# Healthy Efficient Homes: Research Findings

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  - California Air Resources Board Research Division

- Berkeley Lab Collaborators
  - Woody Delp, Rengie Chan, Iain Walker, Jennifer Logue, Erin Hult, Doug Black, Bill Fisk, Mike Apte, Brennan Less

# Buildings Impact Health, Wellness and Productivity

Air Quality

Aesthetics **Microbiome**

Sound **Architecture** Lighting

**Thermal health & comfort** Views

Access to activities



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# Themes

- Quantities matter
- We can reduce exposures; we can’t guarantee health improvements
- There are engineering controls with proven effectiveness
- Occupant activities have a big impact
- Environmental health hazards come from inside and outside



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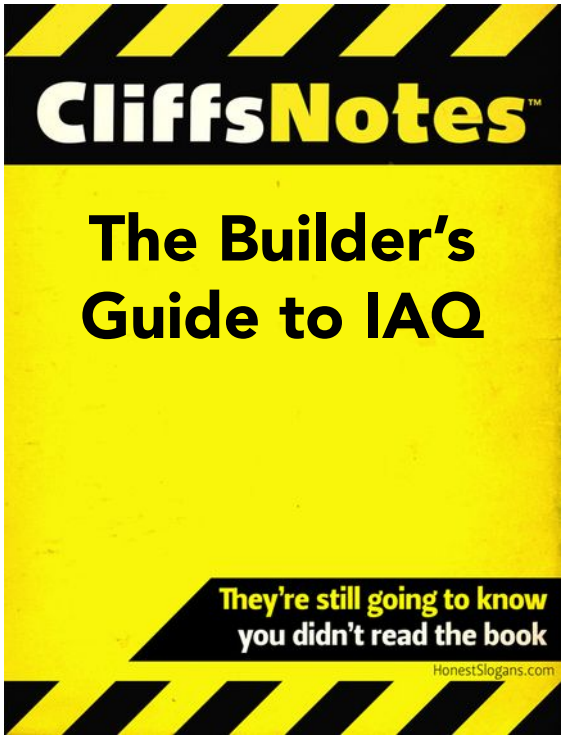
# The risks of air pollution are not evenly distributed

Concentrations and exposures vary

Susceptibility varies

# How to Reduce Risk in Homes

- **Reduce hazard entry**
  - **Airtight envelope and ducts**
  - **Radon-resistant construction**
  - Low-emitting materials
  - **Vent combustion & cooking**
  - Vent kitchen, bath, laundry
  - Filter supply air
  - **Keep it dry**
- **Increase hazard removal rate**
  - **General ventilation**
  - **Filtration**



# Indoor airPLUS Areas of Focus

EPA United States Environmental Protection Agency

look for EPA Indoor airPLUS QUALIFIED HOMES







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# The Dose Makes the Poison

*"Alle Ding sind Gift und nichts ohn Gift; alein die Dosis macht das ein Ding kein Gift ist"*

All things are poison and not without poison; only the dose makes a thing not a poison.

- Paracelsus, 1493-1541

# Which indoor air pollutants most impact health?

Prioritize based on harm to population

Disability Adjusted Life Years (DALYs)

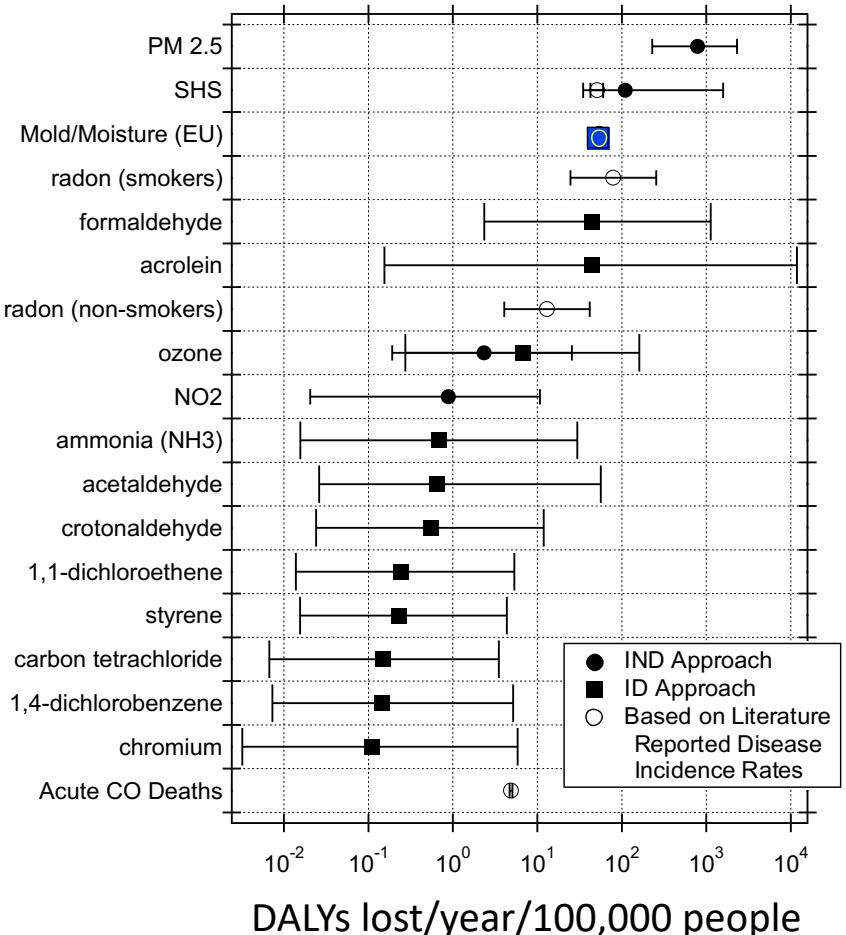
**DALY = YLL + YLD**

YLL = Years lost to premature death

YLD = Equivalent years lost to disability

DALY valued at $50,000 - $160,000

$$Intake \times \frac{\Delta\ Disease}{\Delta\ Intake} \times \frac{\Delta\ DALYs}{\Delta\ Disease} \rightarrow DALYs\ per\ pollutant$$




Logue et al., Environmental Health Perspectives, 2012

# Which indoor air pollutants most impact health?

## Disability Adjusted Life Years

4-11 DALYs per 1000 people per year

**$PM_{2.5}$**

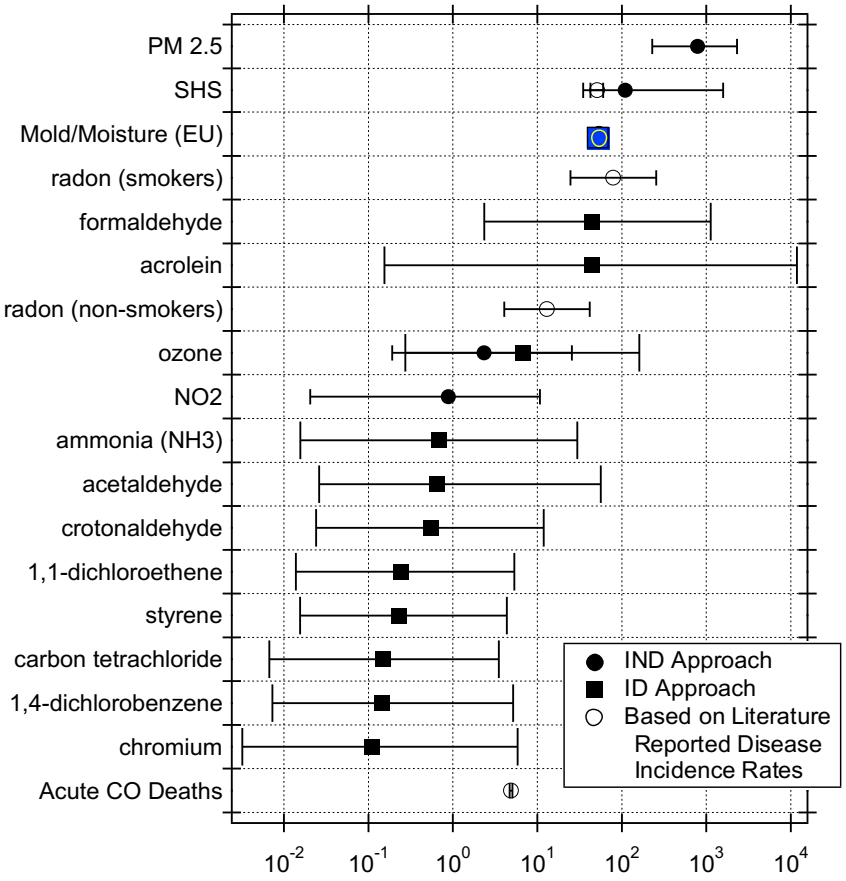
Secondhand smoke

Mold / moisture

Radon

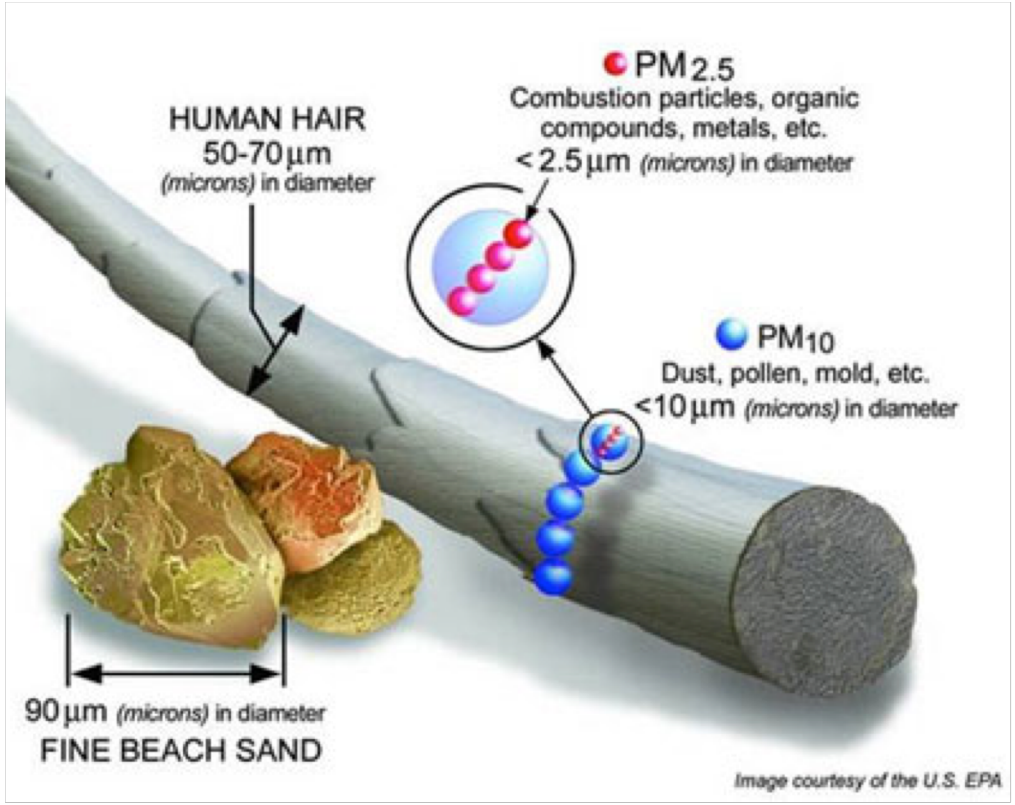
Formaldehyde

Acrolein, Ozone, $NO_2$




Logue et al., Environmental Health Perspectives, 2012

# Fine particulate matter ($PM_{2.5}$)




- **$PM_{2.5}$ effects**
  - Death, strokes, and other cardiovascular illness
  - Increased respiratory illness
  - Linked to many other outcomes

# Sources of $PM_{2.5}$ in homes

Outdoor air pollution is largest source overall


Indoor sources more important if used often in your home



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# PM inside determined by complex dynamics

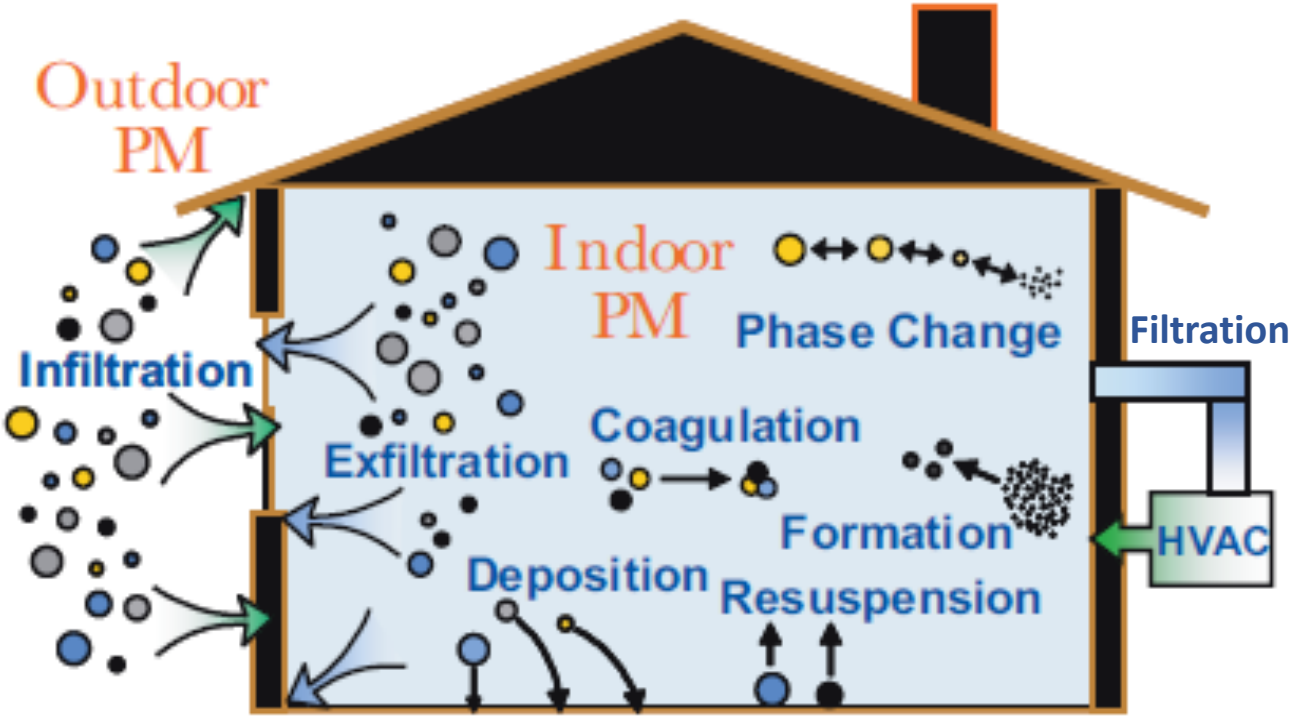


Image Ref*:* http://eetd.lbl.gov/newsletter/nl14/

# Formaldehyde


Urea-formaldehyde foam insulation
Used 1930-1970s
Banned in Canada 1980, in U.S. 1983

Used as binder in plywood, MDF, and particle board; in many finished products




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# Nitrogen dioxide

- Airway irritant
- Exacerbates asthma and other respiratory diseases
- May cause asthma and increase infections
- Asthmatics, elderly, young children most susceptible
- Chronic and acute hazard

* 98th percentile of daily 1h max, averaged over 3 years



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# Unvented combustion biggest threat for $NO_2$

Francisco et al., Indoor Air 2010

30 homes with unvented fireplaces

4 random days of monitoring

80% had $NO_2$ above 100 ppb for 1h



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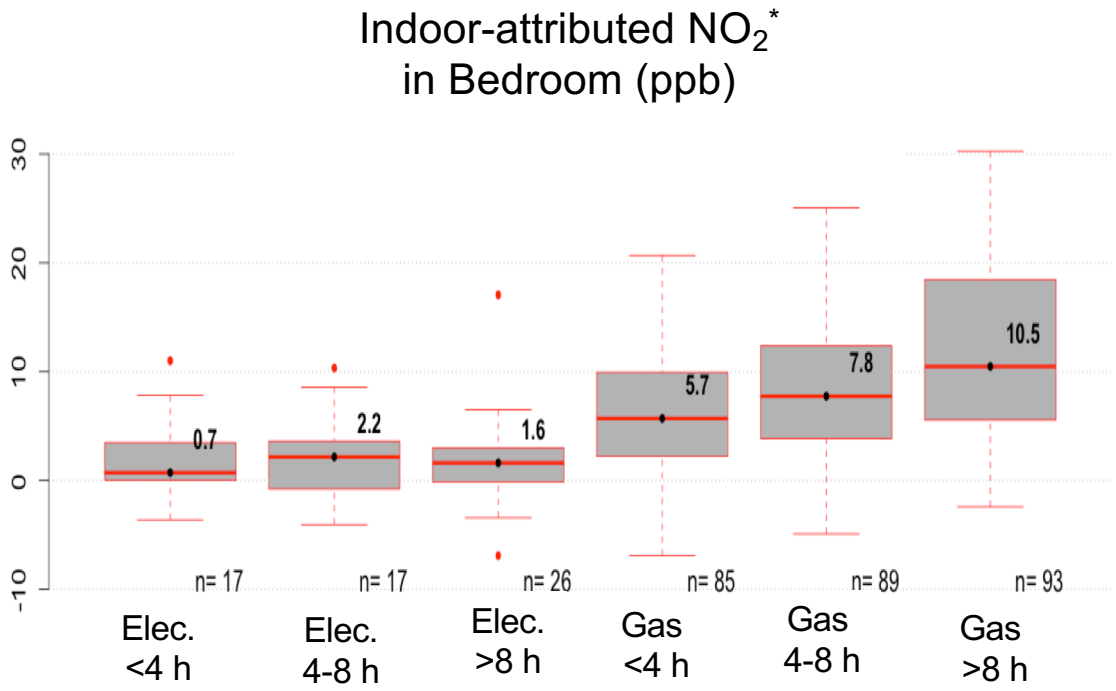
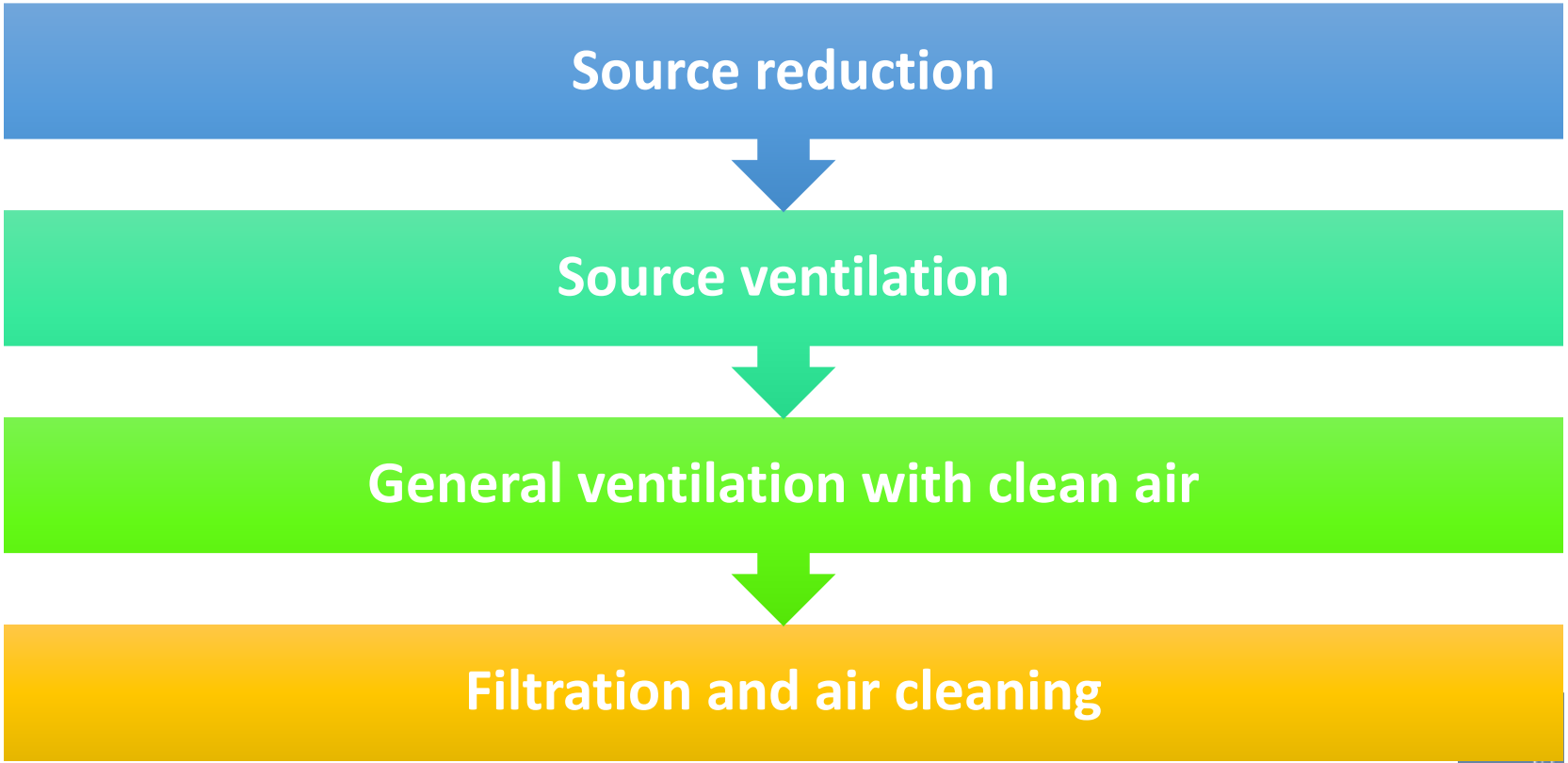
# Cooking burners major source of $NO_2$

- 1 week samples in 352 homes in California, 2011-2013
- **Oversampled homes with higher risk factors**
  - More cooking
  - Smaller volume
  - Wall and floor furnaces




Mullen et al. (2016)

# Reducing IAQ Risks



# Source Reduction

# Formaldehyde Emission Standards

California Environmental Protection Agency | AIR RESOURCES BOARD

**FREQUENTLY ASKED QUESTIONS FOR CONSUMERS**

REDUCING FORMALDEHYDE EMISSIONS FROM

**Composite Wood Products**

California rule effective January 1, 2009

US Formaldehyde Control Act in 2010

Products labeled starting June 1, 2018

https://www.arb.ca.gov/toxics/compwood/compwood.htm



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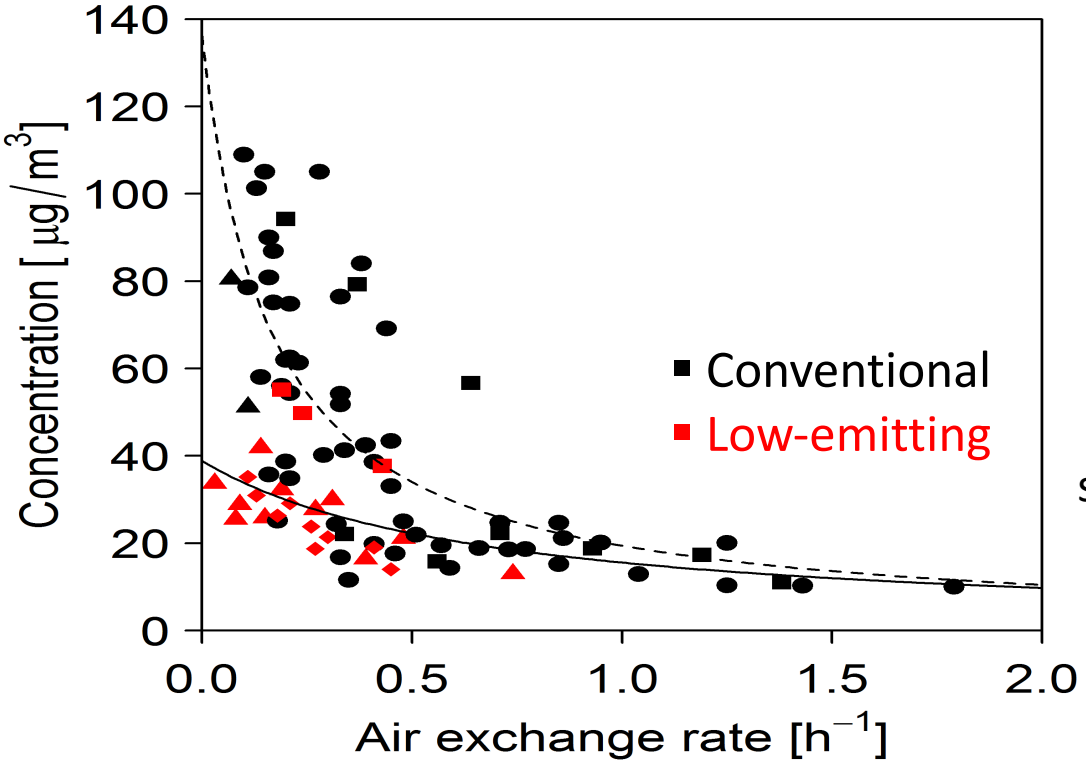
# Homes built with low-emitting materials have lower formaldehyde concentrations



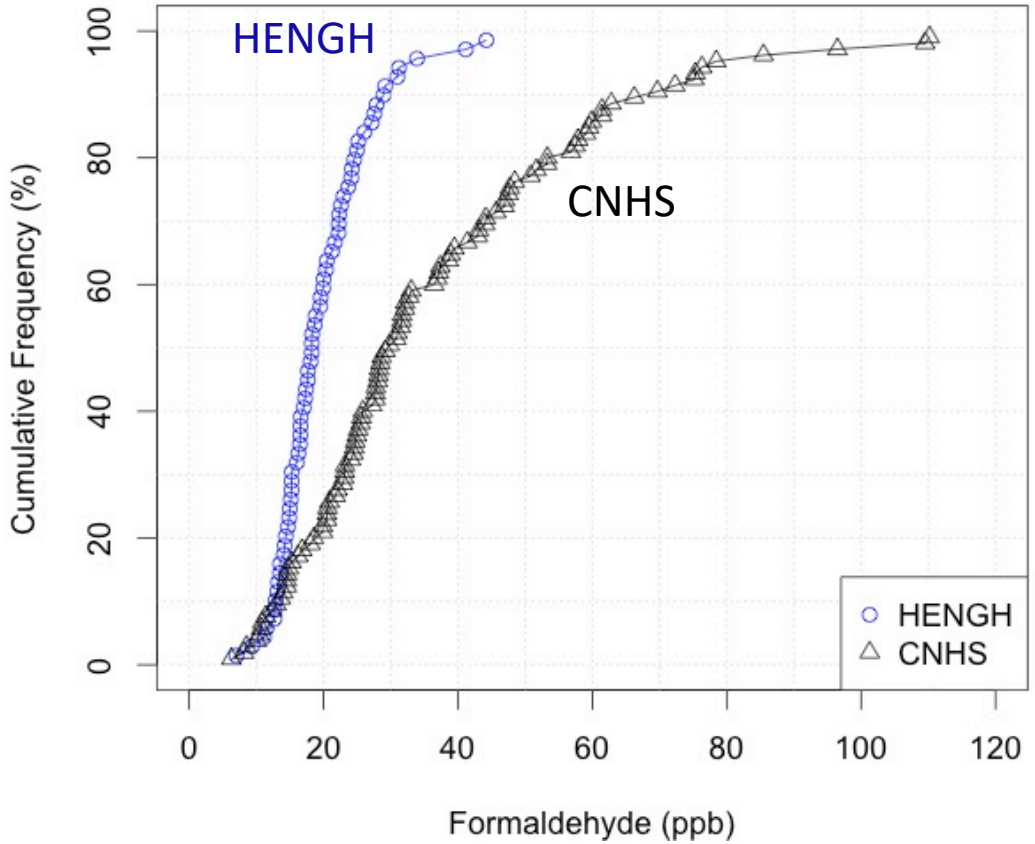

**42% lower at 0.3 ach**

All data from summer; adjusted for temperature, RH, & house age

Hult et al., Indoor Air, 2015 – Compares Indoor Air Plus to Conventional New Homes in US

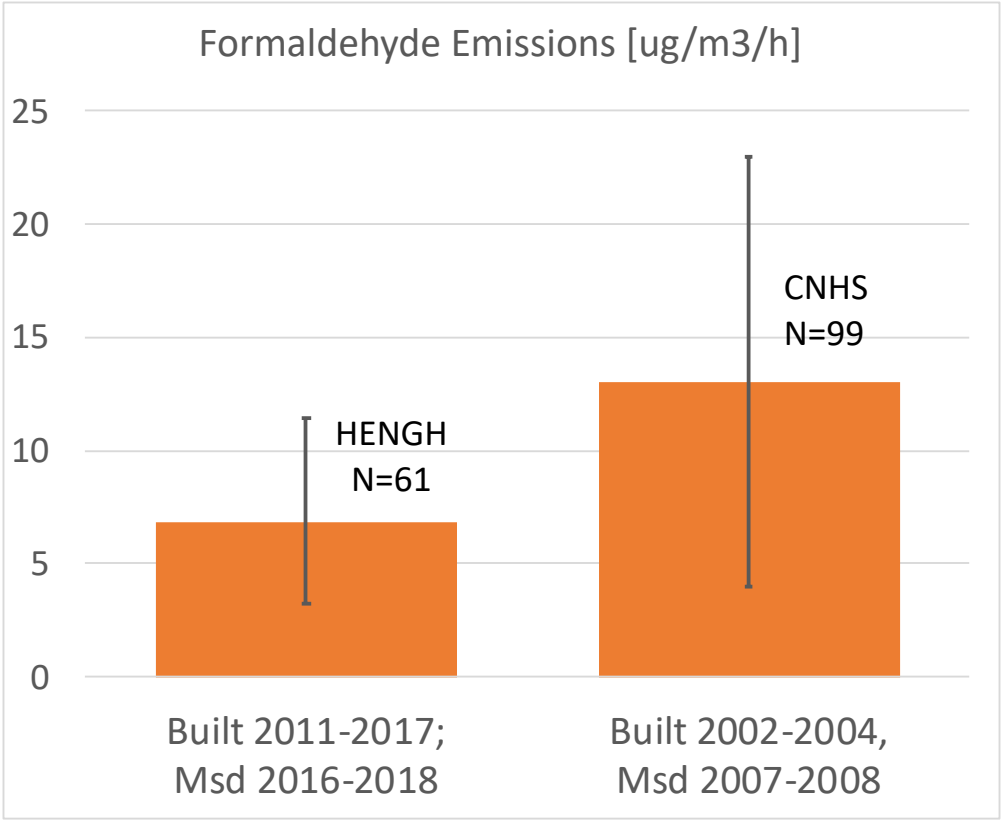
# Emission and ventilation standards reduced formaldehyde in new California homes

HENGH:
Built 2011-2017
Msd 2016-2018



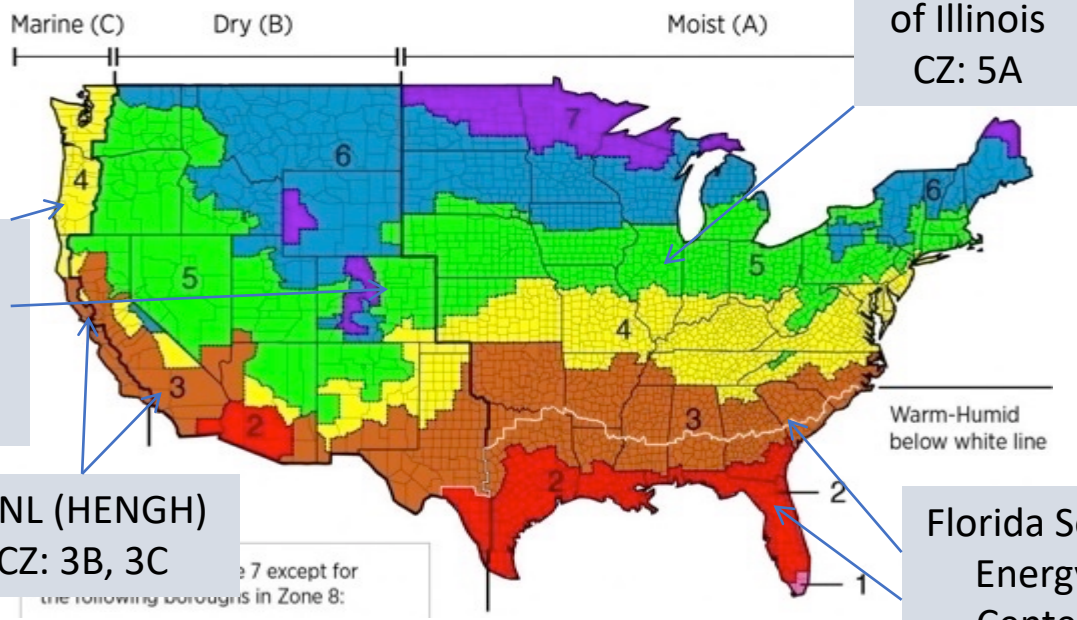

CNHS:
Built 2002-2004
Msd 2007-2008

# Formaldehyde emission and ventilation standards reduced exposures in new California homes



# Building America IAQ Study

- Target 32 homes per climate zone (CZ):
  ~50% with mechanical ventilation (MV)




University of Illinois
CZ: 5A

Pacific NW National Lab
CZ: 4C, 5B

LBNL (HENGH)
CZ: 3B, 3C

Florida Solar Energy Center
CZ: 2A, 3A

- Characterize home, mechanical equipment
- Monitor ventilation, IAQ, activities for 1 week
- Repeat in 8 homes per CZ with/out MV operating



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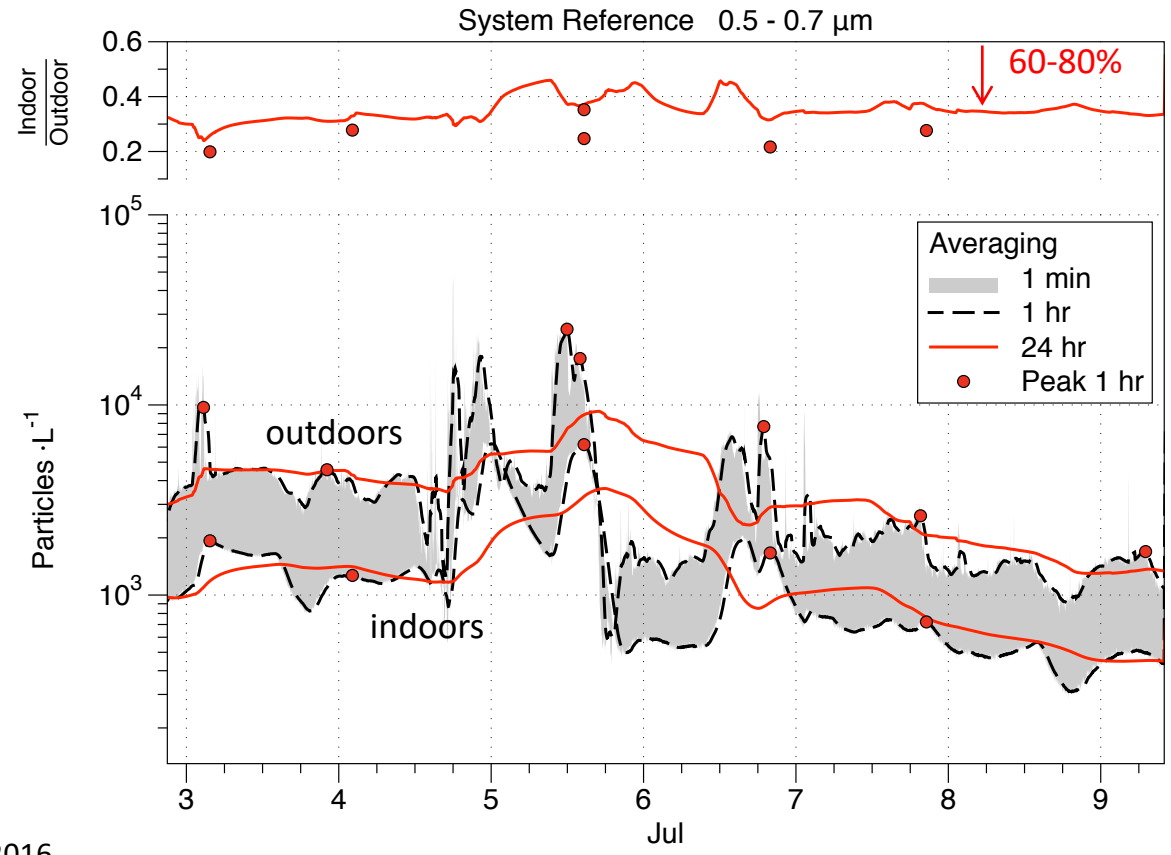
# Air tightness helps reduce outdoor particles

Built 2006, 1200 sf, 5 ach50
Sealed ducts, MERV4 filter
Continuous exhaust vent.

**$PM_{2.5}$ inside ~70% lower than outdoors**




Singer et al., Indoor Air, 2016

# Source (Kitchen) Ventilation

# Cooking & burners are important sources

$CO_2$ & $H_2O$

NO,$NO_2$, HONO, Formaldehyde

Ultrafine particles

Ultrafine particles, $PM_{2.5}$

Formaldehyde, Acetaldehyde

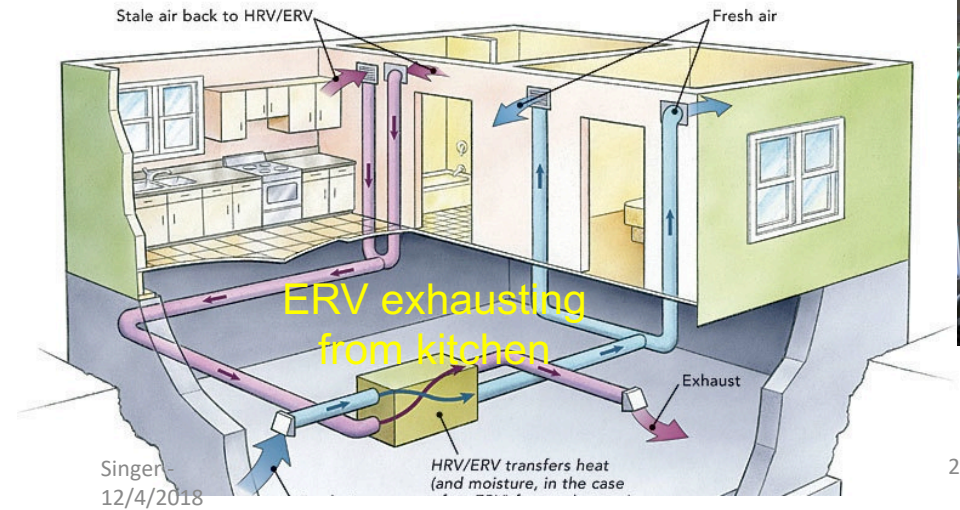
Acrolein, PAH

Ultrafine particles

# Kitchen ventilation options




Exhaust fan on wall





Ceiling exhaust fan

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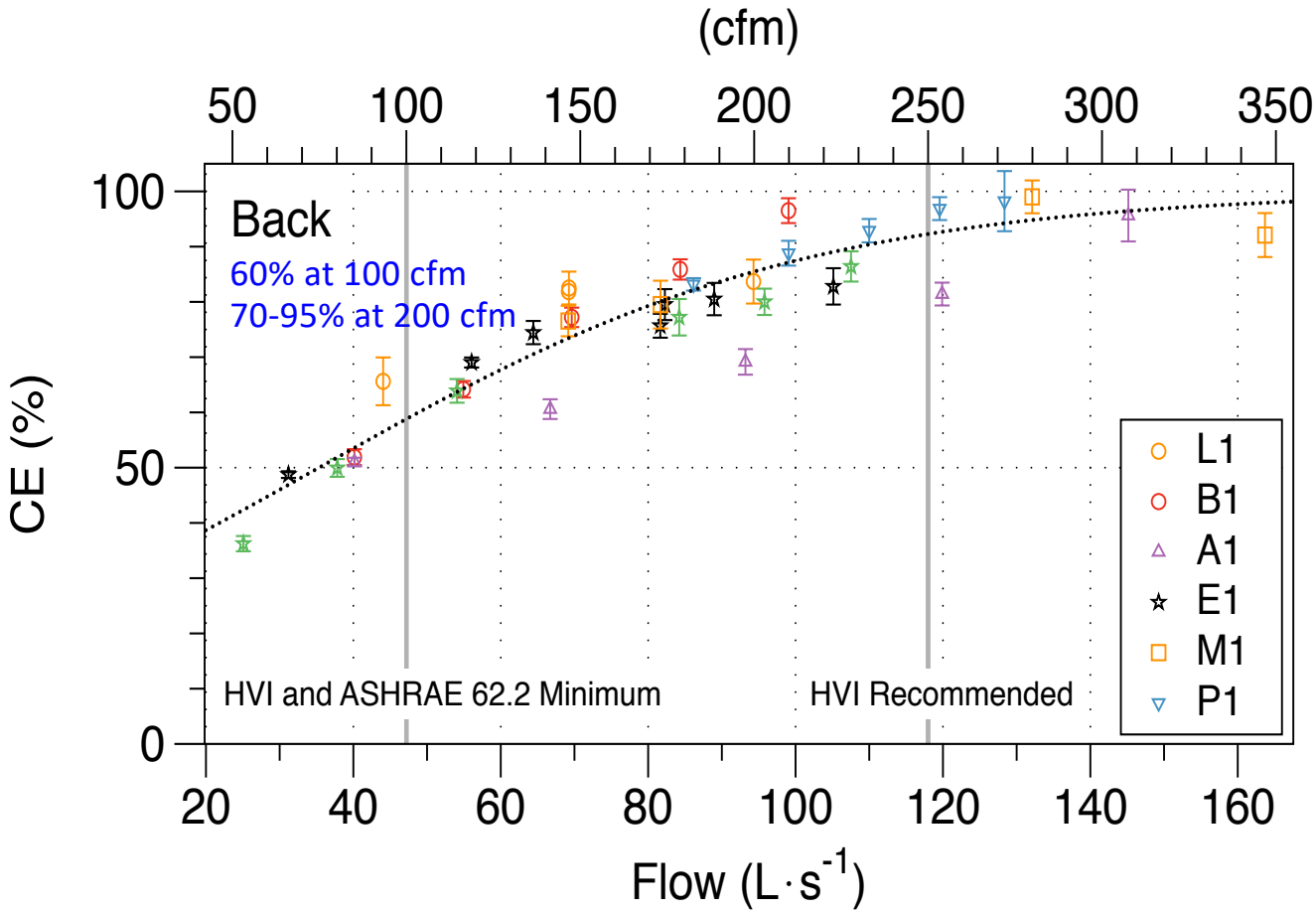
# Lab study of range hood performance


**Capture efficiency** is the fraction of emitted pollutants removed by the range hood.

7 devices
L1: Low-cost $40
B1: Basic, quiet $150
A1: 62.2-compliant, $250
E1: Energy Star, $300
E2: Energy Star, $350
M1: Microwave, $350
P1: Performance, $650

Lab performance: Delp and Singer, 2014

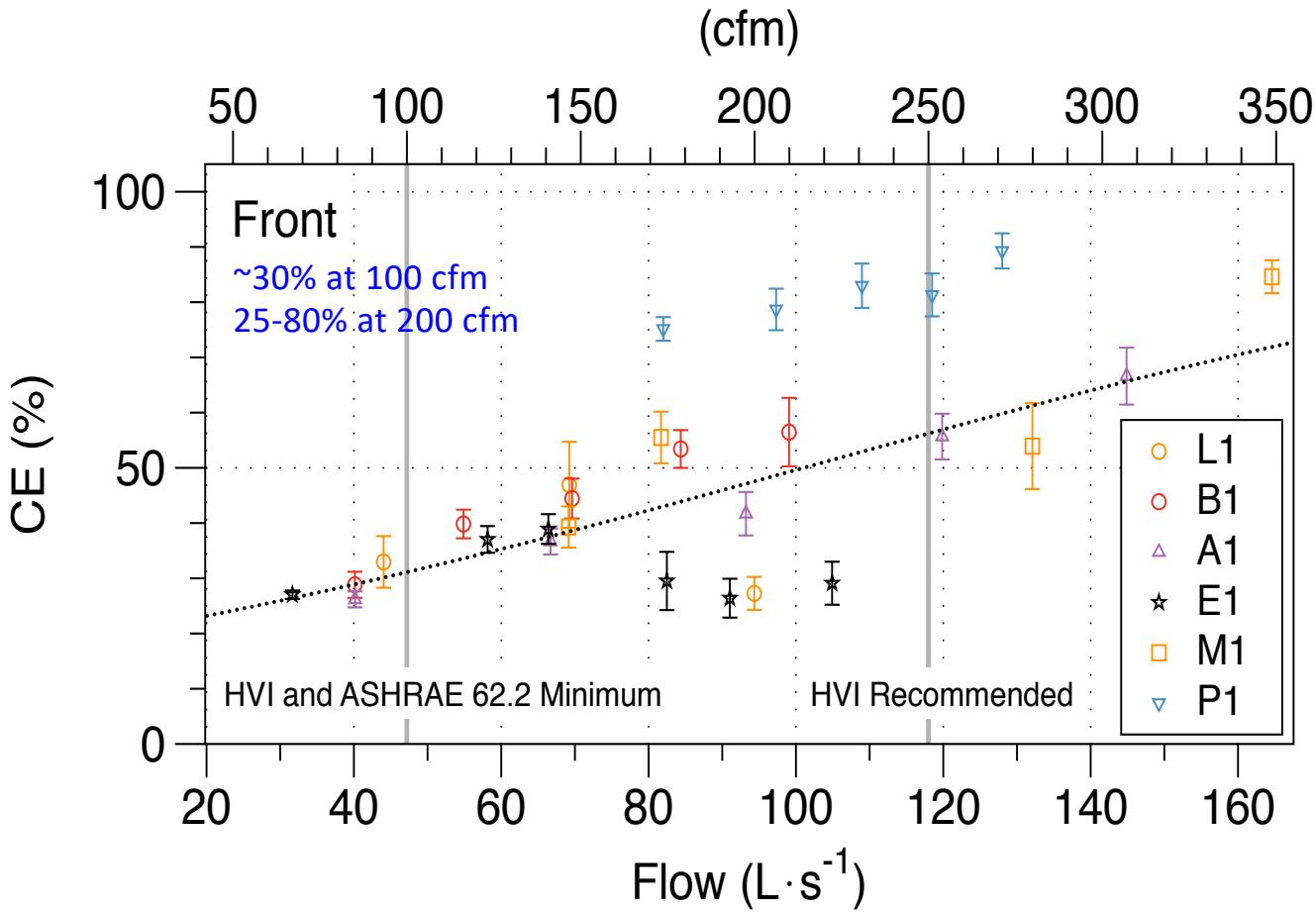
# Good capture for back burners at >200 cfm




Capture increases with airflow.

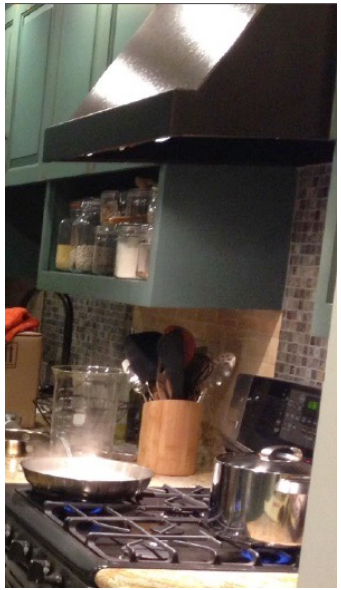
Much better for back burners!

# Performance varies widely for front burners



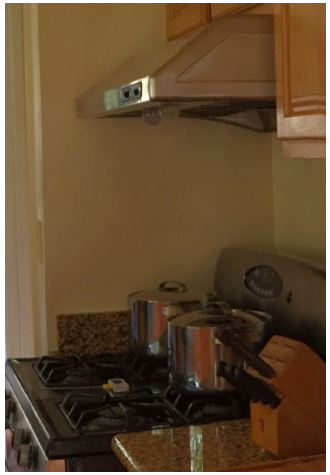

For front burners, typical range hood captures only about 30%

# Field study of range hood benefits



H1

H2



H5

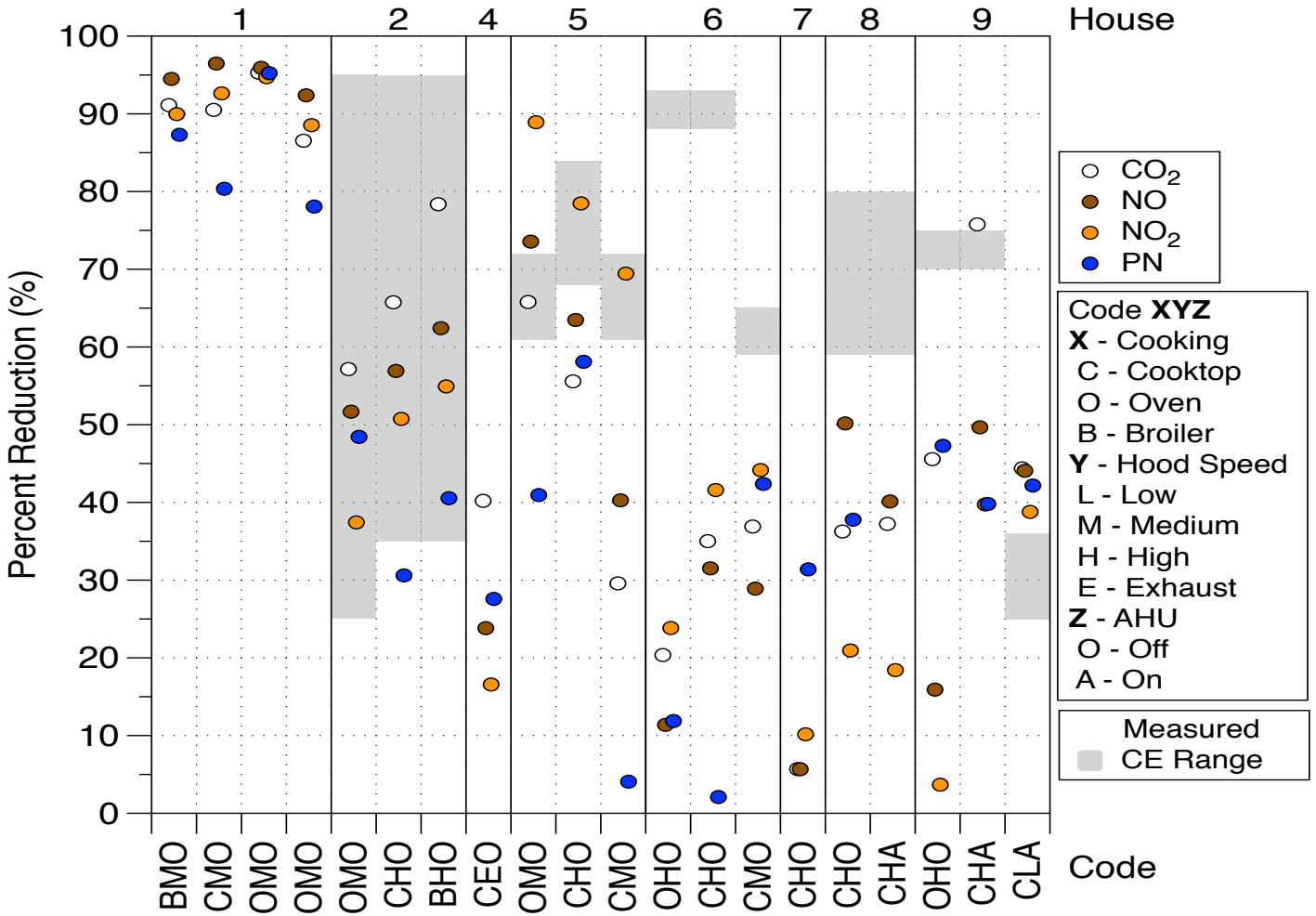
H6

H9

H8

Singer et al., 2017, Building Environment

# Widely varying effectiveness of installed range hoods




Singer et al., 2017, Building Environment

# Many use kitchen exhaust only “as needed”

| Self-reported usage | Number | Percent |
|---|---|---|
| Most times (>75%) when cooktop or oven used | 44 | 13% |
| Most times when cooktop used, but not oven | 39 | 11% |
| About half the time | 45 | 13% |
| **Infrequently, only when needed** | **113** | **32%** |
| Never | 35 | 10% |
| No exhaust fan | 73 | 21% |

Mullen et al. LBNL-5970E

# Range Hood Guidance

**Builder / Contractor**

- Low-resistance ducting
- Hood that covers all burners
- Quiet at 200 cfm

**User**

- Operate the hood
- Cook on back burner
- Higher setting when cooking more

**Roofer**

- Don’t drop debris down the vent

Materials (287 g) extracted from RH vent.
Photo & arrangement: M. Lunden

# Filtration works great for outdoor particles

Built 2006, 1200 sf, 5 ach50
Sealed ducts, MERV4 filter
Continuous exhaust vent.

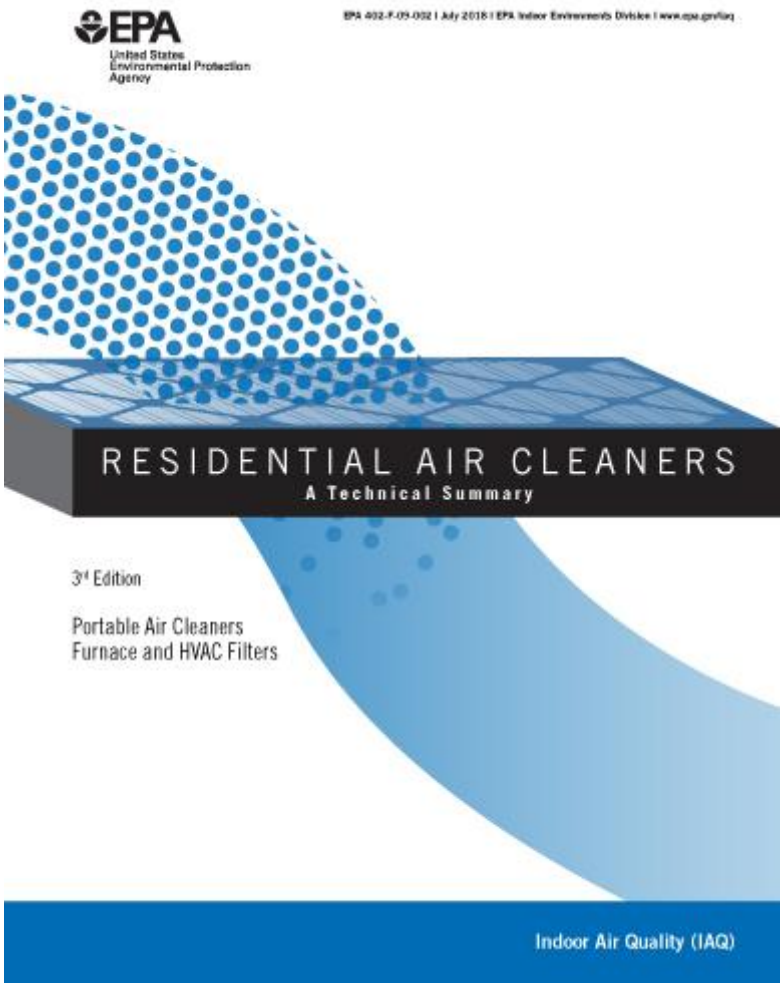
| Ventilation (Filtration) | Reduction* |
|---|---|
| Exhaust, continuous (MERV4) | 66-73% |
| Supply, continuous, MERV13; | 63-66% |
| Supply, continuous, MERV16; | 97-98% |
| Exhaust, continuous; MERV13 on mini-split, low-speed | 88-91% |
| Exhaust w/MERV16 on FAU | 96% |

Singer et al., Indoor Air, 2016

# Filtration and Air Cleaning

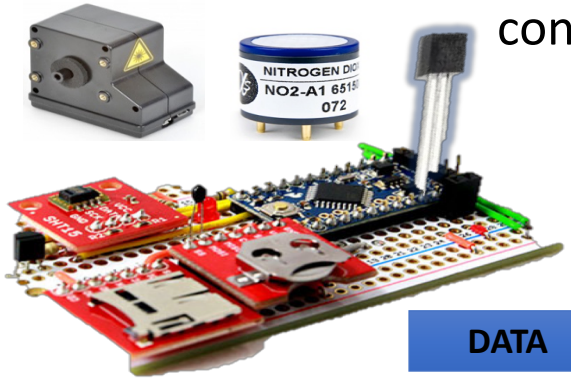
- Potential to drive PM to very low levels
- Field studies find that actual benefits are smaller than theoretical
- Key issues:
  - **People turn them off**
  - FAU doesn't run consistently
  - Thermostat controls confusing
  - Noisy
  - Forced air system fan is typically an energy hog

**https://www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home**



# Low-cost sensors for air quality monitoring

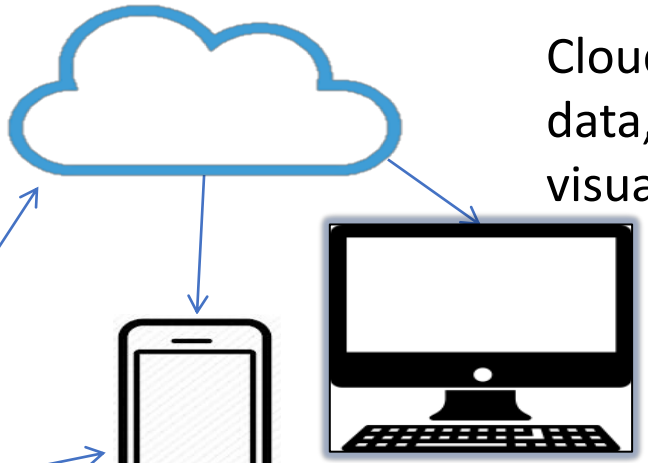
Sensors generate signals in response to environmental conditions




Calibrations translate signals to data

DATA

Cloud stores data, presents visualizations



Local displays indicate hazards and suggest mitigating actions


Data sent to cloud & displays; may be stored onboard



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# Berkeley New Home IAQ Survey

https://iaqsurvey.lbl.gov/

# Romanian Wisdom

*“Unde nu intra soarele pe geam, intra doctorul pe usa”*
*romanian proverb”*

Where the sun doesn’t enter through the window, the doctor enters through the door.

– Translation by Alina Handorean

# Relevant Literature


Chan WR et al. 2018. Indoor Air Quality in New California Homes with Mechanical Ventilation. Paper 633, Proceedings of Indoor Air 2018.

Delp WW, Singer BC. Performance Assessment of U.S. Residential Cooking Exhaust Hoods. *Environ Sci Technol.* 2012;46:6167-6173.

Francisco PW, Gordon JR, Rose B. Measured concentrations of combustion gases from the use of unvented gas fireplaces. *Indoor Air.* 2010;20:370-379.

Hult EL et al. 2015. Formaldehyde exposure mitigation in US residences: In-home measurements of ventilation control and source control. *Indoor Air* 25:523-535.

Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California. *Environ Health Perspect.* 2014;122:43-50.

Lunden MM, Delp WW, Singer BC. Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods. *Indoor Air.* 2015;25:45-58.

Mullen NA, Li J, Russell ML, Spears M, Less BD, Singer BC. Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: impact of natural gas appliances on air pollutant concentrations. *Indoor Air.* 2016;26:231-45.

Singer BC, Pass RZ, Delp WW, Lorenzetti DM, Maddalena RL. Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes. *Build Environ.* 2017;122:215-229.




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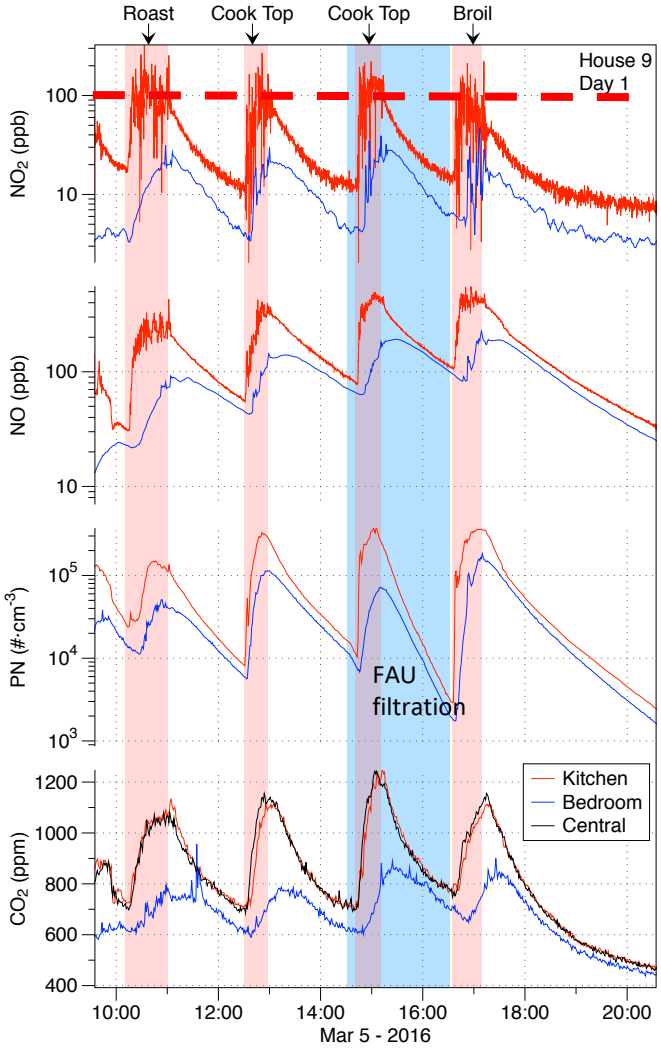
# General ventilation does not protect against acute hazards

Pollutants from gas burner use

- 1400 sf, super efficient house
- ERV providing 0.5 ach
- FAU with MERV16 filter

Cooking particles and VOCs from consumer products present similar challenges




$NO_2$ >100 ppb in kitchen

Singer et al., 2017, Building Environment

# For PM, very helpful to reduce entry from outdoors

## A large fraction of indoor $PM_{2.5}$ comes from outdoors

This fraction varies, and increases as indoor sources are mitigated.

RIOPA Study[1]

- Los Angeles (n=112) – 63%
- Elizabeth, NJ (n=80) – 52%
- Houston, TX (n=76) – 33%

MESA Air[2] (n=353 homes) – 80%

- Baltimore,
- Chicago,
- Los Angeles,
- New York,
- Rockland,
- St. Paul,
- Winston-Salem



[1]Meng, JEAEE, 2005, 15:17-28; [2]Allen, EHP, 2012, 120: 824-830

# Available info on sensor performance

- EPA has done some work focusing on outdoors

  https://www.epa.gov/air-sensor-toolbox

- Air quality in China

  http://aqicn.org/sensor/

- South Coast AQMD tests outdoor & in chambers

  http://www.aqmd.gov/aq-spec/home

# LBNL Evaluation of Consumer PM Monitors

**AB**

PM, T, RH

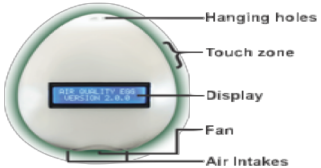
1 sec

**AVN**

$PM_{2.5}$, $PM_{10}$, $CO_2$, T, RH

10 sec – 15 min

**AQE**




PM, T, RH

1 min

**AWA**

PM, $CO_2$, VOC, T, RH,

10 sec – 5 min

**FOB**

PM, $CO_2$, VOC, T, RH,

5 min

**PA**

$PM_{1.0}$, $PM_{2.5}$, $PM_{10}$, T, RH

80 sec

**SPK**

PM, # particles, T, RH

1 min

These use mass-produced particle sensors that cost <$10 to $35

# Evaluated for typical sources of residential PM

Burned incense, candles and cigarettes

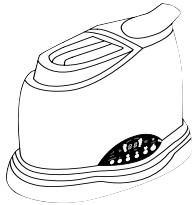





Heated pots of water, an oven, a hair dryer, and an electric burner

Cooked green beans, bacon, pancakes, toast, heated oil

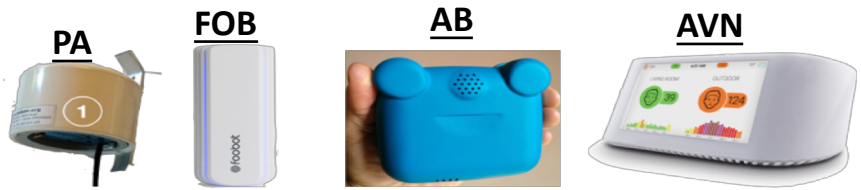


Released AZ test dust, shaked a dust mop, and operated an ultrasonic humidifier using unfiltered tap water

# Four monitors detected most sources and quantitatively measured all large sources of $PM_{2.5}$

These 4 should helpful to manage IAQ.




Two consumer monitors detected many sources but not quantitatively.

One monitor was not informative.

Consumer monitors not suitable to detect & control ultrafine particles.


Results should be verified in homes.

- What fraction of $PM_{2.5}$ detected?
- How durable are the devices?



Complete study: Singer et al. 2018, Indoor Air

# iaqscience.lbl.gov

- Compiles published studies
- Critical review
- High-level summary
- Periodically updated

## Topics

**Building Ventilation**

Ventilation is the supply of outdoor air to a building. This section discusses how ventilation rates influence indoor air quality and occupant health and performance.

**Dampness and Mold**

Topics discussed include the causes of excess building dampness, the influence of dampness on indoor biological and organic chemical contaminants, and the effects of dampness and of dampness-related indoor contaminants on people's health.

**Volatile Organic Compounds**

Indoor volatile organic compounds, or VOCs, are carbon-containing organic chemicals emitted from a variety of sources. The implications of indoor VOCs for health are addressed.


**Human Performance**

This section discusses how the performance of office and school work is affected by indoor environmental conditions and by the features of buildings that influence indoor environmental conditions.

**National-Level Opportunities**

This section provides estimates at the national level of some of the benefits and costs of taking practical steps to improve indoor environmental conditions in U.S. buildings.

**Air Cleaning**

Indoor air cleaning is the process of intentionally removing pollutants from indoor air, or from the outdoor air as it enters a building. This section of the web site addresses the relationship of air cleaning to health and perceived air quality, focusing on application of air cleaning to buildings outside of the health care and industrial sectors.

**Climate Change**

Climate change will modify outdoor environmental conditions which, in turn, will

**IAQ in Schools**

This section provides an overview of indoor air quality (IAQ) in schools and its influence