You can’t always get what you want… but can buildings give us what we need?

BC Lung Workshop

Gimme Shelter: Adapting the Indoor Environment to Reduce the Harmful Impacts of Climate Change

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Healthy Buildings Research Lab

Portland State University

The Corsi Code

	Indoors		In bed		Outside
79	70	50	26	5	4
Average life expectancy		At home		In transit	

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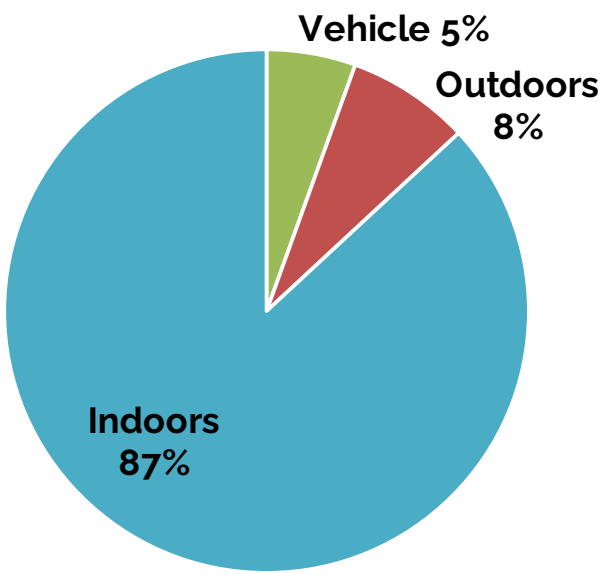
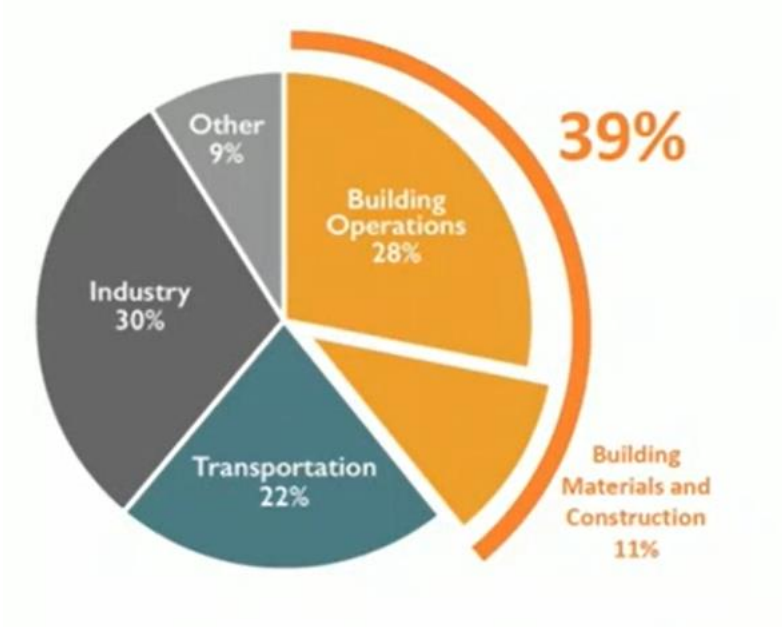
We are indoor creatures

~21 h/day spent indoors[1]



~40% of energy production[2]



We are often unsatisfied with the quality of our indoor spaces:

- A large survey of offices (34,000 responses, 215 buildings):[3,4]
  80% occupant satisfaction with air quality: **26% of buildings**

References: 1 Klepeis et al 2001 2 U.S. Department of Energy and IEA http://www.iea.org/aboutus/faqs/energyefficiency/
3Huizenga et al. 2006, Proc. Of Healthy Buildings 2006; 4 Schiavon and Altomonte, Build. and Env. 2014

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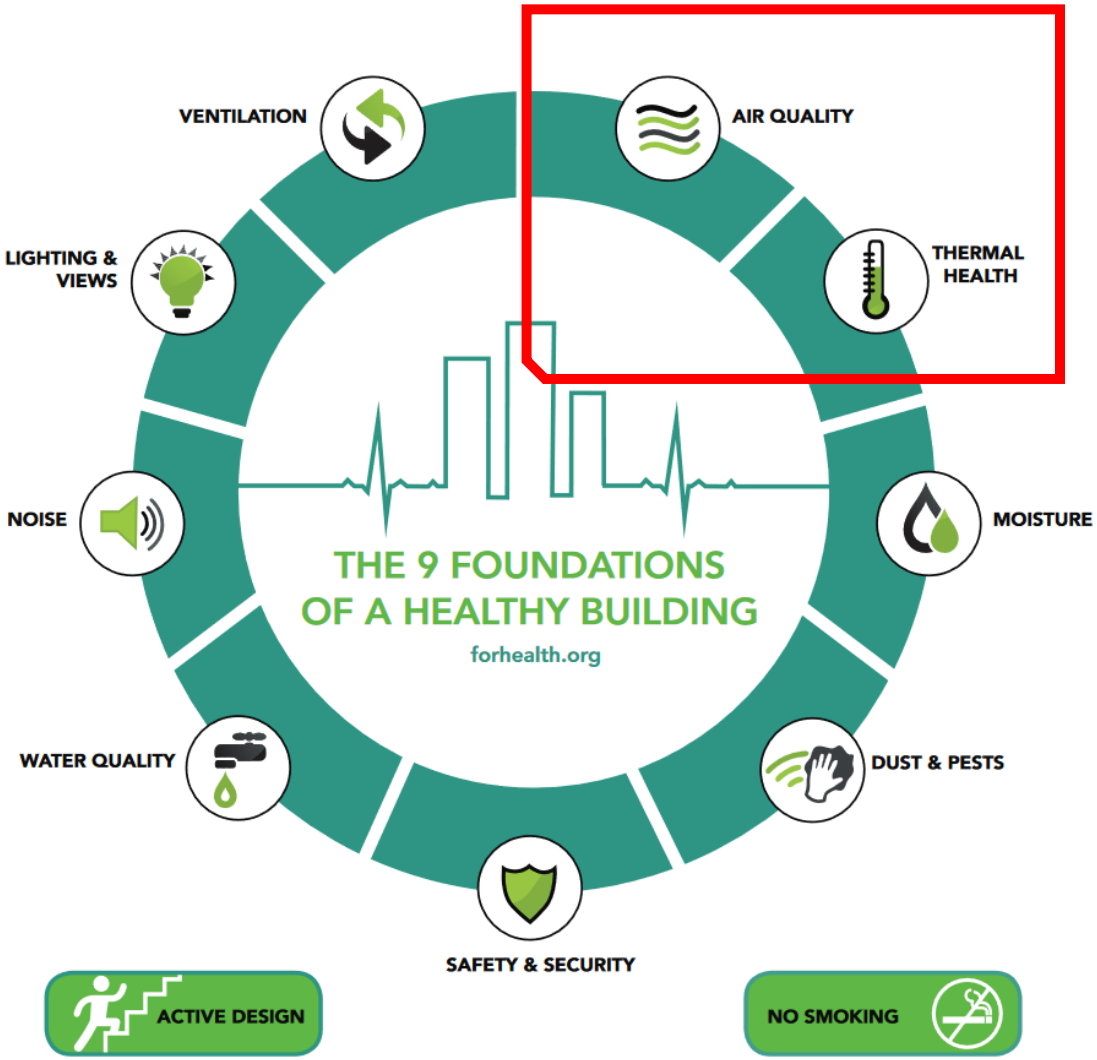
What do we want from a building?



Source: forhealth.org

Climate change and buildings

1. We must rapidly decarbonize our buildings
2. Buildings expected to ameliorate exposure to heat + smoke
3. Adaption approaches must include vulnerable populations

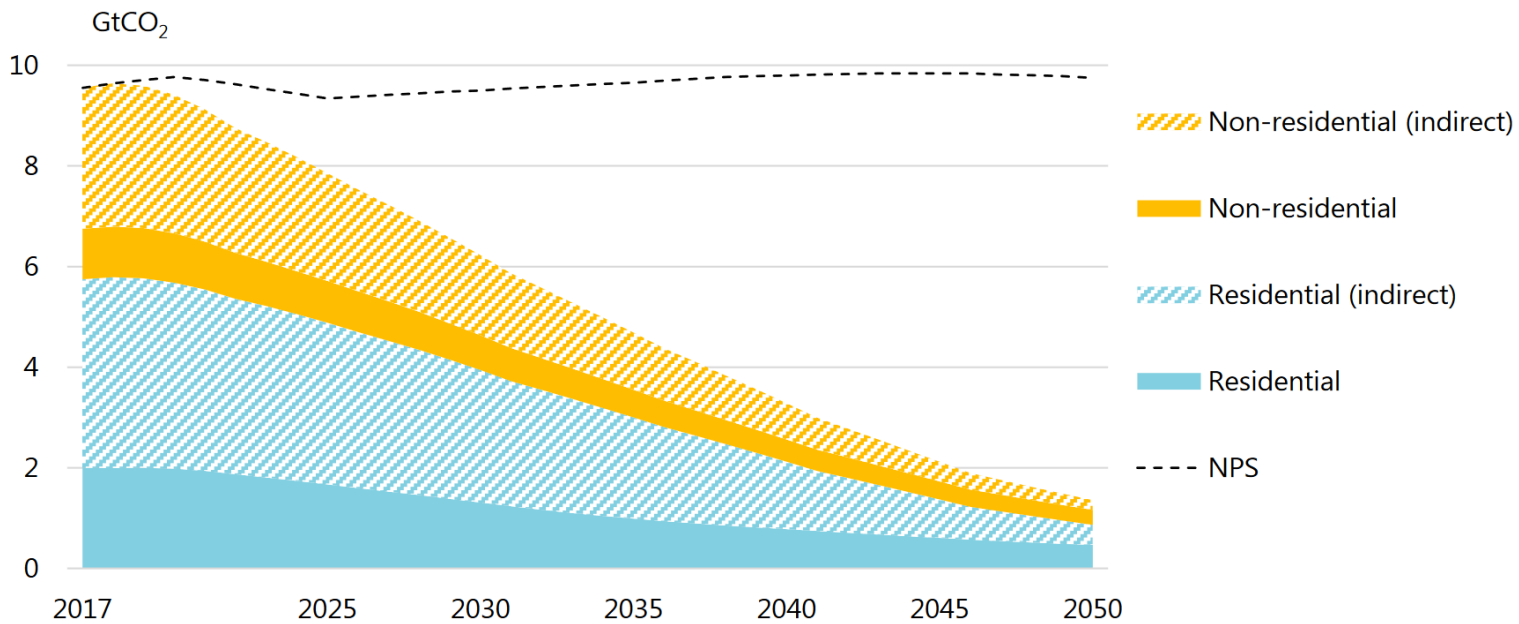
PSU Engineering Building

PSU Engineering Building (mid-day)
Summer 2020 wildfires

1. Need to decarbonize

Clean tech + energy transition could cut building GHG by 87%[1]:

- Double rate of renovations to promote **envelope improvements**
- Shift to new tech: **heat pumps** and LEDs
- Phase out inefficient versions of technology (e.g., inefficient air-conditioners)



Note: Indirect CO_2 emissions result from upstream generation of electricity and heat used in buildings.

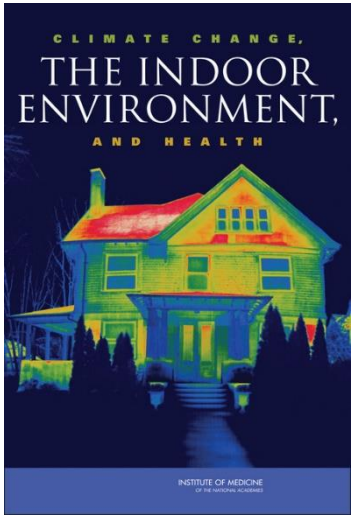
Upside: Tech for transition can support heat + smoke responses

[1]International Energy Agency, 2019, Perspectives for the Clean Energy Transition

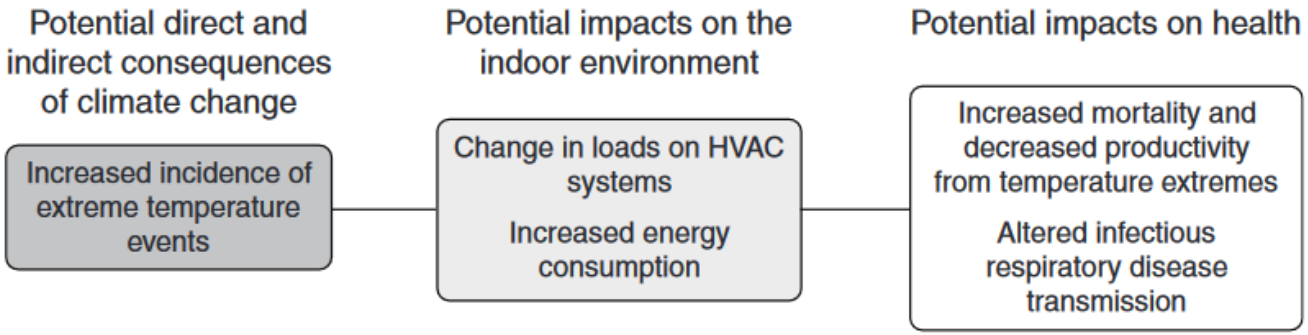
2. Buildings are front line defense

Climate change impacts our health through our buildings[1]

- Downside: heat + air pollution degrade indoor env. quality (IEQ)
- Upside: Buildings enable interventions, comparatively fast time-scale



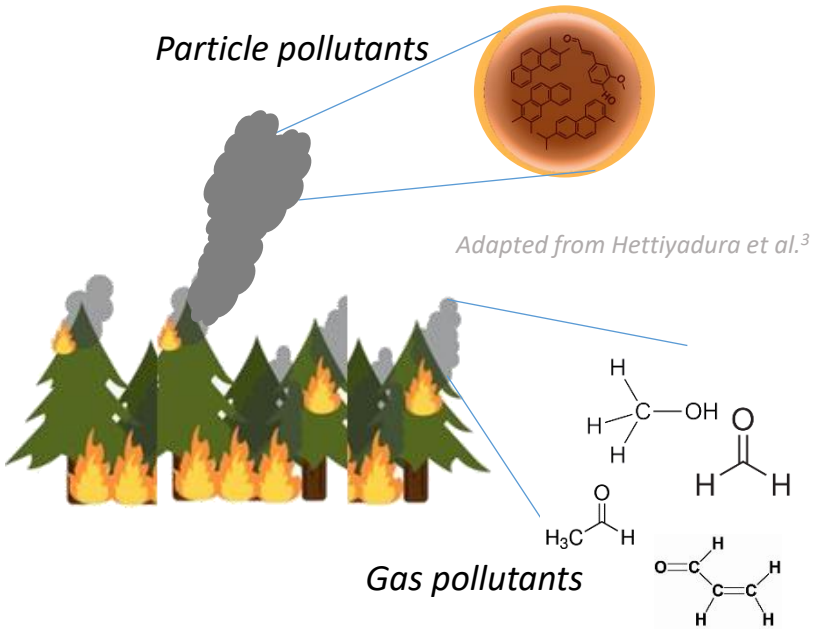
NASEM Report from 2011[1]



Heat and smoke challenges must be addressed while driving down GHG emissions

[1]Institute of Medicine. 2011. *Climate Change, the Indoor Environment, and Health*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13115.

Increasingly frequent wildfires



Fires challenges entire countries:

- 50 million U.S. homes in the wildland-urban interface[1]
- In the U.S. 25% of $PM_{2.5}$ is from wildfires[1]

Plumes transport of long distances:

- Most (~75%) mortality and morbidity from fires occurs in the Eastern U.S.[2]

Gases and particles are elevated

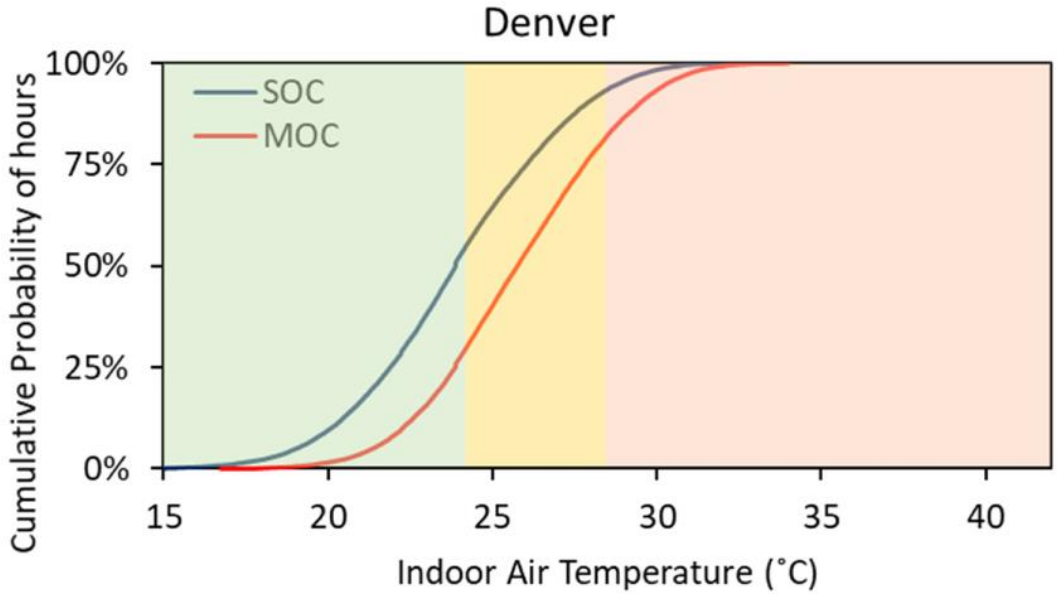
- Require distinct control methods
- Particles have larger health impact[2]

1 Burke et al. 2021 PNAS 118(2): e2011048118; 2 O'dell et a. 2021 GeoHealth 5(9): e2021GH000457; 3 Hettiyadura et al. 2021, *ES&T* 55(4): 2511-2521

Increased temperatures + heatwaves

Buildings are increasingly reliant on mechanical cooling[1]

- Increases in outdoor temperatures
- Reliance on air-conditioning has changed building design



Modeled indoor air temp at
SOC = start of century; MOC = middle of century

Buildings will lose ability to maintain comfortable indoor temp w/o mechanical systems

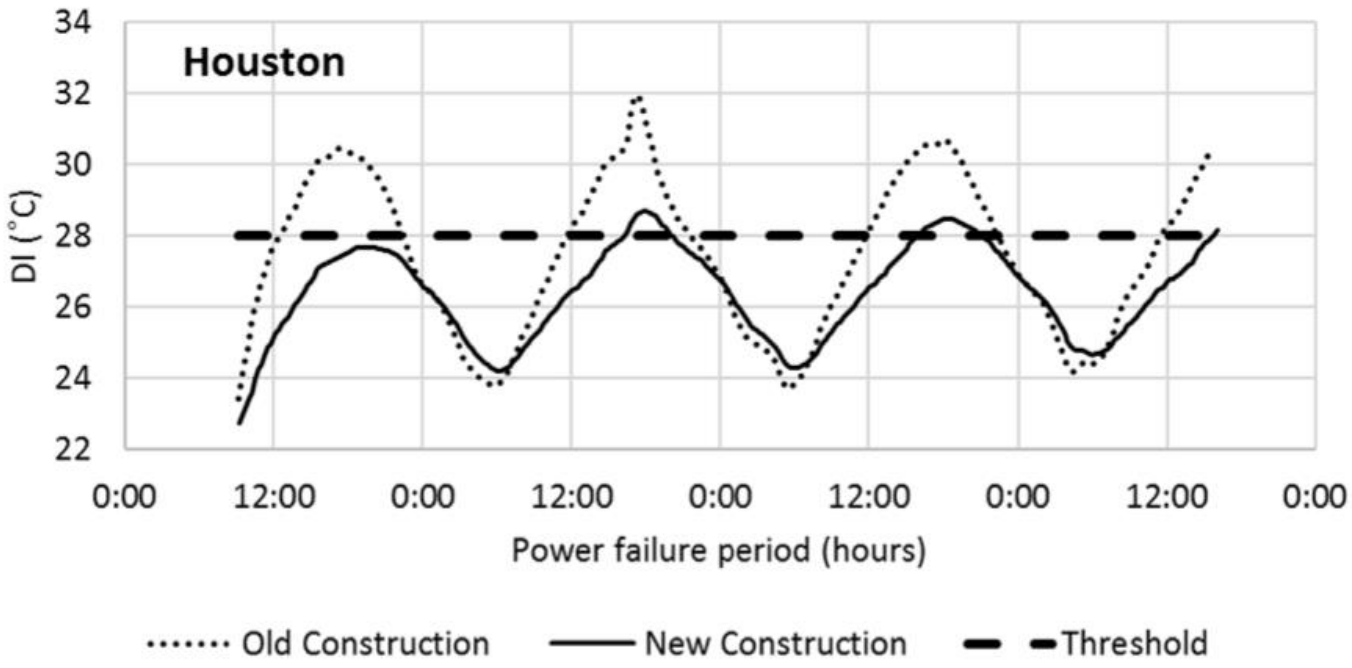
1 Baniassadi et al. 2019 Env. Res. Letters 14 074028

Healthy Buildings Research Lab

Designing for multiple extremes

Buildings are part of interconnected infrastructure

- Heat waves and power outages impact on indoor temp + RH (DI = discomfort index)[1]:



How do we improve passive survivability in homes in the event of a power outage?

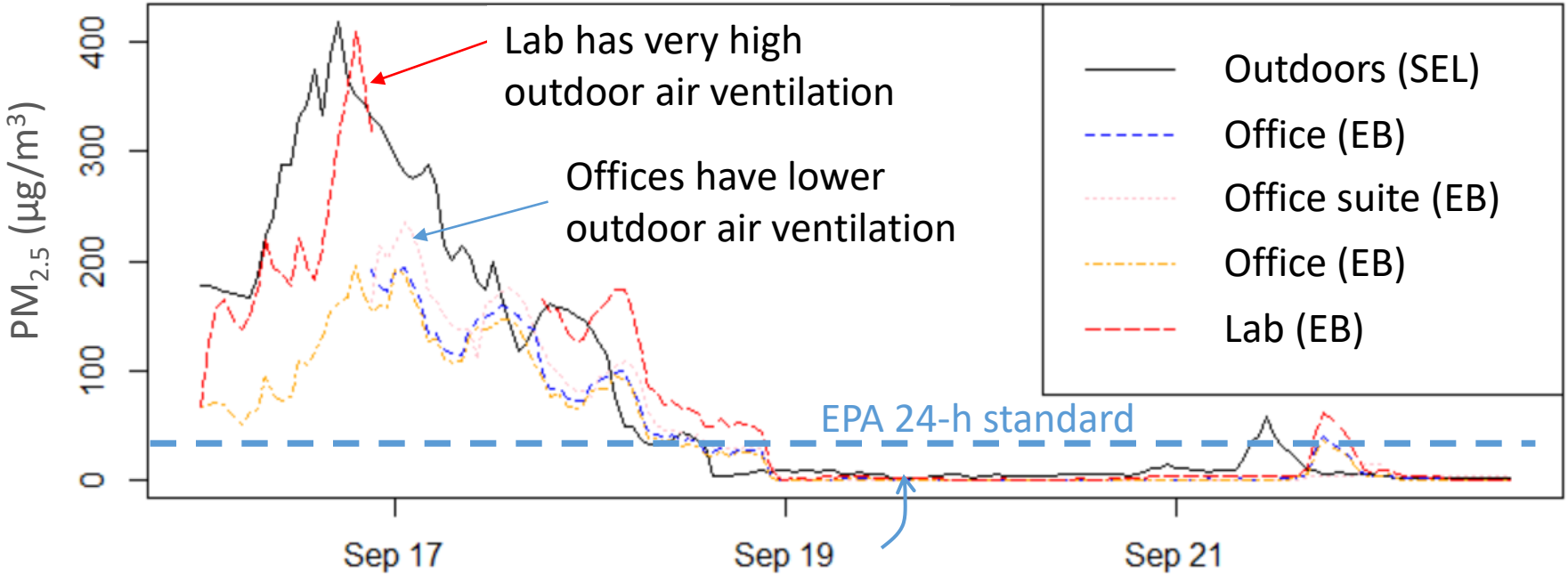
1 Baniassadi and Sailor 2018, Building and Env. 132(15): 263-272

Healthy Buildings Research Lab

Designing for multiple extremes

Indoor air monitoring during 2020 wildfires

- Very high levels of $PM_{2.5}$ in high performance building



Building COVID protocols call for high outdoor air ventilation rates. **Need dynamic, responsive people and systems to manage multiple criteria**

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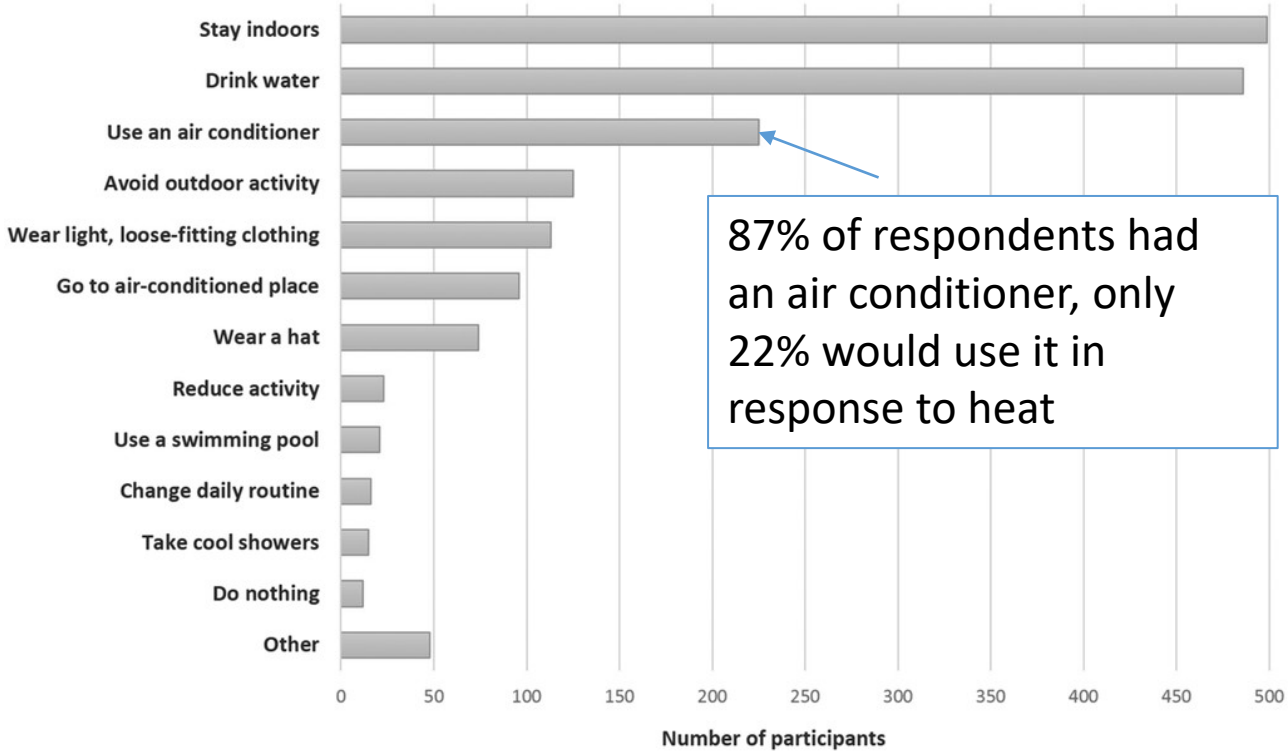
How does a population respond?

Buildings and behavior are key determinants of vulnerability

- Survey of 901 households in Houston, TX re: extreme heat[1]

Participants were asked, "During very hot weather, what steps do you take to protect yourself from the heat?"



87% of respondents had an air conditioner, only 22% would use it in response to heat

Why do people respond the way the do?

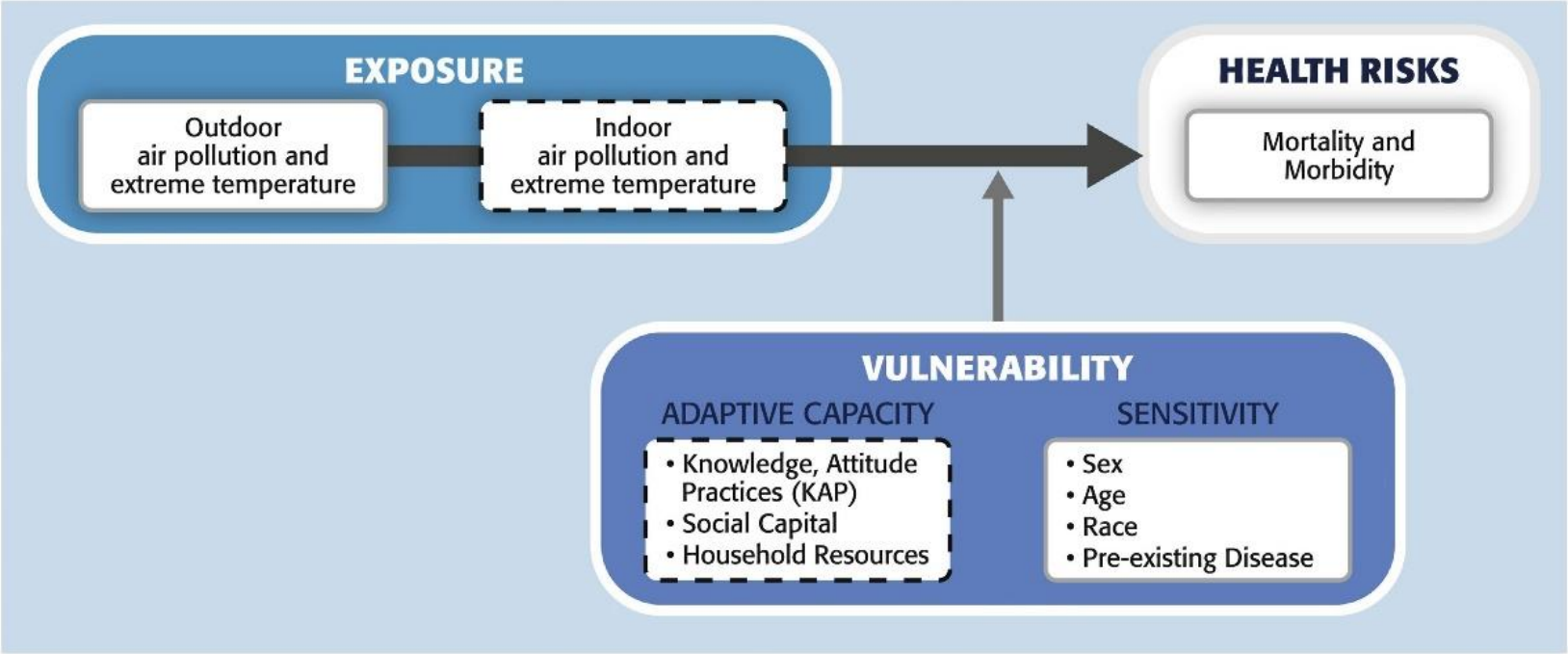
Participants who earn less than $30,000 /year were 2.3 times less likely to change daily activities in response to heat than those earning >$75,000[1]

[1]Hayden et al. 2017 Weather, Climate Society 9(4): 787-799

3. Framework must include vulnerability

Interdisciplinary response needed[1]:

- Exposure models of energy + air pollution
- Surveys of susceptibility + adaptive capacity
- Prediction of health impacts + health benefit



[1]O'Lenick et al. 2019, STOTEN 660(10): 715-723

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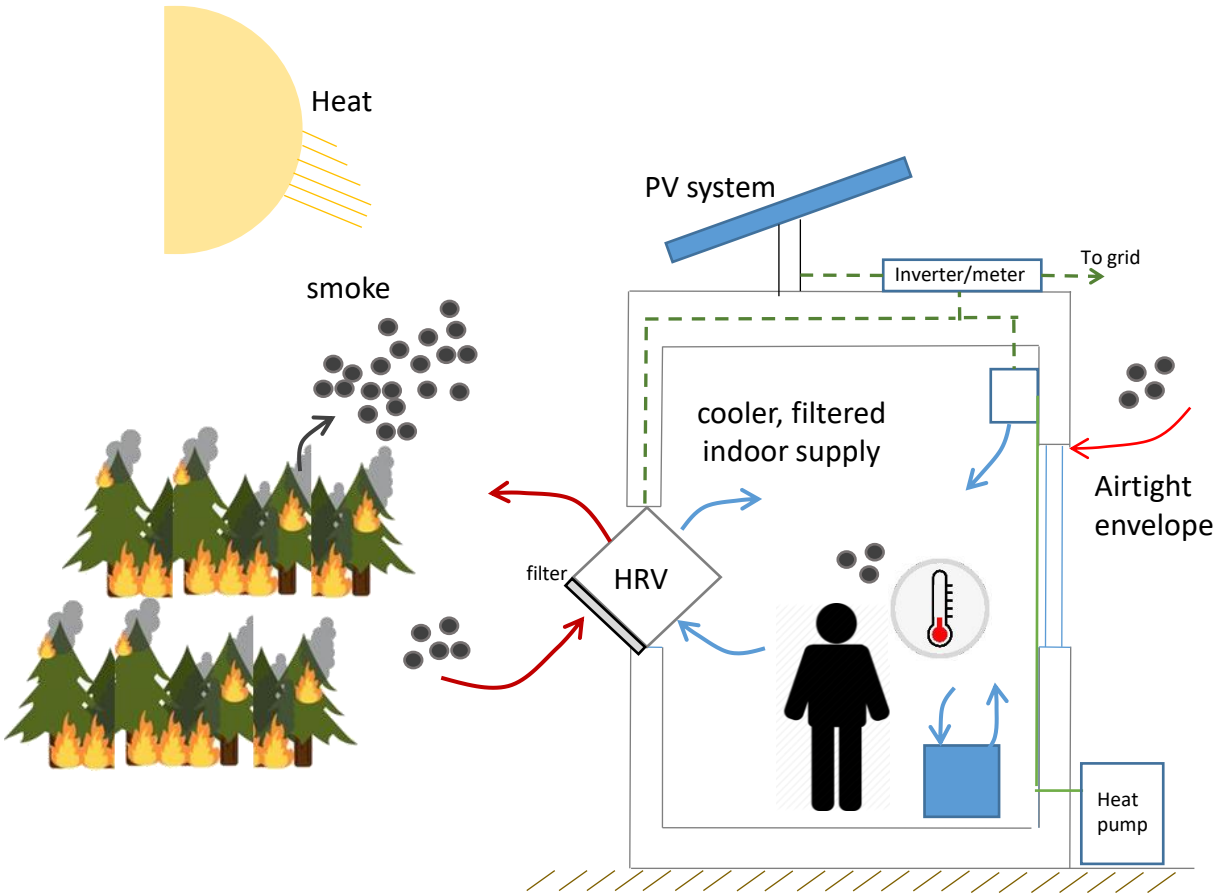
Buildings impact air quality + temp



Building shell

Ventilation

Indoor sources

Air cleaning

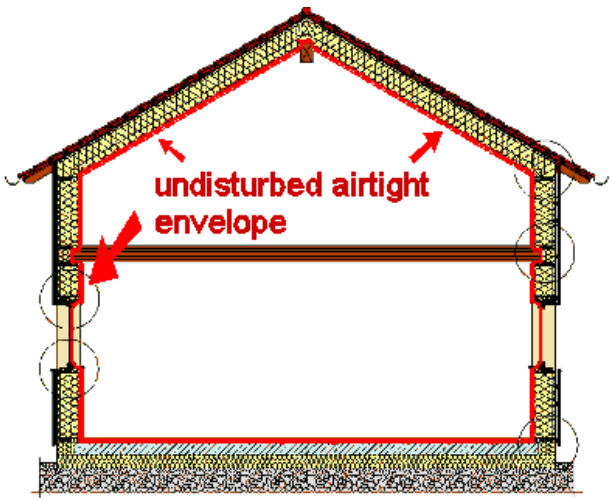
Air conditioning

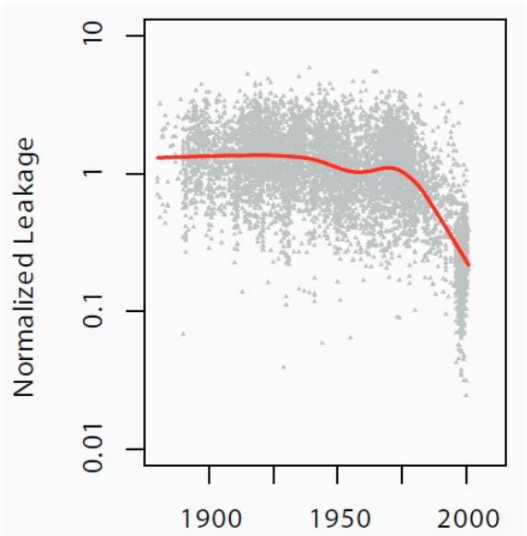
Indoor accumulation

Building envelope increasingly airtight

Heat and air pollution transfer indoors via the building envelope

- Buildings are increasingly airtight[1]
- Can increase energy efficiency
- Control indoor exposure to outdoor air pollution





Airtight shells require best practices in:

- construction + operation
- occupant education

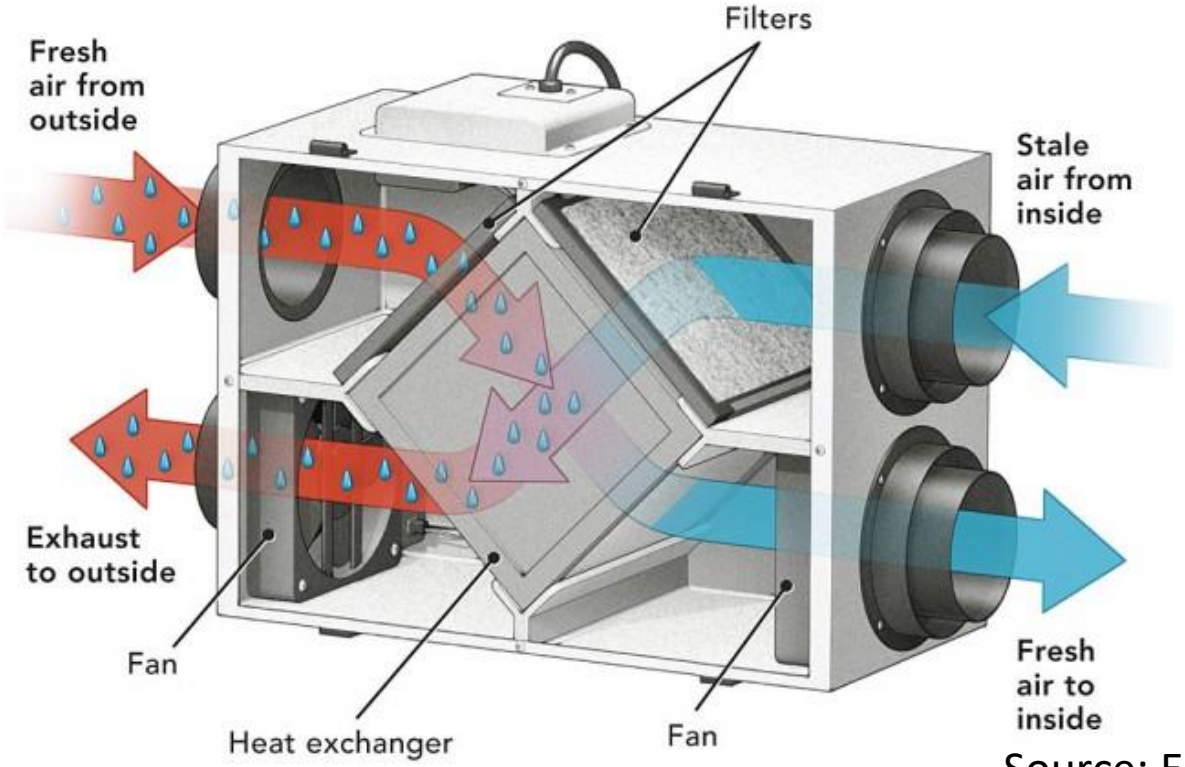
or an airtight shell can degrade IAQ[2]

[1]Chan et al., 2003, from NAP report on IAQ and climate change: [2]https://mdpi-res.com/d_attachment/ijerph/ijerph-17-04749/article_deploy/ijerph-17-04749-v2.pdf?version=1594000922

Airtight → mechanical ventilation

Airtight designs need mechanical ventilation to provide outdoor air

- Heat recovery ventilation
- Pro: opportunity for energy-efficient ventilation
- Con: System must be appropriately designed and maintained



Source: EPsales Inc.

Remove indoor sources

Source control is important in airtight space

- Low emitting materials, removal of combustion sources

Opportunities for public health + climate wins

- Gas combustion appliances emit GHG[1]
- Gas combustion appliances cause NO_2 exposures[1], other air pollution

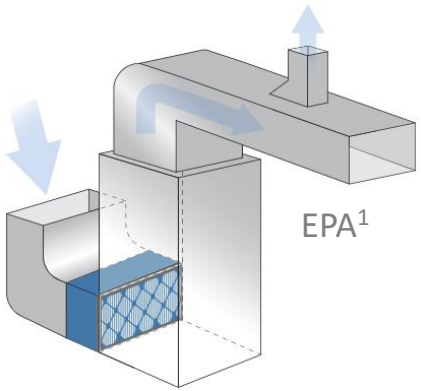
Gas combusting stoves:

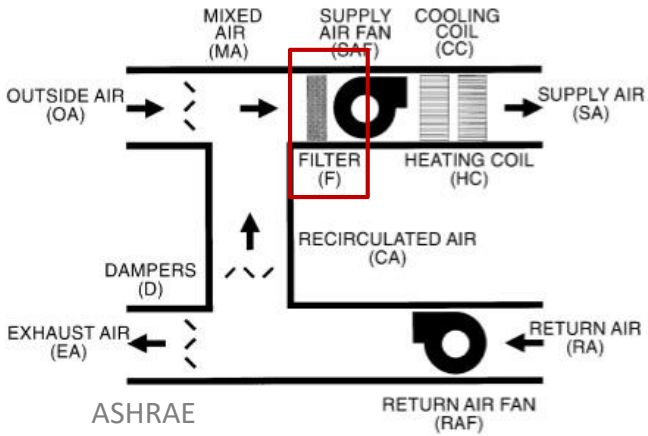
NO_2 Levels can **surpass the 1-h national standard of NO_2** (100 ppb) within a few minutes of stove usage**.**

[1]https://www.epa.gov/indoor-air-quality-iaq/create-clean-room-protect-indoor-air-quality-during-wildfire; https://pubs.acs.org/doi/full/10.1021/acs.est.1c04707

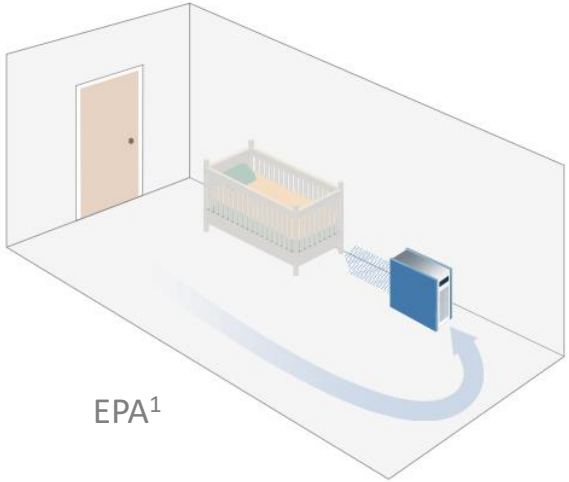
Clean outdoor + recirc air

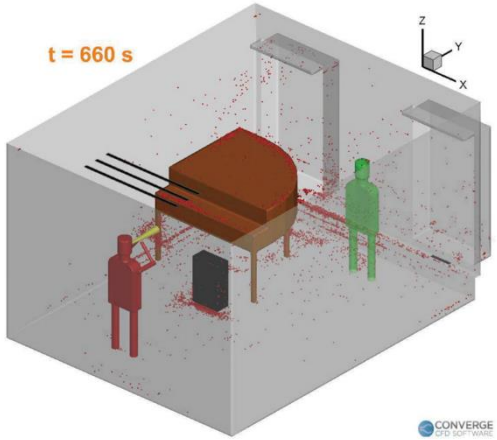
Clean and condition air entering the building





Clean the air inside the building





Narayanan and Yang 2021
Phys. Fluids 33, 033307

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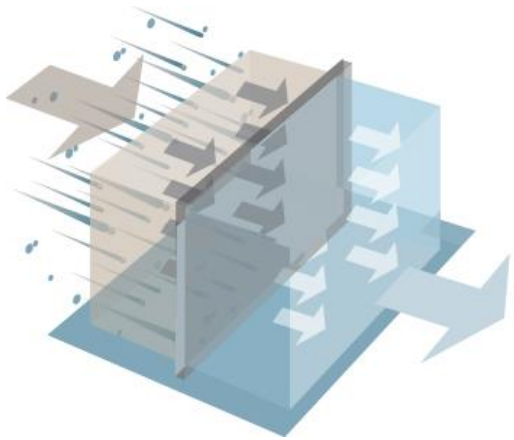
Use proven air cleaning tech

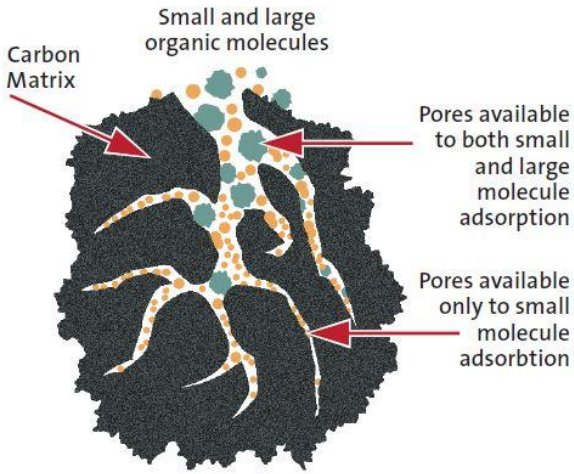
Particles: Mechanical filtration

- Proven effective
- Studies show health improvements



Gases: Sorbents

- May be effective
- Less clear links to health improvement

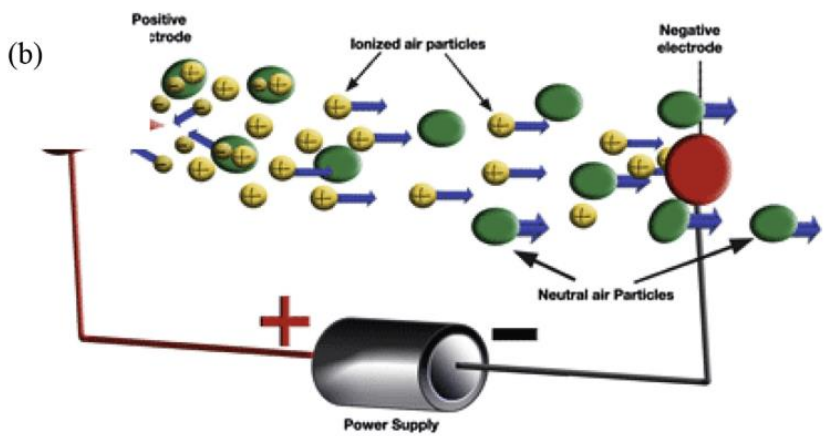


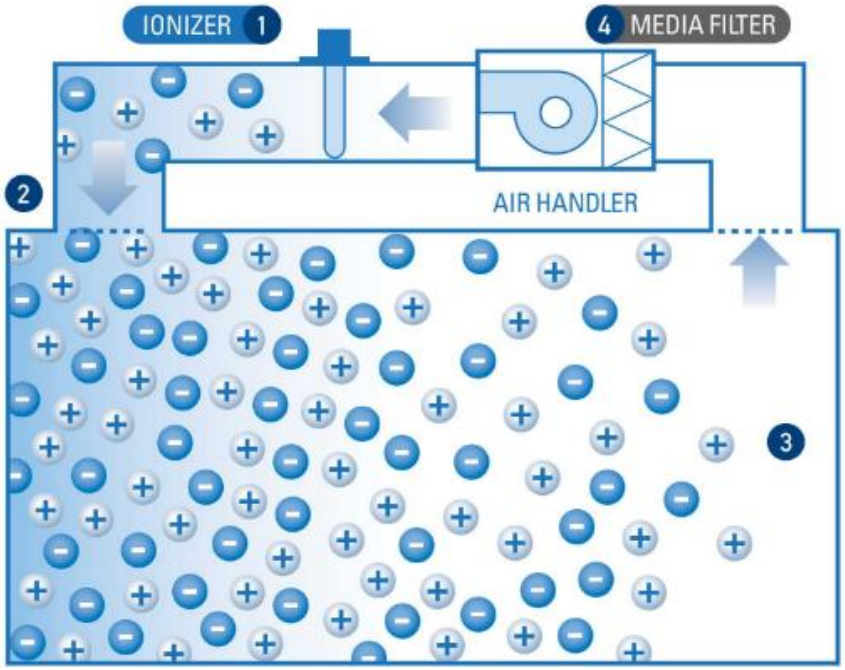
See ASHRAE Position Document for more detail

Avoid unproven tech

Ionizers, radical generators, etc. are aggressively marketed

- Capabilities often oversold
- Exposure to oxidants, byproducts
- No performance standards

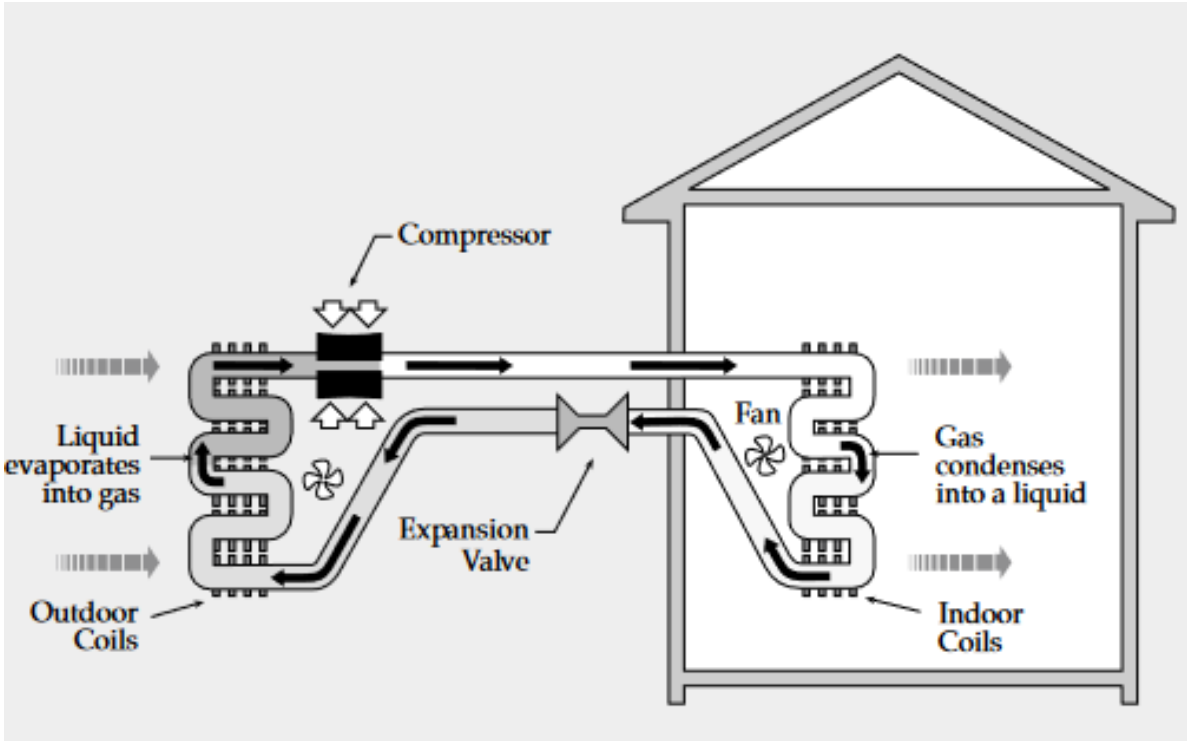




[1] K.-H. Kim et al. 2017, Environmental Pollution 729-743 (Figure); [1]Zeng et al. Experimental evaluations of the impact of an additive oxidizing electronic air cleaner on particles and gases *Pollutants* ; Zeng et al. 2021, Building and Environment, doi:10.1016/j.buildenv.2021.107750

Efficient heating and cooling

- Heat pumps cut typical energy use by factor of 4[1]
  - Move heat from one place to another
  - Can heat and cool an indoor space



Heat pump in heating cycle[2]

[1]International Energy Agency, 2019, Perspectives for the Clean Energy Transition:
[2]NREL EERE Heat Pump Fact Sheet: https://www.nrel.gov/docs/fy01osti/28037.pdf

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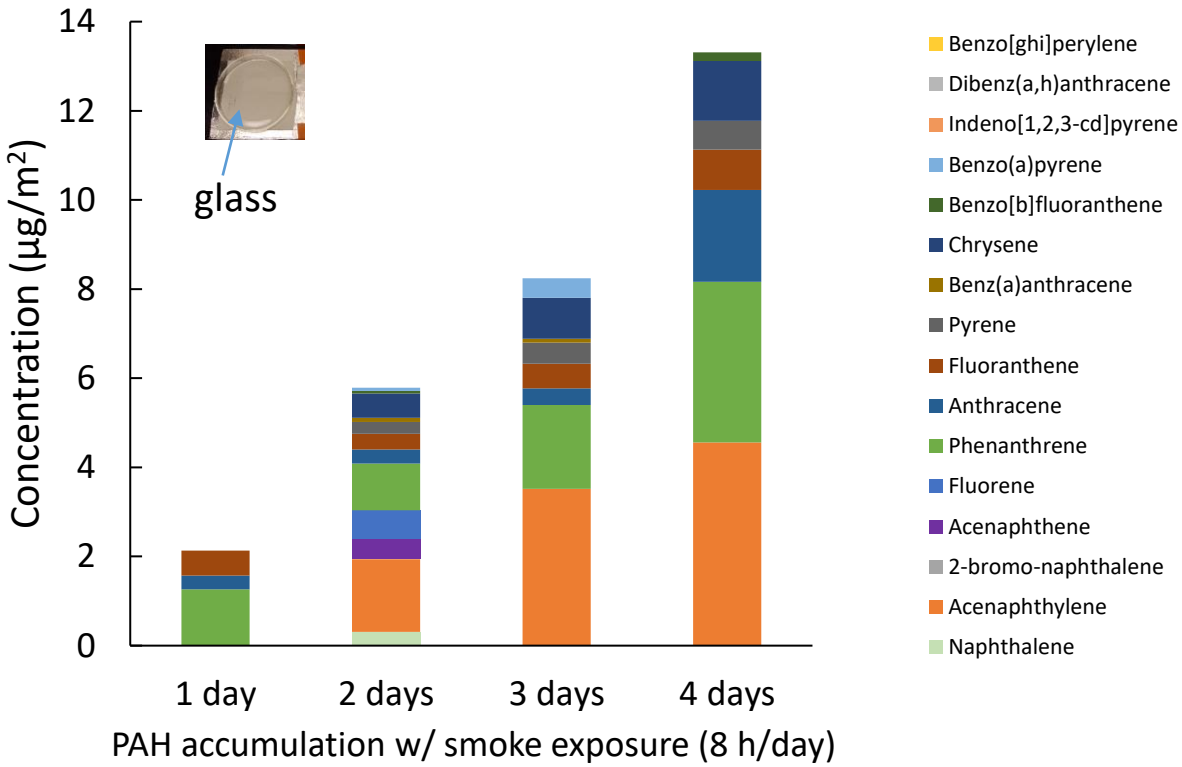
Do extreme events change our spaces?

Heat and smoke may damage/alter our indoor spaces

- What practices are needed to ensure our buildings are healthy when event is over?
- Damage/changes to materials
- E.g., surfaces accumulate polycyclic aromatic hydrocarbons



[1] US EPA Funded HADES project:
https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/11203/report/0

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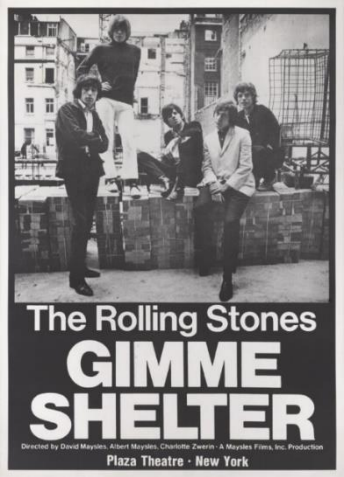
Gimme shelter: How can buildings help?

- Goal: ↓ carbon and ↑ climate resilience of buildings
- Tools:
  - Building shell + HVAC
  - Energy-efficiency measures
  - Automation + controls
  - Indoor air monitoring
  - Protocols for post-extreme event
- Needs:
  - Buildings and health knowledge
    - Vulnerability + exposure framework
    - Who's vulnerable? Why? How to intervene?
  - Top down: Multi-stakeholder buy-in re: building codes
  - Bottom up: Awareness to drive demand for change



- Thank you!
- Questions?

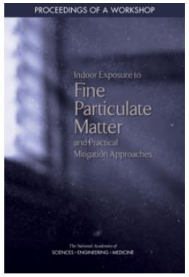
Healthy Buildings
Research Lab

www.pdx.edu/healthy-buildings/

Portland State
UNIVERSITY

https://www.youtube.com/watch?v=vGnuM21nbaY

https://www.youtube.com/watch?v=sJ1D7zlG_rQ



https://www.youtube.com/watch?v=-19MF4x0784&list=PLJ8uEbBRJZKezE0UJQnrVn2oWnFpcXMG-&t=3s

- Extra slides

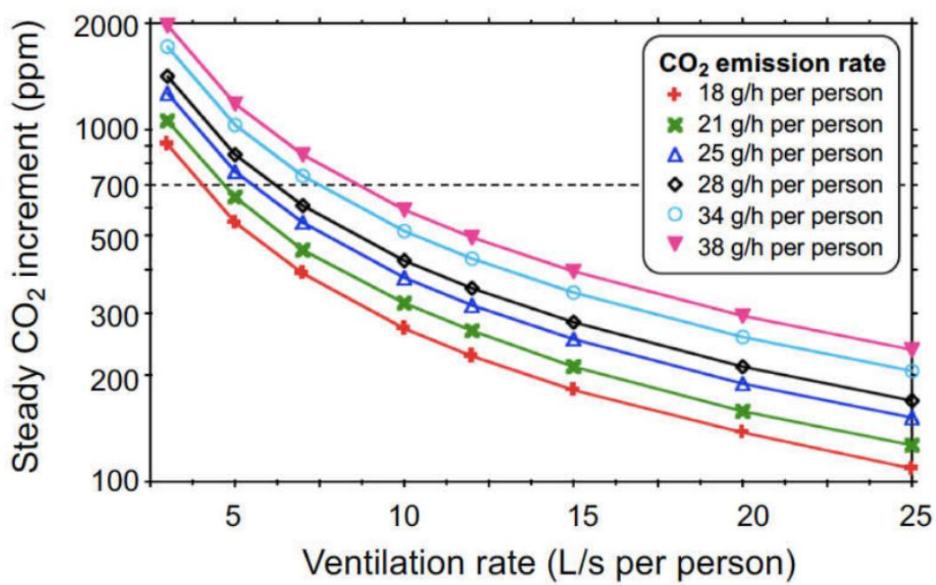
Buildings require ventilation

Building require outdoor air b/c of indoor sources

- Indoor air (usually) more pollutant than outdoor
- Usually, more ventilation improves IEQ
- More outdoor air → less sick building syndrome[1] and allergies[2]

CO_2, VOCs, viruses

CO_2 is a proxy for human emissions, guide for outdoor air ventilation



Need for studies to address polluted outdoor air conditions[1]

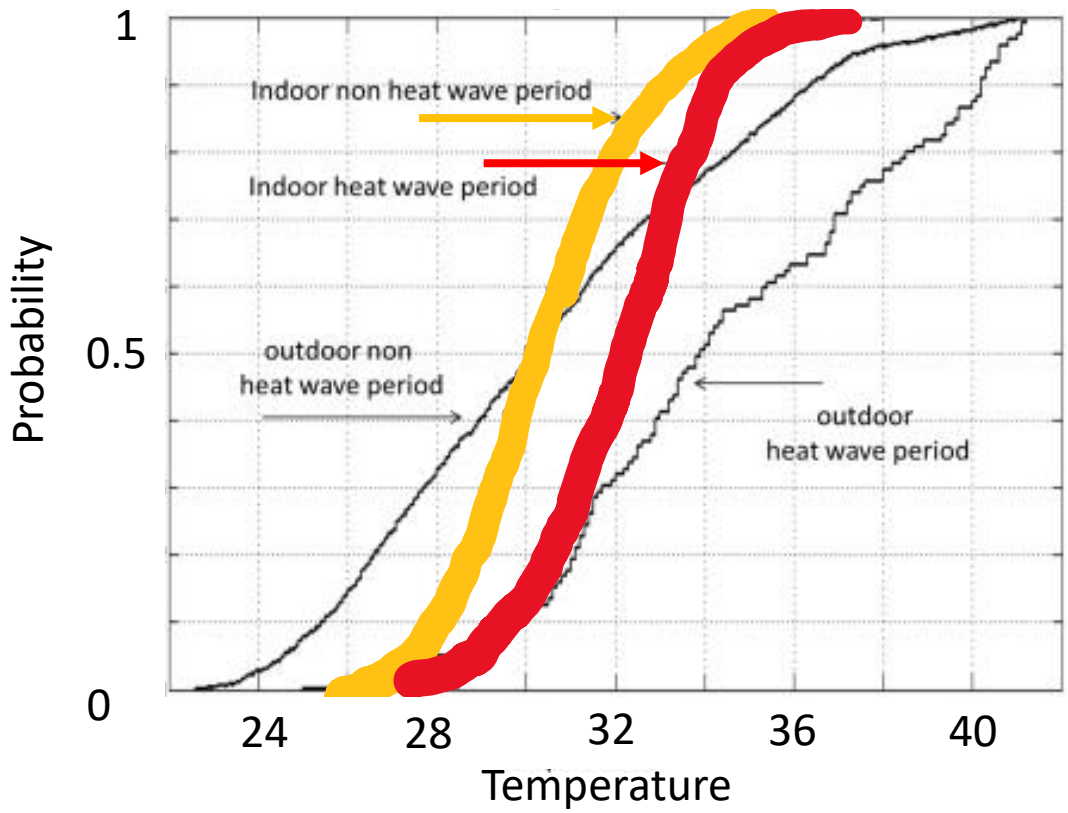
References: 1 Sundell et al. 2011 21: 191-204; 2 Bornchag et al. 2005 Indoor Air 15: 275-280

Increasingly frequent heatwaves

During 2007 Heat waves in Athens[1]:

- Low-incomes housing put vulnerable populations at-risk
- Older construction, leaky, poorly insulated

Indoor median temps >2 C hotter during heatwave



Indoor "hot spells" in low-income housing: **> 33 °C for 150 hours five times in one month**

1 Sakka et al. 2012 Energy and Buildings 49: 69-77

Monitor IAQ performance

Aranet4 retails for ~$250

PurpleAir PA-II retails for ~$250

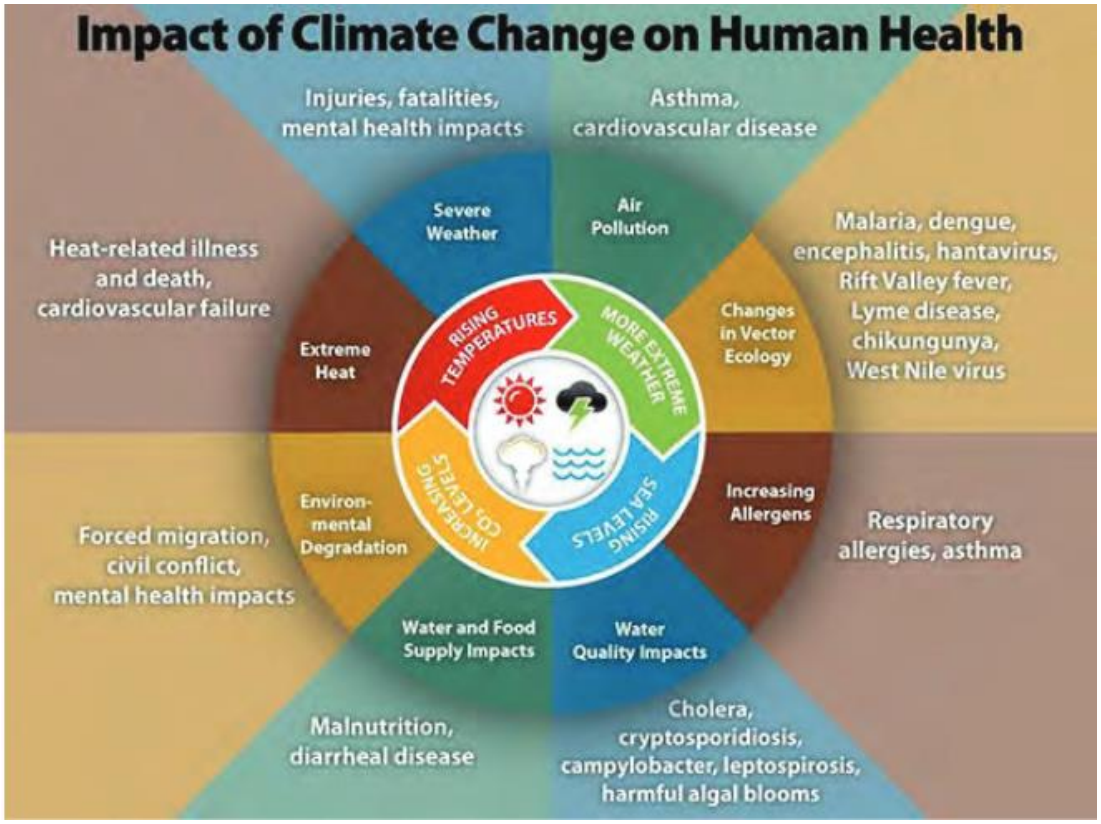
Performance-based monitoring of CO_2 and PM

- Sensor costs are rapidly decreasing
- CO_2 and PM[1] can be monitored with accuracy and precision
- Enable new control strategies
- Validation of building performance, including during extreme events
  - Ventilation
  - Air cleaning

[1]https://newscenter.lbl.gov/2020/08/18/low-cost-home-air-quality-monitors-prove-useful-for-wildfire-smoke/

Conclusions

Buildings will prominently impact a wide array of potential climate change + health impacts:



We need effective, interdisciplinary teams that understand these challenges to design effective interventions

Figure: Centers for Disease Control and Prevention. National Center for Environmental Health. (2014). Impact of climate change on mental health. Retrieved from https://www.cdc.gov/climateandhealth/effects/

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Community cooling + clean air centers

Pre-renovation

Post-renovation

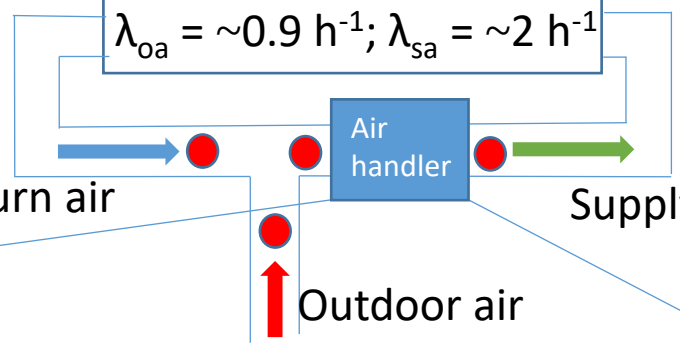
Air monitoring locations[1]

Middle School

N = ~500 students

V = 36,800 m^3

λ_{oa} = ~0.9 h^{-1}; λ_{sa} = ~2 h^{-1}



MERV8 pre-filter

protect lifespan of downstream high efficiency filter + AC downstream

MERV16 filter

effective across broad range of particles, <10 nm – 10+ µm

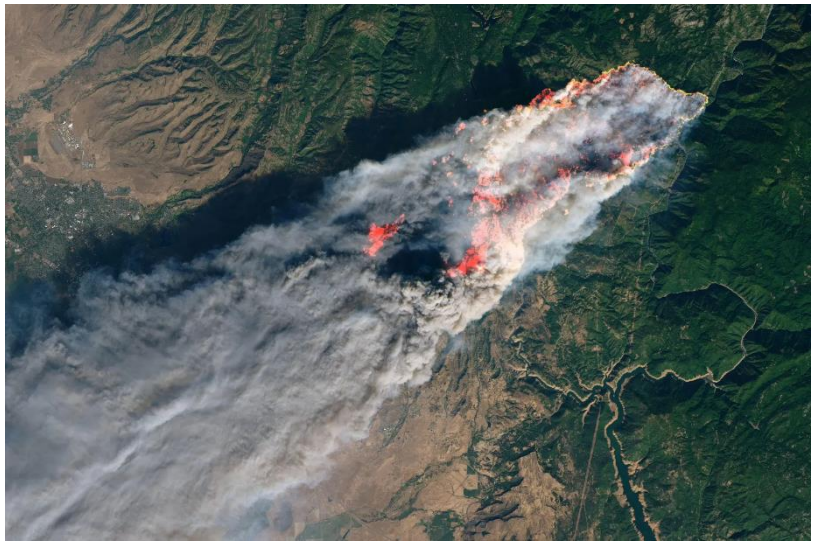
Functionalized carbon

VOC and NO_2 removal, large mass required, ↑cost

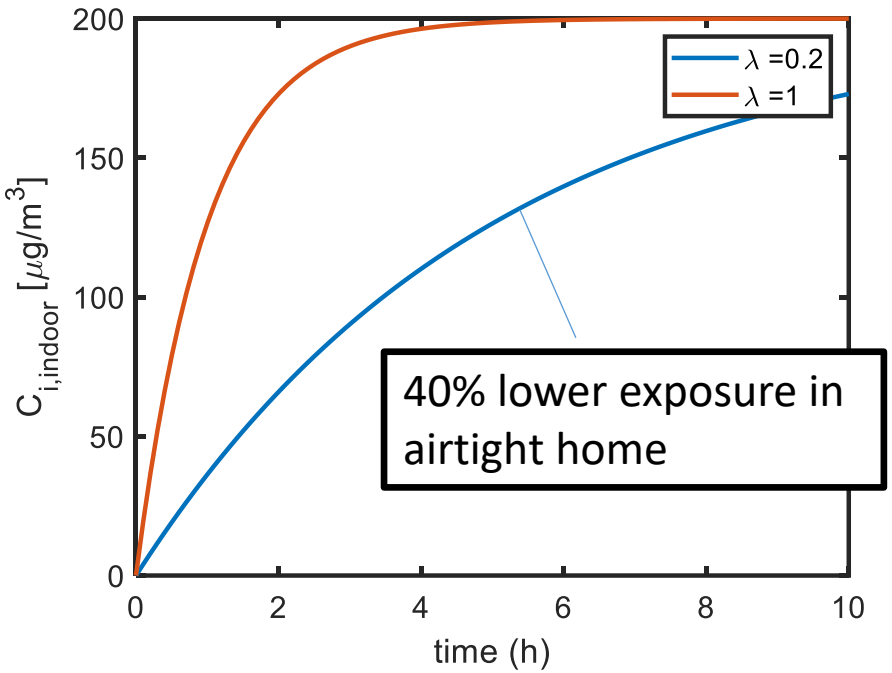
[1]See Laguerre et al., 2020, ES&T 54(19):11798-11808 for description of monitoring activities

Airtight buildings can be protective

- Imagine a fire plume directed towards Vancouver
  - One house is well-sealed, another "leaky"
  - All other things equal, how does leakiness impact?



Source: theverge.com



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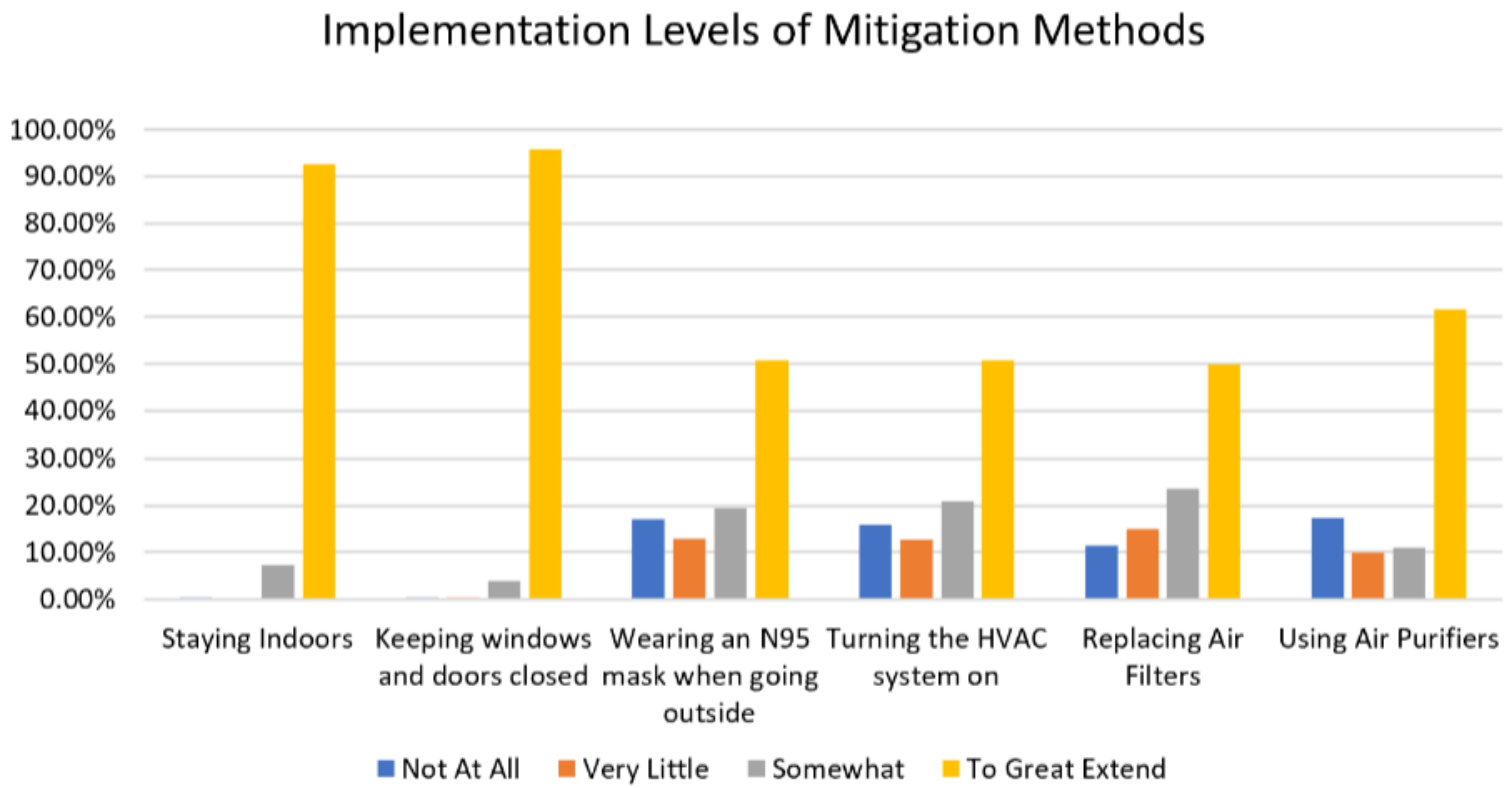
How does a population respond?

Buildings and behavior are key determinants of vulnerability

- Survey of 500 individuals in Portland, OR post 2020 Labor Day Fires:



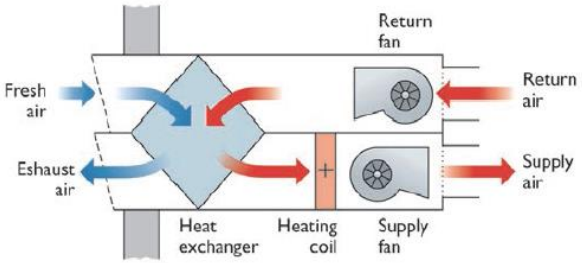
Mechanisms of air exchange

The outdoor **air change rate** is the rate of turnover of indoor air in the space with outdoor air.

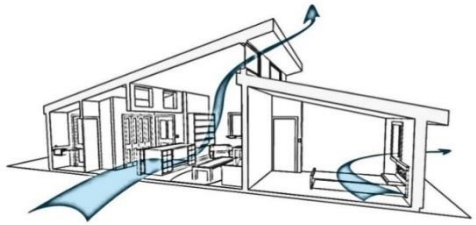
- Units are typically h^{-1}, or "air changes per hour" (ACH)
  - Inverse is how long air spends inside a building
- The outdoor ACH is a key parameter for indoor air quality
  - In a residence, 0.5 ACH outdoor air is typical
  - Commercial spaces may be higher

Outdoor air is provided to the building in three ways:

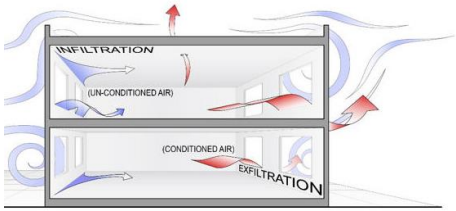
Mechanical ventilation



Natural ventilation



Infiltration



A “clean room” for wildfires

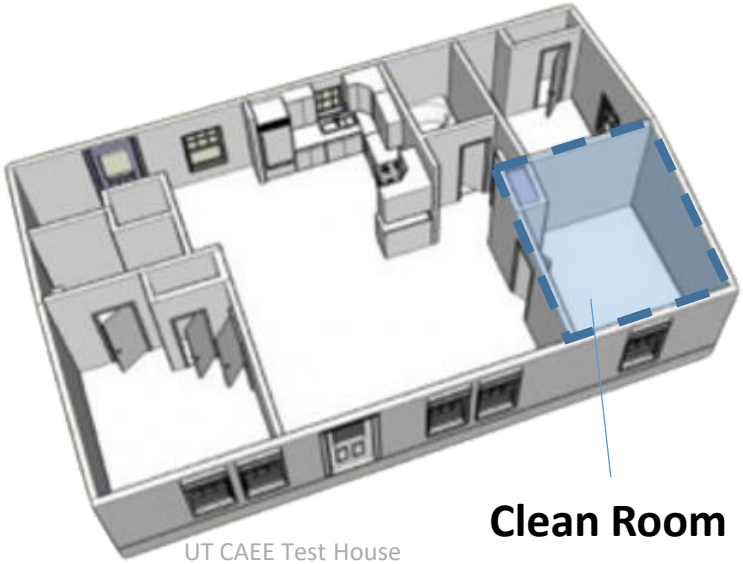
Create a Clean Room to Protect Indoor Air Quality During a Wildfire

American Lung Association.

EPA United States Environmental Protection Agency

https://www.epa.gov/indoor-air-quality-iaq/create-clean-room-protect-indoor-air-quality-during-wildfire

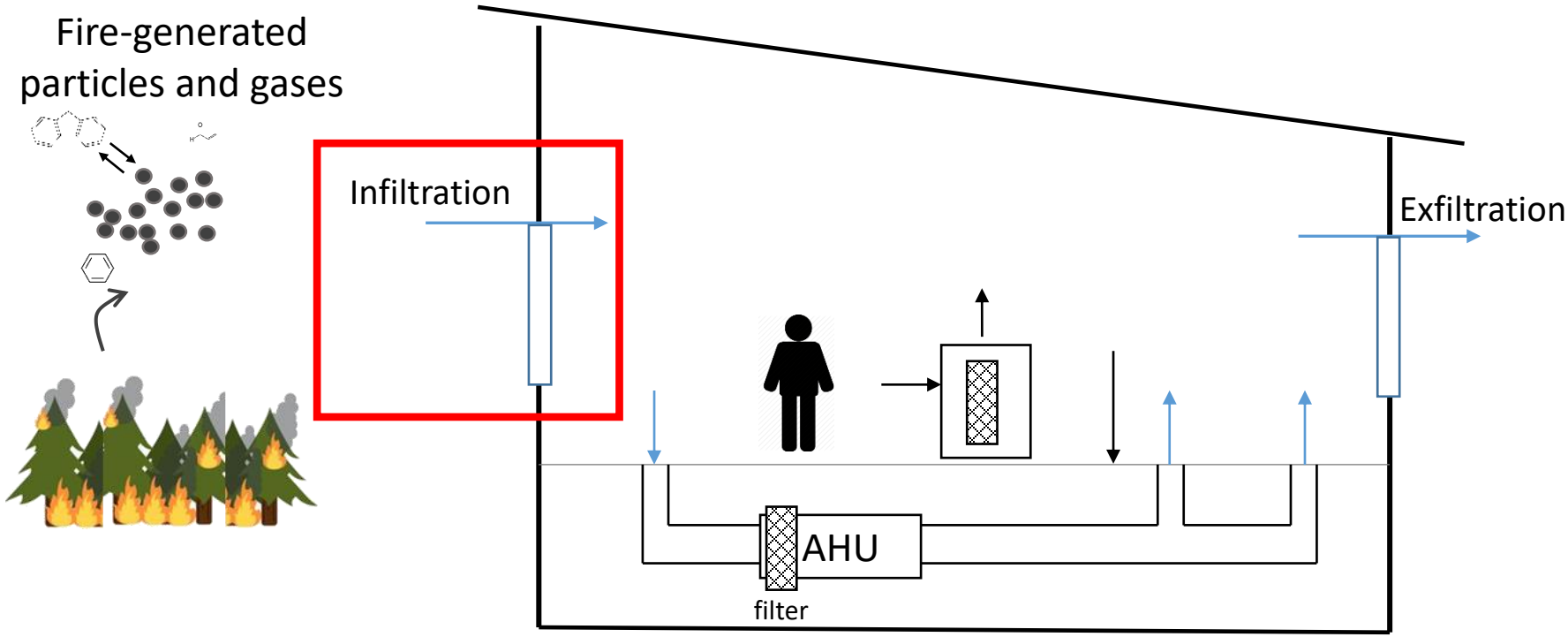
What is a Clean Room?
A room in your home set up to keep levels of woodsmoke particles as low as possible while managing indoor emissions



Healthy Buildings Research Lab

How does woodsmoke enter a home?

- Most residences are ventilated by:
  - Open windows and doors (closed these during a wildfire)
  - HVAC outdoor air intake (rarely, closed during a wildfire)
  - **Infiltration**: uncontrolled "leakage" of outdoor air indoors



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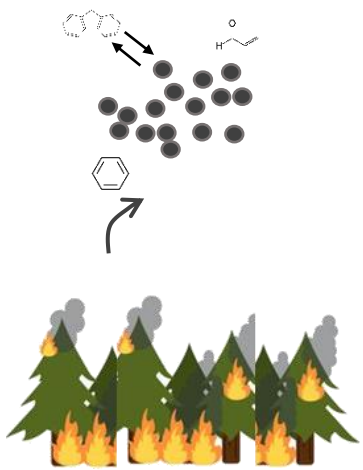
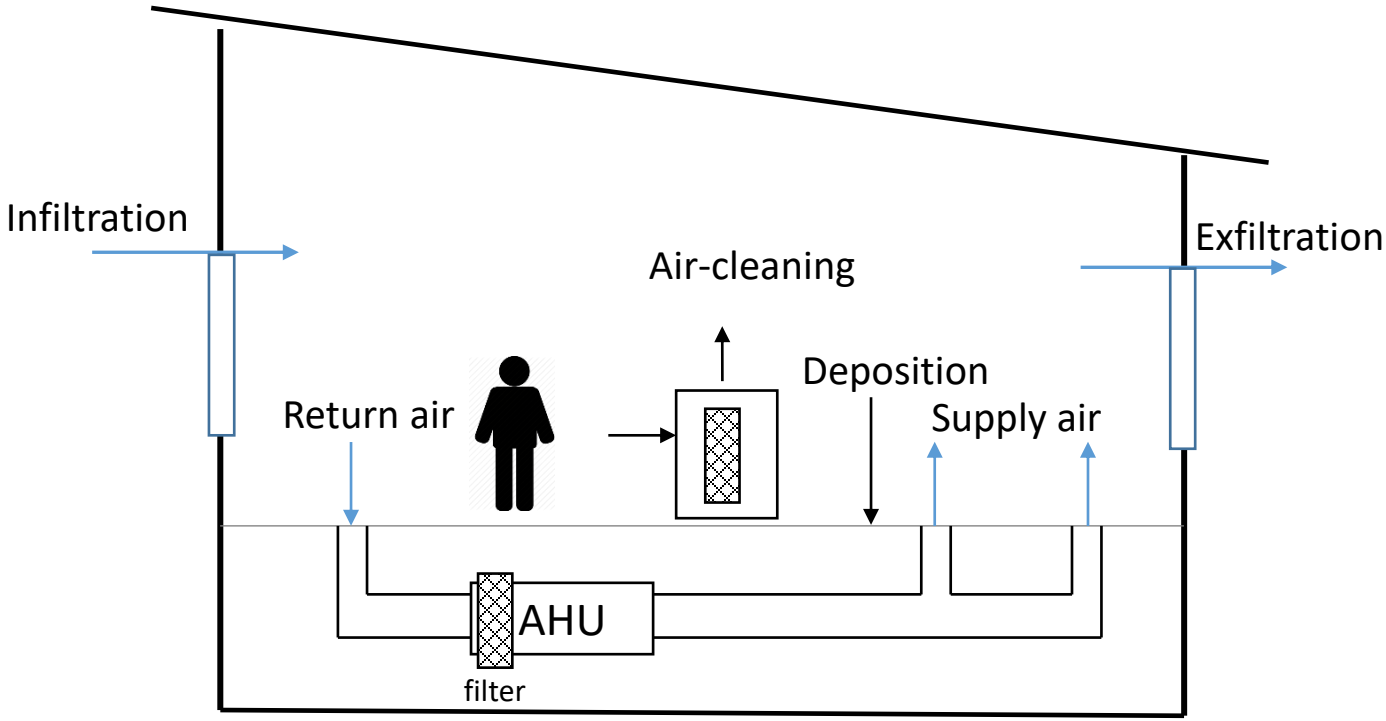
How can we reduce indoor woodsmoke?

1. Prevent it from entering by **reducing infiltration**
2. Remove it via **air cleaning**
   - Portable (stand-alone) air cleaning
   - Air cleaning in central HVAC system
3. Remove it via particle **deposition** (e.g., settling of particles to surfaces)

Air sealing and air cleaning are most effective interventions

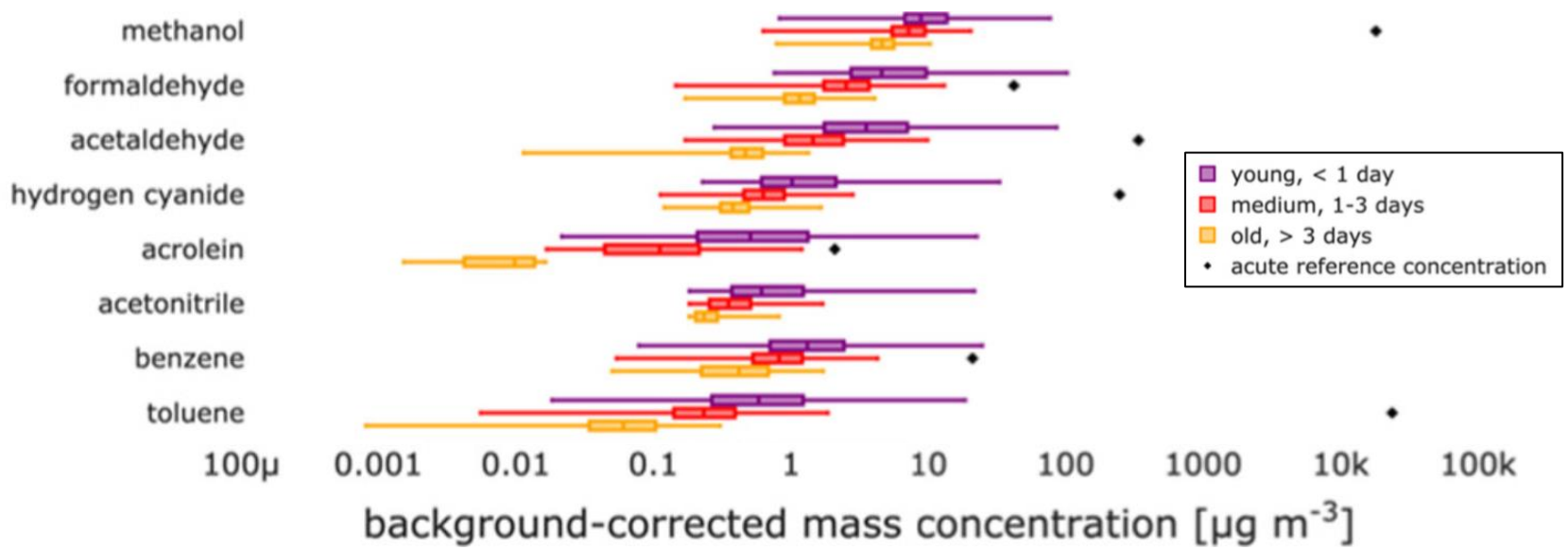
Fire-generated particles and gases





Gases elevated during a wildfires

Selected results from a 2018 study of aircraft measurements of wildfire smoke plumes[1]



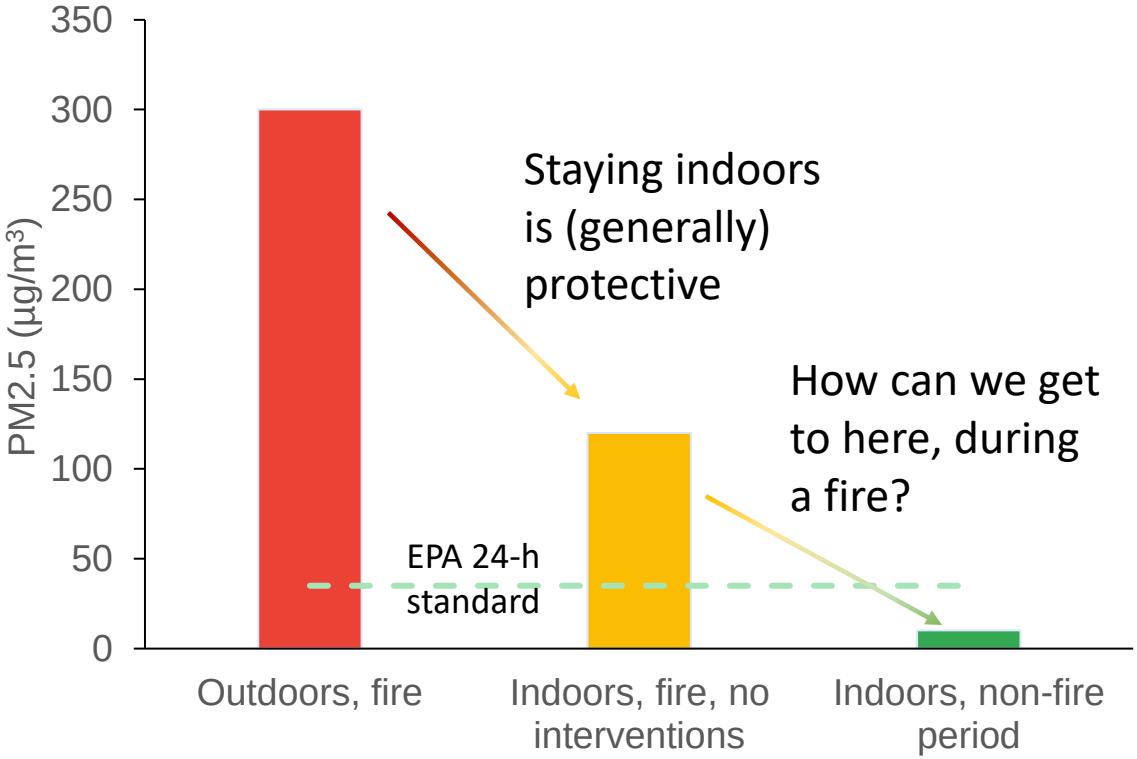
Adapted from O'Dell et al. 2020[1]

- Organic **gases** are elevated by as much as 10× than typical
- May reach levels of acute health concern

[1]O'Dell et al. 2020, *ES&T* 54(19): 11838-11847

The challenge

- **Challenge**: outdoor particles ~50× greater than normal
- **Goal**: reduce indoor particulate matter concentrations to as close to "normal" levels as possible



Intervention effectiveness

$$\epsilon = 1 - \frac{PM_{2.5,intervention}}{PM_{2.5,no\ intervention}}$$

$$\epsilon = 1 - \frac{12\ \frac{\mu g}{m^3}}{120\ \frac{\mu g}{m^3}} = 0.90$$

Our interventions should aim for > 90% effectiveness

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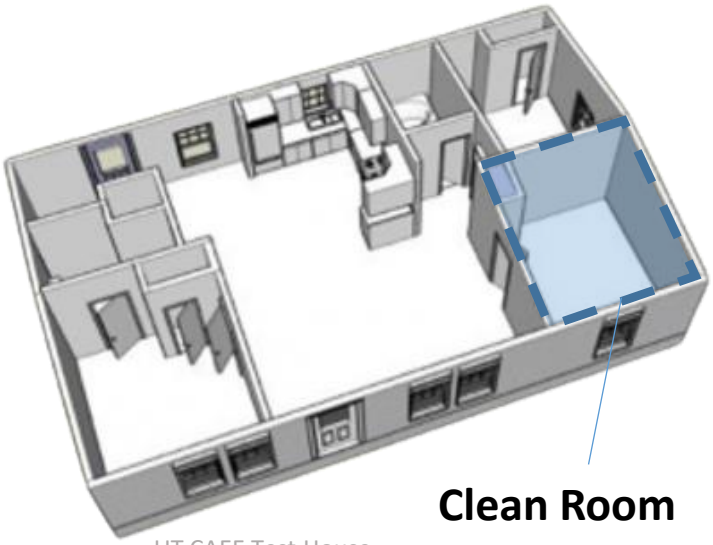
Step 1. Identify a small area room



UT CAEE Test House

Focus efforts on a small room

- Bedroom is good candidate
- 100-200 ft^2 floor area
- Fewer exterior windows
- With a door to interior space

Why?

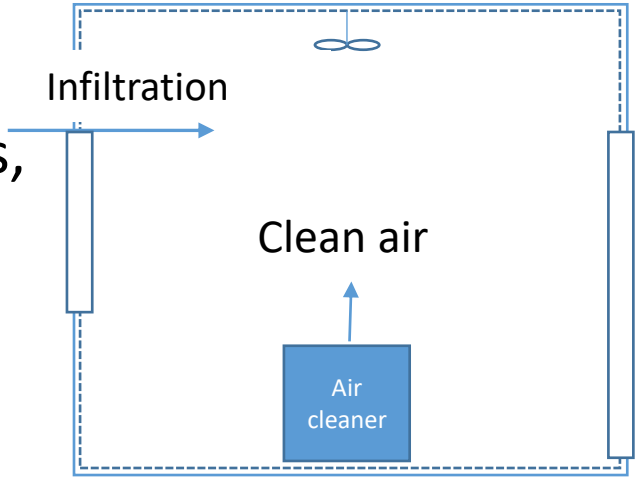
- Larger volume requires larger air cleaner
- All these equal, smaller volume means more effective air cleaning
- Fewer windows means less infiltration
- Interior door allows some interzonal mixing

For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238

Step 2. Select an air cleaner

Size an air cleaner

- Use mechanical filters (HEPA, high MERV)
- Avoid "additive" air cleaners, e.g., ionizers, radical or ozone generators, etc.
- Look for **clean air delivery rate (CADR)**



This is an example of a label from a portable air cleaner. Used with permission from the Association of Homes Appliance Manufacturers (AHAM).

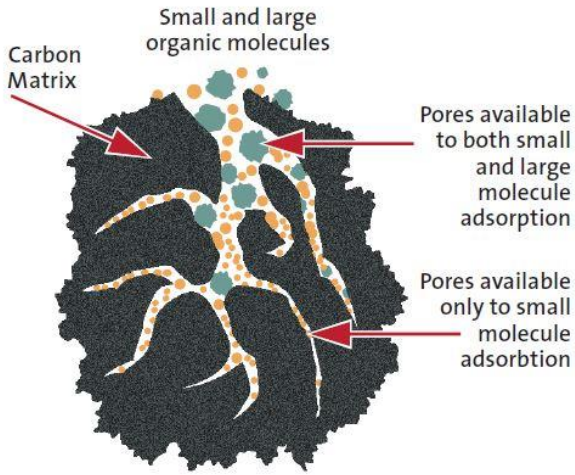
- CADR is the volume flow rate of air free of **particles** of the indicated type
- A useful rule of thumb for sizing

$$CADR\ (cfm) > \frac{2}{3} \times Area\ (ft^2)$$

Example: a 150 ft^2 bedroom would require a 100 cfm CADR for **smoke**

For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238

Optional: gas-phase air cleaning



A large mass of sorbent is needed for effective gas-phase air cleaning

- ***Rule of thumb:***
  4.5 lb of sorbent/1000 ft^3 volume, every year
- For 150 ft^2 room with 8 ft ceilings

$$Sorbent = \frac{4.5\ lb}{1000\ ft^3} \times 150\ ft^2 \times 8\ ft$$
$$= \mathbf{5.4\ lb\ sorbent\ (replace\ yearly)}$$

Air cleaners with this mass of carbon exist, usually costing ~$400 with ~$200 filter cost.

- **5-year material cost: $1200**
  First year filter included in air cleaner cost, price includes particle filters (usually)

More research is needed re: control strategies for gases during wildfires.

DIY Air Cleaner

Household MERV13 filter is ~$20/filter

https://www.texairfilters.com/how-to-improve-the-efficiency-of-the-box-fan-and-merv-13-filter-air-cleaner/

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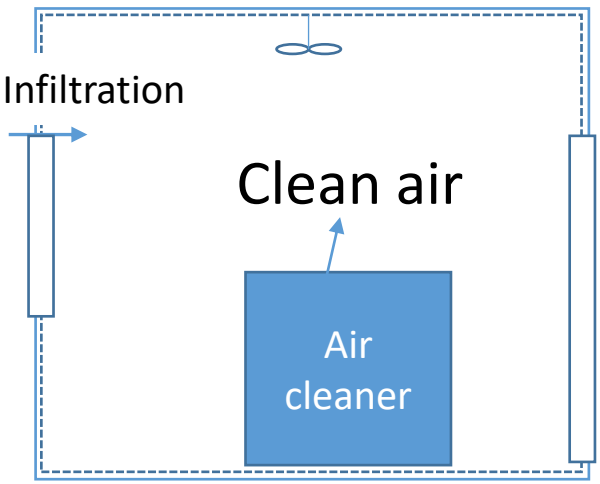
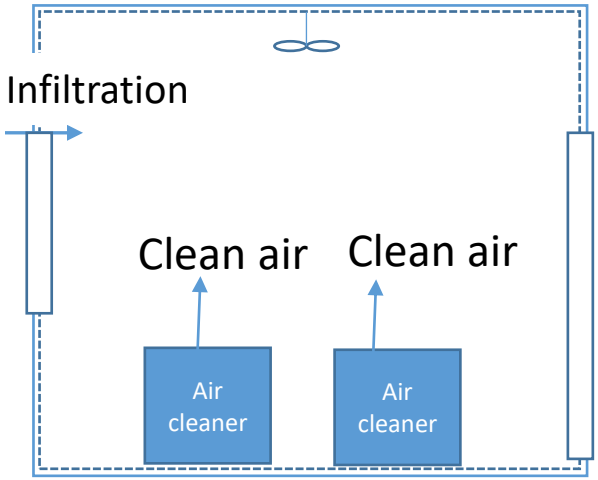
Options for increasing effectiveness

Option 1:
Larger air cleaner



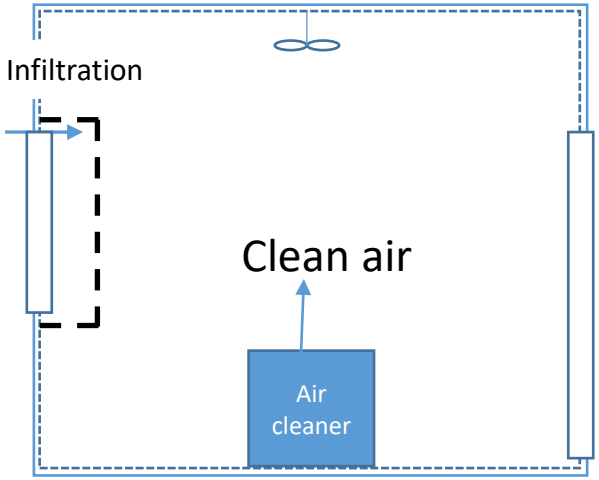
Pro: Lower indoor PM
Cons: cost (units + filters), noisier

Option 2:
More air cleaners



Pro: Lower indoor PM, little noise increase
Cons: cost (units + filters)

Option 3:
Temporary air sealing



Pro: Lower indoor PM, Inexpensive, no noise increase
Cons: increase exposure to *metabolic bioeffluents* (CO_2 and other organic compounds)

For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238

Step 3. Temporary air sealing

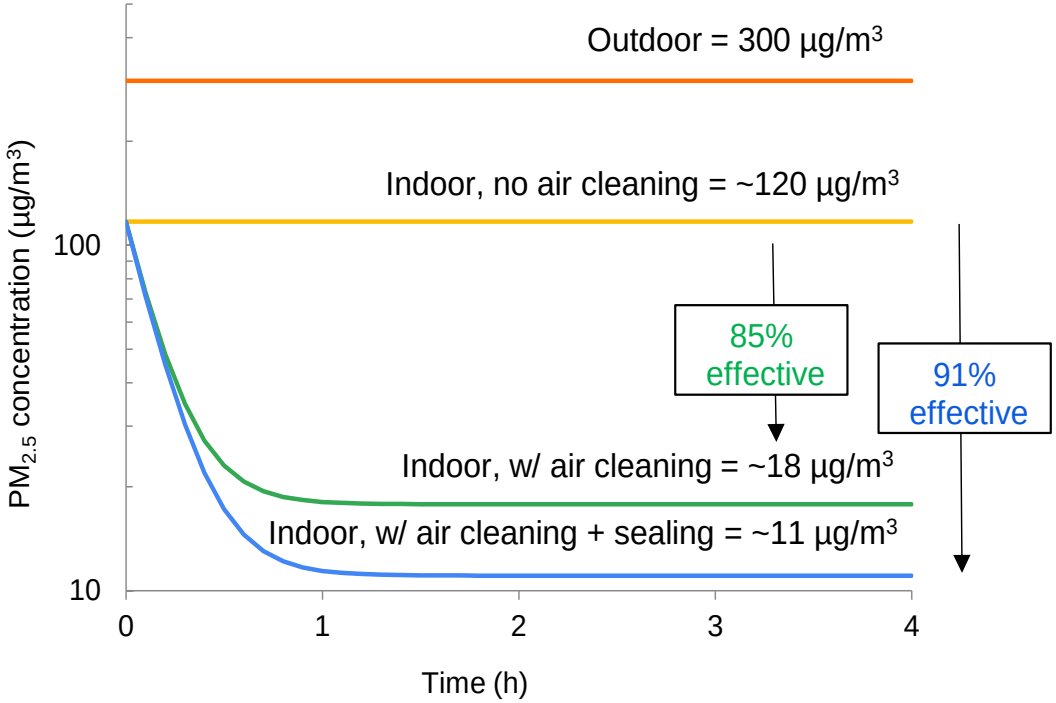
https://www.energystar.gov

Temporary air sealing reduces outdoor air infiltration

- Increases air cleaner effectiveness
  - "Competing" against a smaller woodsmoke source
  - Weatherization kits for windows to exterior
- Consider disconnecting room from HVAC supply + return
  - But not a simple/single answer in this case

In our example 150 ft² clean room:

- Intervention effectiveness >90%
- Air sealing is equivalent to adding another air cleaner
  - (+70 cfm CADR)
- No noise
- Low cost ($1-3 dollars/window)
- Take down after fire ends



For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238

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Step 4. Address indoor air pollution

- Limit activities that generate air pollution
  - Cooking, cleaning, product use (e.g., candles, freshener)
- Some sources cannot be "turned off"

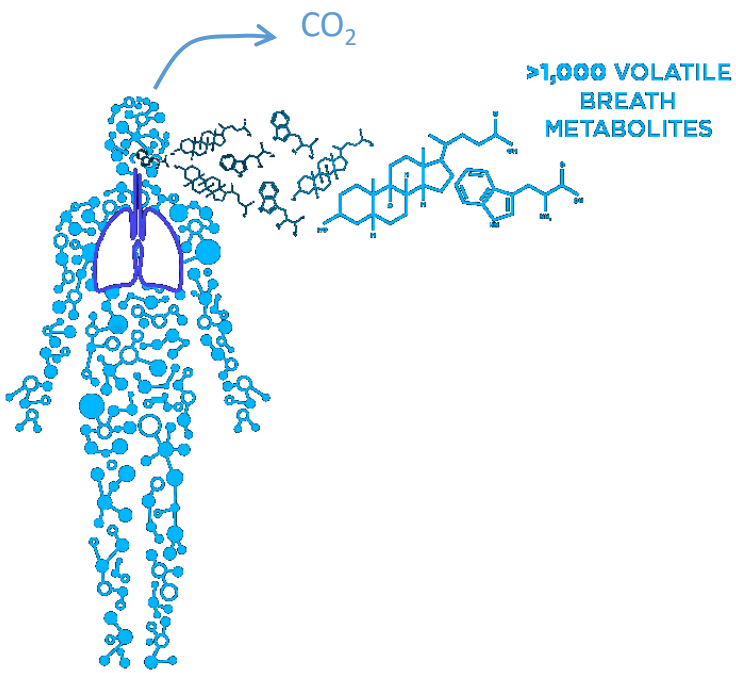


Image adapted from owlstonemedical.com

- Humans continuously emit carbon dioxide and organic compounds, called **metabolic bioeffluents**
  - Degrade indoor air perceptions[1]
  - May degrade cognition[2]
  - May cause respiratory impacts[3]
- CO_2 is a proxy for all human emissions

How can we manage our exposures to metabolic bioeffluents in our clean room?

[1]Persily, Proceedings of AIVC 2015, Paper 810-819; [2]Zhang et al. 2017, Indoor Air 27(1): 47-64; [3]Mishra et al., Indoor Air, https://doi.org/10.1111/ina.12823.

Healthy Buildings Research Lab

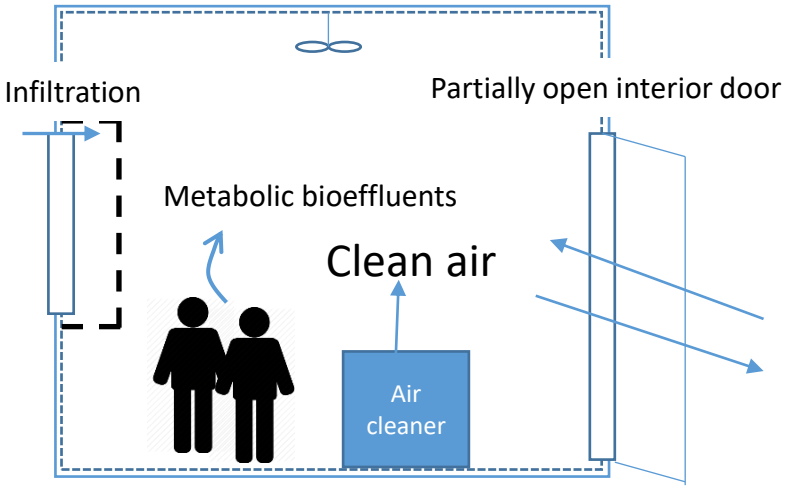
But… are mech systems reliable?

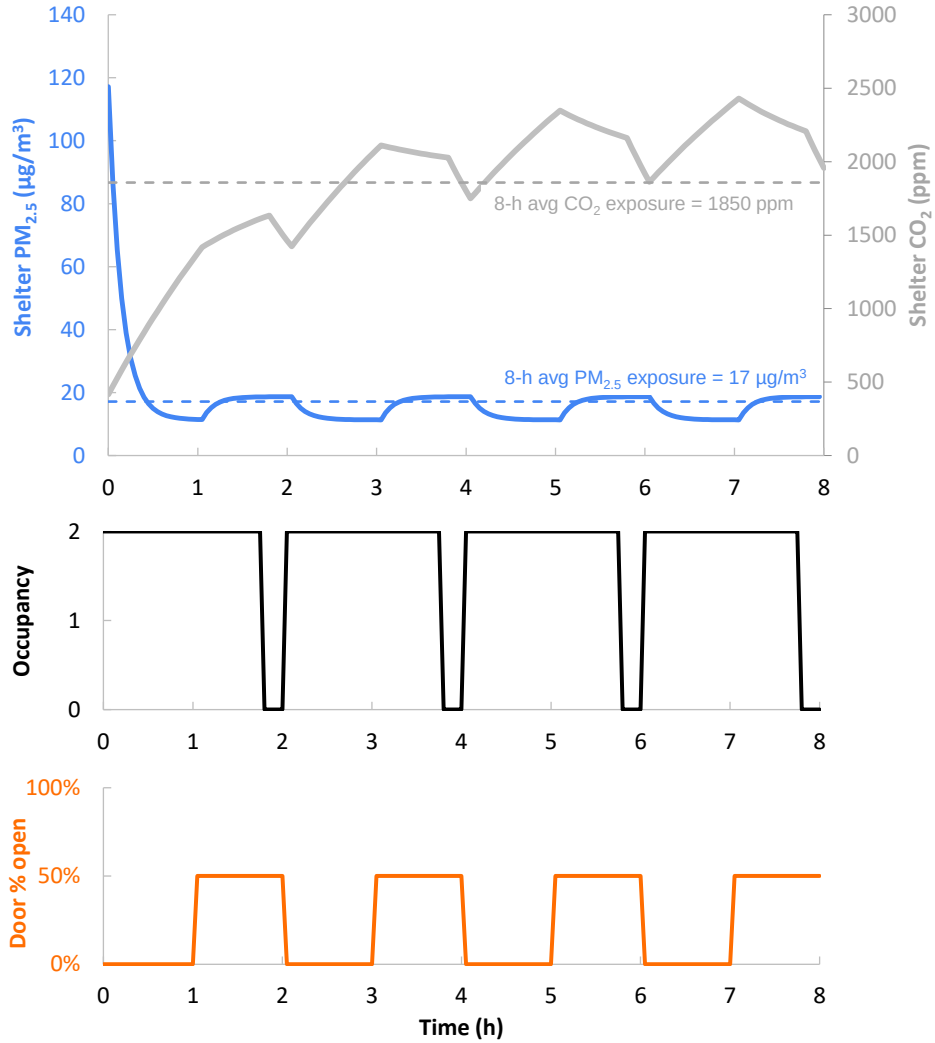
Offermann (2010) simultaneously measured indoor and outdoor VOCs, aldehyde, CO2, and PM2.5 levels, and air-exchange rates in 108 newly constructed homes in California. Of the 108 homes, 26 had intermittently operating outside makeup-air systems6 or continuously operating air-to-air heat exchangers.7 Some 57% of the homes had 24-h air-exchange rates below the 0.3 ACH recommended in ASHRAE Standard 62.28 for residential buildings, and 25% had below 0.18 ACH (Offermann, 2010). The California Office of Environmental Health Hazard Assessment (COEHHA) chronic 8-h reference exposure level (REL) for formaldehyde of 9 μg/m3 was exceeded in 98% of the homes (Offermann, 2009). COEHHA's acute-irritation REL of 55 μg/m3 was exceeded in 28% of the homes (Wolkoff and Nielson, 2010). Of homes with less than 0.3 ACH, 37% exceeded the 55 μg/m3 acute-irritation REL for formaldehyde, and 14% of homes with more than 0.3 ACH exceeded that acute-irritation REL (Offermann, 2010)

https://nap.nationalacademies.org/cart/download.cgi?record_id=13115

Healthy Buildings Research Lab

Managing indoor and outdoor sources





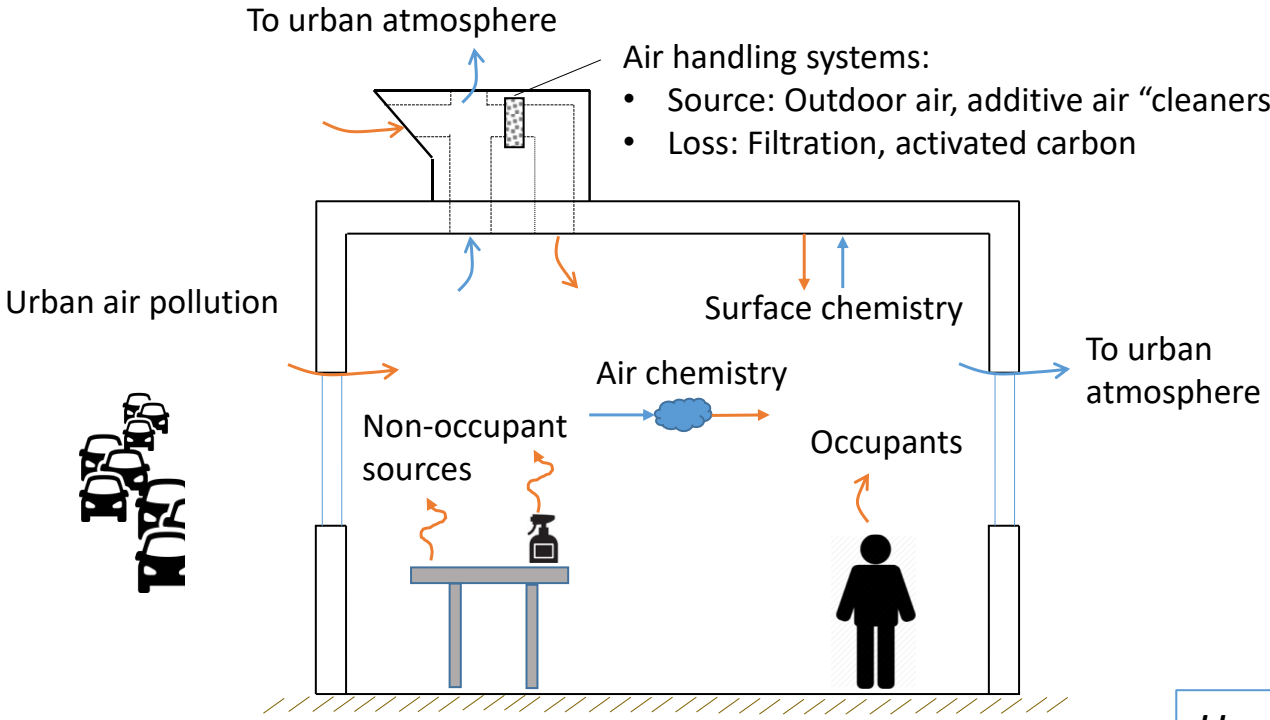
1. Wear a respirator and take breaks from the space

2. Use door as "damper" to create modest interzonal airflow between clean room and home

- Allows a trade-off:
- Home air: lower CO_2, higher $PM_{2.5}$
- Clean room: higher CO_2, lower $PM_{2.5}$

For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238

Models of heat + air pollution



Accumulation = Sources - Losses

Heat and mass conservation

Important sources:

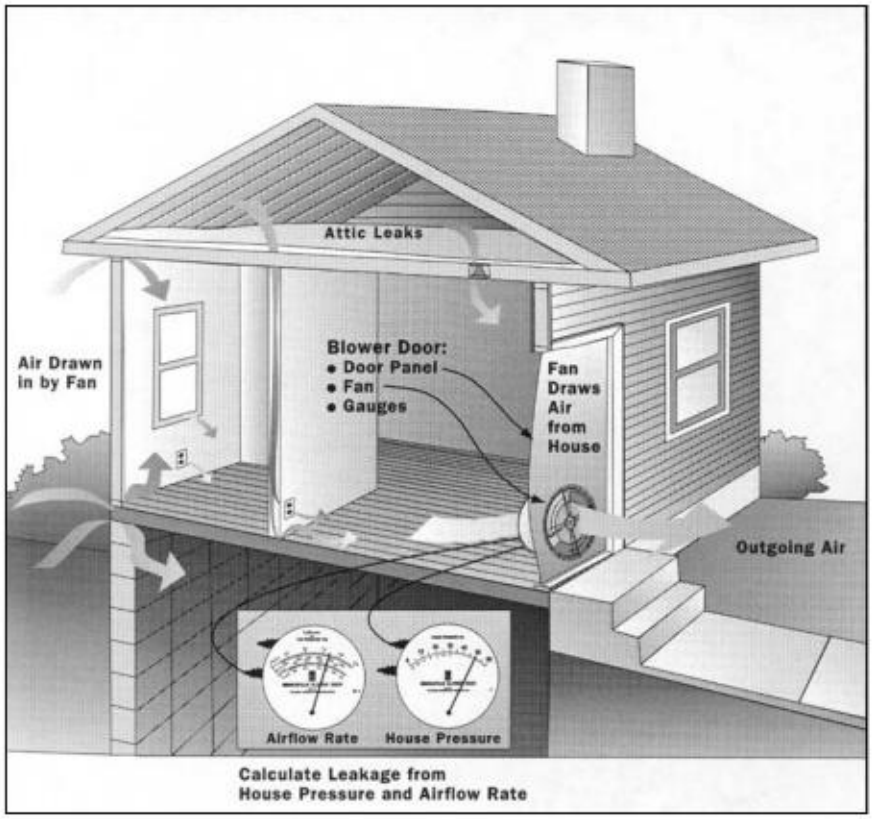
- Supply of outdoor air (ventilation)
- Occupants
- Activities (e.g. cooking)

Important losses:

- Exhaust of indoor air (ventilation)
- Air cleaning
- Deposition

Airtightness

Figure 1: Blower Door Depressurization Test



Airtightness is an important part of a modern building:

- **Can increase energy efficiency**
- Improve durability
- **Allow control over IAQ**

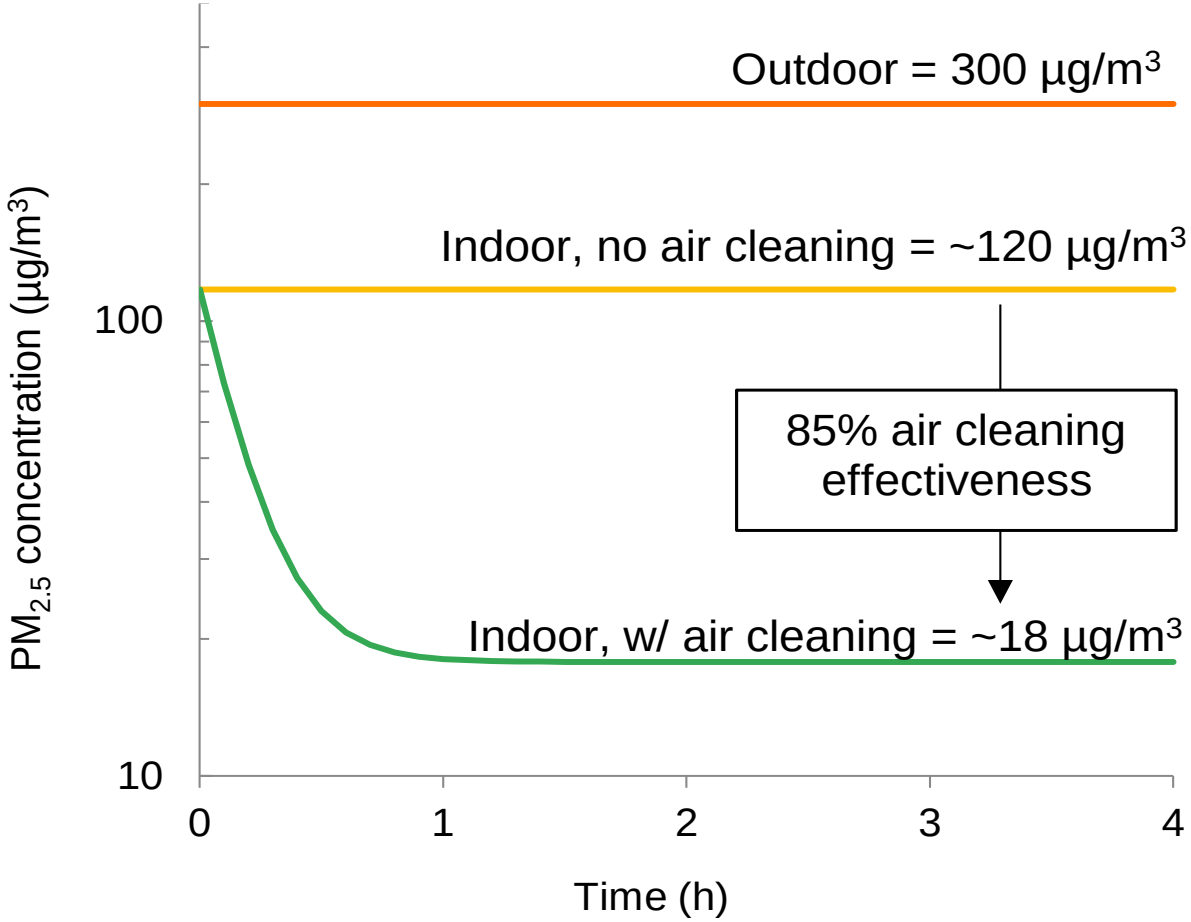
However, an airtight shell removes a "baseline" of outdoor air that ensures some amount of ventilation.

Airtight shells must adhere to best practices in construction, operation, and occupant education or these strategies may degrade IAQ[1]

Impact of air-cleaning in a small room

Mass-balance models enable us to predict the impact of interventions

- Returning to our wildfire scenario for $PM_{2.5}$ in a **150 ft² bedroom:**



Appropriately sized air cleaner for 150 ft² can **dramatically reduce $PM_{2.5}$ concentrations** in the clean room

For more information: https://elliott-gall.medium.com/wildfires-and-the-air-quality-inside-your-home-54961e374238