IAQ Challenges and Solutions in Net Zero Homes

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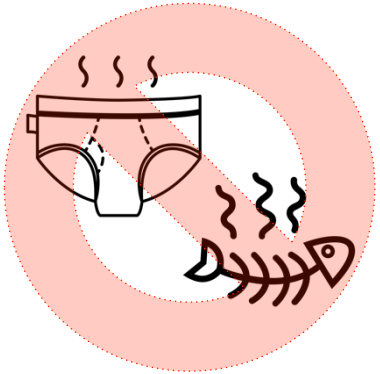
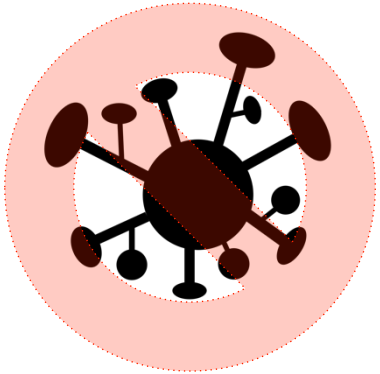
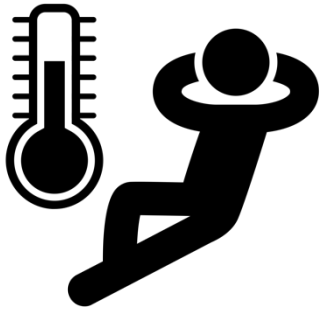
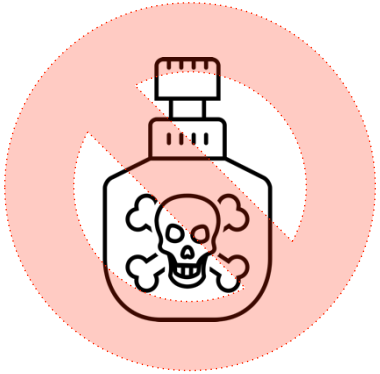
What is Indoor Air Quality?









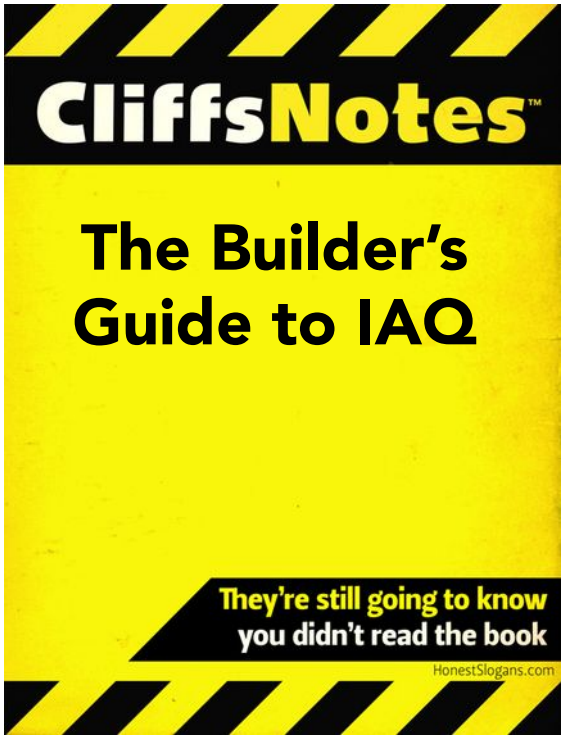
Good IAQ = Low-Risk of Bad IAQ

Recipe for a low-risk home

- Start with watertight and airtight envelope
- Ventilate
- Manage humidity
- Minimize hazardous chemicals
- Integrated pest management
- Filter air as needed
- Maintain & keep it clean
- Labels and instructions
- ~~Disinfect~~

Reducing air pollutant hazards

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



What contaminants do we have to worry about?

From Inside

Formaldehyde

Nitrogen dioxide

Acrolein

Carbon monoxide

Semivolatile organics

Irritants

Odors

From Inside + Outside

Particulate matter

Volatile Organic Compounds

Mold and Dampness

Allergens

From Outside

Radon

Ozone

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Particles

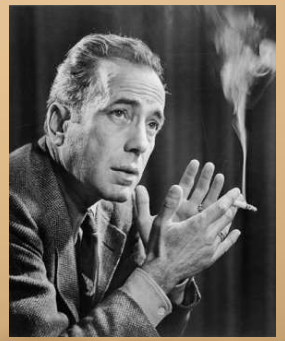
outdoors

- **Higher $PM_{2.5}$ associated with adverse health outcomes:**
  - Death, strokes, and other cardiovascular illness
  - Increased respiratory illness
  - Linked to many other outcomes

<u>CalEPA Ambient Standard</u>

12 µg/m^3

indoors



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

California Standards
Acute: 45 ppb
8h & Annual: 7 ppb

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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

EPA Ambient Benchmarks

100 ppb for 1h

53 ppb annual

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Nitrogen dioxide – high risk sources

Biggest risk is unvented heating
- frequent and long events
- more BTU/h = more 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

Don't Use These

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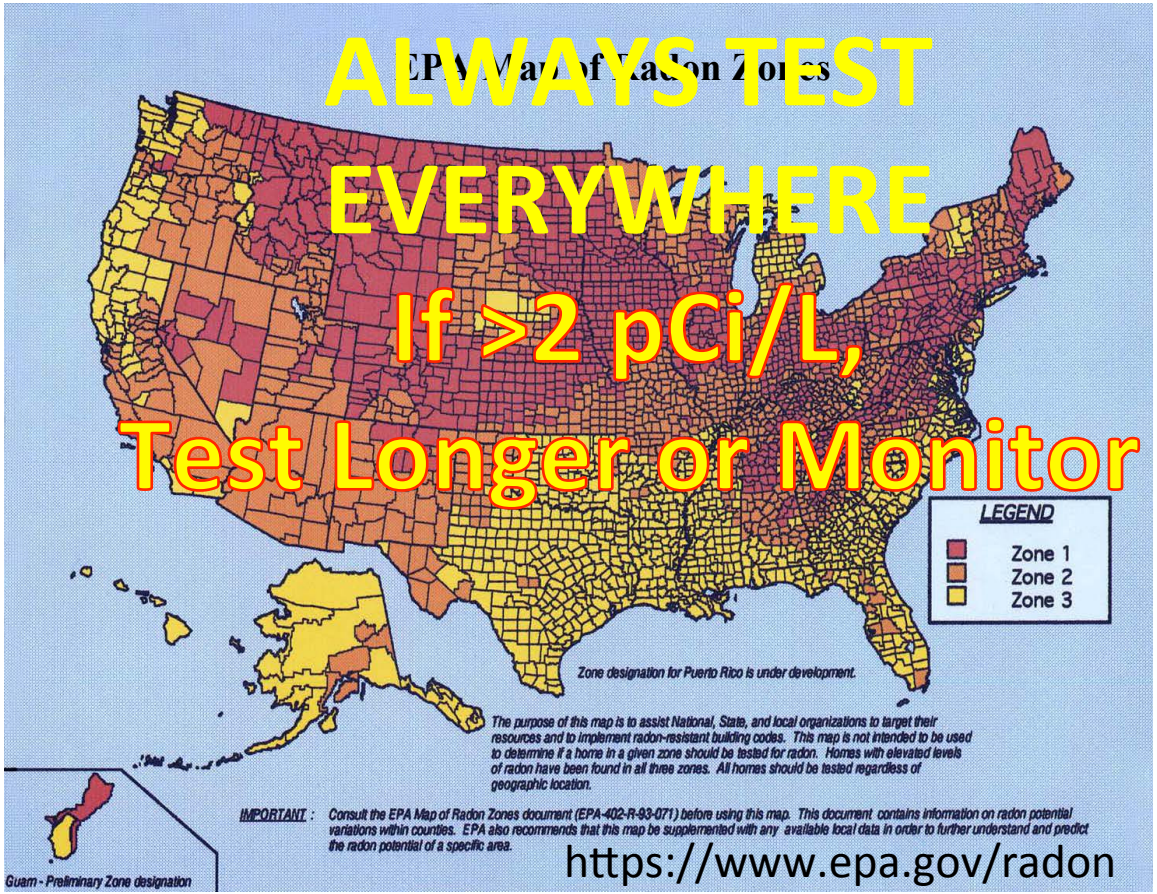
Radon

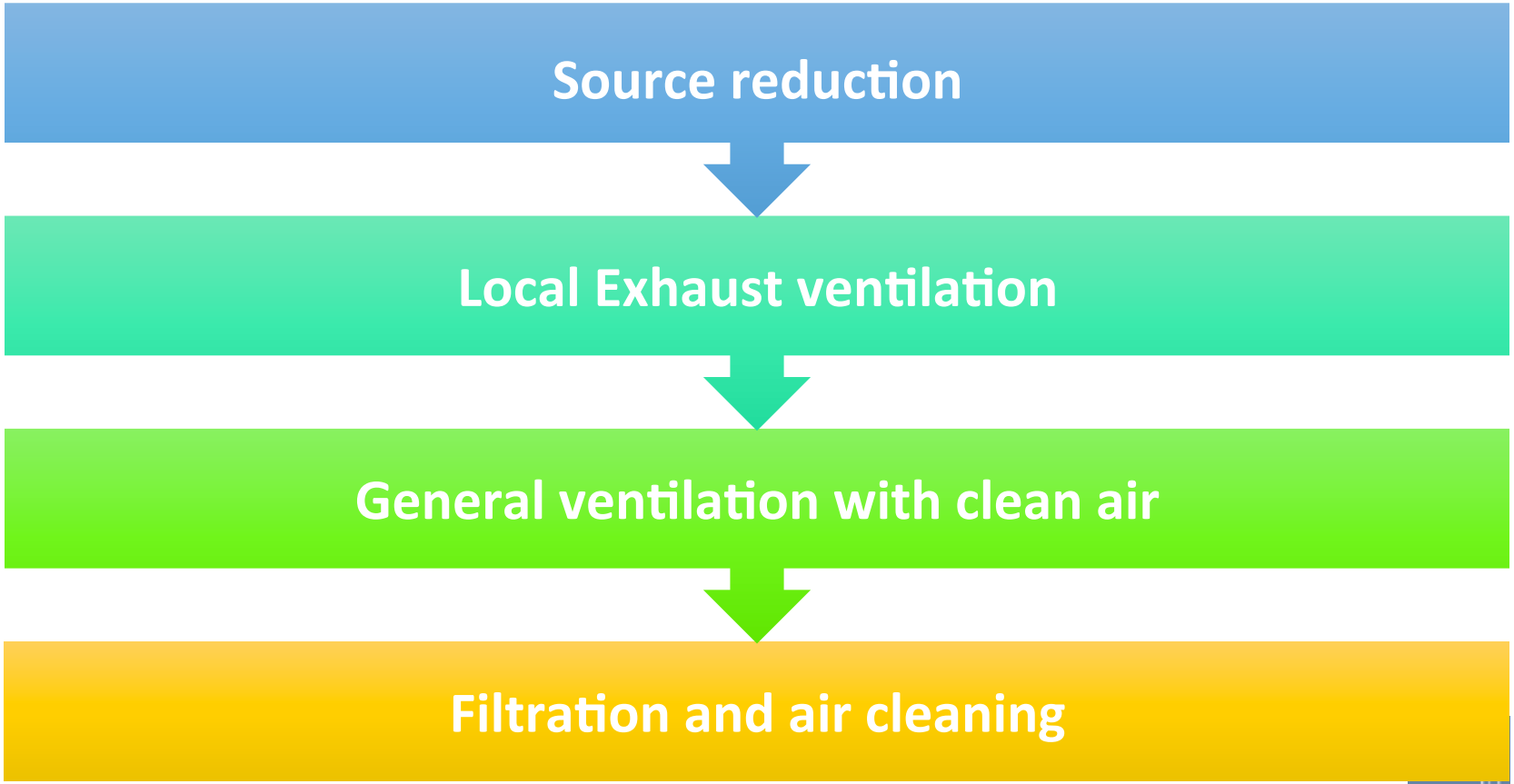
Radon entry varies with soil, season, weather.

Lung Cancer Risk, per 1000 Lifetime Exposure

Radon pCi/L	Non-smokers	Smokers
2	4	32
4	7	62
8	15	120
20	36	260



Reducing IAQ Risks


Source reduction
Local Exhaust ventilation
General ventilation with clean air
Filtration and air cleaning

Pollutant Source Reduction

Source Control

- Formaldehyde & VOCs
  - What's in the house structure?
    - Building materials
    - Furniture
    - Consumer products
- Combustion and cooking
  - Local exhaust
  - Induction
- Moisture and odors
  - Local Exhaust
  - Supplemental dehumidificiation

California Department of Public Health CDPH

OEHHA Office of Environmental Health Hazard Assessment

CA Formaldehyde limits and regulation

California Air Resources Board

Use low emitting materials and finishes

- Use certified green building materials

- Prioritize materials with:
  - Most surface area
  - Direct paths of exposure (e.g., flooring over attic insulation)

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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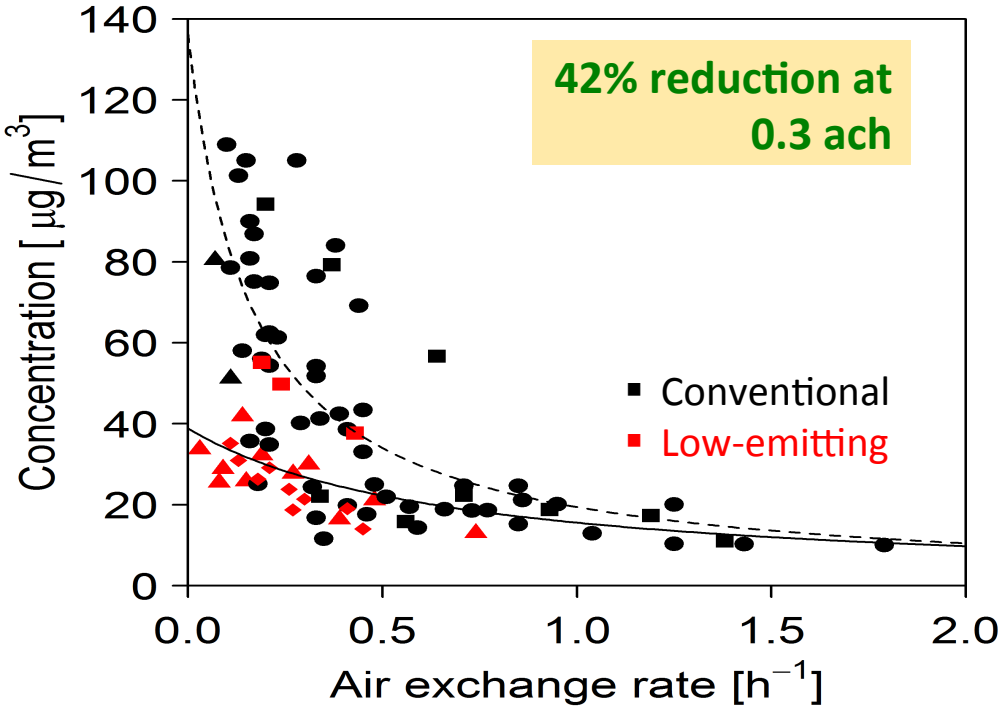
Homes built with low-emitting materials have lower formaldehyde concentrations



Data adjusted for temperature, RH, house age

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

Dealing with Combustion in ZNE homes

No unvented combustion:

- Furnaces, boilers and water heaters either outside conditioned space or sealed combustion
- Fires/woodstoves must use outside air for combustion
- Gas cooking only if range hood exhausts to outside
- Eliminates CO from the building systems

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 (112 homes) – 63%
- Elizabeth, NJ (80 homes) – 52%
- Houston, TX (76 homes) – 33%

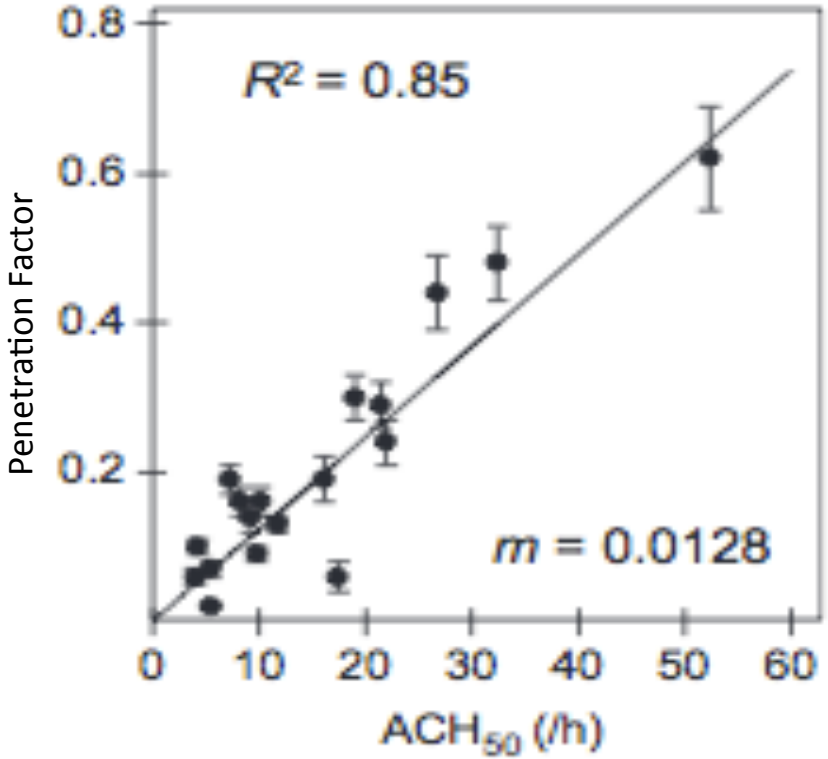
MESA Air[2] (353 homes) – 80%

- 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

A tighter envelope is a better filter

- Field testing of envelope penetration of **submicron** particles
- Tight homes are good protection against outdoor particles:
  - 1.5 ACH_{50} = 2% penetration
- Need data for larger particles: PM2.5



Stephens, B., & Siegel, J. A. (2012). Penetration of ambient submicron particles into single-family residences and associations with building characteristics. *Indoor Air*, *22*(6), 501–513. doi:10.1111/j.1600-0668.2012.00779.x

Local Exhaust: Kitchen Ventilation

Cooking & burners are important sources

CO_2 & H_2O

NO,NO_2, HONO, Formaldehyde

Ultrafine particles

Ultrafine particles

Ultrafine particles, $PM_{2.5}$

Formaldehyde, Acetaldehyde

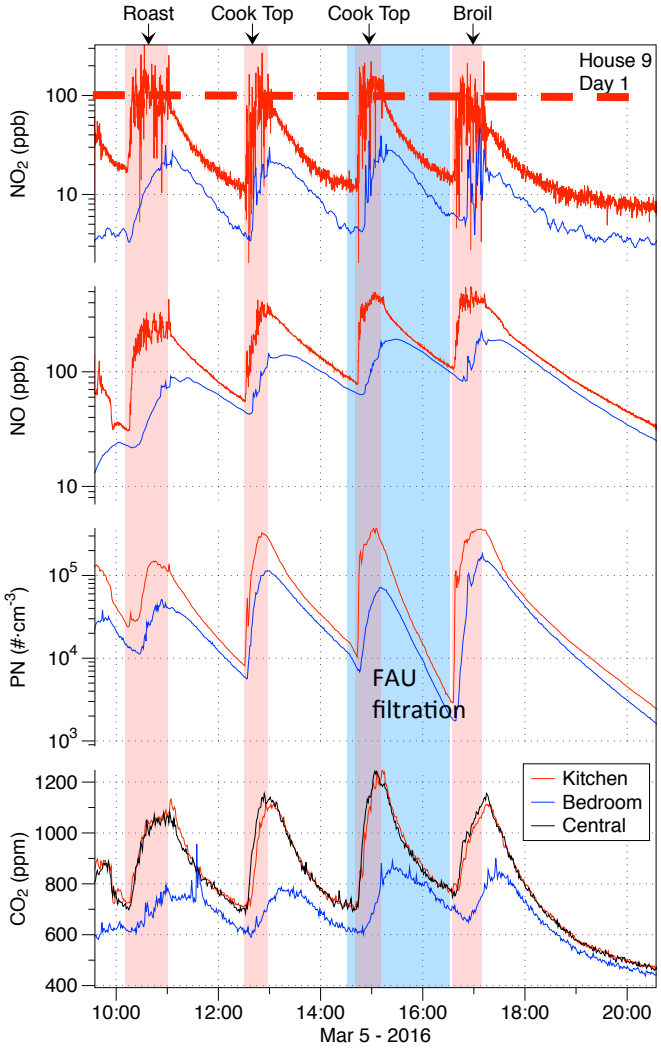
Acrolein, PAH

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

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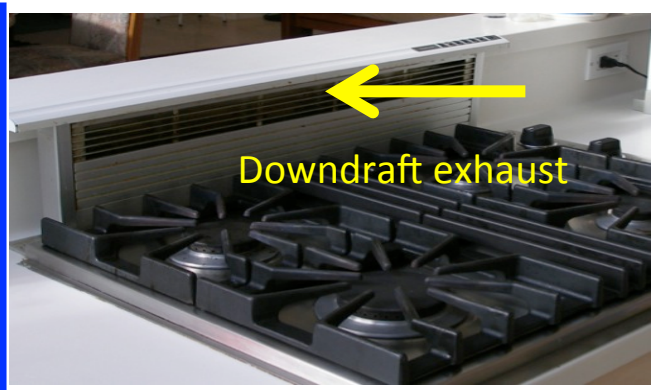
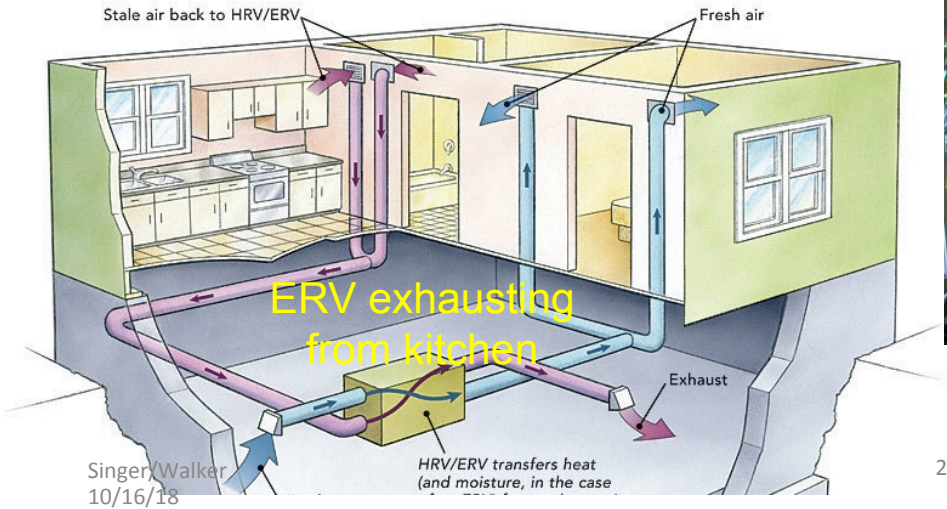
Kitchen ventilation options



Exhaust fan on wall



Ceiling exhaust fan

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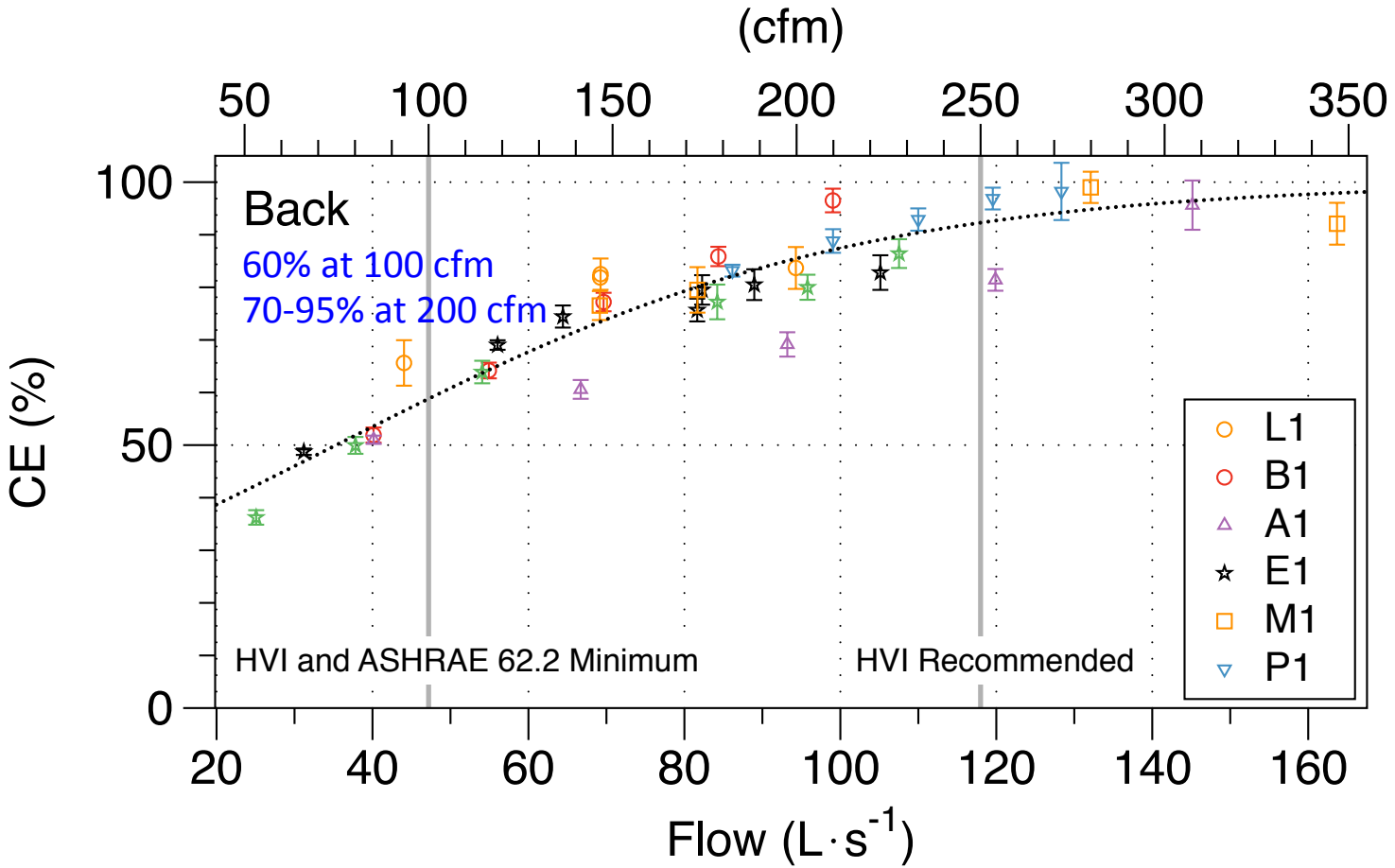
Lab study of range hood performance

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

Lab study of range hood performance



Capture increases with airflow.

Much better for back burners!

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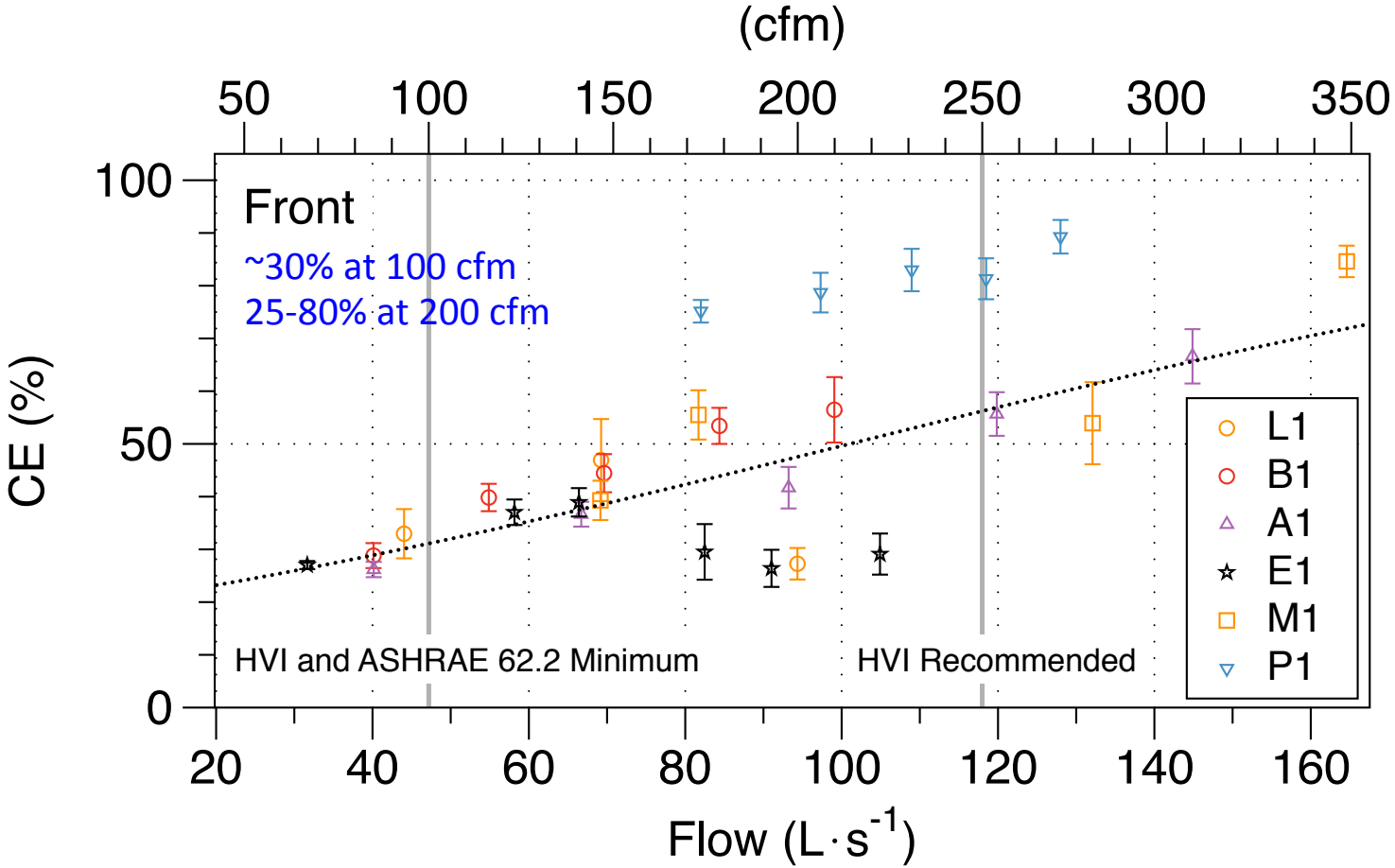
Lab study of range hood performance



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

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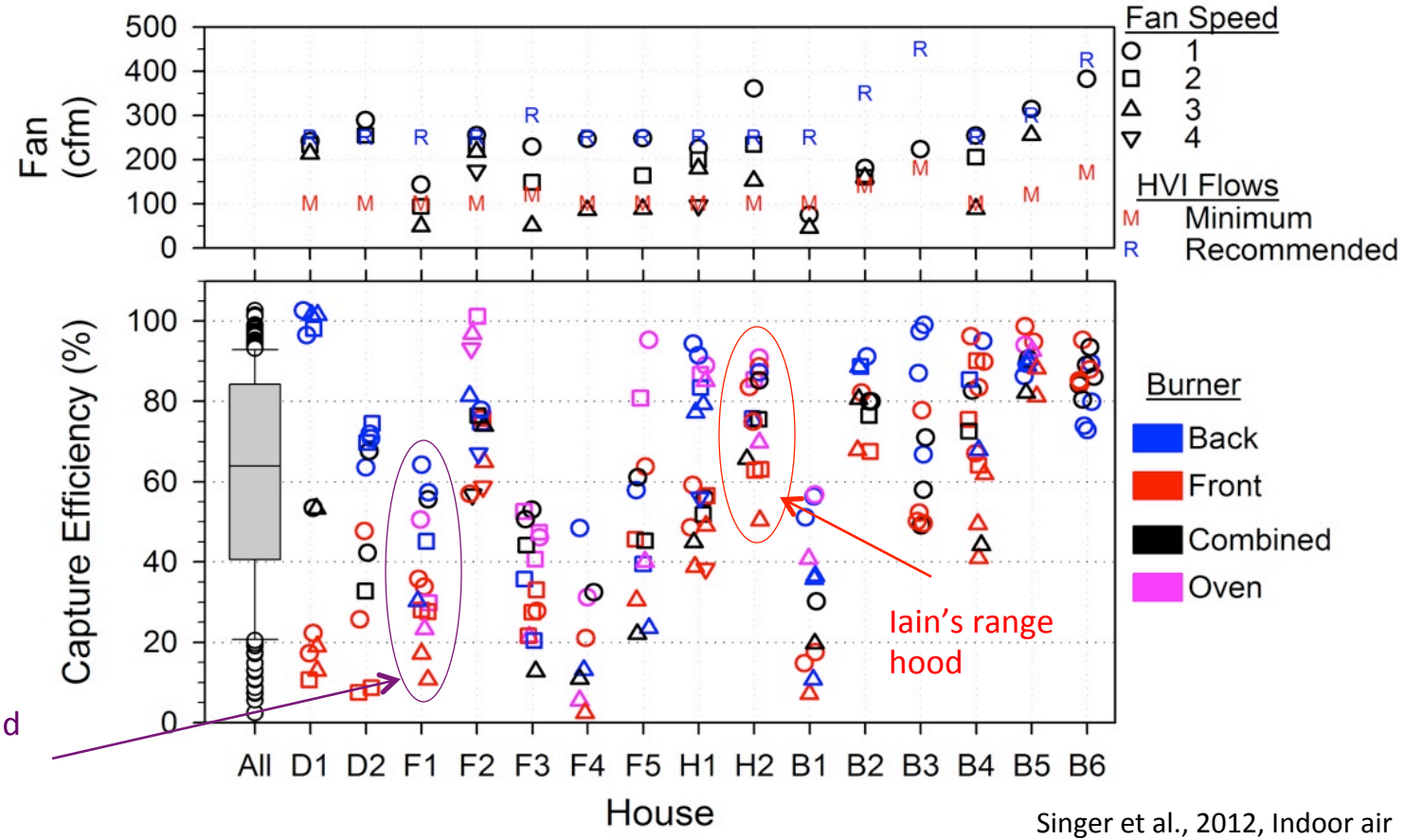
As installed range hood performance

Large range of performance



Singer et al., 2012, Indoor air

Good coverage

So-so coverage

Bad coverage

Range Hood Guidance

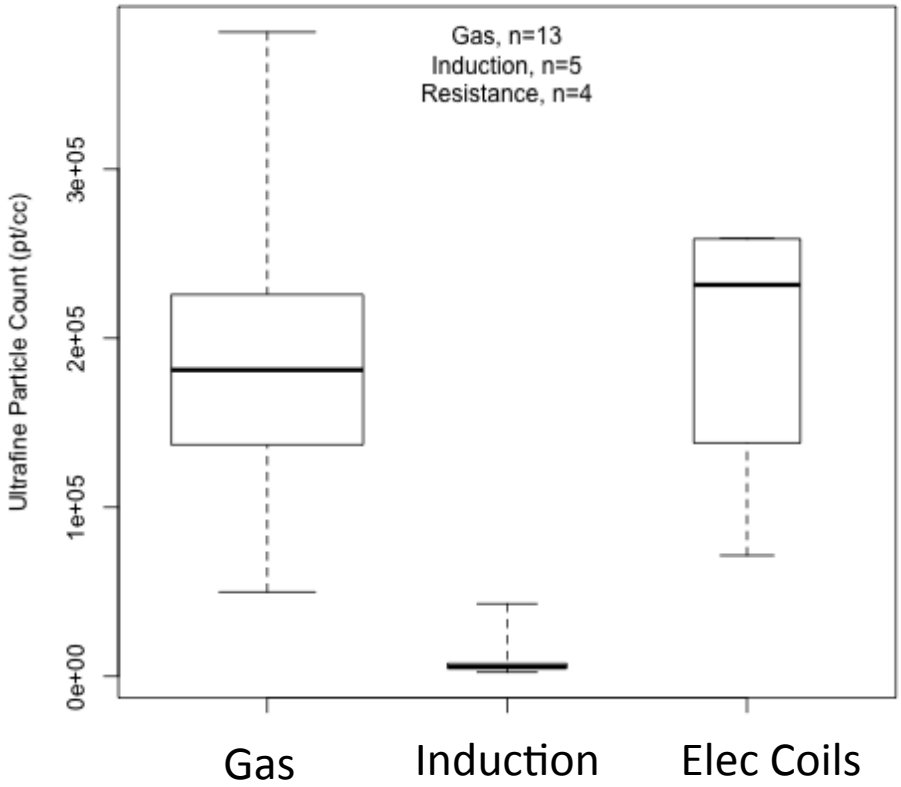
Builder / Contractor

- Low-resistance ducting
- Hood that covers all burners
- Quiet at 200 cfm
- Install make up air
  - If > 400 cfm
  - If <2 ACH50*

User

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

Induction appears to have lower emissions of ultrafine particles



*2500 sq.ft. home with 10 Pa depress limit (door slam

What's New for Range Hoods

Automation

- Turn on and off automatically
- Detecting cooking events

Capture Ratings

- ASTM standard test method
- HVI certification and listing

CERTIFIED HOME VENTILATING PRODUCTS DIRECTORY

HVI
HOME VENTILATING INSTITUTE

This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: E3087 – 17

Standard Test Method for
Measuring Capture Efficiency of Domestic Range Hoods[1]

This standard is issued under the fixed designation E3087; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ertified Ratings in Air Delivery, Sound and Energy for Accurate Specifications and Comparisons

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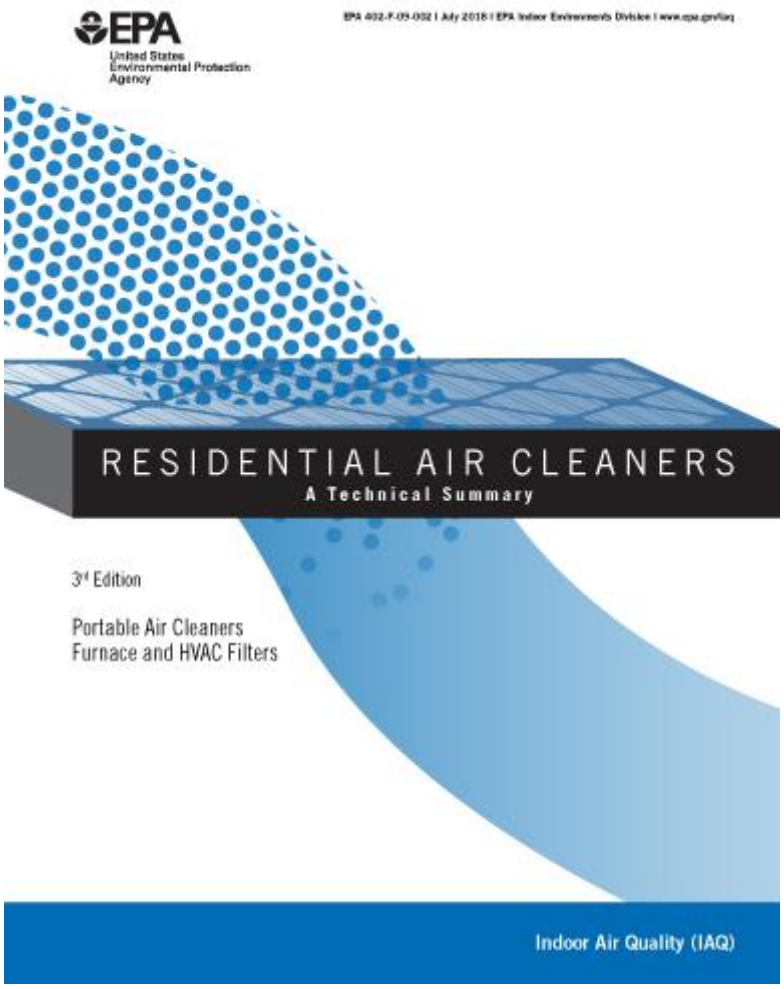
Filtration and Air Cleaning

Potential to drive PM to very low levels

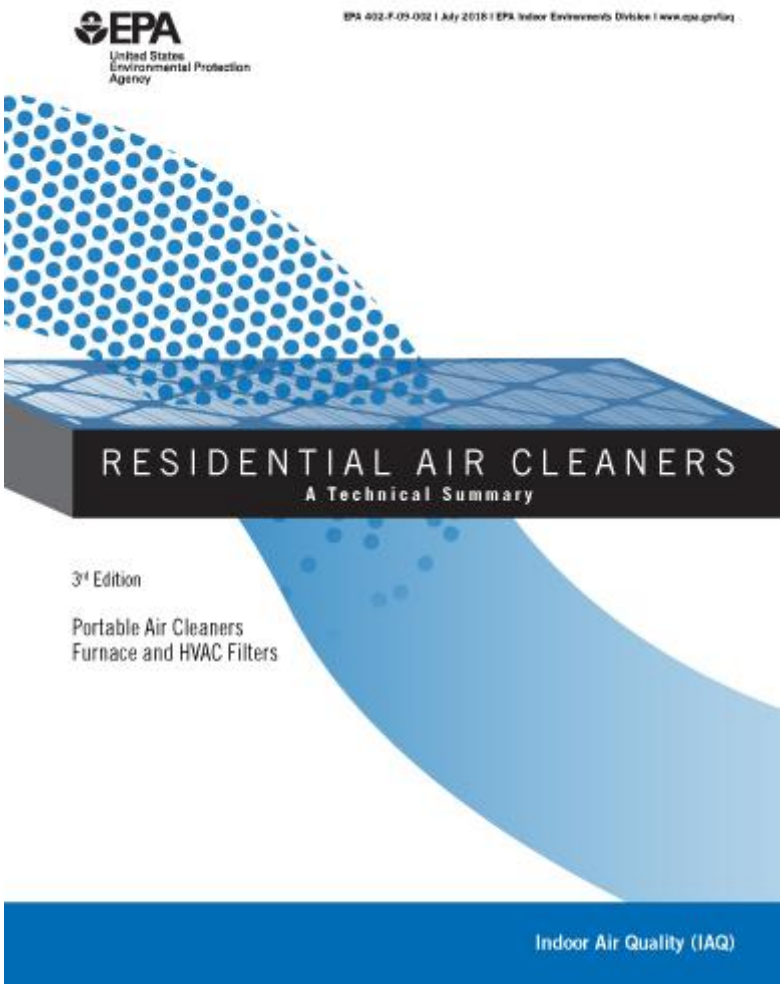
- Upgrade central forced air system filter
- Use a MERV 13 filter
- 2” minimum filter depth
- Accessible and clearly labeled
- Needs a minimum air flow:
  - 2500 sq.ft. ~ 500 cfm continuous, or 1500 cfm 20/60



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

Filtration and Air Cleaning

- Key issues:
  - **People turn them off**
  - Confusing controls
  - Noise
  - Energy
- What if you don't have central forced air?
  - Filter incoming ventilation air?
  - Use stand-alone devices?



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

Ventilation and filtration impact outdoor particles

Built 2006, 1200 sf, 5 ach50
Sealed ducts,

Reference System:

- Exhaust at Title 24 rate
- MERV 4 filter on FAU

$PM_{2.5}$ inside 66-73% lower than outdoors

Ventilation & Filtration	Reduction*
Supply, continuous, MERV13; MERV4 on FAU	63-66%
Supply, continuous, MERV16; MERV4 on FAU	97-98%
Exhaust, continuous; MERV13 on FAU, 20/60 runtime	97-98%
Exhaust, continuous MERV13 on m-split, low-speed cont	88-91%
Exhaust w/MERV16 on FAU	96%

Singer et al., Indoor Air, 201

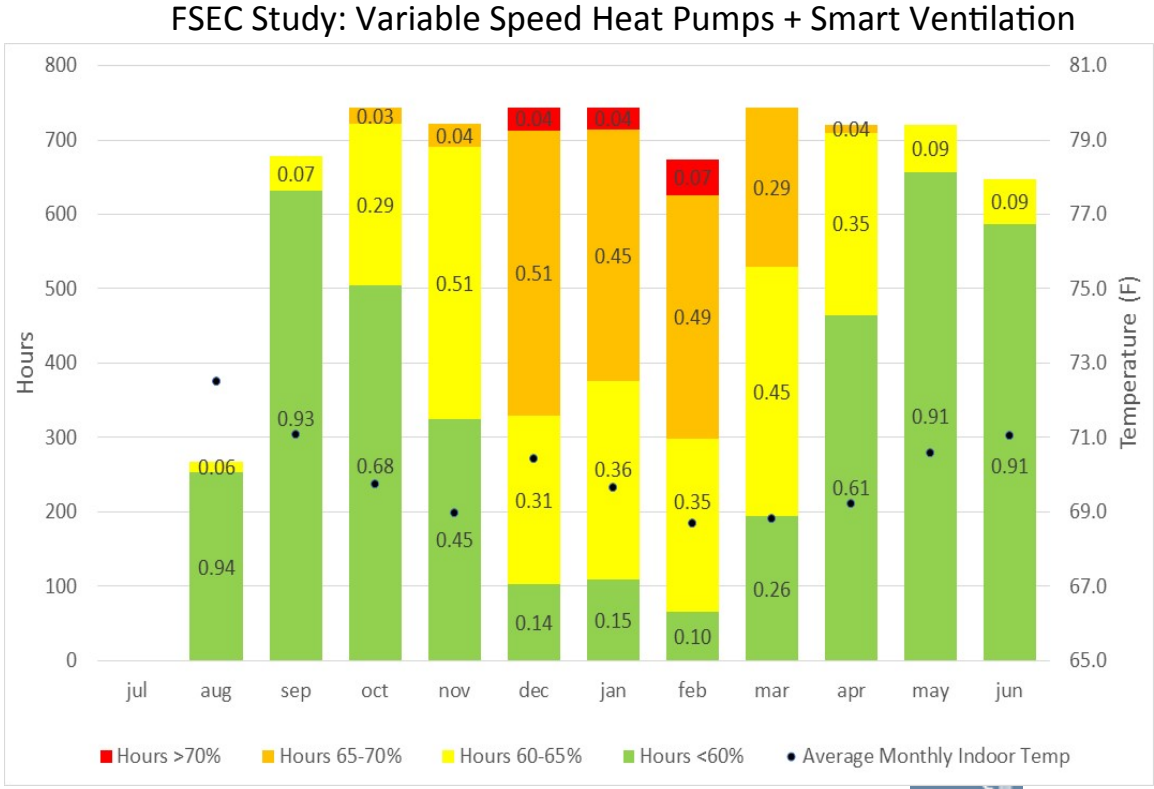
Local Exhaust: Wet rooms

Bathroom/Laundry Exhaust Removes Moisture, Odors, Cleaning Product Emissions

- Continuous low-flow (20 cfm) or intermittent flow (50 cfm)
- Manually operated our automated
  - Humidistat control
  - Timers
- Energy Star lists energy efficient quiet fans

Humidity Control

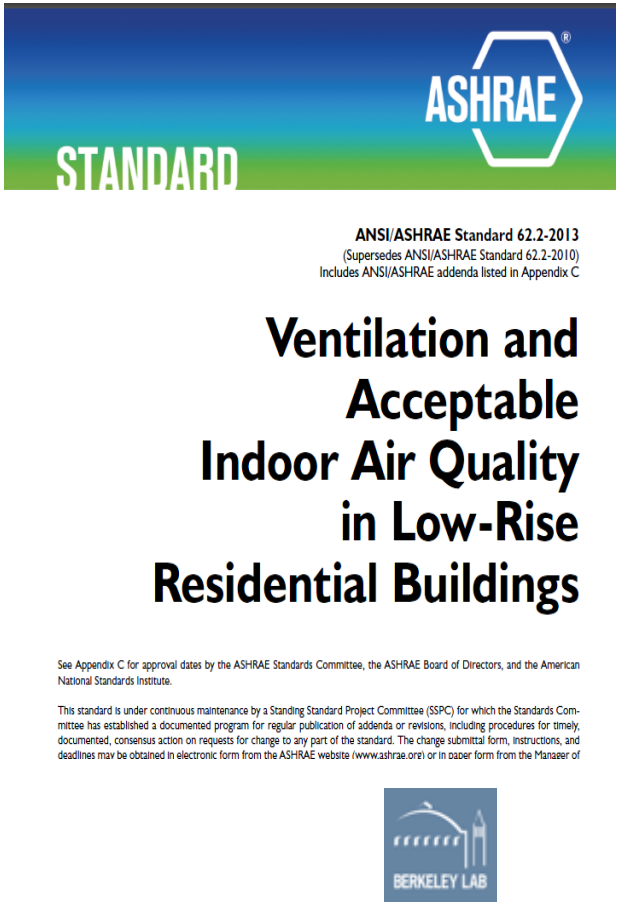
- Tight homes have higher indoor humidity
- Energy efficient homes have low sensible loads and little dehumidification from air conditioning
- ZEH need independent humidity control in humid SE climates
- Integrate with Smart Ventilation system to take advantage of indoor-outdoor humidity differences



General Ventilation

How Much Do I Need?

- Minimum requirement: ASHRAE 62.2-2016
  - Whole house flow—with blower door credit (not in MF)
  - Local exhaust in kitchens and bathrooms
  - Duct leak limits, minimum filtration
  - Existing home allowances for local exhaust
  - Requires CO alarm
  - Filtration credit
  - Measure air flows
  - Allows for "smart" energy efficient ventilation controls
- "Good" = anything "better" than this minimum



General Ventilation

Exhaust, supply or balanced?

Exhaust

– Cheapest & easiest to install and operate

- Needs good ceiling and garage wall sealing
- Easiest to measure/ commission
- Interacts with combustion devices
- Must be installed in a wet room
- Can't guarantee distribution

Balanced

– Most expensive to install

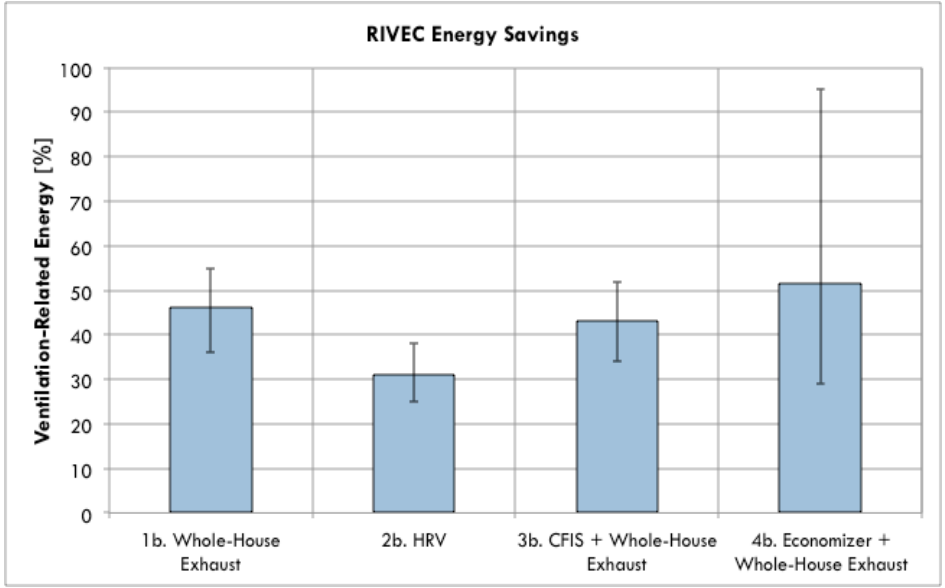
- Allows for heat recovery in cold climates
- Good for tight homes
- Good for distribution: exhaust from wet rooms, supply to living spaces
- Needs a MERV 13 filter on air inlet – maintenance issue
- Hard to measure/ commission
- Best with its own ducting

Supply

- Can be ducted to living spaces
- Needs a MERV 13 filter on air inlet– maintenance issue
- Hard to measure/ commission
- Caution needed in cold climates
- Uses lots of energy if integrated into CFA

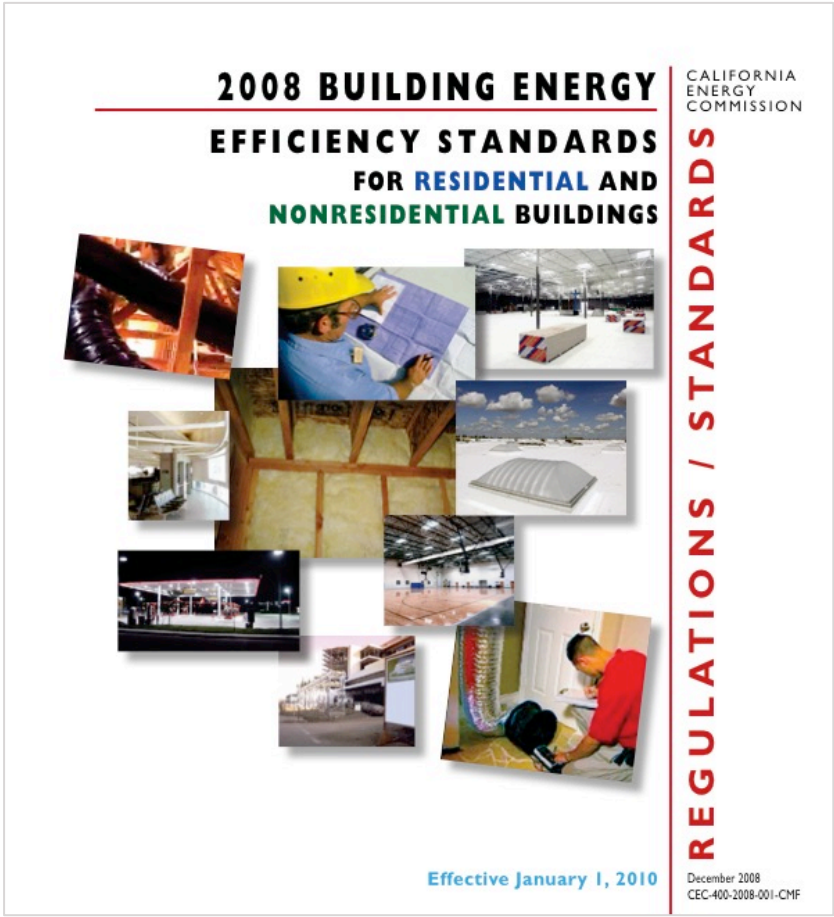
Coming Soon: Smart Ventilation

- Reduce outdoor air when too hot, cold, humid, or polluted
- Reduce air flow at times of utility peak load
- Increase airflow at other times to achieve same contaminant exposure
- Sense operation of economizers, local exhaust and dryers
- Account for emissions when homes are unoccupied: better occupancy-based controls



Healthy Efficient New Gas Homes (HENGH)

- Air sealing is a key measure
- Prior studies raised IAQ concerns
- Since 2008, California code has required mechanical ventilation



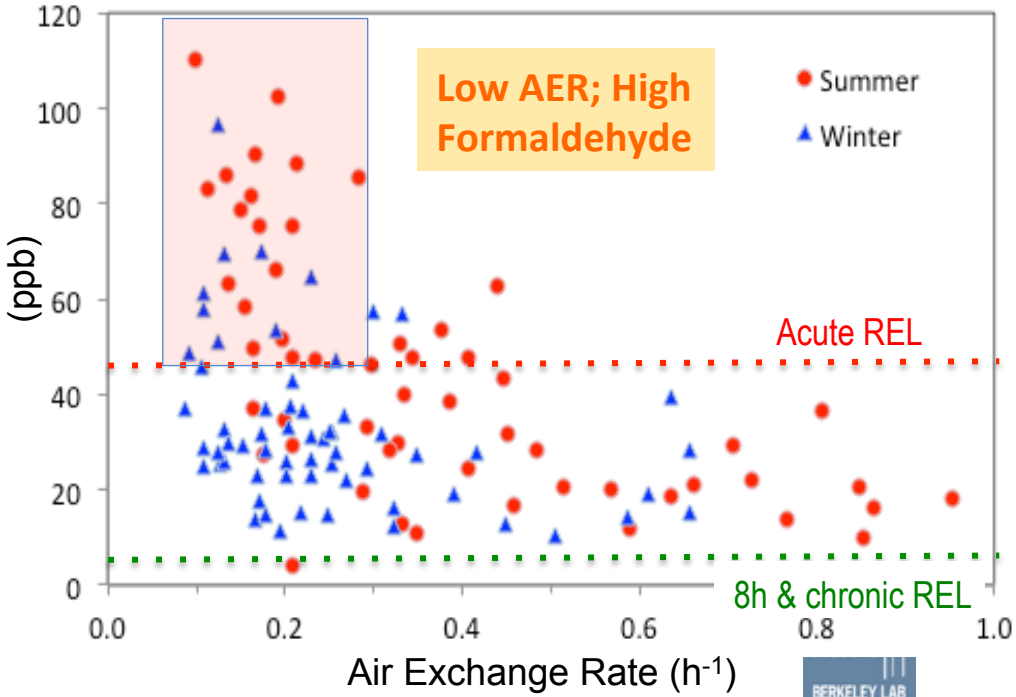
Prior California Studies

New Home Survey: 2004-5

- 1500 responses by mail
- Homes built 2002-3
- Self-reported window use
  - 50% didn't use in winter
  - 20% didn't use in spring & fall
- Kitchen & bath fans not used routinely

Field study: 2006-7 (CNHS)

- 108 homes, built 2002-05, 98% electric



Price & Sherman, 2006, LBNL-59620;
Offermann, 2009, CEC-500-2009-085

HENGH Field Study

- 70 detached homes, built 2011-17
- Natural gas cooking burners

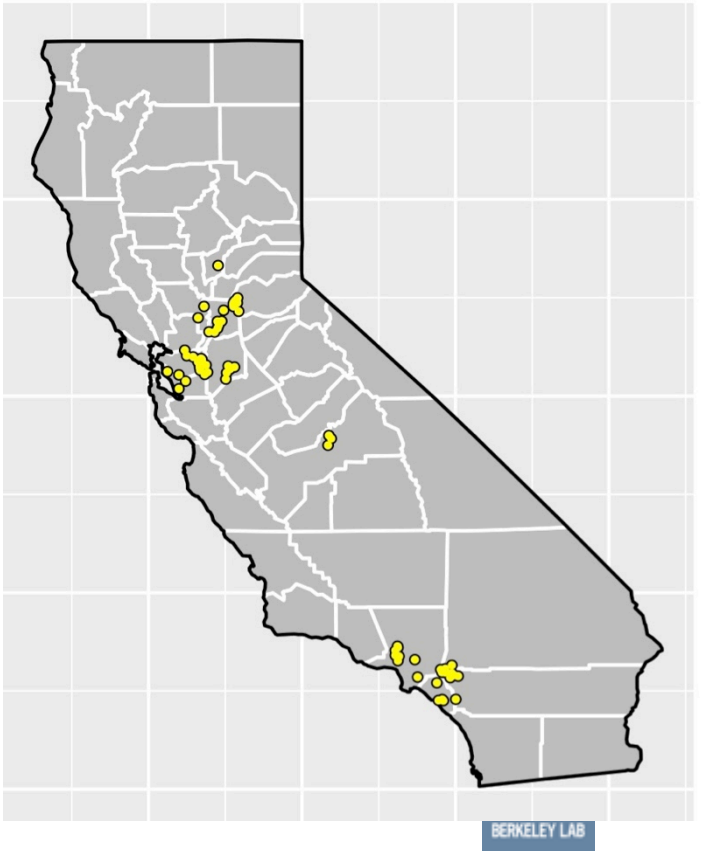
- Measurements in 2016-2018
- Characterized ventilation equipment
- Measured IAQ & ventilation use, tracked activities for 1 week
- Windows closed; Central MV operating

Core Funding

In-Kind Support

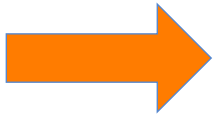
HENGH Field Study

- Average floor area: 2700 sq.ft.
- Average envelope leakage: 4.5 ACH50
- Average density: 1000 sf per person
- 90% of homes less than three years old



Central MV systems exceeded required airflow

Mean required: 63 cfm
Mean provided: 96 cfm



~50% above code

- Easy to verify:
  - Continuous exhaust (N=55)
  - Intermittent exhaust (N=9)

- Hard to verify:
  - Continuous inline fan connected to central forced air system (N=4)
  - Central fan integrated supply with motorized damper (N=2)

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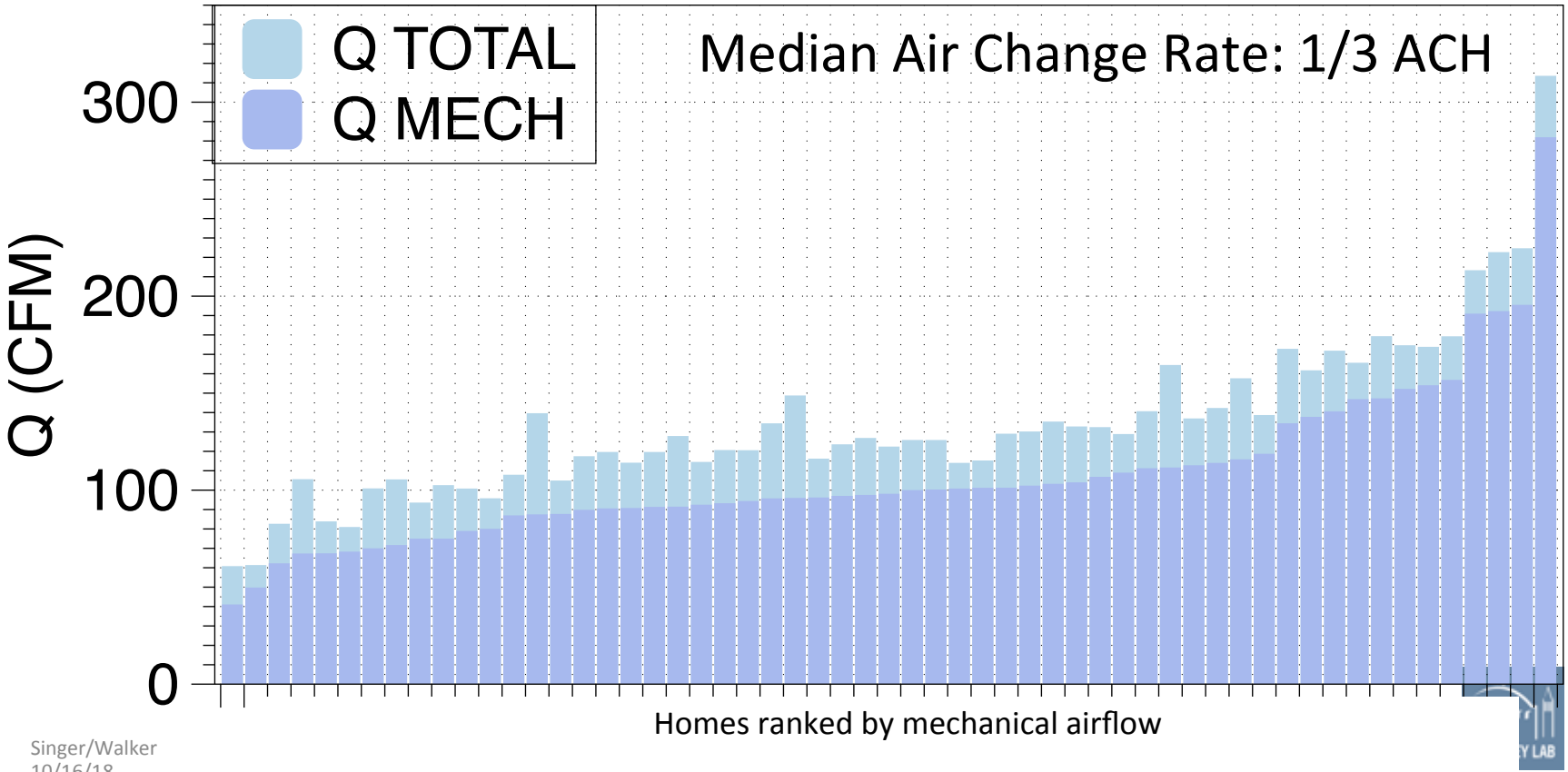
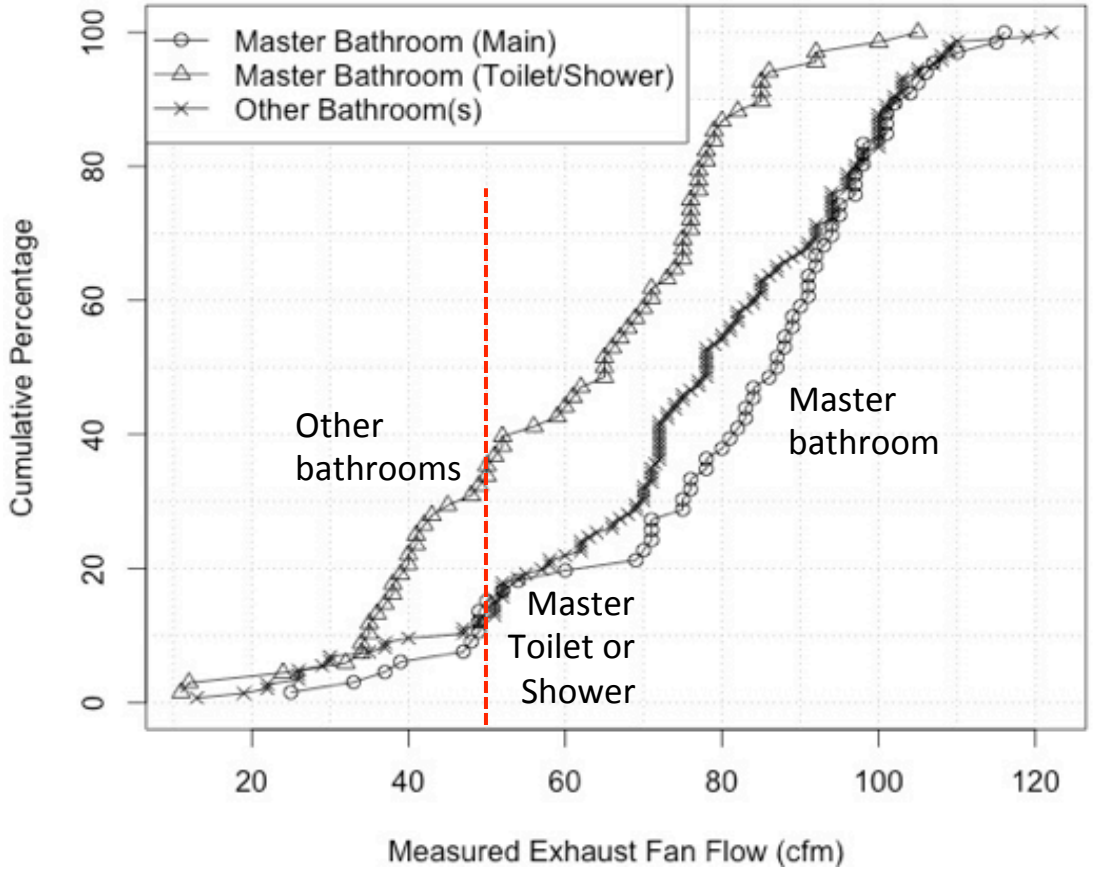
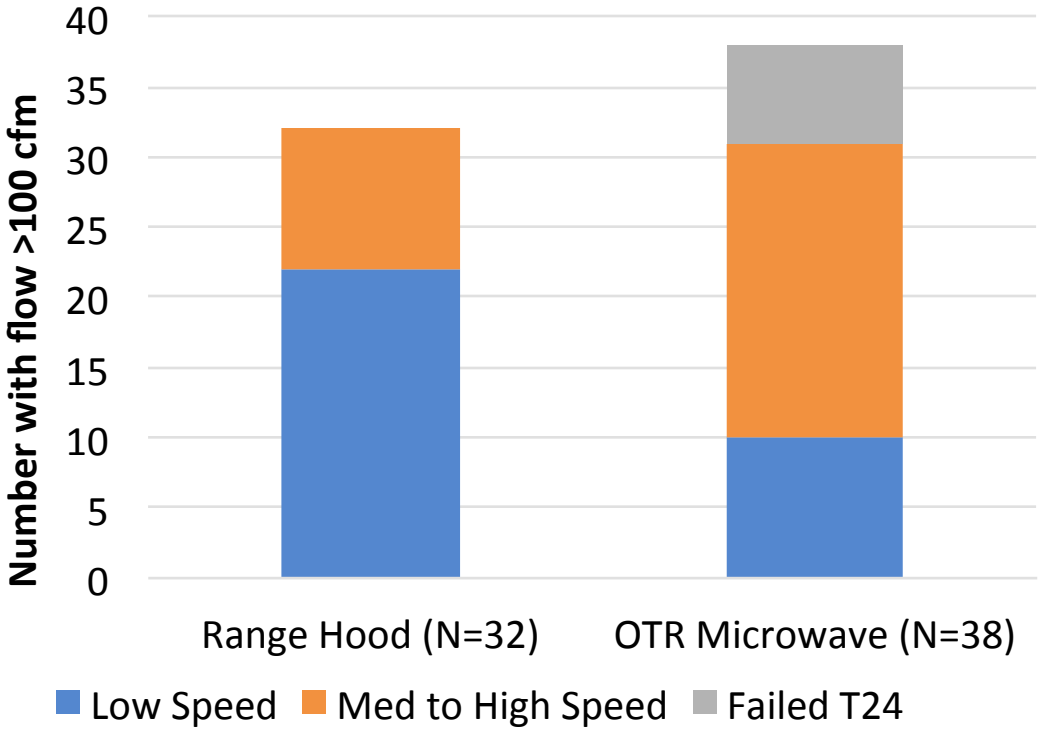
MV provided 78% of total estimated outdoor air



Code-compliant ventilation in 85% of master baths 1/3 of other bathrooms below code



Most range hoods met minimum airflow
Many OTR microwaves did not



$PM_{2.5}$ and formaldehyde lower in HENGH

Median Indoor Concentration	CNHS* – 98% Electric 2006–07	HENGH - Gas Homes 2016–18
Formaldehyde	30 ppb	18 ppb
$PM_{2.5}$	10.4 microg/m^3	5.0 microg/m^3
NO_2	3.1 ppb	4.4 ppb

*Offermann (2009).

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Only **1 in 4** homes had the whole house ventilation system running as found.

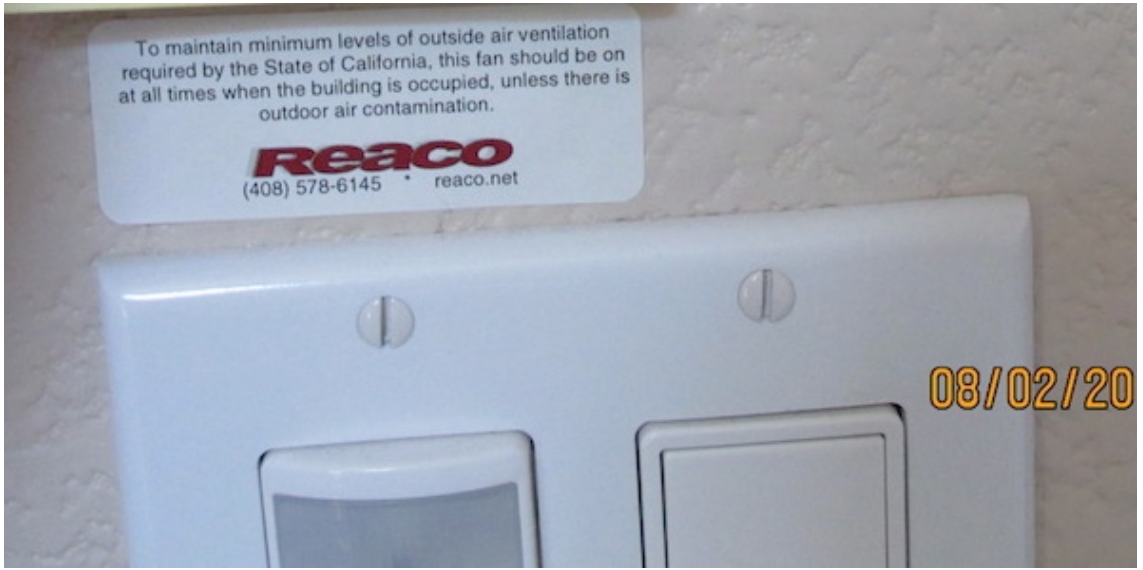
Labels made a difference

Whole-House Ventilation Control	Controller Labelled?	% On As-Found
On/Off Switch	No (N=42)	5%
	Yes (N=12)	58%
Programmable Controller	No (N=10)	50%
Thermostat	No (N=2)	0%
Breaker Panel	No (N=1)	100%
No Controller	No (N=3)	100%

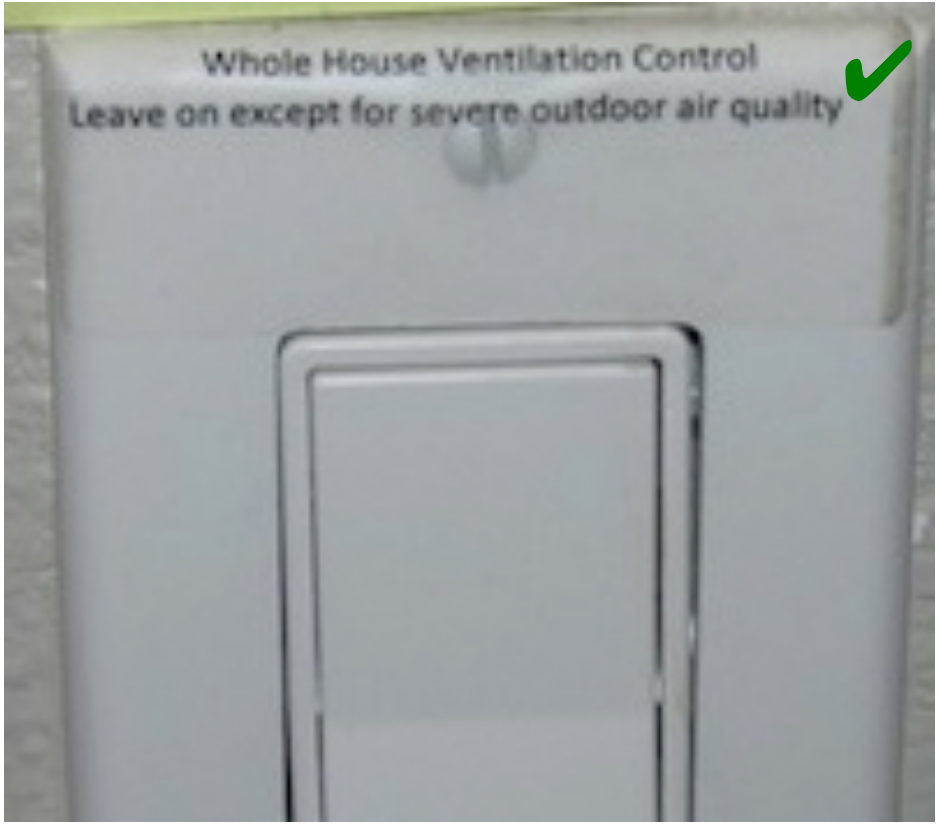
Labels not always clear

✖ CONTINUOUS DUTY

✔ To maintain minimum levels of outside air ventilation required by the State of California, this fan should be on at all times when the building is occupied, unless there is outdoor air contamination.

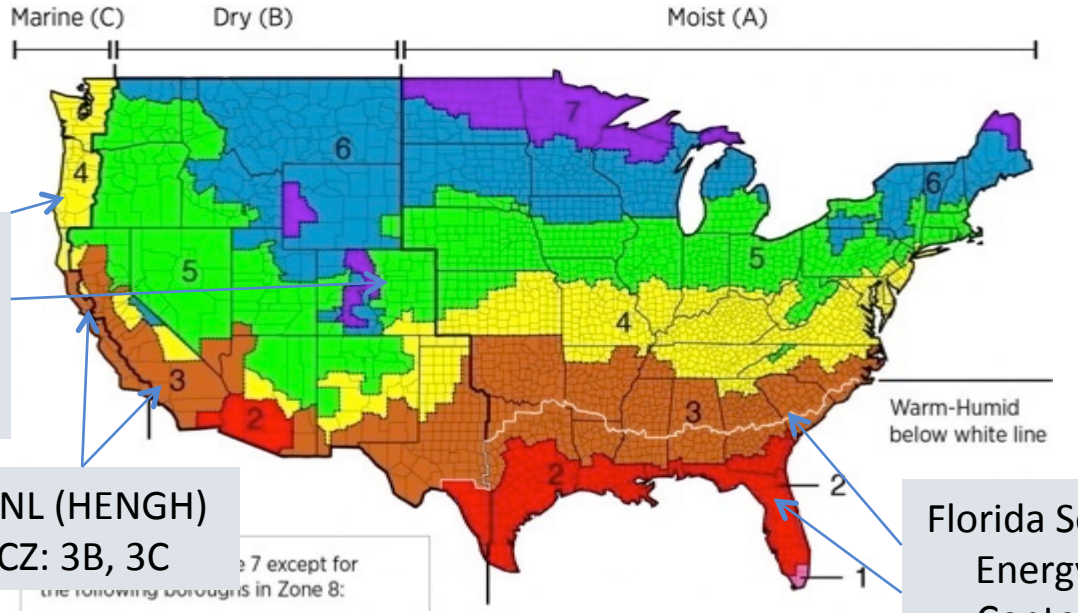



Keep fan
"ON" at
all times
except in
case of
outdoor air
contamination
or if home
is vacant
for more
than 7 days


Whole House Ventilation Control
Leave on except for severe outdoor air quality

Building America IAQ Study

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



Pacific NW National Lab
CZ: 4C, 5B

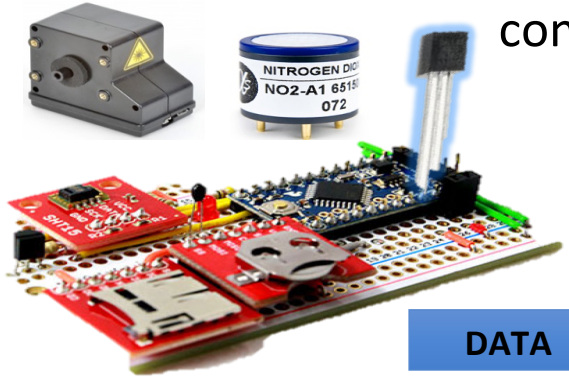
LBNL (HENGH)
CZ: 3B, 3C

Florida Solar Energy Center
CZ: 2A, 3A

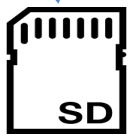
- Characterize home, mechanical equipment
- Monitor ventilation, IAQ, activities for 1 week
- Repeat in 8 homes per CZ with/out MV operating

Low-cost sensors for air quality monitoring

Sensors generate signals in response to environmental conditions



Calibrations translate signals to data



Data sent to cloud & displays; may be stored onboard

Cloud stores data, presents visualizations

Local displays indicate hazards and suggest mitigating actions

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Available info on sensor performance

- EPA has done some work focusing on outdoors

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

- South Coast AQMD tests outdoor & in chambers

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

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LBNL Evaluation of Consumer PM Monitors

AB

PM, T, RH

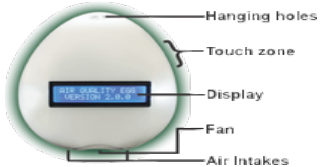
1 sec

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

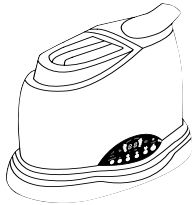





Heated pots of water, an oven, a hair dryer, and an electric burner

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

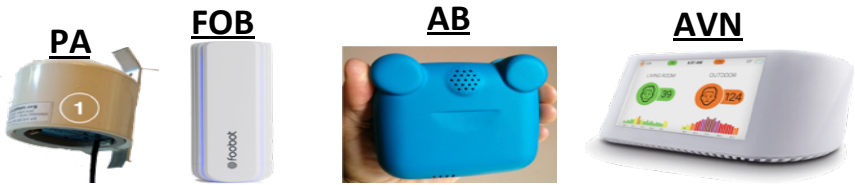


Released AZ test dust, shaked a dust mop, and operated an ultrasonic humidifier

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

These 4 could be used in managing 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

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

Problems Affecting Occupant Comfort a Few Times per Week or More Frequently	Online Survey Built 2002-8 SoCal (N=2271)	Field Study Built 2011-7 California (N=70)
Too hot in summer	41%	31%
Too cold in winter	20%	29%
Not enough air movement	18%	21%
Too hot in winter	10%	14%
Indoor air too dry	11%	9%
Too cold in summer	9%	4%
Too much air movement	5%	1%
Musty odor	3%	1%
Indoor air too damp	2%	1%

Take the Berkeley New Home IAQ Survey

https://iaqsurvey.lbl.gov/

EXTRA SLIDES

Recipe for good IAQ in ZEH

- Take care of water / moisture
  - drainage, vapor barriers, etc.
- No combustion appliance uses house air
  - Except gas cooking w/good range hood
- Low-emitting materials
- Induction cooking?
- Exhaust ventilation in wet rooms
  - Energy Star quiet & efficient fans
  - Kitchens must vent to outside
  - Kitchen MUA >400 cfm and < 2ACH50
  - Automate range hoods and bathroom exhaust?
- Test for Radon
- Whole House Ventilation
  - ASHRAE 62.2 minimum
  - Balanced best in tight homes
- MERV 13 filters on supply ventilation and central forced air
  - 2 in., sealed filter slot
  - Minimum runtime
- Dedicated dehumidification in humid SE climates
- Label everything
- Easy access for maintenance

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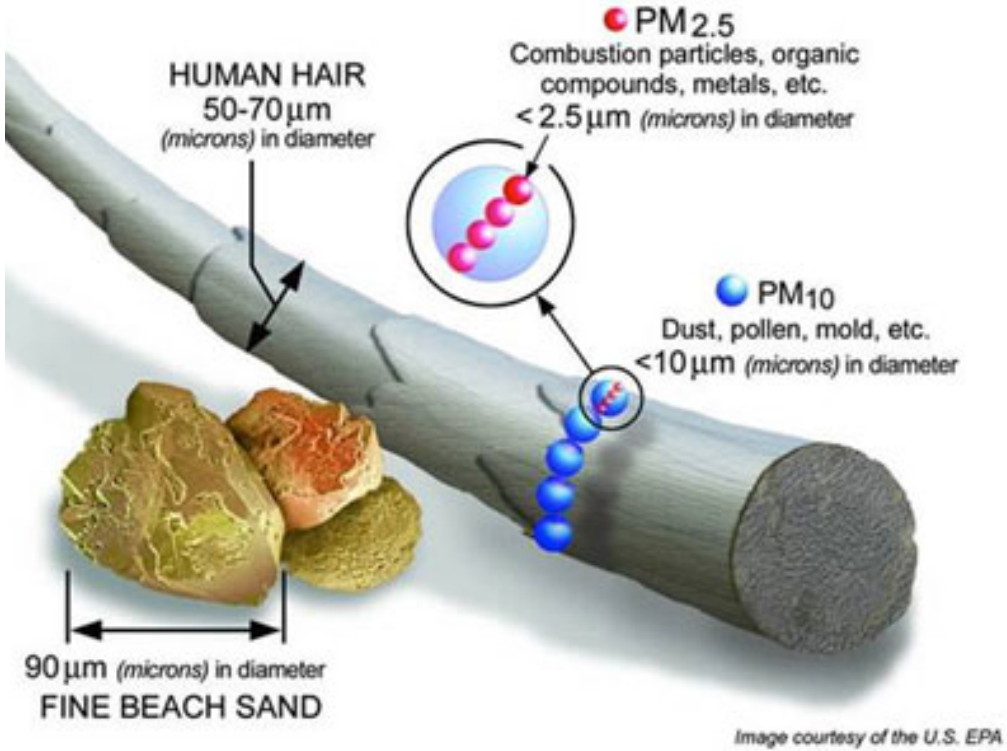
Fine particulate matter ($PM_{2.5}$)



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

Sources of $PM_{2.5}$ in homes

Outdoor pollution is largest source overall

Indoor sources more important if used often in your home

CalEPA Ambient Standard

12 µg/m^3

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Which IAQ parameters do we want to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- Odors

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ultrafines
  - Acrolein, NO_2, CO
  - Formaldehyde, radon
  - Irritants
  - Allergens

- Outdoor pollutants
  - Diesel PM / black carbon
  - Ozone
  - $PM_{2.5}$, PM_{10}, ultrafines, NO_2

- Dampness & mold

Which IAQ parameters do we want to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Available & affordable

Available, but costly

Coming soon?

~~X~~ Not needed

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ultrafines
  - ~~Acrolein~~, NO_2, CO
  - Formaldehyde, radon
  - ~~Irritants~~
  - ~~Allergens~~
- Outdoor pollutants
  - Diesel PM / black carbon
  - Ozone
  - $PM_{2.5}$, PM_{10}, ultrafines, NO_2
- ~~Dampness & mold~~

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.

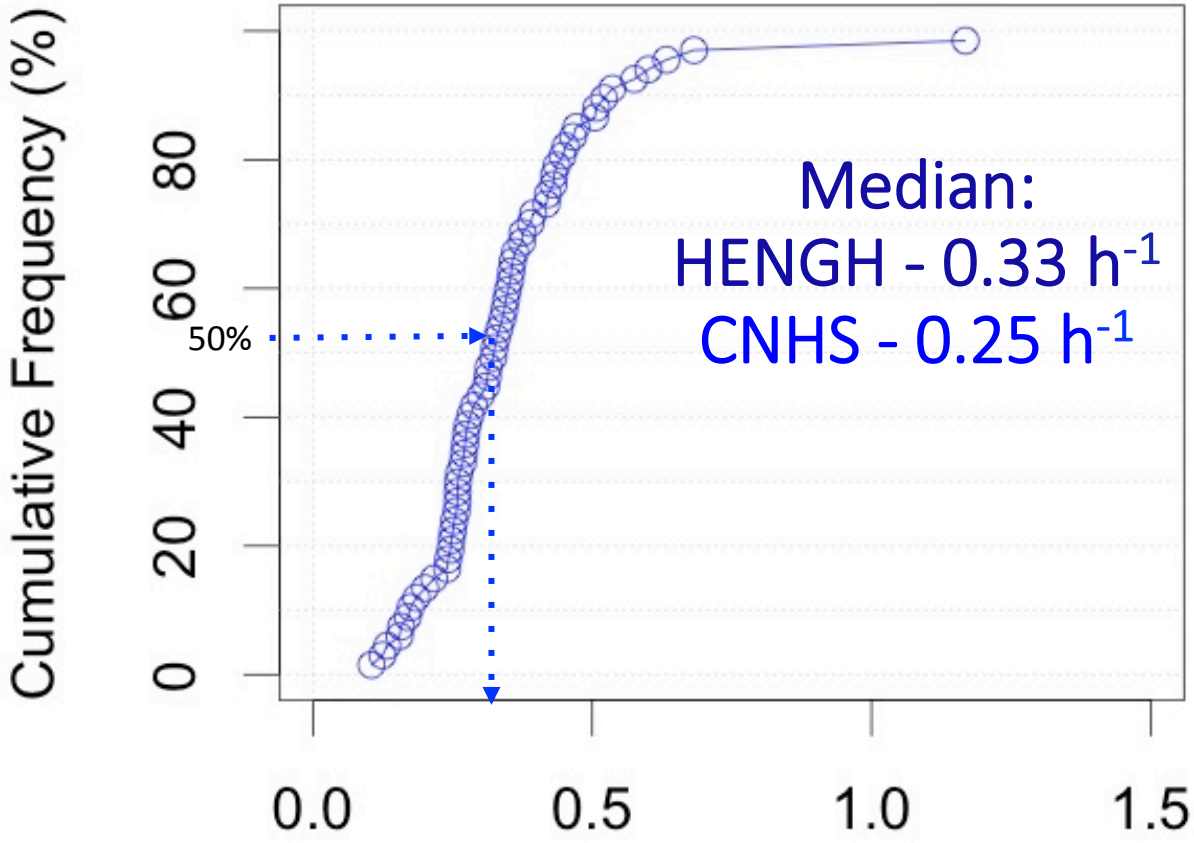
Climate Change

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

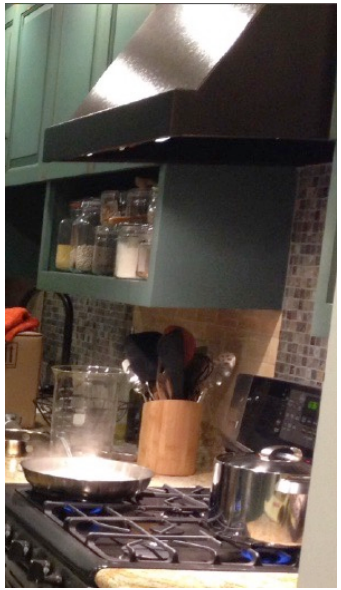
IAQ in Schools

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

Most homes between 0.2 and 0.6 ach

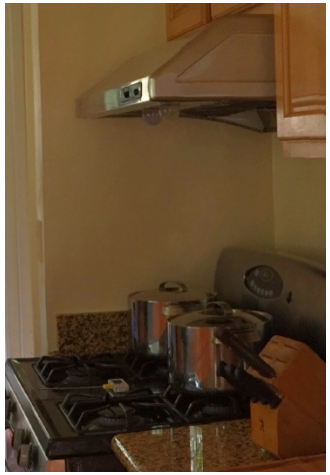


Field study of range hood benefits



H1

H2



H5

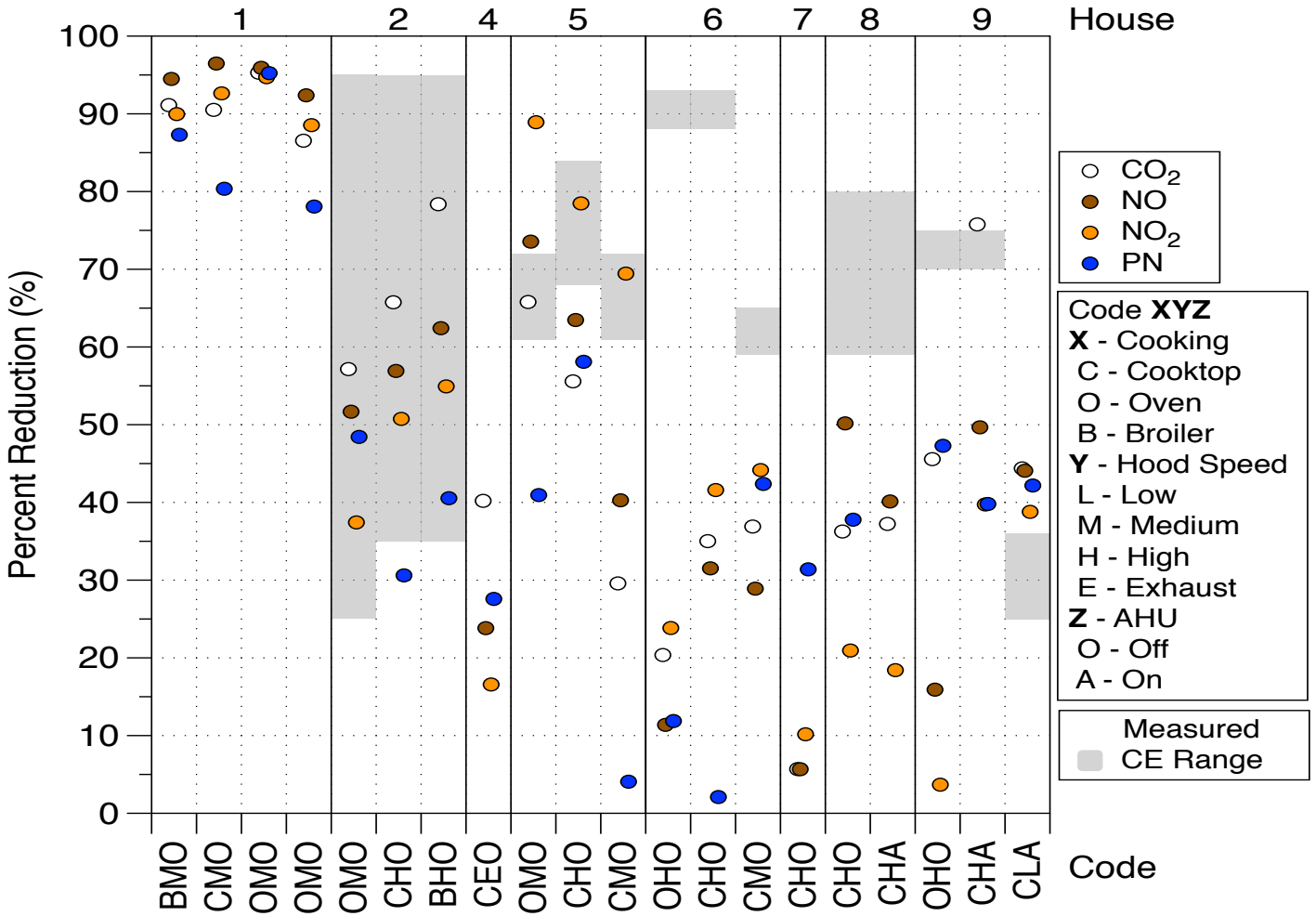
H6

H9

H8

Singer et al., 2017, Building Environment

Installed range hoods provide varying benefits



Singer et al., 2017, Building Environment

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

What pollutants do we have to worry about?

From Inside **From Inside + Outside** **From Outside**

Particulate matter:

- **PM_{10}, $PM_{2.5}$, Ultrafine particles**
- **Metals; Acids; Condensed organics**

Nitrogen dioxide: NO_2

Carbon monoxide: CO

Ozone

Gas-phase organics (VOC)

- **Formaldehyde**
- **Other aldehydes**
- Benzene
- **Acrolein**
- Organic acids
- **Semi-volatile organics (SVOC)**

Mold and dampness
Allergens in air and dust

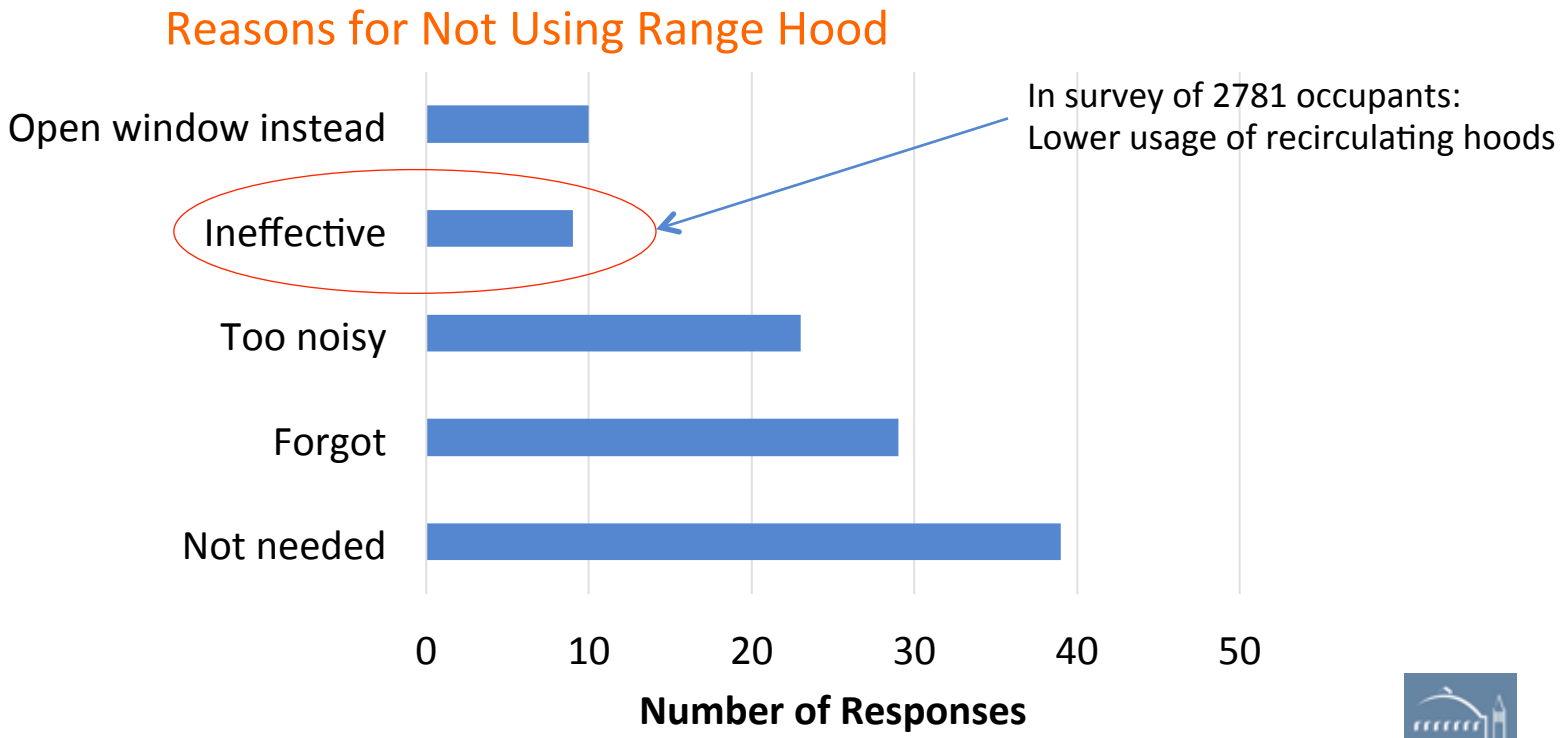
Bioeffluents including CO_2
Viruses (maybe)

Radon

Formaldehyde

From building materials

Half of the HENGH households reported using range hood sometimes or less frequently



Nitrogen Dioxide

Exceeds Outdoor Standards in> 60 million homes

Carbon Monoxide from BAD combustion

Exceeds Outdoor Standards in 5-10 million homes

Kills 180 people/year

150 of those are very dumb

Healthy Efficient New Gas Homes Study (HENGH)

Rengie Chan

Yang-Seon Kim

Brett Singer

Iain Walker

BERKELEY LAB

STATE OF CALIFORNIA ENERGY COMMISSION

Building AMERICA U.S. Department of Energy

PG&E

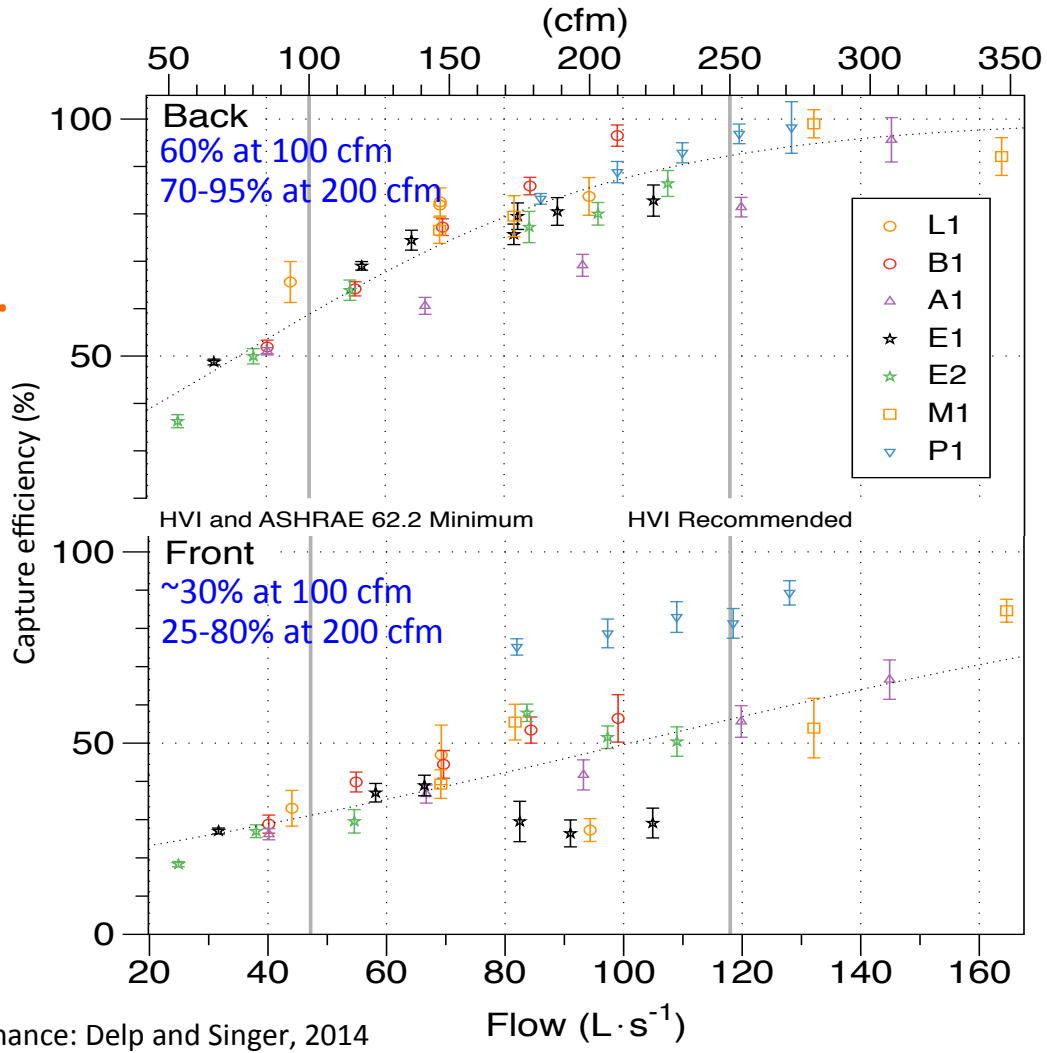
SoCalGas A Sempra Energy utility

gti

Lab study of range hood performance

Capture increases with airflow.
Much better for back burners!

For front burners, range hood at 100 cfm captures ~30%

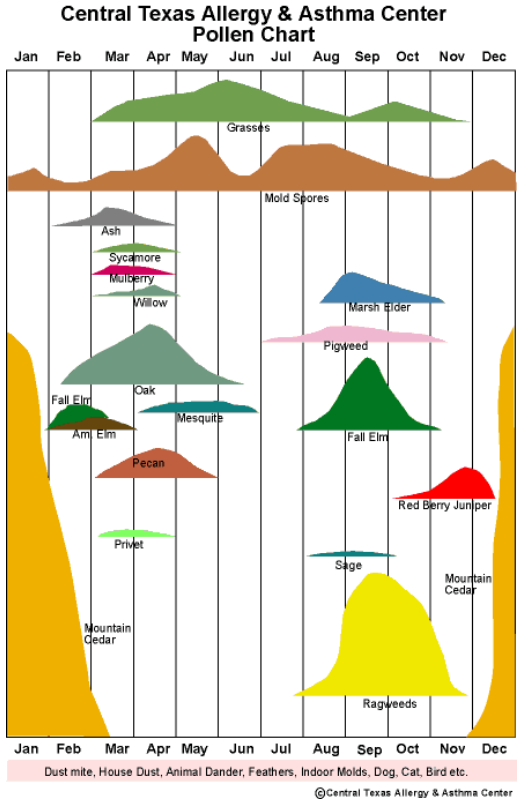


Lab performance: Delp and Singer, 2014

Air pollutants

Odors

& Allergens



Moisture