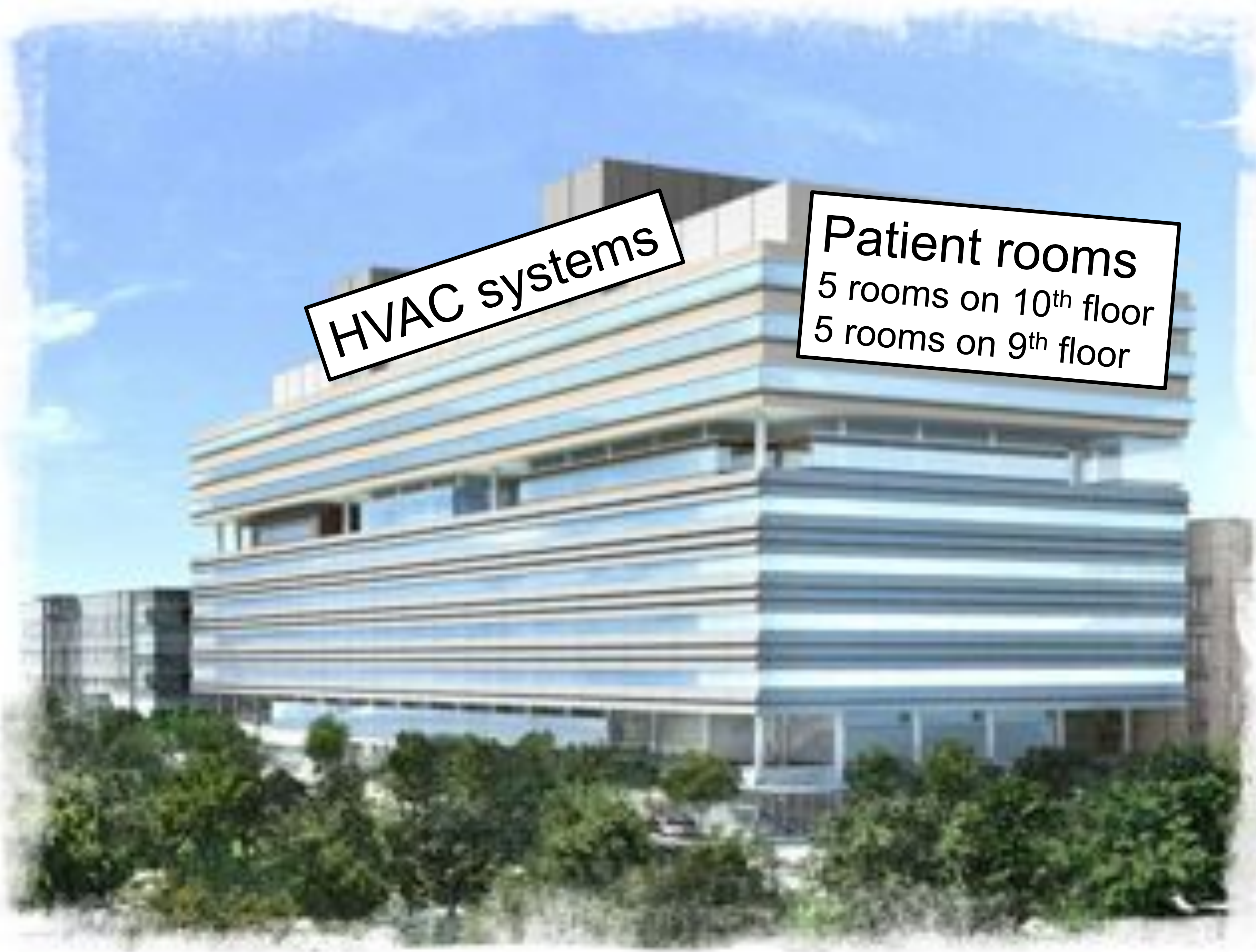
Patient and staff sampling



*Floor, Bedrail, Cold water tap, Glove Box, and Air Filter**

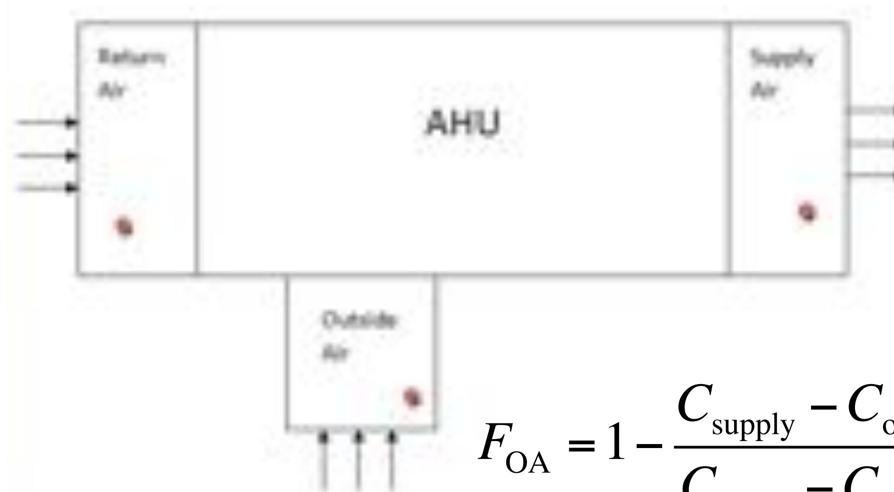
Building science measurements in HMP

- We also worked to characterize a number of building environmental and operational characteristics of the hospital during the yearlong HMP
  - Within 10 patient rooms
  - Within mechanical rooms serving each floor
- Our goal was to define a set of building science parameters that may have implications for biological findings
  - And that we could measure (within budget) robustly and accurately
- Many recent indoor microbial studies have not adequately characterized the indoor environments and operational parameters of buildings in which sampling takes place


HVAC systems
Patient rooms
5 rooms on 10th floor
5 rooms on 9th floor

Mechanical room measurements

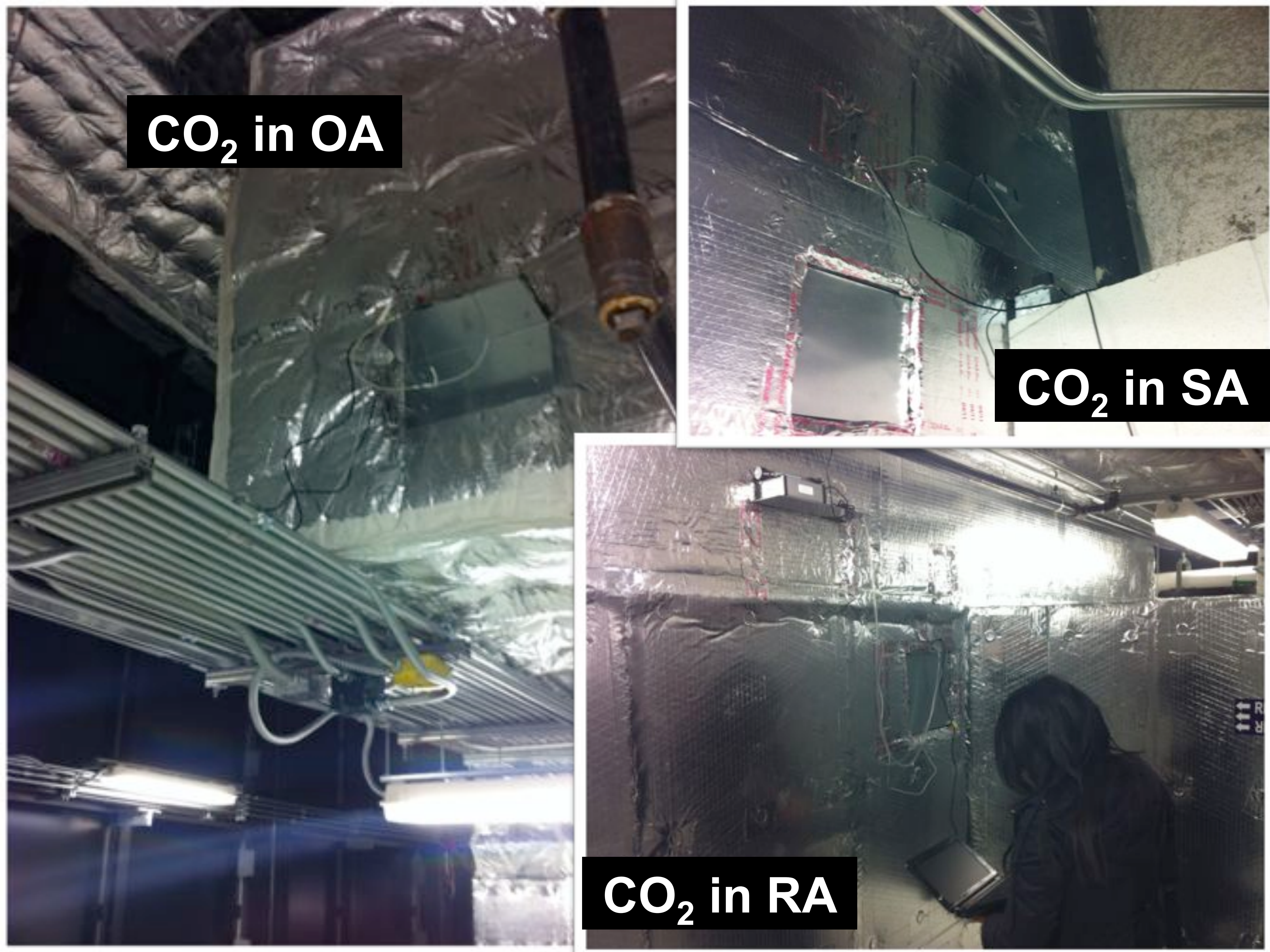
- Outdoor air ventilation fraction (%OA) delivered to each floor
  - Each floor is served by a different HVAC system
  - CO_2 measurements in return, supply, and outdoor airstreams
  - Outdoor T and RH
    - 5-minute intervals



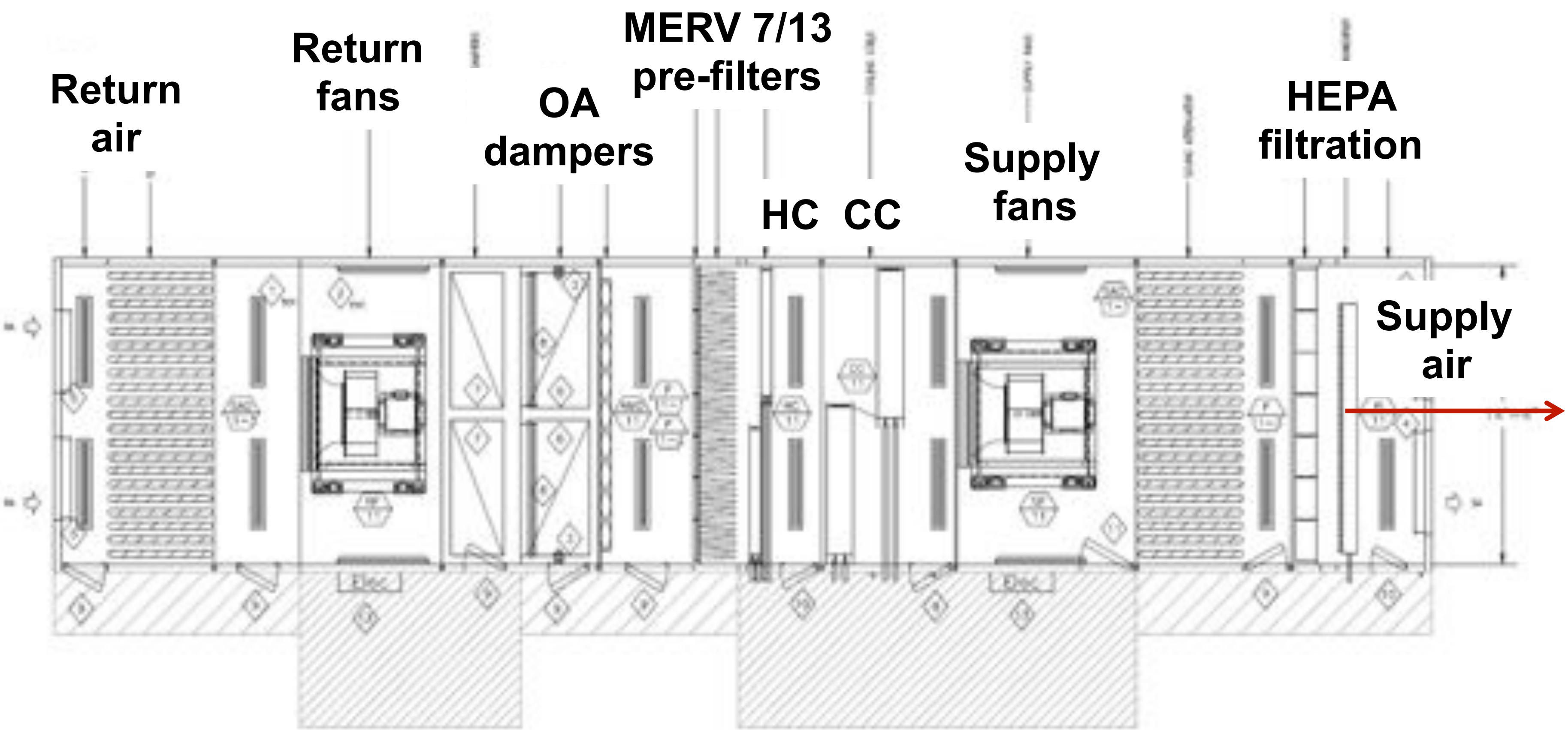
$$F_{OA} = 1 - \frac{C_{supply} - C_{out}}{C_{return} - C_{out}}$$

AHU 6: 50,000 cfm


Outside Air
Supply Air


CO_2 in OA
CO_2 in SA
CO_2 in RA

HVAC systems



Patient room measurements

- Supply, return, and exhaust airflow rates (constant flow)
  - Measurements made during early stages of project
  - Estimates made using CO_2 mass balance throughout project
- Temperature + relative humidity + light intensity
  - Data loggers at 5-min intervals
    - Also at nurse stations
- Human occupancy
  - Beam break IR sensor at doorway (total breaks at 5 min intervals)
  - Patient room CO_2 concentrations (5 min intervals)
- Room pressurization (with respect to hallway)
  - Pressure transducers (5 min intervals)
- Air sampling via HVAC filter media
  - Periodic (weekly) → the only air sampling in the project

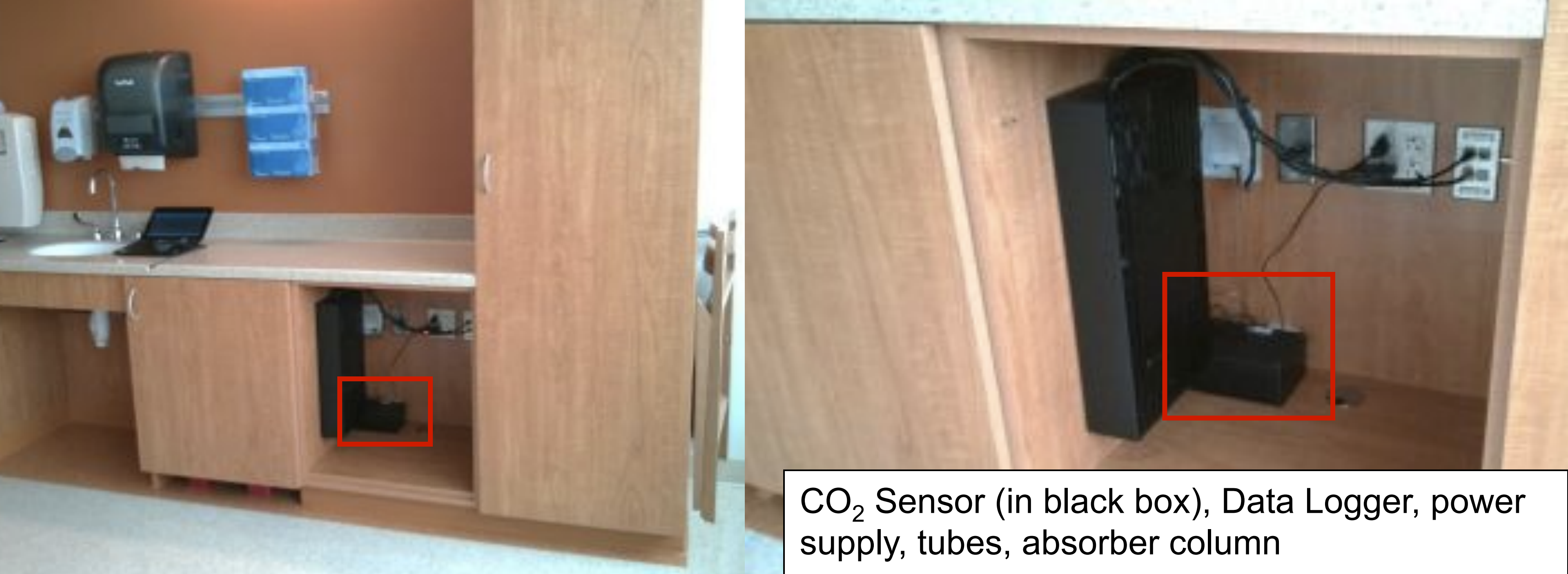

Patient rooms


Return Air 400 cfm
Bathroom exhaust 100 cfm
Supply Air Slot Diffuser 500 cfm

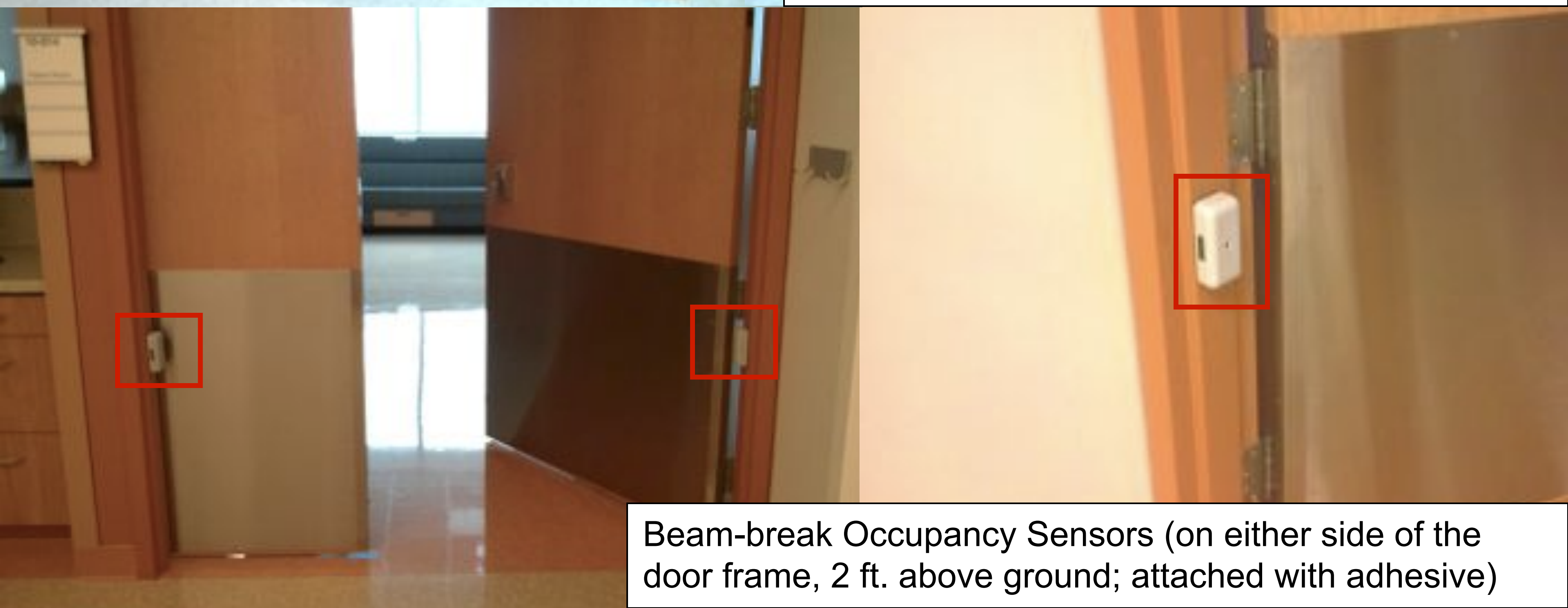

Supply Air Slot Diffuser ~500 cfm
w/ reheat coils

Data Logger (attached with adhesive) measuring temperature, relative humidity and light

Differential Pressure Sensors (in black box with batteries, attached with adhesive), data logger, clear tube running to outer door frame



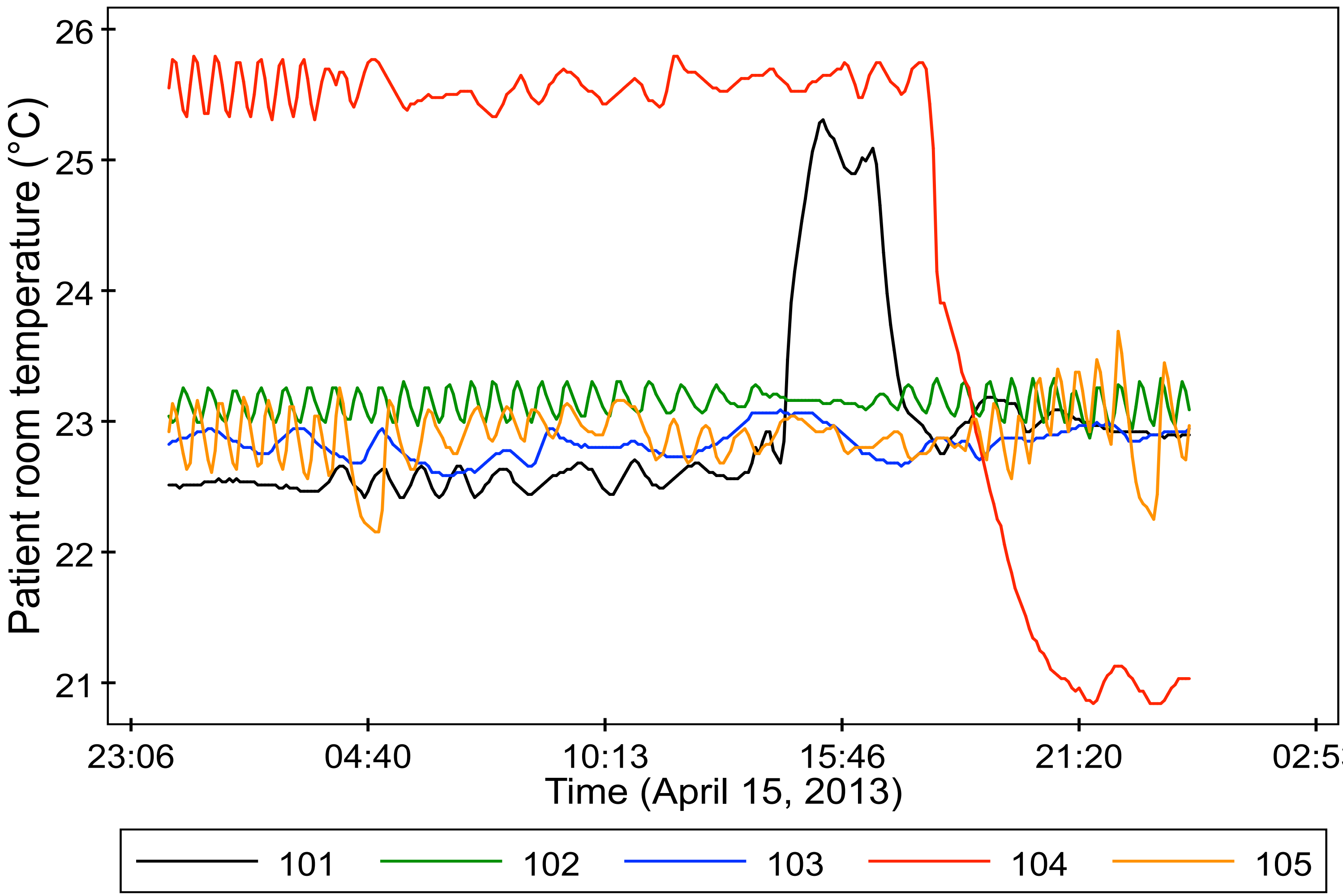
CO_2 Sensor (in black box), Data Logger, power supply, tubes, absorber column



Beam-break Occupancy Sensors (on either side of the door frame, 2 ft. above ground; attached with adhesive)

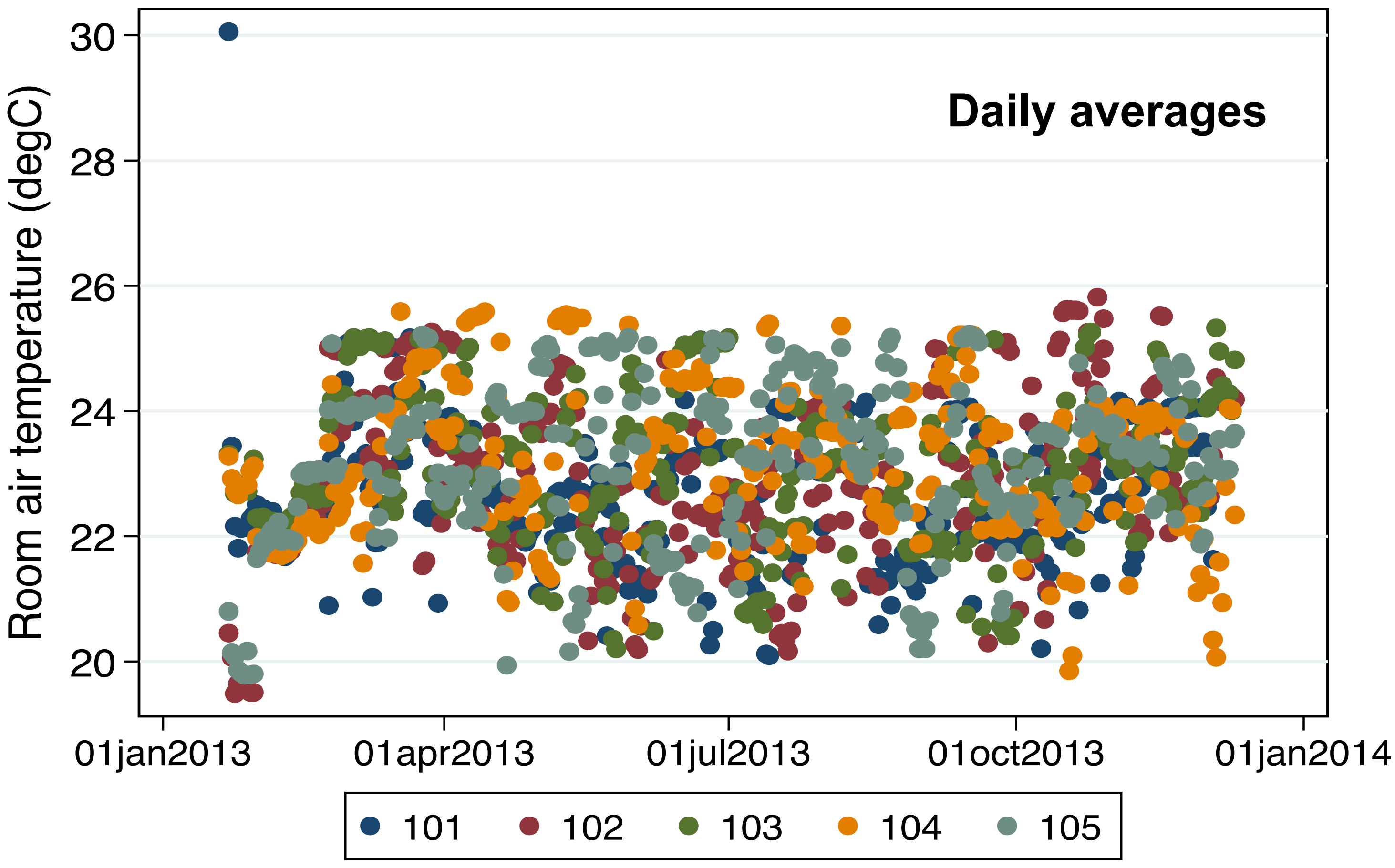
PRELIMINARY BUILDING SCIENCE DATA IN HMP

Data snapshot: Patient room air temperatures



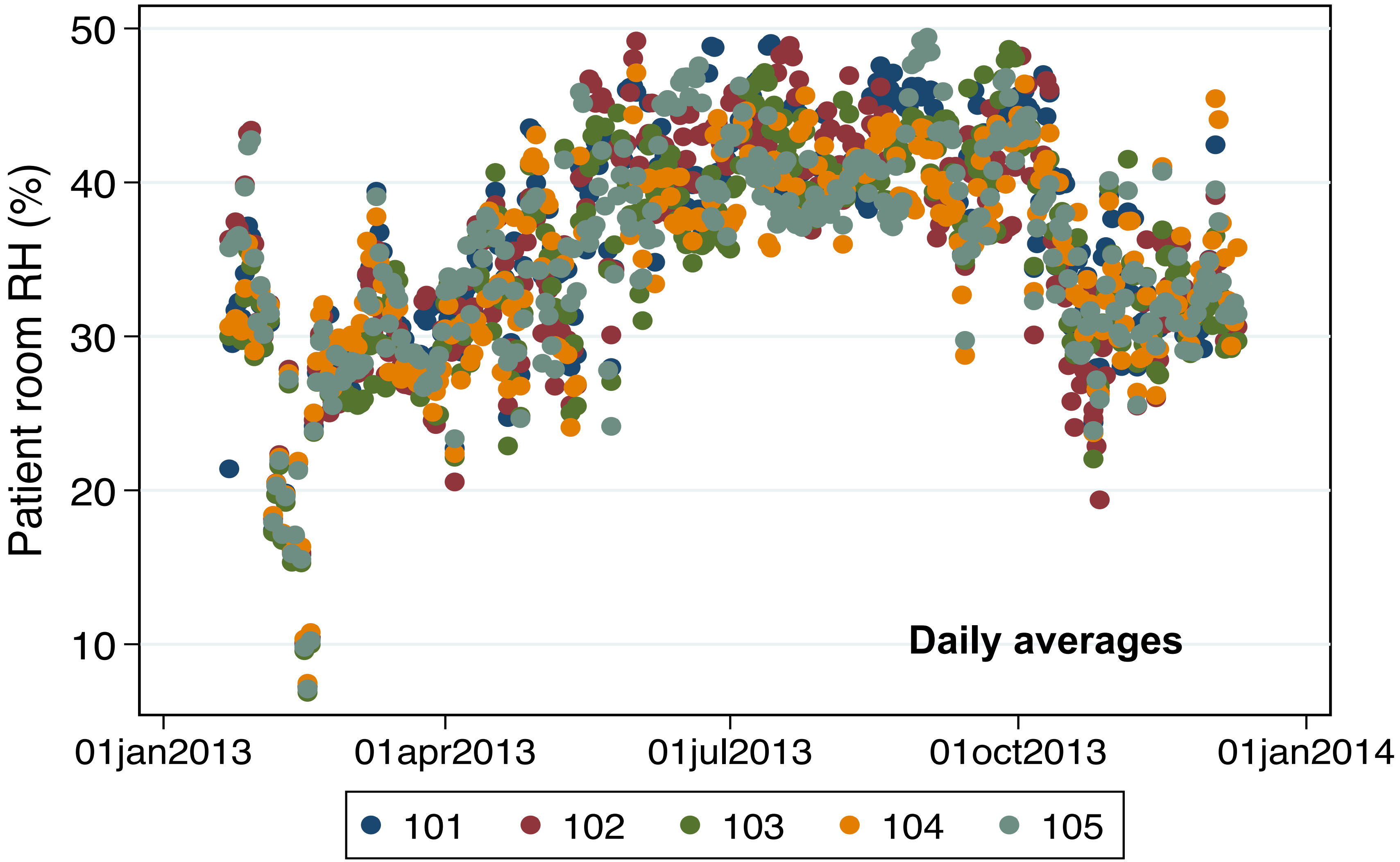
Considerable variation in temperatures both between and within rooms

Data summary: Patient room air temperatures

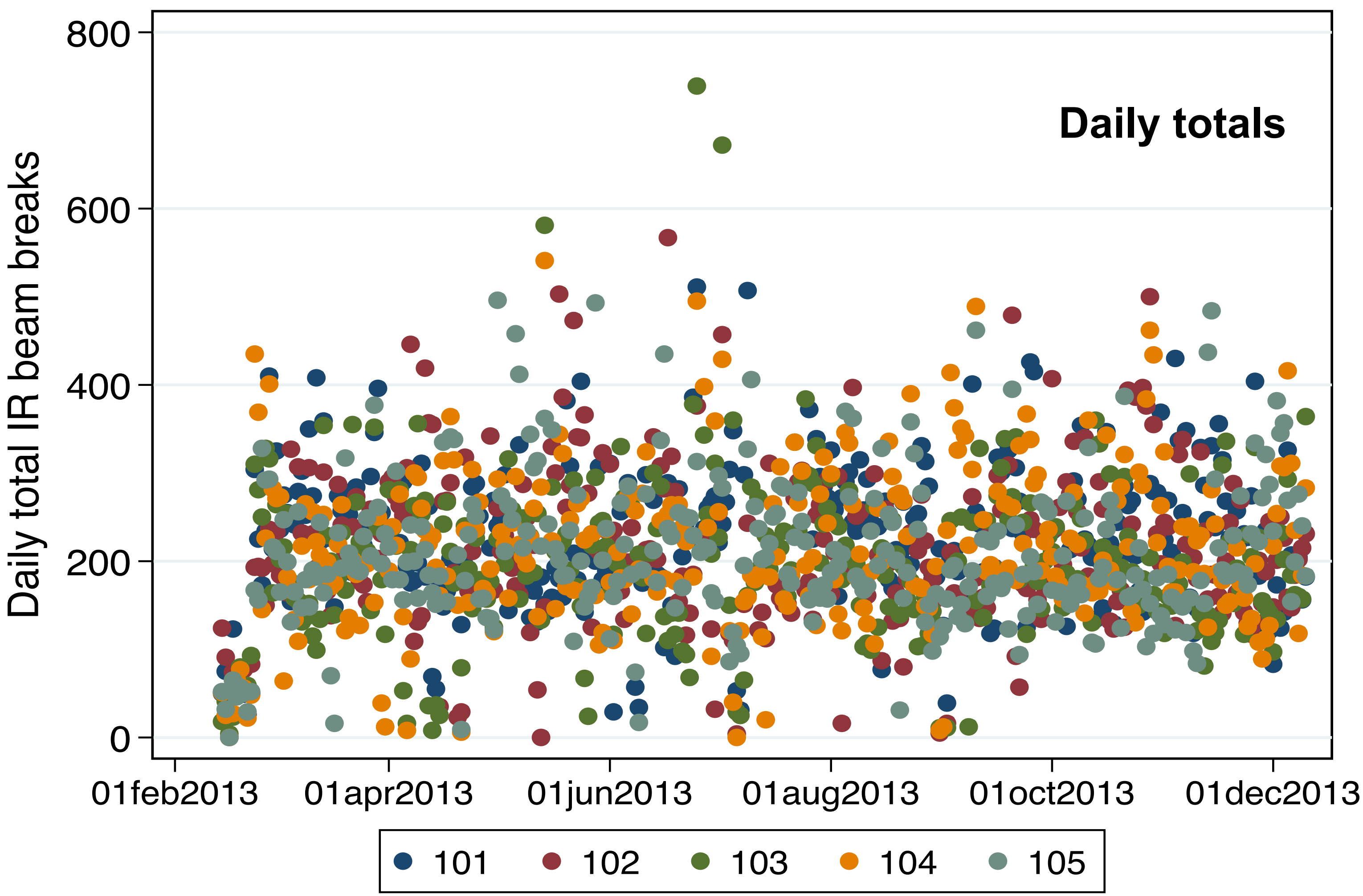


Considerable variation in temperatures both between and within rooms

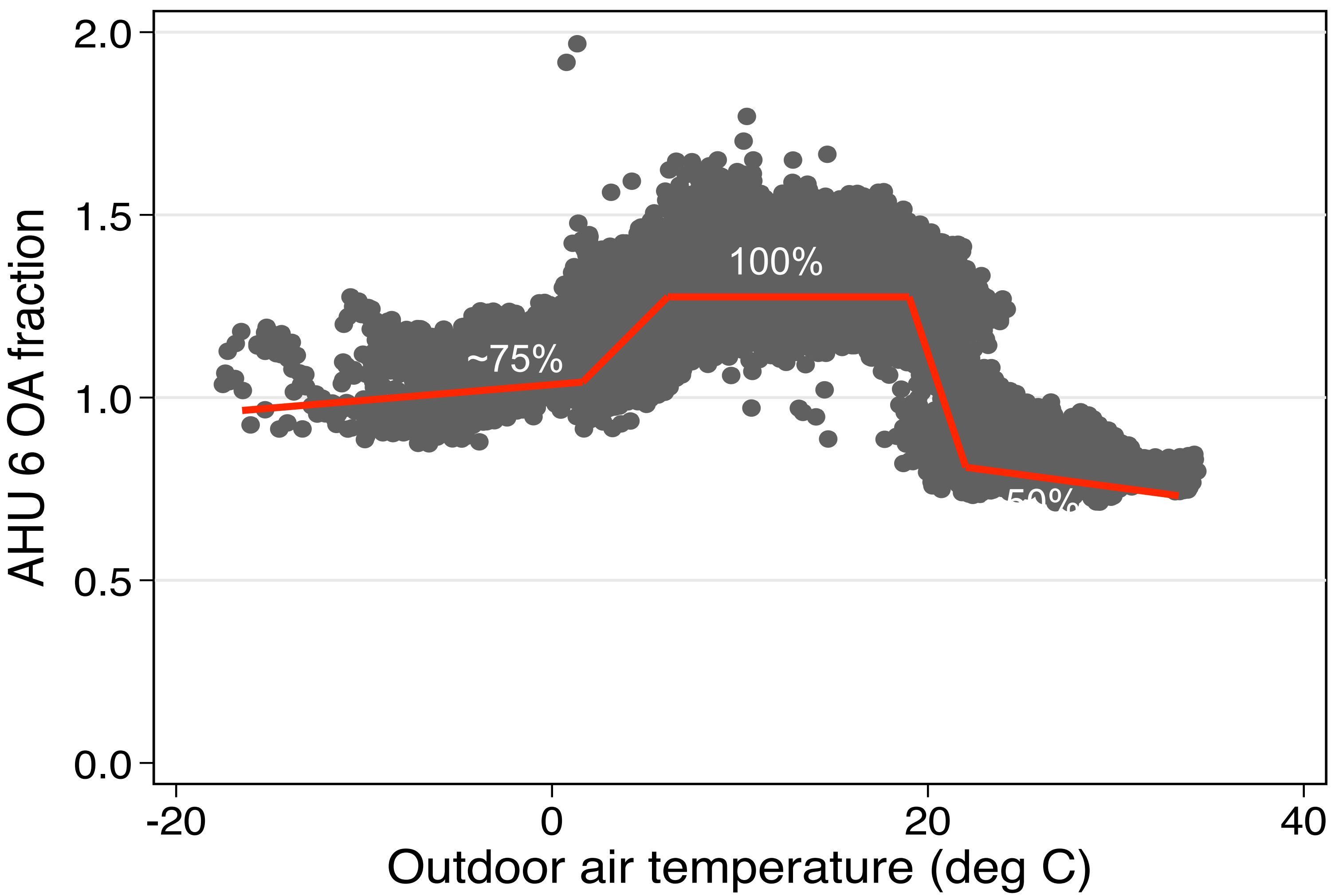
Data summary: Patient room RH



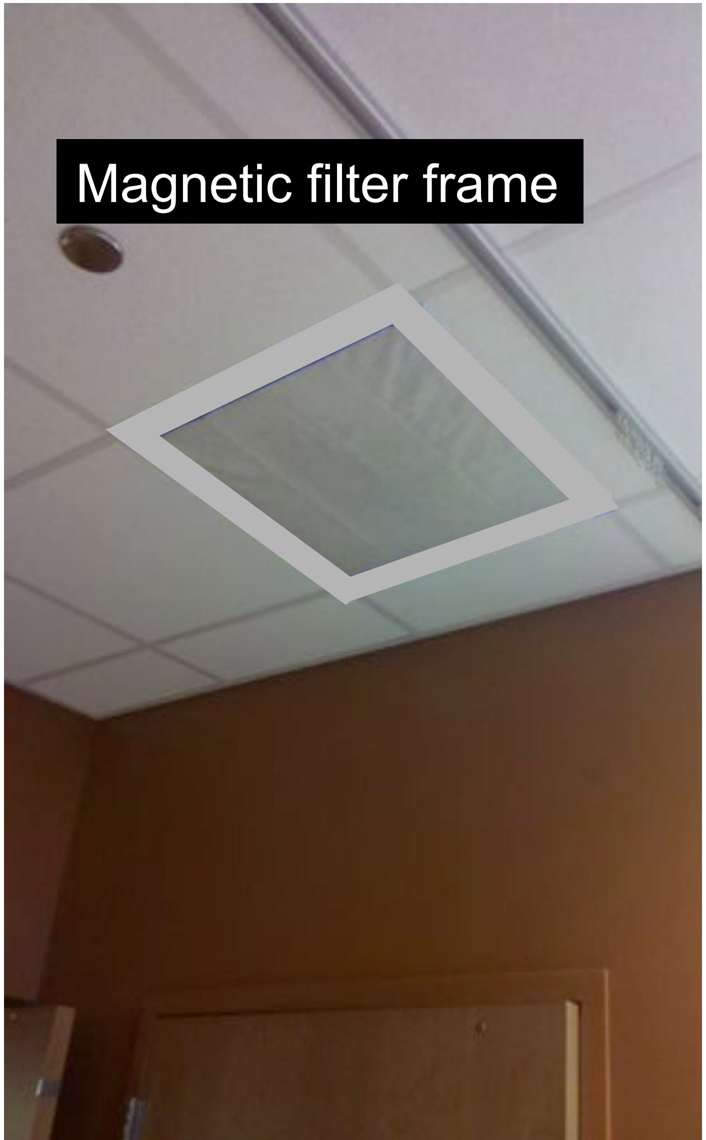
Data summary: Occupancy sensors



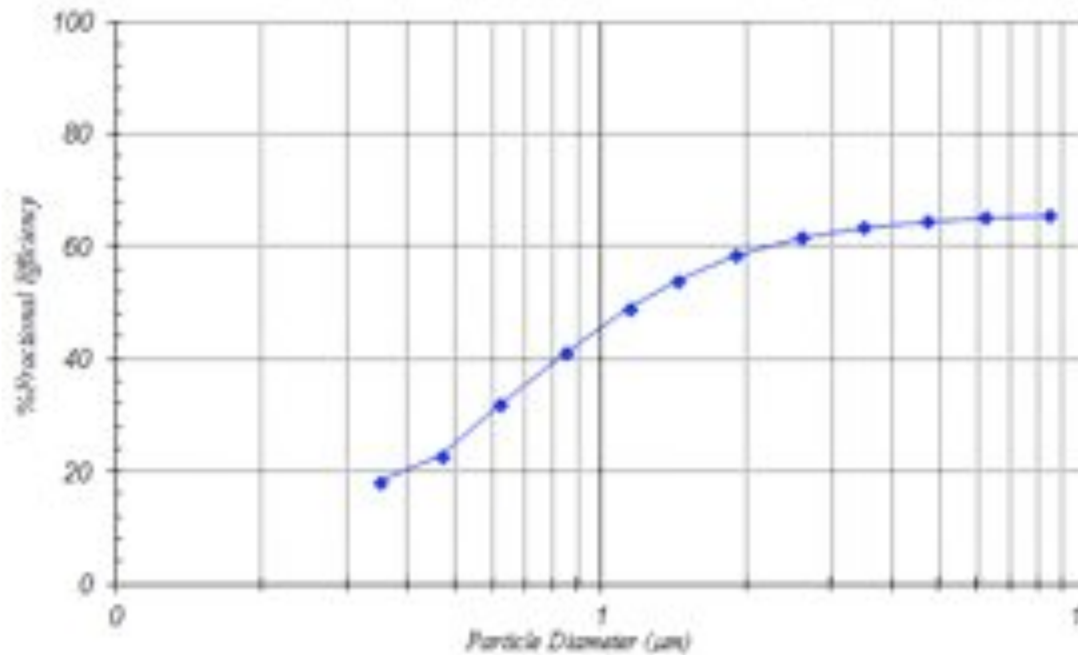
Calibrating OA measurements: %OA vs. outdoor T



HVAC filter bioaerosol ‘sampler’



- Sterilized and replaced weekly in all 10 patient rooms



*Courtesy of Kevin Kinzer, 3M

Noris et al. **2011** *Atmospheric Environment* 45:338-346

4. OPEN SOURCE BUILDING SCIENCE SENSORS

Open Source Building Science Sensors (OSBSS)

osbss
open source building science sensors

Home Sensor Tutorials Blog Affiliations People

The Open Source Building Science Sensors (OSBSS) project demonstrates how to build inexpensive building environmental and operational sensors for long-term studies of the indoor environment using open source hardware and software.

IR LED emitter & receiver - $3

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Differential pressure

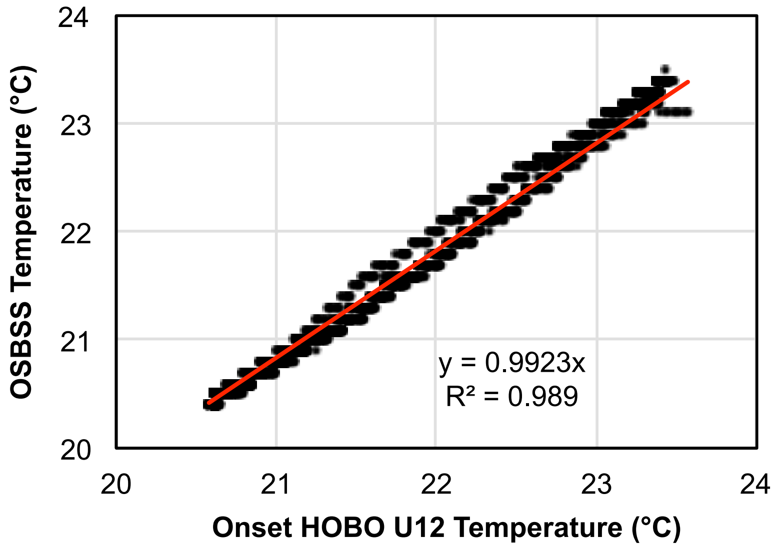
Proximity occupancy

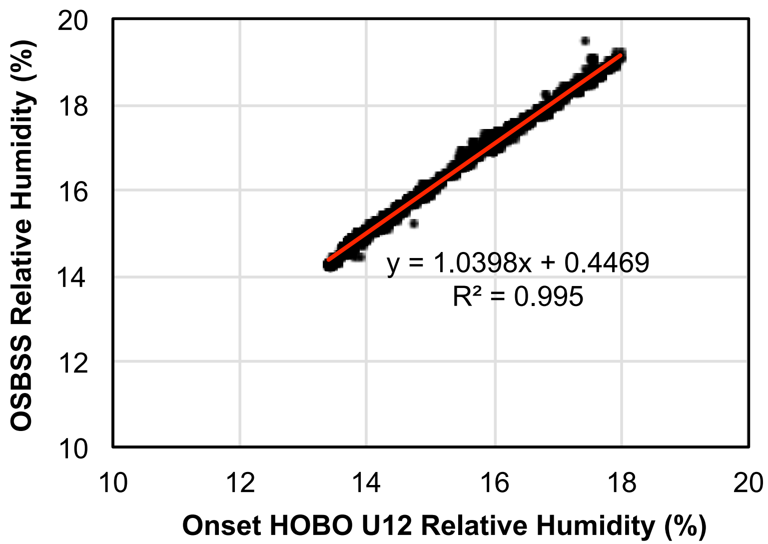
Generic datalogger

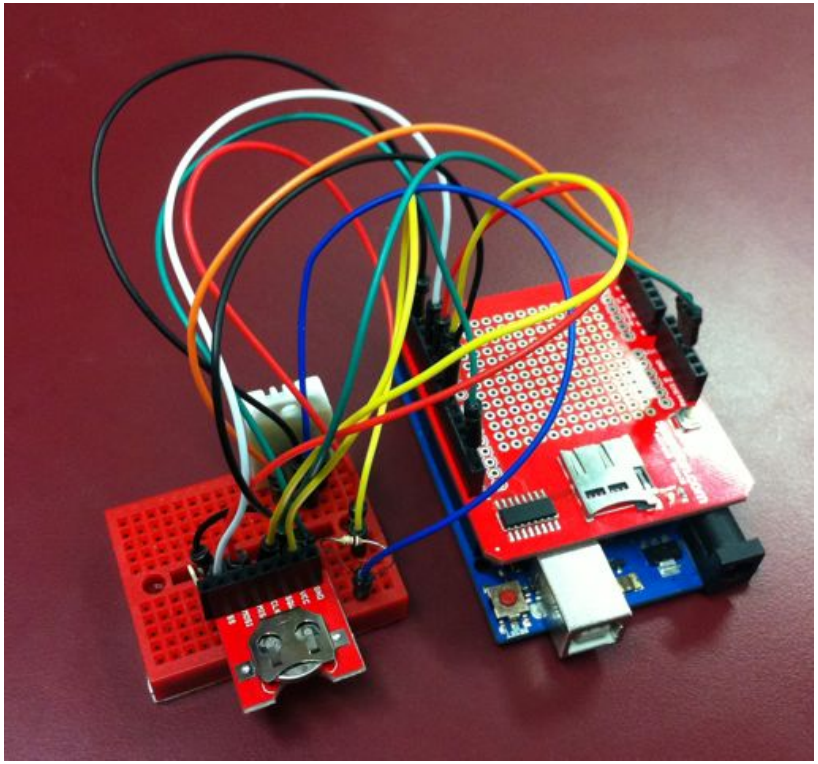
IR beam break occupancy

Open Source Building Science Sensors (OSBSS)

Status: Initial builds + calibration







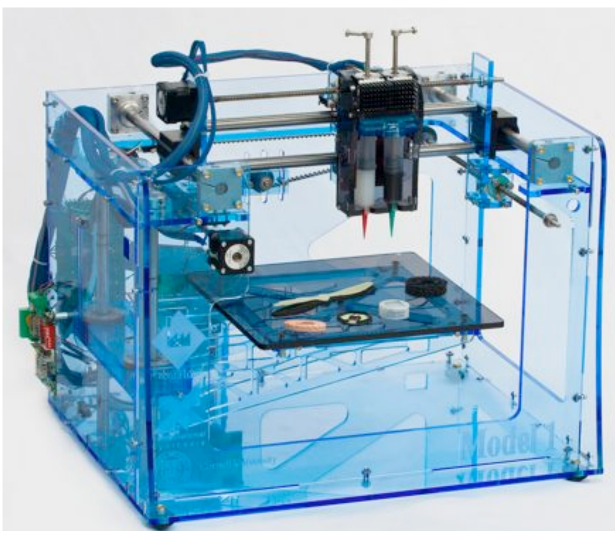
Prototype T/RH data logger

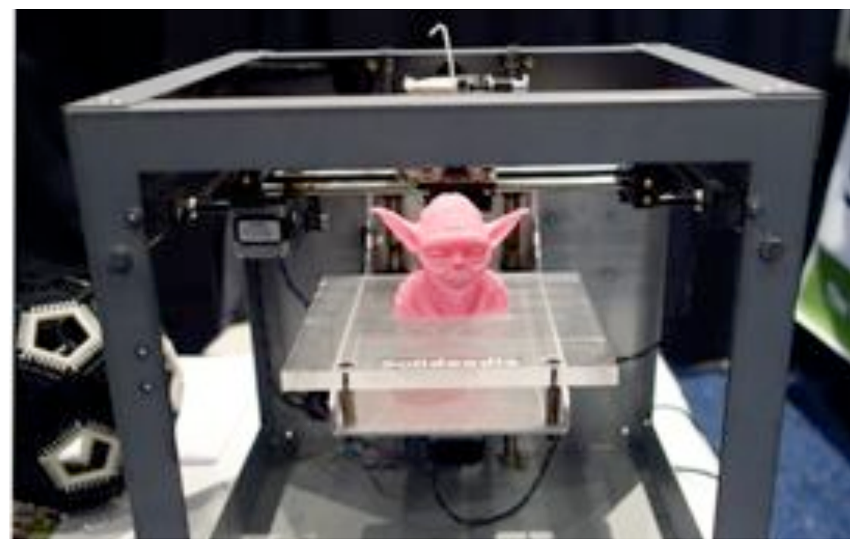
5. ULTRAFINE PARTICLE EMISSIONS FROM DESKTOP 3D PRINTERS

Desktop 3D printers: Cause for concern?

3D printing – or additive manufacturing – is a process of making a three-dimensional solid object from a digital model

- Widely used in rapid prototyping and custom fabrication
- Commercial applications include industrial design, architecture, engineering, fashion, dental industries, biotech, food, and many others





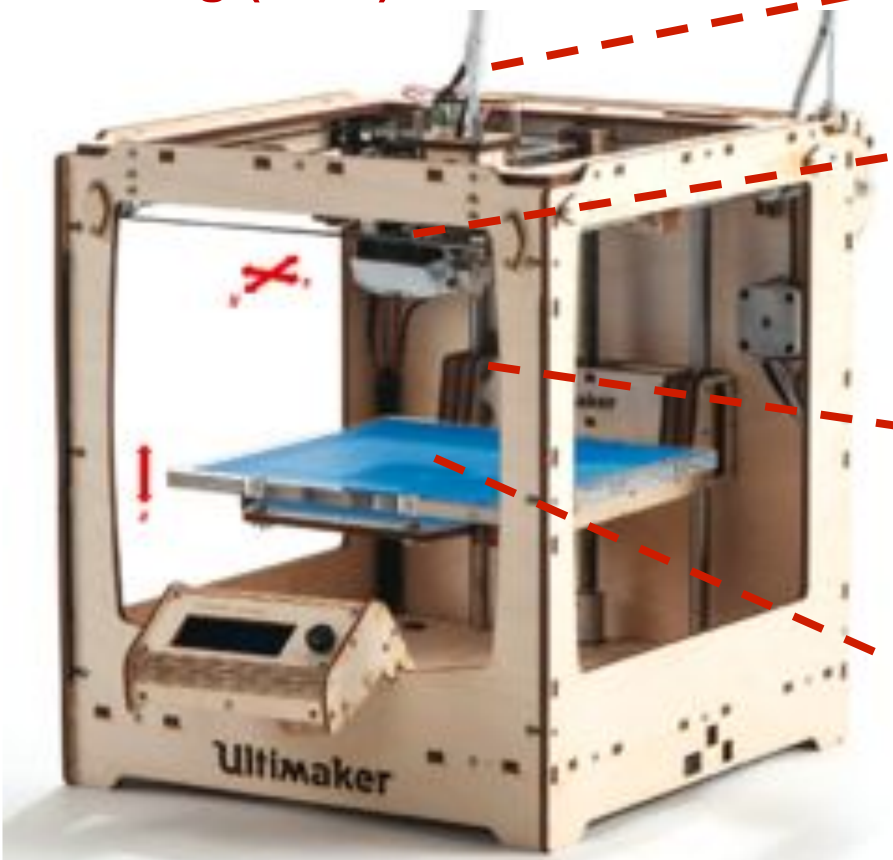
Recent advances have greatly reduced costs and made 3D printers widely available for less than $2,500 (or as little as $500)

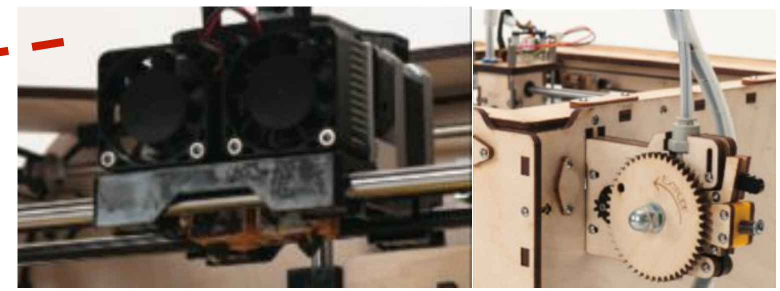
For as little as $500…

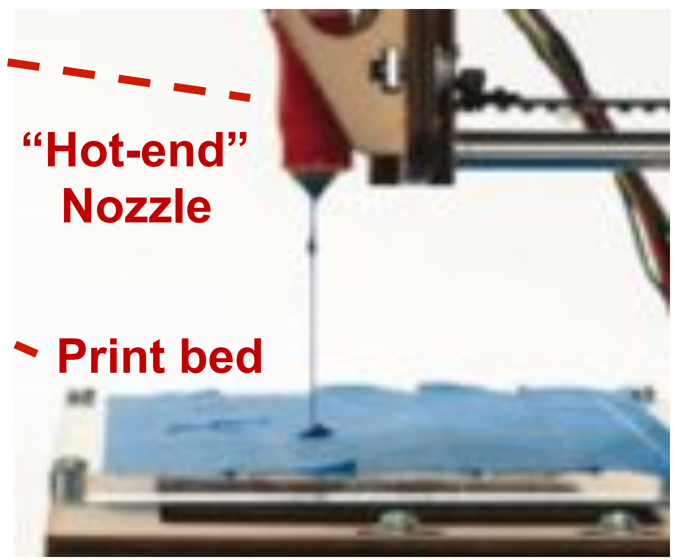
You can make all this ~~junk~~ interesting stuff!

Additive 3D printers: MPD/FDM

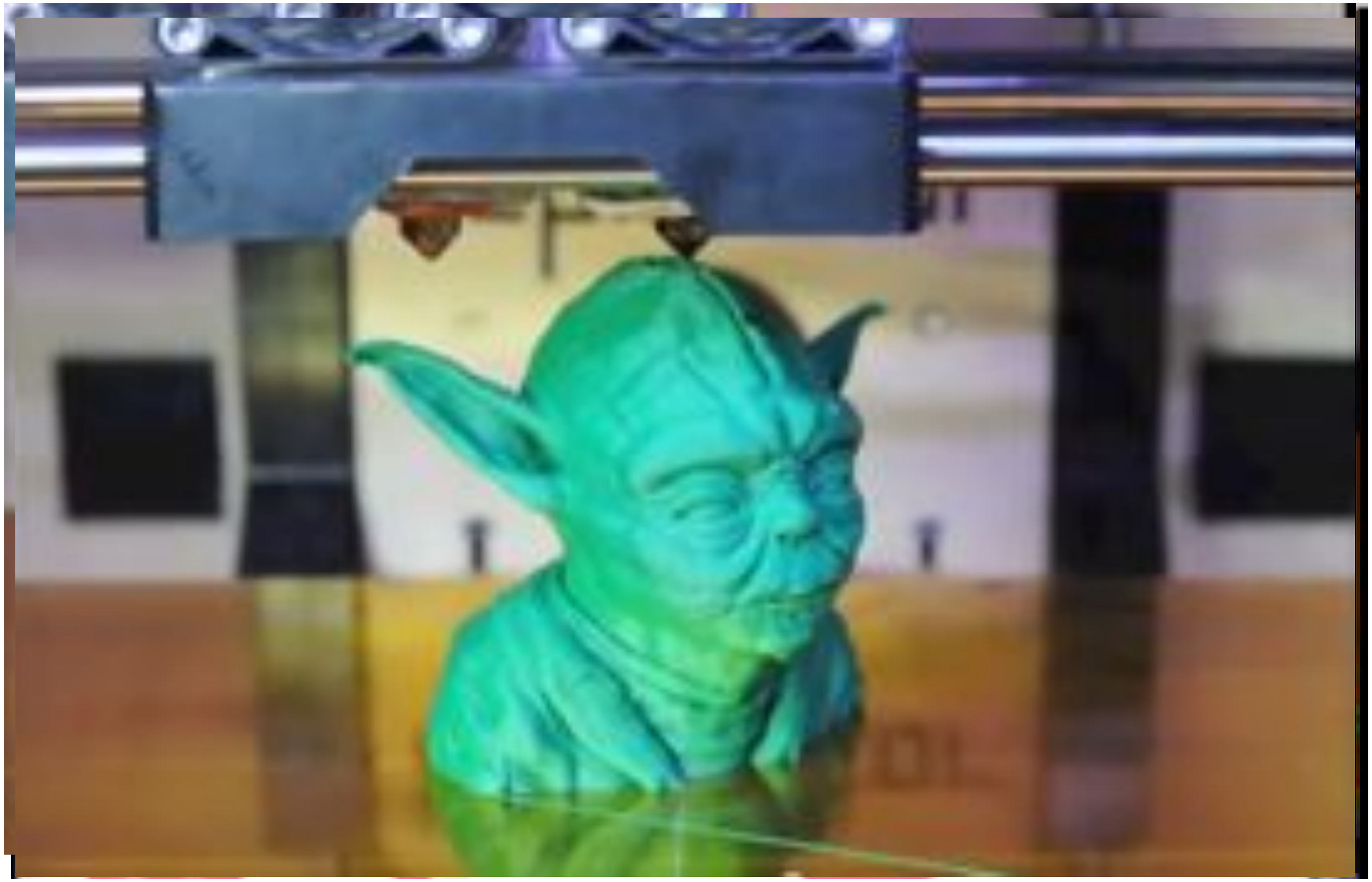
Most 3D printers use a technique called **molten polymer deposition (MPD)**, also known as **fused deposition modeling (FDM)**







MPD/FDM 3D printer in action



Yoda head @ 0.1 mm layer height | http://www.youtube.com/watch?v=8_vIoWVgf0o

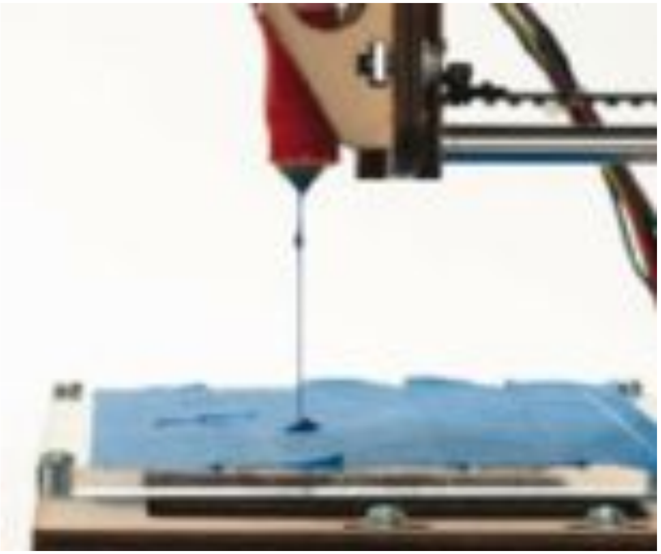
Additive 3D printers: MPD/FDM

Thermoplastic filaments

Acrylonitrile butadiene styrene (ABS)
Polylactic acid (PLA)
Polyvinyl alcohol (PVA)
Many others

Hot-end nozzle

0.2-0.8 mm diameter hole
~160-220°C for PLA
~190°C for PVA
~215-250°C for ABS



Print bed

<40°C for PLA
~110°C for ABS

Thermoplastic extrusion/deposition: Cause for concern?

- Previous work on large scale industrial thermoplastic processing showed that both gases and particles are emitted during operation

  Rutkowski and Levin **1986** *Fire and Materials* 10:93-105; Contos et al. **1995** *J Air Waste Manag Assoc* 45:686-694; Unwin et al. **2013** *Ann Occ Hygiene* 57(3):399-406

- Exposure to decomposition products from ABS thermal processing has been shown to have toxic effects in rats and mice

  Zitting and Savolainen **1980** *Archives of Toxicology* 46:295-304; Schaper et al. **1994** *Am Indust Hyg Assoc J* 55:924-934

- Exposure to fumes from thermal decomposition of other plastics (e.g. PTFE) has been shown to be acutely toxic to mammals

  Oberdörster et al. **2005** *Environ Health Persp* 113:823-839

  - Ultrafine particles appear to be more toxic than gases

    Oberdörster et al. **1995** *Inhal Toxicol* 7:111-124; Johnston et al. **2000** *Toxicol Applied Pharmacol* 168:208-215

Our ad-hoc experiment

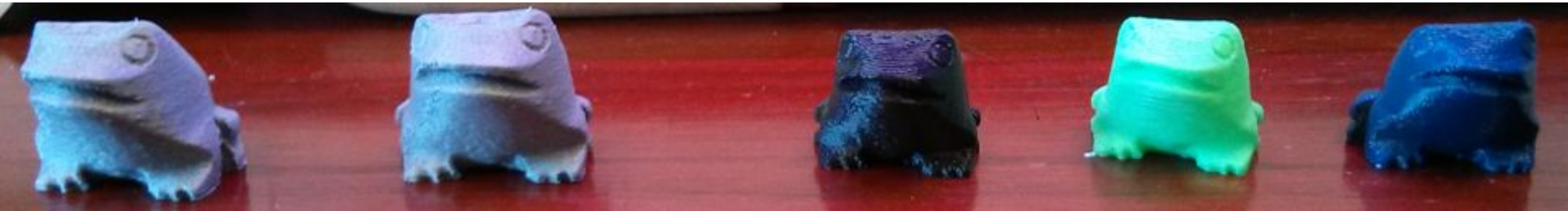
THE 3D PRINTER EXPERIENCE

- Five 3D printers were tested
  - All 5 were the same popular commercial variety
  - All unenclosed designs

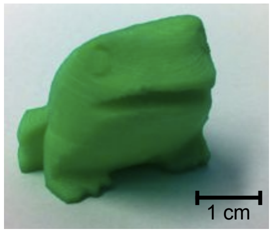
Stephens et al. **2013** *Atmos Environ* 79:334-339

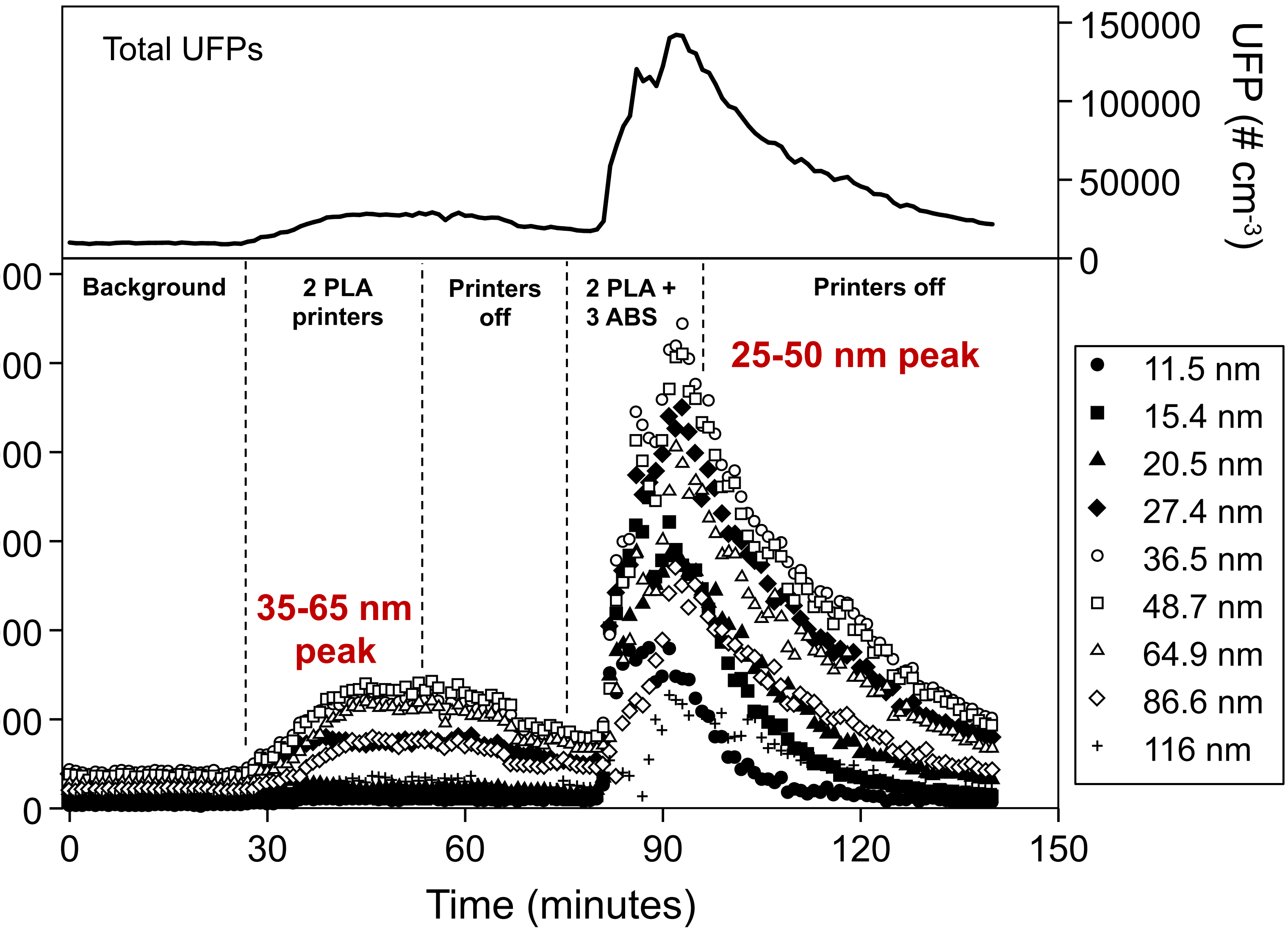
- Two types of filaments at different operational conditions
  - 2 PLA @ 200°C nozzle T and 18°C bed T
  - 3 ABS @ 220°C nozzle T and 118° bed T
- Operating in a closed 45 m^3 office environment
- Ultrafine particle concentrations measured w/ TSI NanoScan SMPS

Tritscher et al. **2013** *J Physics* 429



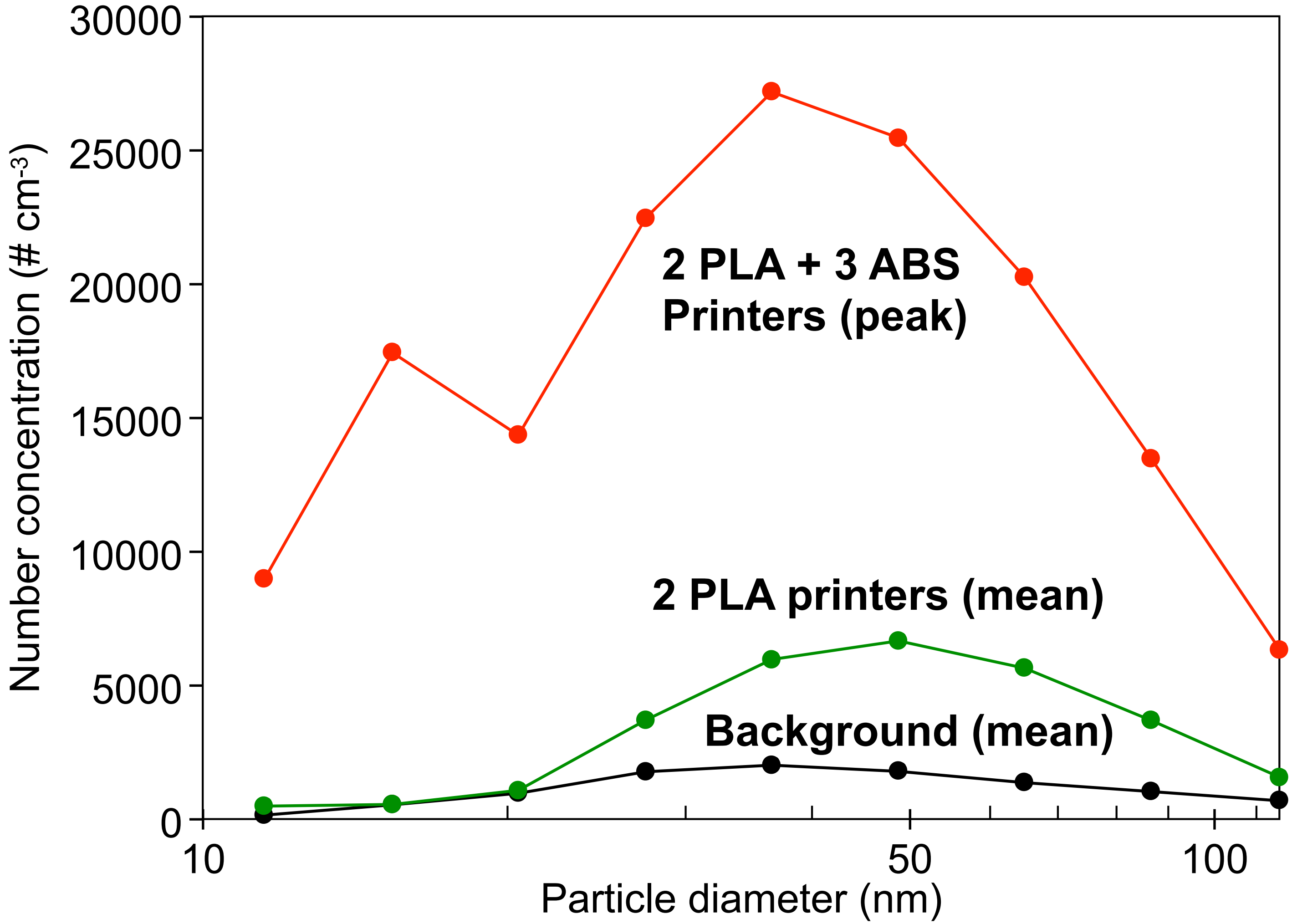
Measured ultrafine particle concentrations





Stephens et al. **2013** *Atmos Environ* 79:334-339

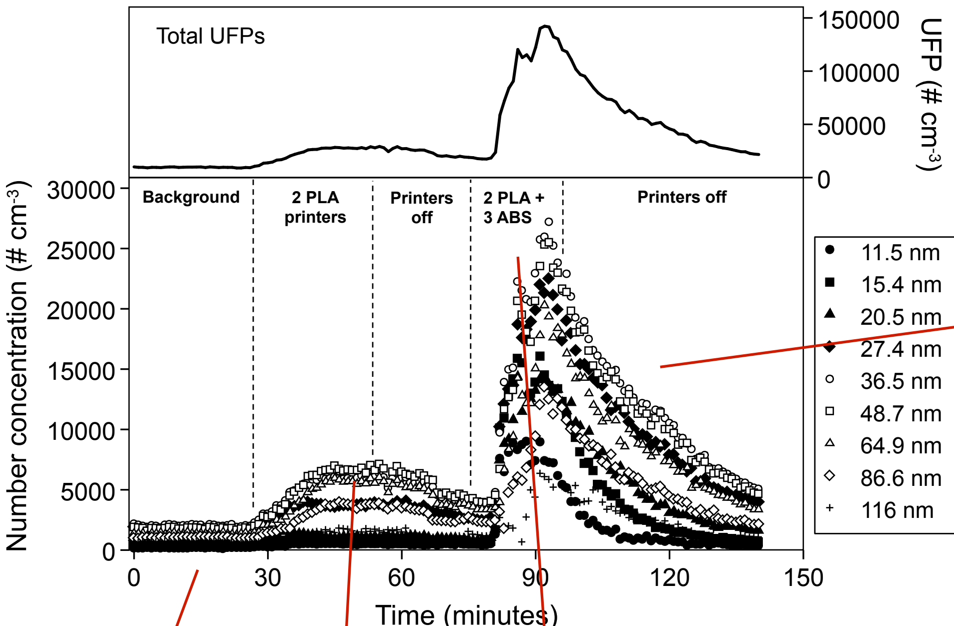
Mean and peak UFP size distributions



UFP summary
Background mean
~10,000 #/cm^3
2 PLA mean
~28,000 #/cm^3
2 PLA + 3 ABS peak
~142,000 #/cm^3

Stephens et al. **2013** *Atmos Environ* 79:334-339

Estimating emission rates



$$\ln\left(\frac{C_{i,in}(t)-C_{i,in,ss,bg}}{C_{i,in}(t=0)-C_{i,in,ss,bg}}\right)=-L_i t$$

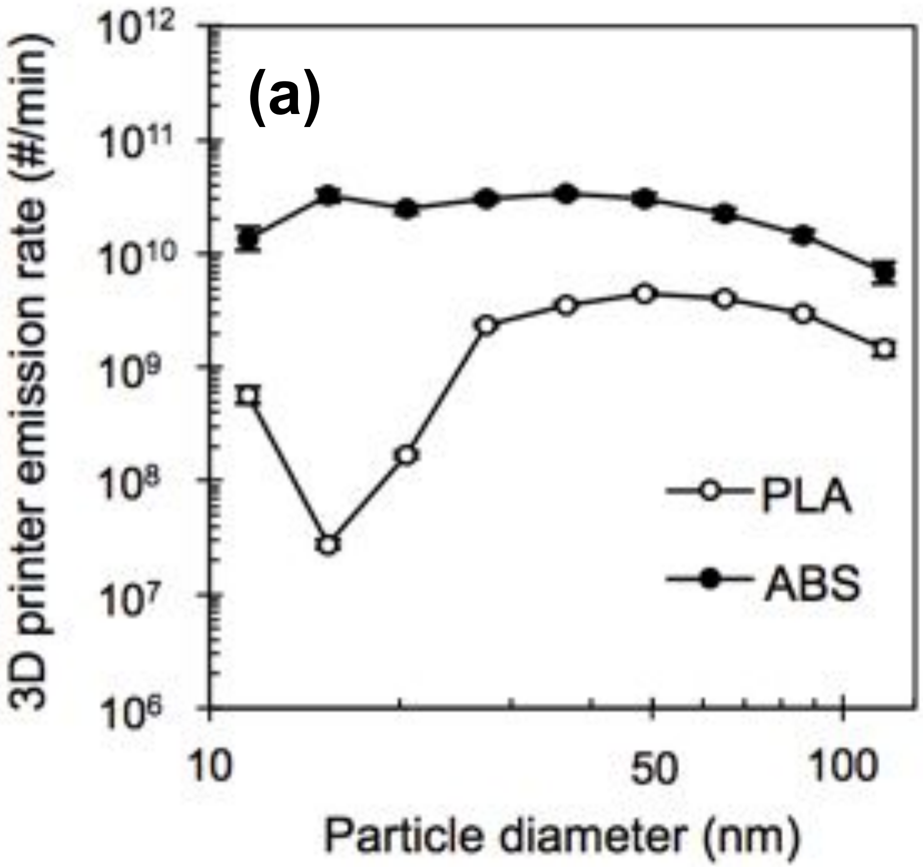
$$C_{i,in,ss,bg}$$

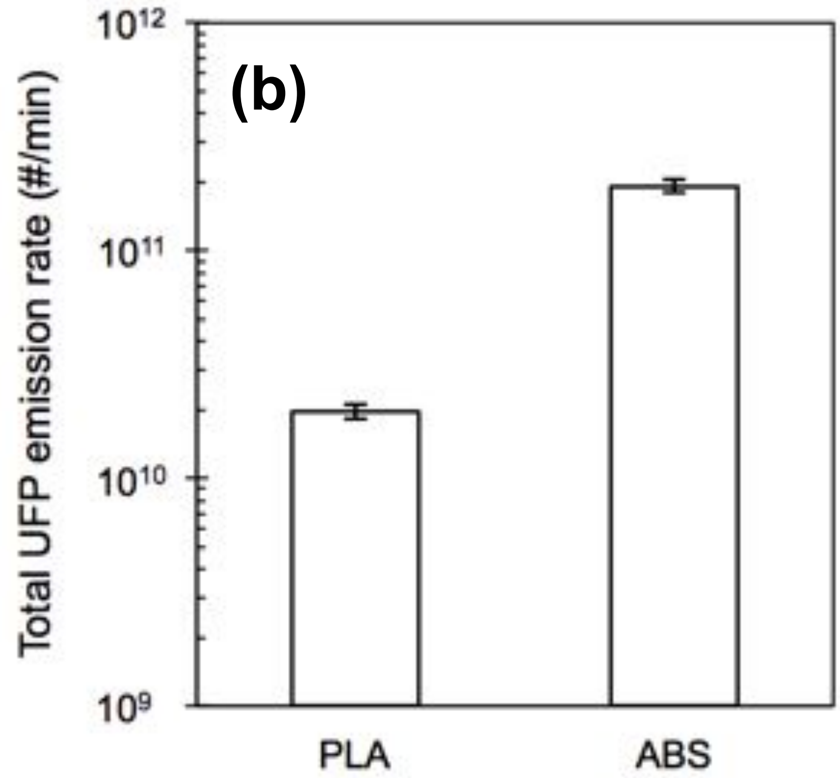
$$C_{i,in,ss,2PLA}=C_{i,in,ss,bg}+\frac{2\left(E_{i,PLA}/V\right)}{L_i}$$

$$C_{i,in}\left(t\right)=C_{i,in,t=0}e^{-L_i t}+\left[C_{i,in,ss,bg}+\frac{2\left(E_{i,PLA}/V\right)+3\left(E_{i,ABS}/V\right)}{L_i}\right]\left(1-e^{-L_i t}\right)$$

Stephens et al. **2013** *Atmos Environ* 79:334-339

Size-resolved and total UFP emission rates





Total UFP emission rates:
~1.9×10^{11} #/min from ABS printer
~2.0×10^{10} #/min from PLA printer

Stephens et al. **2013** *Atmos Environ* 79:334-339

Comparison of emission rates to other indoor emitters

UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
PLA	10-100 nm	$\sim2.0\times10^{10}$	*This study*
Vacuum cleaner	20-1000 nm	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1000 nm	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1000 nm	1.3×10^{11}	Afshari et al. (2005)
ABS	10-100 nm	$\sim1.9\times10^{11}$	*This study*
Cigarette	20-1000 nm	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1000 nm	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1000 nm	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1000 nm	8.9×10^{11}	Afshari et al. (2005)
Laser printers	6-3000 nm	4.3×10^{9} to 3.3×10^{12}	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

News coverage: Tell your own story

FOX NEWS .com Fair & Balanced

Are 3D printers harmful to your health?

BETA D NEWS

GEAR AND GADGETS

3-D Printers Might Be Hazardous To Your Health

JUL 25, 2013 03:34 PM ET // BY JESSE EMSPAK

Airborne particles from 3D printers could be as harmful to your health as cigarette smoke

Mail Online

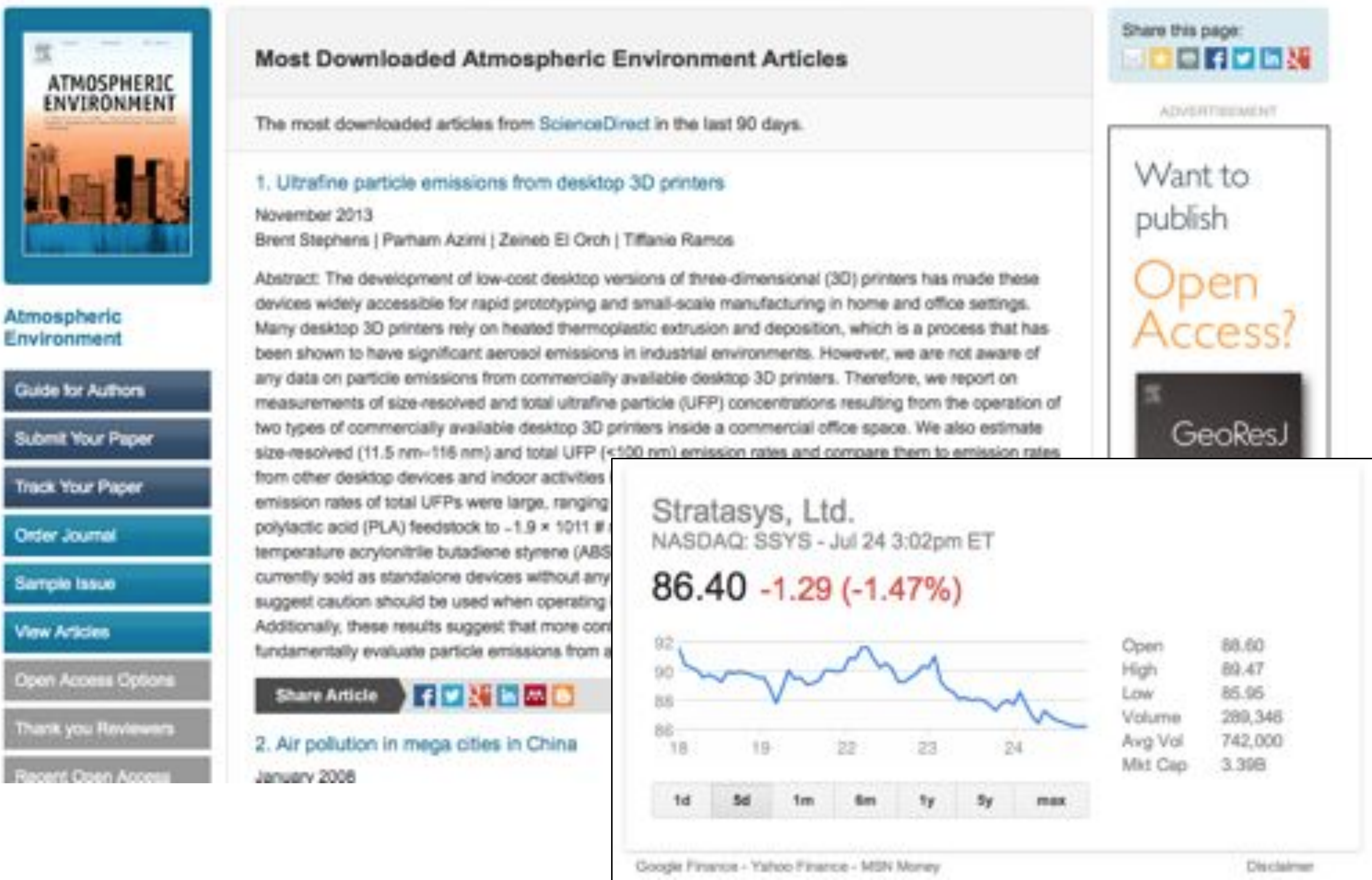
The Telegraph 3D printers could cause strokes, researchers warn

FAST COMPANY **Will A 3-D Printer Destroy Your Lungs?**

Is There Long-Term Health Risks to 3-D Printing? One Study Says 'Yes'

StreetInsider.com
if you're not inside...you're outside

More good (and bad) press…



Potential for 3D printed 3D printer filtration systems

Photos courtesy Mike Moceri, The 3D Printer Experience

Moving forward…

We continue to conduct research at the intersection of energy and air quality in the built environment

New projects:

- OSBSS, Nov 2013 – April 2015
- Sloan Foundation MoBE Post-doc, Stevie Kunkel, Biology, 2014 – 2016
  - Control/filtration of airborne microorganisms (experimental)
- ASHRAE 1691-TRP Modeling impact of HVAC filters on indoor PM in homes, starting later this year

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Acknowledgments

- Many thanks to all of the homeowners, occupants, and business owners that let us inside their buildings

- **Funding sources, people, and projects:**
  - **I/O PM:** University of Texas at Austin Continuing Fellowship, NSF IGERT Award DGE #0549428, ASHRAE Grant-In-Aid & RP-1299, Thrust 2000 Endowed Graduate Fellowship (all UT-Austin), Jeff Siegel, Zeineb El Orch
  - **Infectious aerosols:** National Air Filtration Association (NAFA) Foundation, Al Veeck, Parham Azimi
  - **HMP:** Alfred P. Sloan Foundation, Jack Gilbert, Jeff Siegel, Tiffanie Ramos, Parham Azimi, Laurit Dide
  - **OSBSS:** Alfred P. Sloan Foundation, ACE PURE, Deion Debose, Akram Ali, Boyang “Bobo” Dong, Torkan Fazli
  - **3D printers:** Armour College of Engineering, Bobby Zylstra, Julie Steele (3D Printer Experience), Mike Moceri, Parham Azimi, Zeineb El Orch, Tiffanie Ramos, Sara Glade