INDOOR AIR QUALITY IN HIGH PERFORMANCE HOMES

Iain Walker & Brett Singer
2017 RESNET Conference

Overview of Presentation

- Recommendations – Iain and Brett
- Introduction to IAQ challenges – Brett
- History of IAQ studies in efficient homes – Iain
- Build tight, ventilate right – Iain
- Formaldehyde, kitchen ventilation and filtration – Brett
- Commissioning and installed performance – Iain
- Recommendations, reprised
- Questions - Audience

Iain's IAQ Recommendations

- Use low-emitting materials
- Encourage occupants to consider safety of consumer products
- ASHRAE 62.2-2016 is a minimum
- Pick good range hoods (will be easier in the future with capture efficiency standard))
- Commission everything
- Use at least MERV 13 filters on central forced air and supply air ventilation
- For health:
  - Focus on particles, formaldehyde, cooking and other unvented combustion
- Talk to occupants/owners –
  - Main Hazards: combustion, cleaning products, formaldehyde

Brett's IAQ Recommendations I

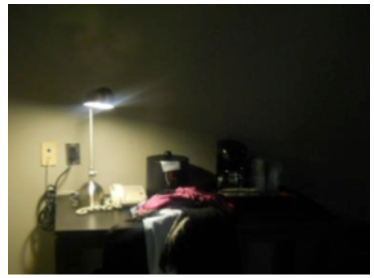
- Recognize that people have the biggest impact on IAQ in most homes
- Keep it dry (and mold free); dehumidify as needed
- Avoid emitting large quantities of contaminants in home. Ventilate when emitting.
  - Ventilate when cleaning, doing hobbies
  - Pay attention to chemicals in consumer and personal care products
- Provide task ventilation and use it as needed
  - Kitchen, bath, toilet exhaust;
  - Laundry and clothes closet as needed
- NO UNVENTED COMBUSTION HEATERS!!!

Brett's IAQ Recommendations II

- Use natural ventilation when outdoors is clean
- Tight envelope and ducts; close house when outdoors is polluted
- Check radon and formaldehyde using integrated samplers
- Very good FAU filter with seal (no bypass); confirm low static P
- If more filtration needed (occupant health challenges), use efficient standalone or central system with very efficient FAU motor

Housing impacts health in many ways

Thermal, sound, and light conditions



Anything that affects sleep

Control over environmental conditions

Accessible play areas

Mobility

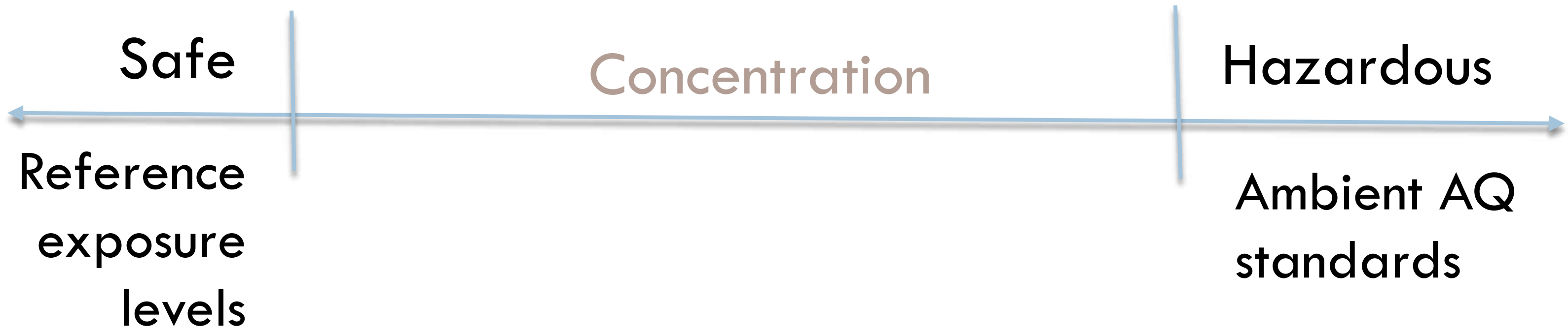
Connections to nature

Environmental health hazards

What is good indoor air quality?

- No unpleasant odors
- Air seems “fresh” and pleasant
- Comfortable temperature and humidity
- Allergens minimized
- No dampness or mold issues
- Pollutant concentrations at safe levels

What are the target pollutant levels?



- **Ambient Air Quality Standards**
  - Set to protect sensitive sub-populations, e.g. **asthmatics**
  - Mostly based on human exposure data
  - CO, NO_2, $PM_{2.5}$, PM_{10}, Ozone, Lead, SO_2
- **Reference Exposure Levels (RELs)**
  - Level below which **no adverse effects expected**
  - **Acute (hours)** and **Chronic (years to lifetime)**

Indoor Sources: Biological agents

Indoor Pollutant Sources: Chemicals

Indoor Pollutant Sources: Combustion

Indoor Pollutant Sources: Outdoor Air

Which contaminants are of greatest concern?

Prioritize based on population harm

Disability Adjusted Life Years (DALYs)

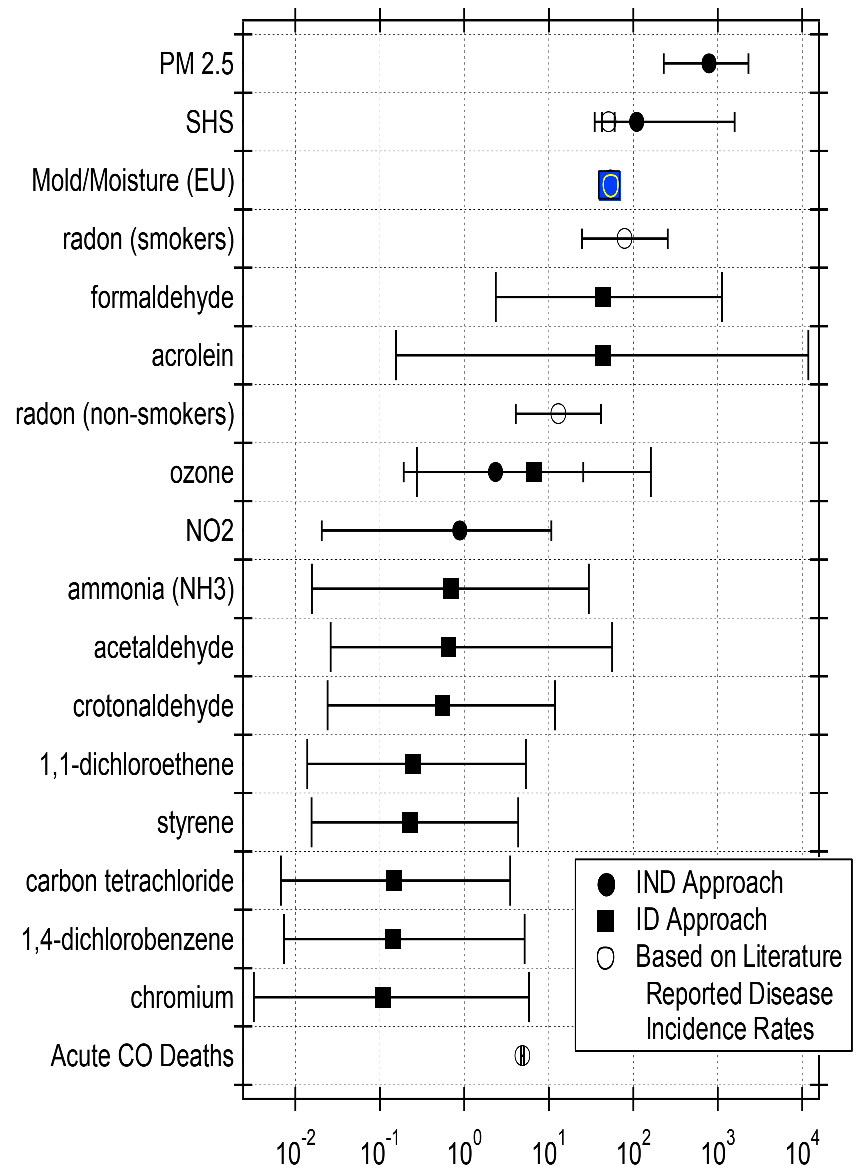
DALY = YLL + YLD

YLL = Years lost to premature death

YLD = Equiv. years lost to disability

$$\textit{Intake} \times \frac{\Delta \textit{Disease}}{\Delta \textit{Intake}} \times \frac{\Delta \textit{DALYs}}{\Delta \textit{Disease}}$$

→ ***DALYs per pollutant***

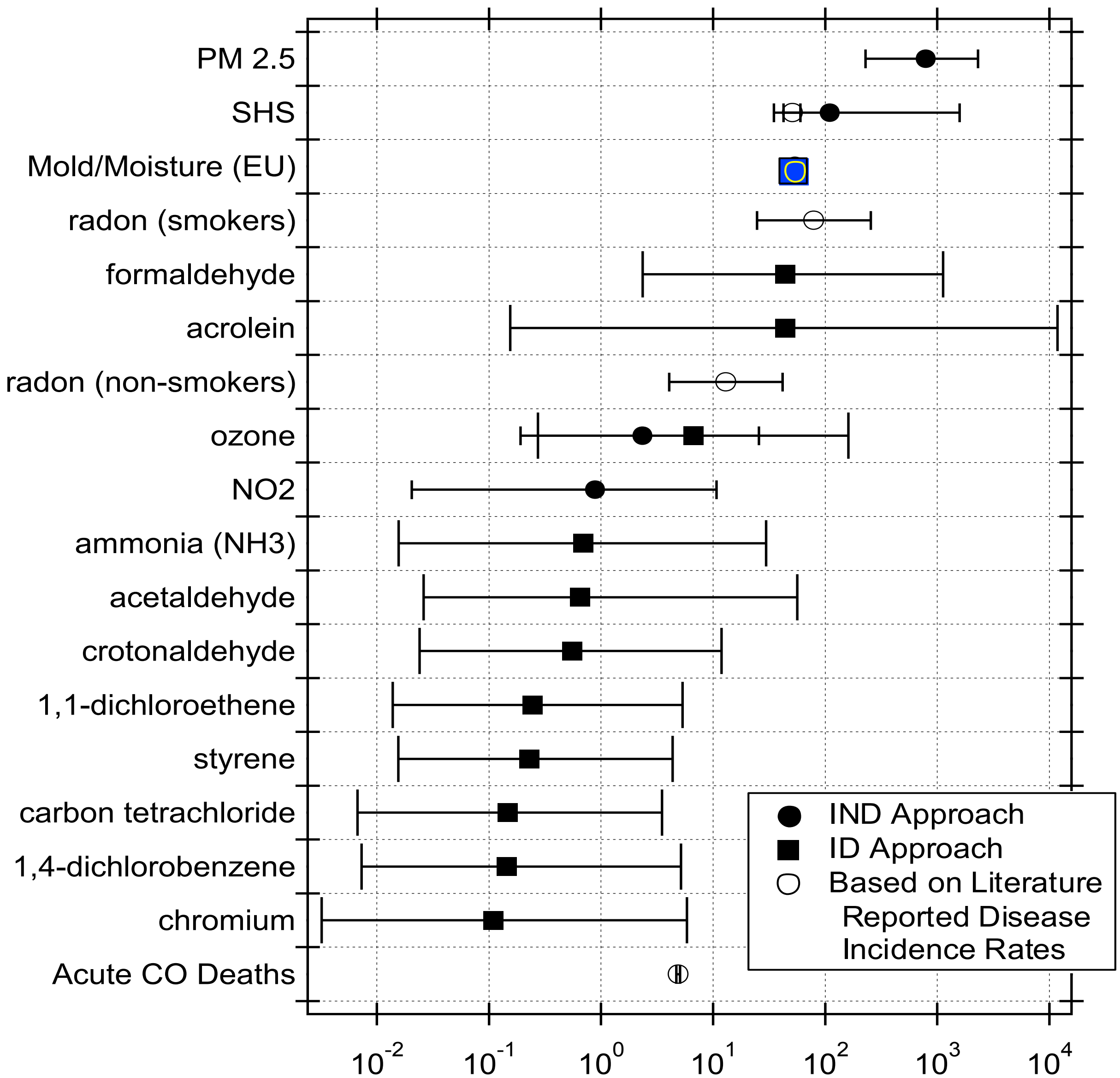


Consider exposure and severity of health outcomes

Logue et al., Environmental Health Perspectives, 2012

Which contaminants are of greatest concern?

$PM_{2.5}$
Tobacco smoke
Radon
Formaldehyde
Acrolein
Ozone
NO_2



Logue et al., Environmental Health Perspectives, 2012

History of IAQ in Efficient Homes: Canada

IAQ in R-2000 & conventional Canadian homes, since ~1984

- R-2000 requirements:
  - Airtightness (1.5 ACH_{50})
  - Mechanical ventilation with ERV/HRV
  - Low-emitting materials
  - Commissioning
- Results:
  - IAQ and efficiency can be compatible
  - Equivalent or lower pollutants in R-2000 homes

vs.

Coordinated national effort, requirements and specifications refined over time, informed by measurements of pollutants and ventilation parameters in homes that participated in the program.

Summarized in Less (2012)

Riley & Piersol, 1988; Gusdorf & Hamlin, 1995; Gusdorf & Parekh, 2000; Shaw et al., 2001; Leech et al., 2004

History of IAQ in Efficient Homes: U.S.

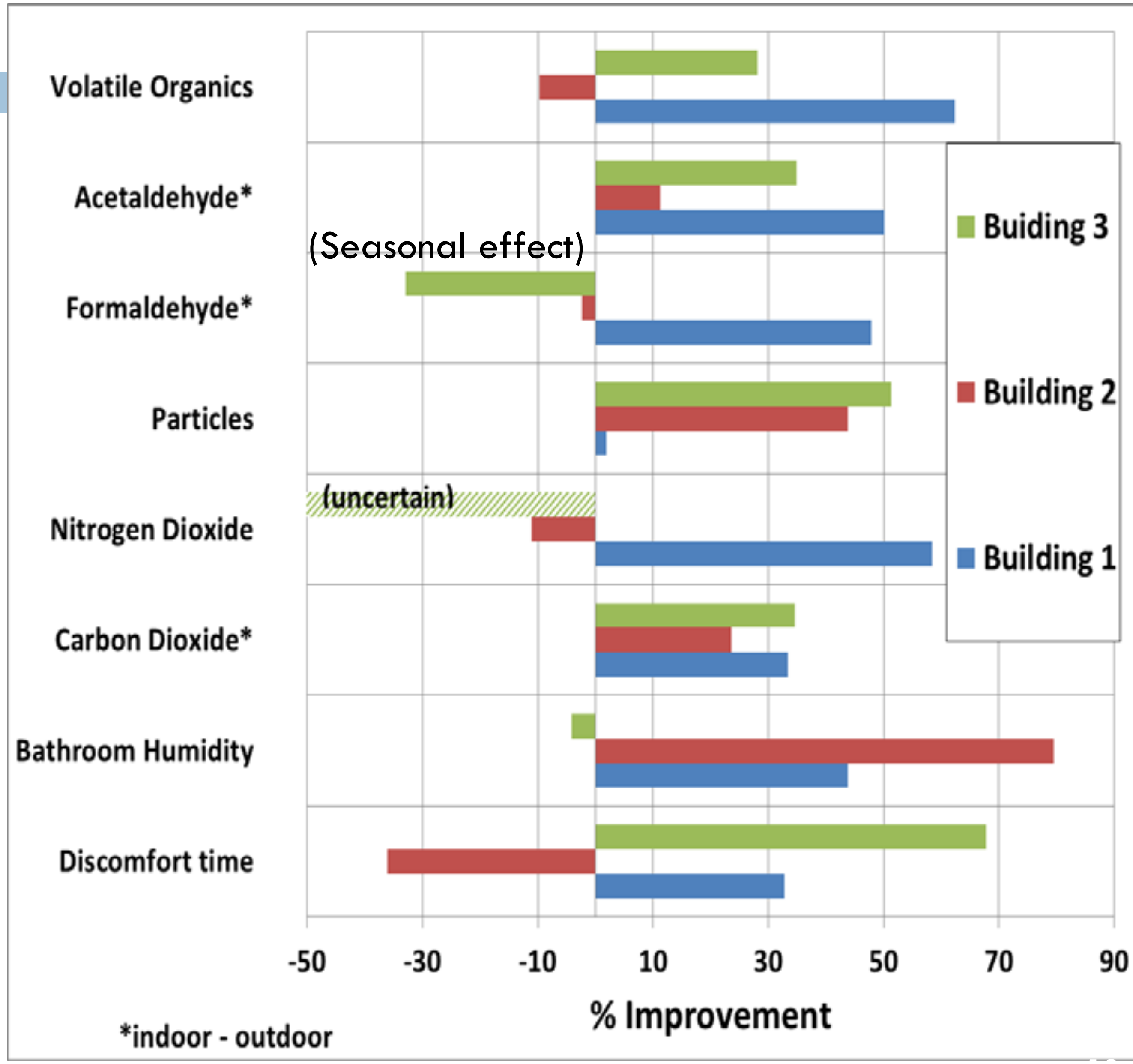
- Assessments in U.S. homes much less clear
  - Uncoordinated efforts
  - Inconsistent definitions of "efficient"
  - Less stringent or optional efficiency requirements
  - Small sample sizes
- Early research suggested efficient homes had increased pollutant levels
  - Hollowell et al., 1978; Berk et al., 1980; Fleischer et al., 1982
- More rigorous studies found similar levels in efficient and conventional homes
  - Offermann et al, 1982; Grimsrud et al., 1988; Harris, 1987; Turk et al., 1988; Hekmat et al., 1986

Recent Consensus

- Energy efficient homes can have BETTER IAQ
  - Sealed crawlspaces have lower moisture levels, mold and spore transmission to inside home (Coulter et al., 2007)
  - Increased airtightness reduces pollutant entry from attached garages (Emmerich et al., 2003)
  - Tighter ducts limit transport from attics, crawlspaces and garages
  - Mechanical ventilation results in more consistent air exchange, without under-venting periods
  - Combustion safety testing, sealed combustion appliances, filtration, etc.

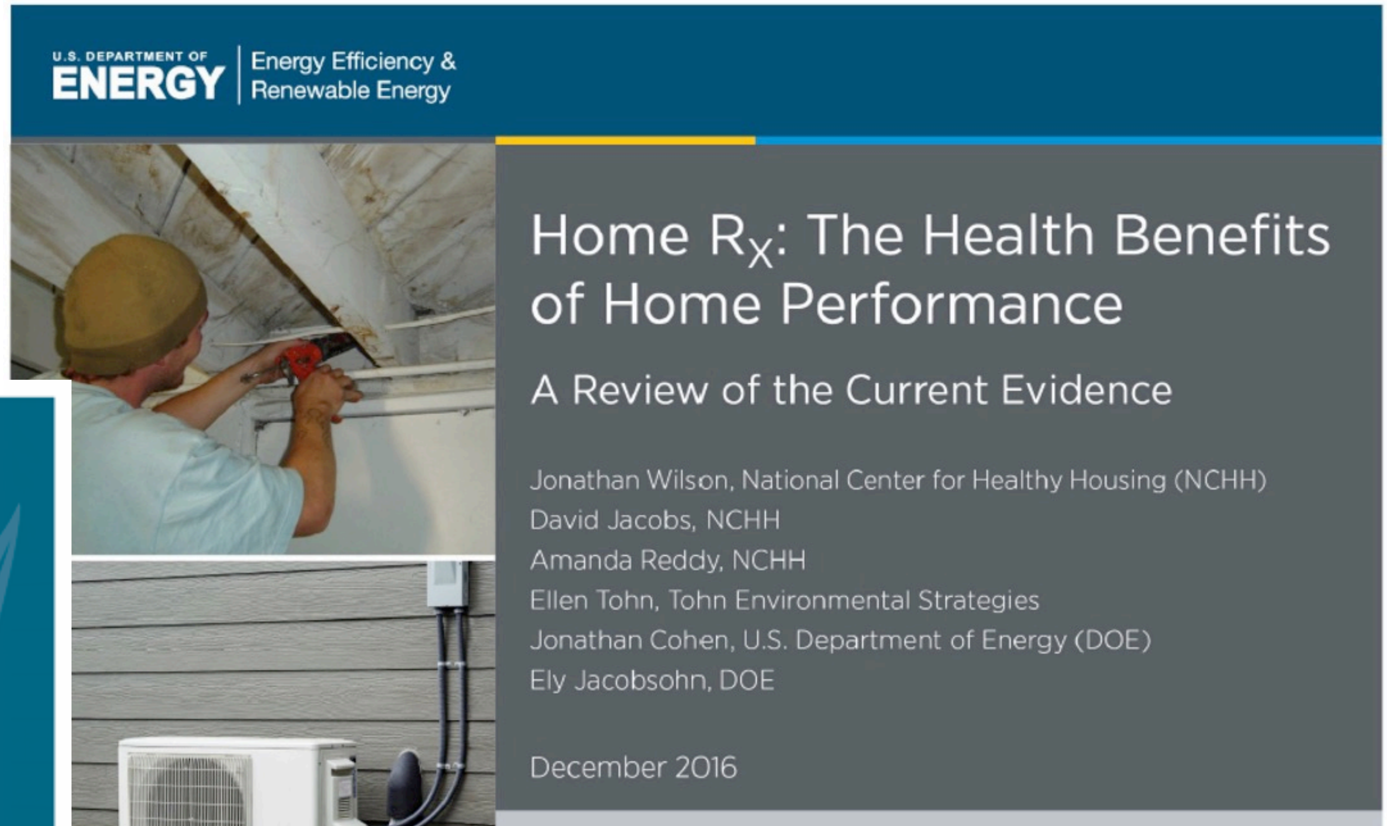
CA MF retrofits study: improved energy and IAQ

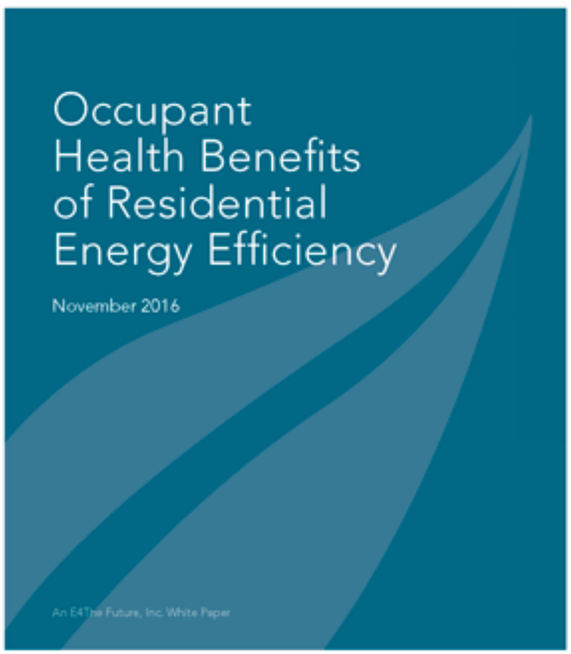
- 18 California low-income apartments in 3 buildings
- Air-sealed
- 1.5x 62.2 dwell unit ventilation
- Range hoods & bath fans
- Efficient standalone air filters



Noris et al., Building and Environment, 2013; Slide credit: Fisk

Very Recent Literature Reviews





E4 THE FUTURE

Summary of Recent IAQ studies

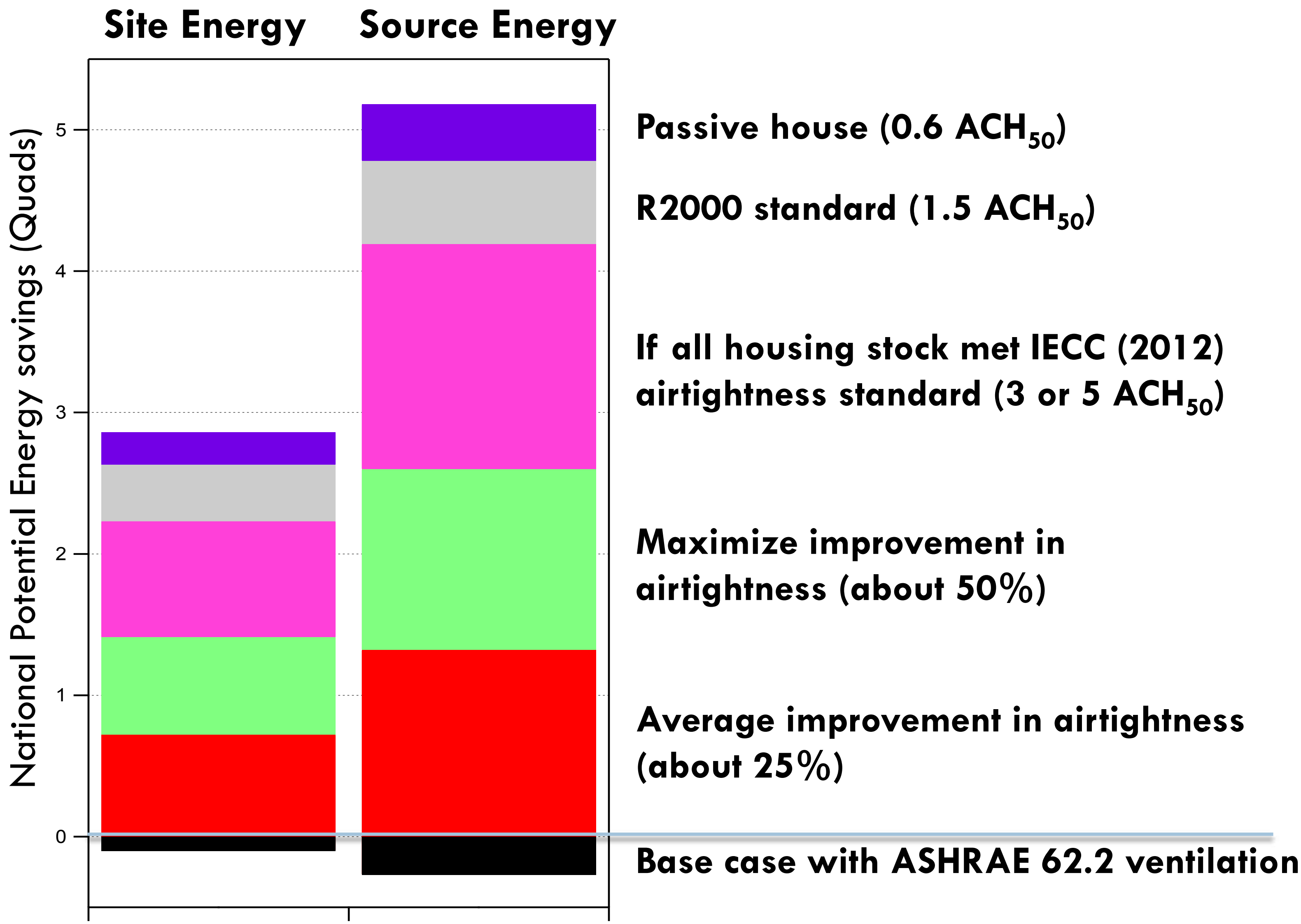
- Failure to follow best practices—ventilation, source control, occupant education—may lead to increases in pollutant levels and health effects
  - Tohn, 2012; Wilson et al., 2013; Emmerich, Howard-Reed, & Gupte, 2005; Milner et al., 2014; Offermann, 2009
- Substantial evidence suggests that with careful design and operation, high performance homes may improve occupant health and reduce pollutant levels
  - Breysse et al., 2011; Jacobs, 2013; Leech et al., 2004; Kovesi et al., 2009; Weichenthal et al., 2013; Norris et al., 2012

"BUILD TIGHT, VENTILATE RIGHT"

But what the heck does that mean?!?

How tight?
Ventilate how much?
Where and with what?
Is that all I need to do?

Big Energy Rewards for Airtightening, But Returns Diminish



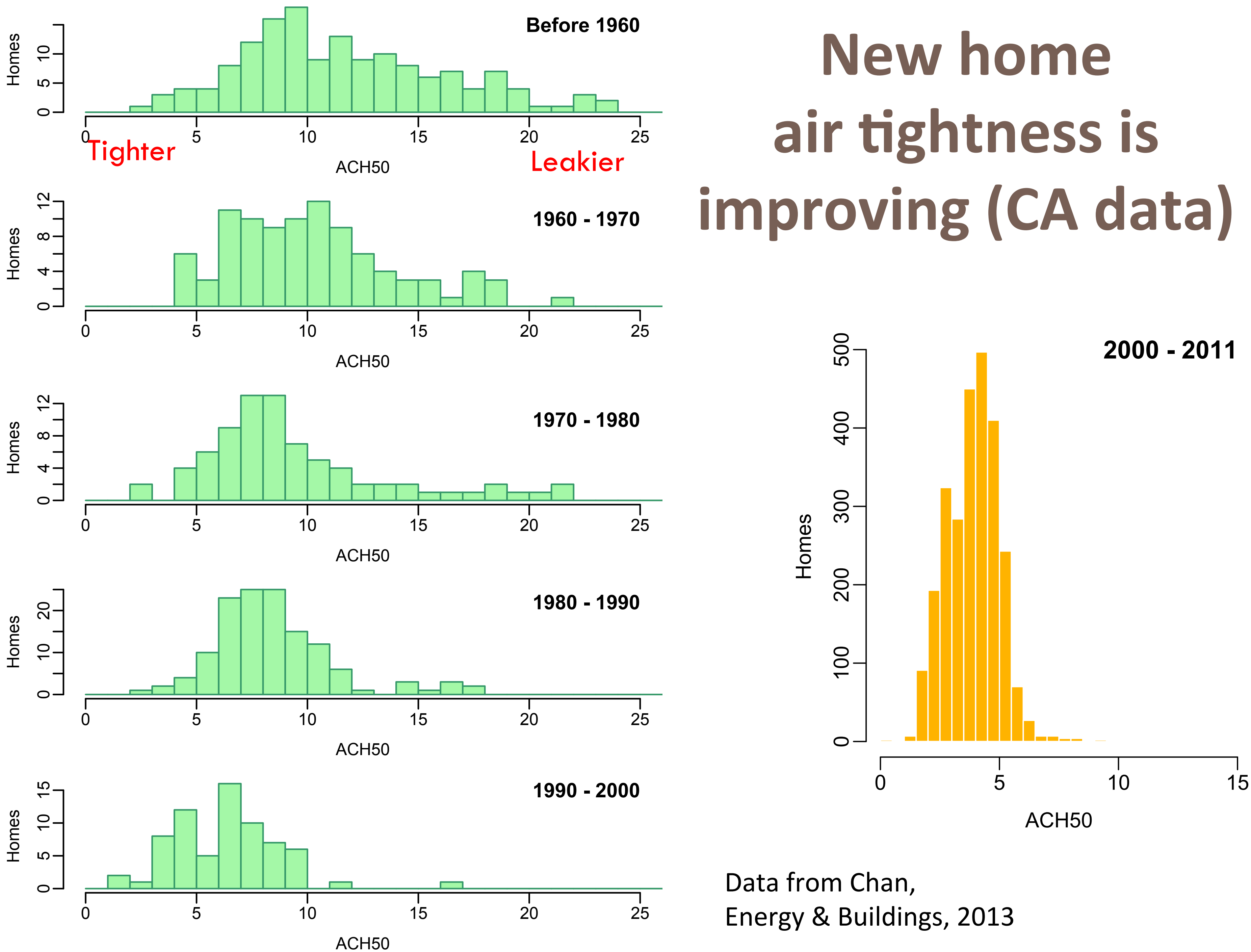
Slide courtesy Rengie Chan, LBNL

New Homes Getting Tighter

LBNL Air Leakage Database: > 130,000 blower door tests

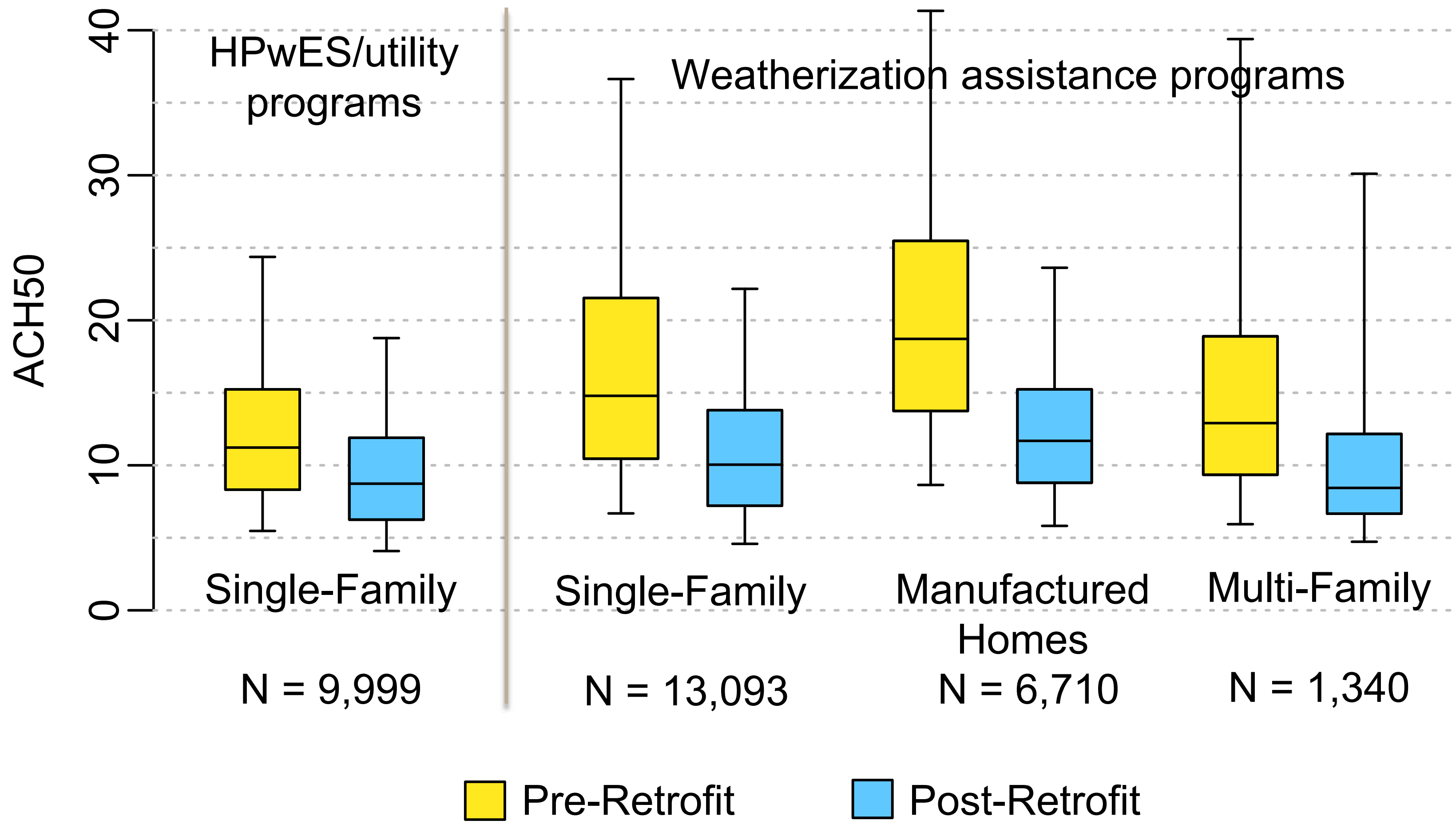
- Housing stock average: 15 ACH50
- 90's homes: 7 ACH50
- Post-2000 homes: 5.5 ACH50
- 2012 IECC : 3 to 5 ACH50
- ZEH < 2 ACH50

New home air tightness is improving (CA data)



Data from Chan,
Energy & Buildings, 2013

Retrofits improve existing buildings (National data) – resdb.lbl.gov



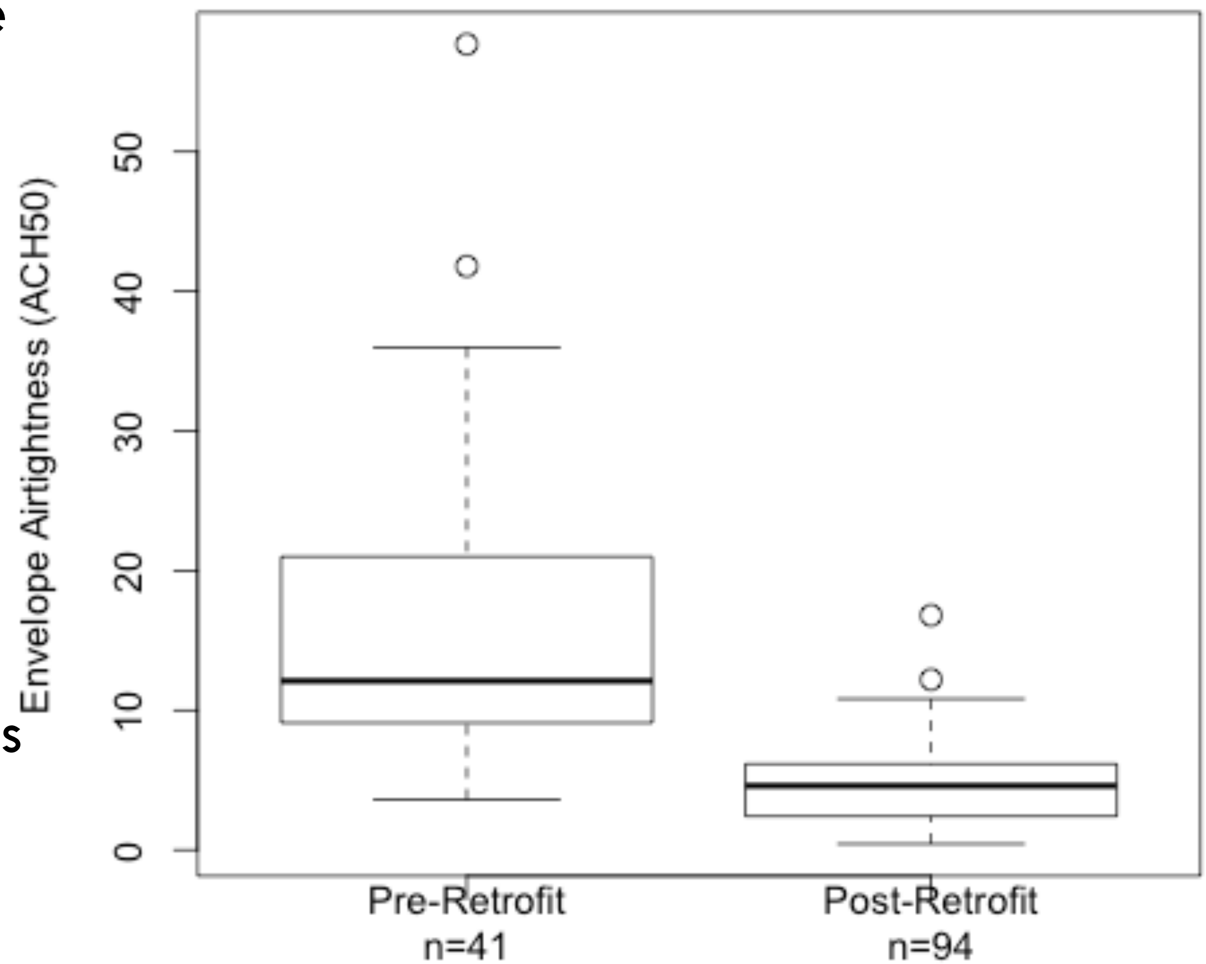
Median:	-20%	-30%	-35%	-28%

Airtightness in U.S. Deep Energy Retrofits

Summary of available DER literature

- **63% average leakage reduction**

- **NOT VENTILATED RIGHT!**
  - 71% mechancially vented in 103 projects
  - **Only 47% vented in 47 non-Cold climate projects**



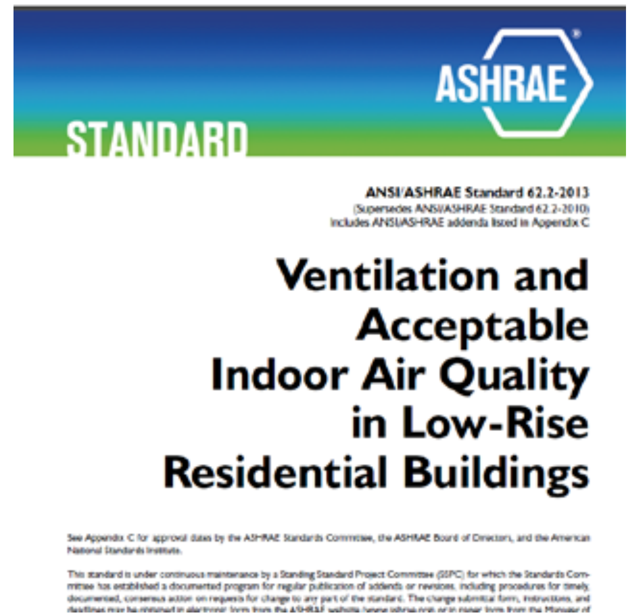
Mean = 16.1 ***Mean = 4.7***

So… How Tight Is Tight Enough?

- New homes
  - 3 ACH_{50} captures ~80% of savings
  - 1.5 ACH_{50} good high performance target
    - Achievable: <0.6 ACH_{50}
- Retrofit
  - >50% reduction
  - <5 ACH_{50}

How Much Ventilation?

- 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
  - Measure air flows
- "Good" = anything "better" than this minimum



62.2 Changes for 2016

- Includes dwelling units in MF buildings
- Existing buildings: no fan required if < 15cfm
- New time-varying (intermittent) calculations – will enable smart time shifted ventilation
- Changed local exhaust specifications so that non-enclosed kitchens do not need to meet the 5 ACH requirement. Also changed requirement for downdraft fans and other kitchen exhaust to be 300 cfm.
- Loosened air sealing requirements for MF compartmentalization from 0.2 to 0.3 cfm/sq.ft at 50 Pa.

Source Control

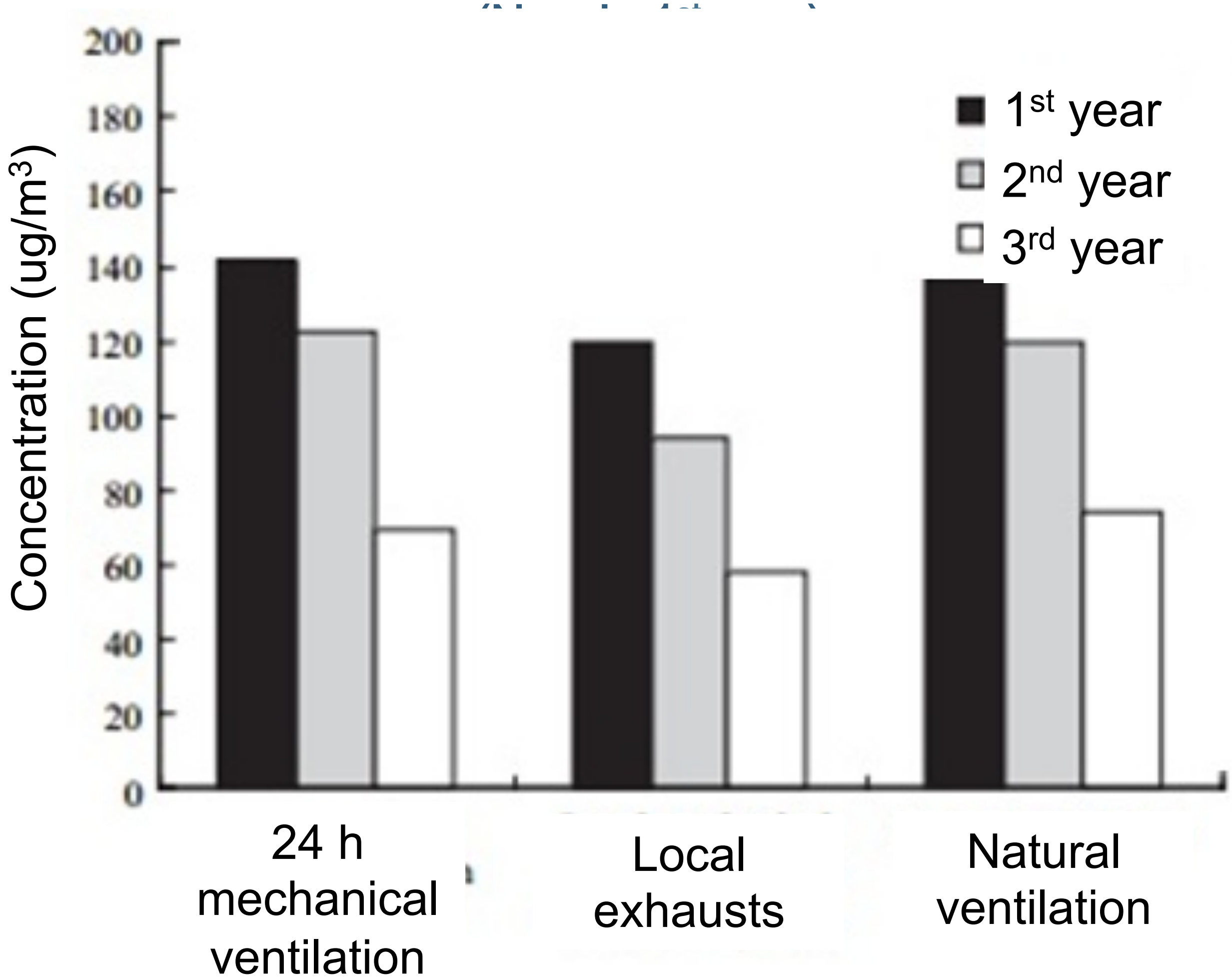
- VOCs emitted from materials built into the home
- VOCs in cleaning, personal care and other products
- Cooking and related combustion
- Candles, incense, oils
- Moisture and odors
- Carpets?

Building Material Source Control

- Lots of info and certifications for green building materials:
  - Scientific Certification Systems
  - Green Guard
  - Green Seal
  - Carpet and Rug Institute
  - Collaborative for High Performance Schools products database
  - Pharos database
  - Cradle-to-Cradle
  - GreenScreen assessed
- Prioritize materials with:
  - Most surface area
  - Direct paths of exposure (e.g., flooring over attic insulation)
  - Documented histories of contributing to IAQ issues

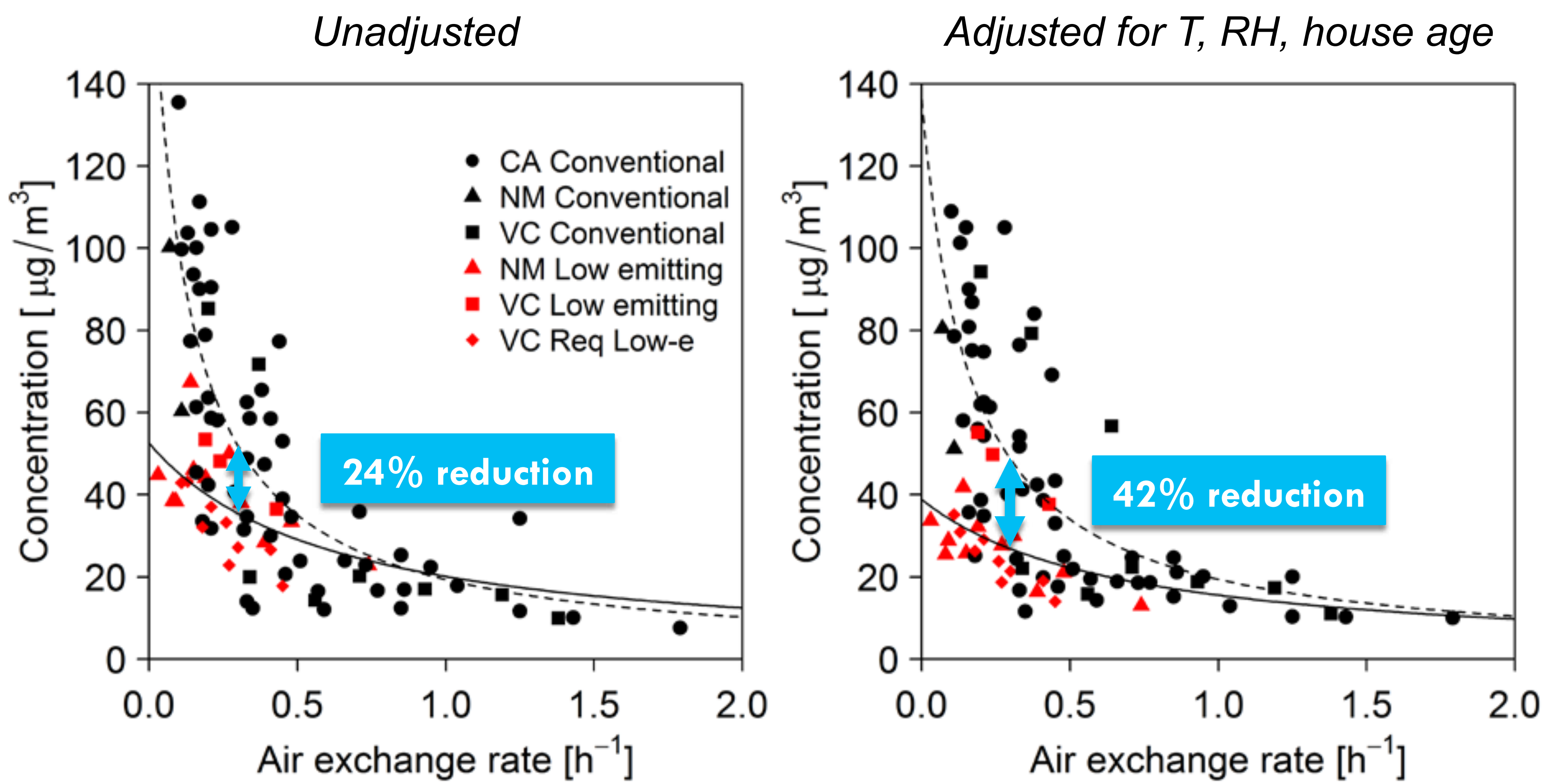
Formaldehyde highest in new homes; Concentrations decrease with age

Single-family houses in Japan



Park JS, Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air. 2006 Apr;16(2):129-35.

Homes with low-emitting materials have lower formaldehyde concentrations



Hult et al., Indoor Air, 2015

Cooking & burners emit air pollutants

CO_2 & H_2O

NO, NO_2, HONO, Formaldehyde

Ultrafine particles

Ultrafine particles, NO_X

Ultrafine particles

Formaldehyde

Acetaldehyde

Acrolein

$PM_{2.5}$

PAH

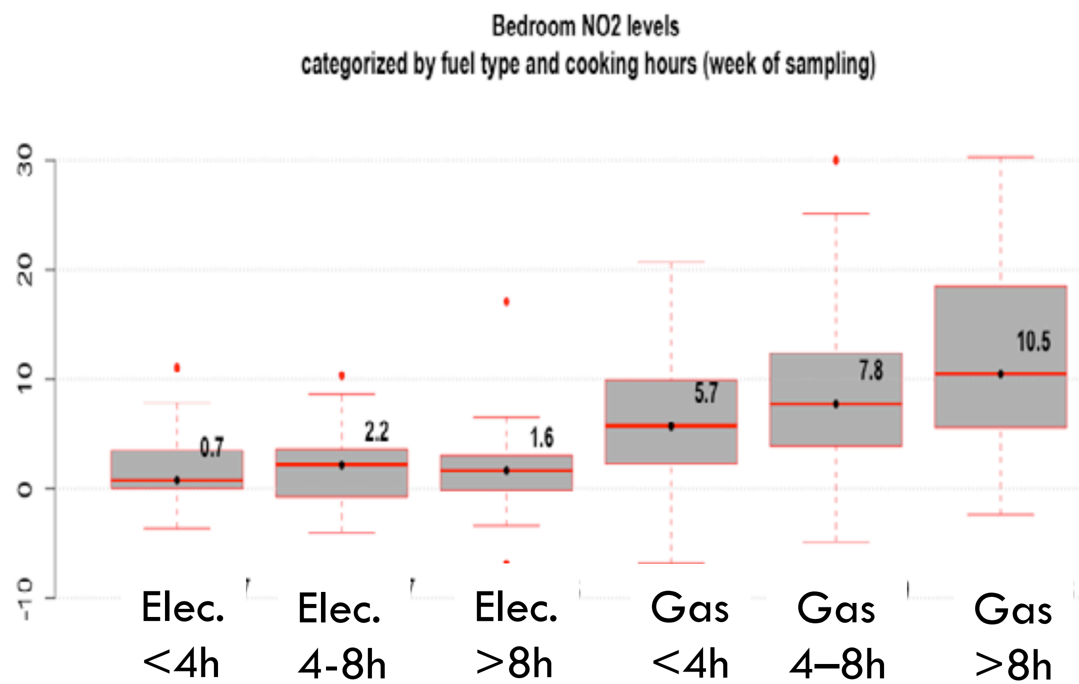
Gas cooking burners can impact IAQ

Simulations of 6634 SoCal homes;
Typical winter week;
Empirical AERs

	% above acute std	# in CA (est.)	# in US (est.)
CO	**7-8%**	**1.7M**	**10M**
NO_2	**55-70%**	**12M**	**66M**

Logue et al., 2014,
Environ. Health Perspec.

Measurements in 350 California homes;
1-week integrated, winter season

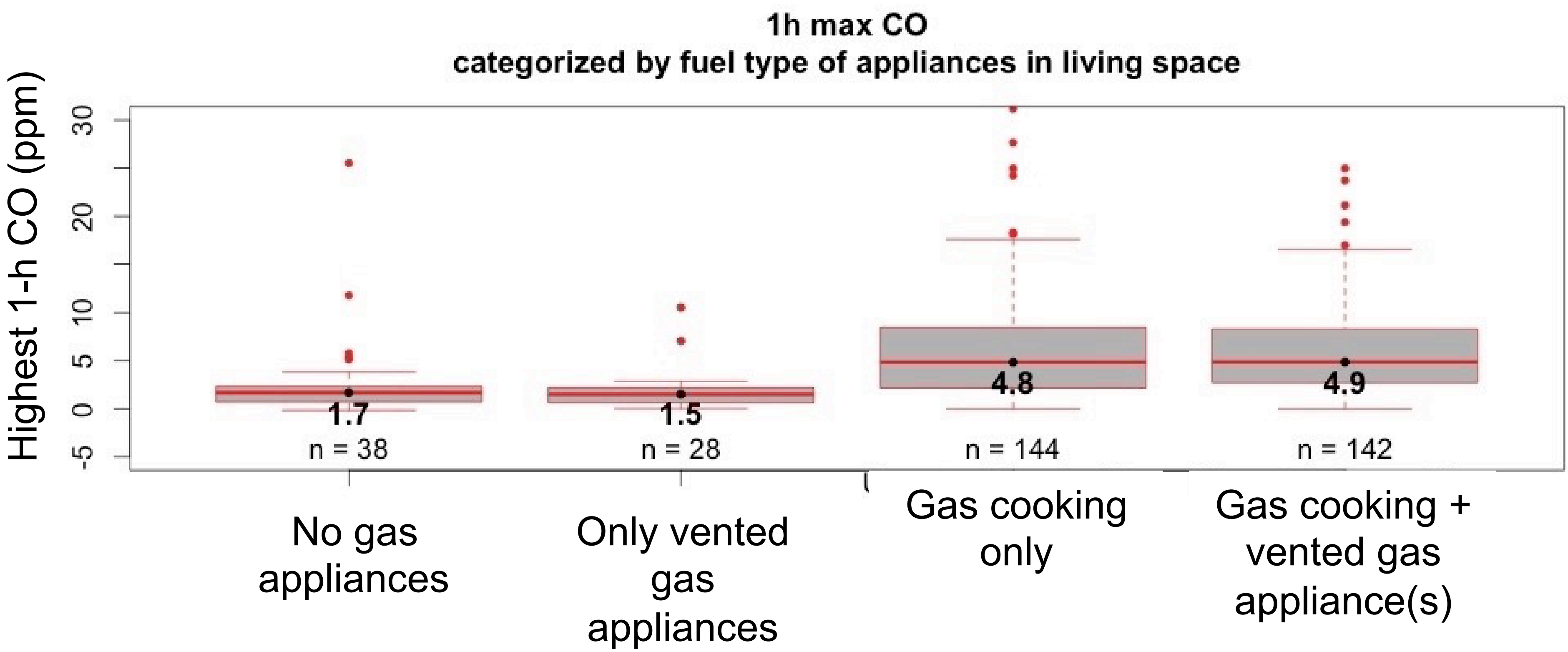


Mullen et al., 2015,
Indoor Air

Gas burners can impact CO as well

Measured CO concentrations indoors over a 6-day period

Mullen et al. 2012; Mullen et al. 2013



Inconsistent use of kitchen exhaust

Data from Cal. IAQ study; may be biased high

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

Kitchen exhaust use in Cal. IAQ study:

Reasons for using exhaust system	Number	Percent of 241 users
Remove smoke	**111**	**46%**
Remove odors	**75**	**31%**
Remove steam / moisture	38	16%
Remove heat	11	5%
Other reasons	5	2%
No reason selected	80	33%

Mullen et al. LBNL-5970E

Kitchen exhaust use in Cal. IAQ study:

Reasons for NOT using exhaust system	Number	% of 193 using <50% of time
Not needed	**92**	**48%**
Too noisy	**40**	**21%**
Don't think about it	**31**	**16%**
Doesn't work	19	10%
Open window instead	17	9%
Other reasons	7	<4%
Wastes energy	3	<2%
No reason selected or don't know	23	12%

Mullen et al. LBNL-5970E

Combustion and Cooking Source Control Recommendations for Tight Homes

- Install a range hood with high capture eff. and **use it**
  - Use even if oven separate from cooktop
- Don't overdue the range hood flow – consider need for make-up air
- Use direct-vented, sealed combustion equipment (furnace and water heater.)
- Avoid standing pilot lights, mostly on vintage gas ranges

How can you tell if a hood works well?

The effectiveness of range hoods at capturing cooking pollutants is called capture efficiency.

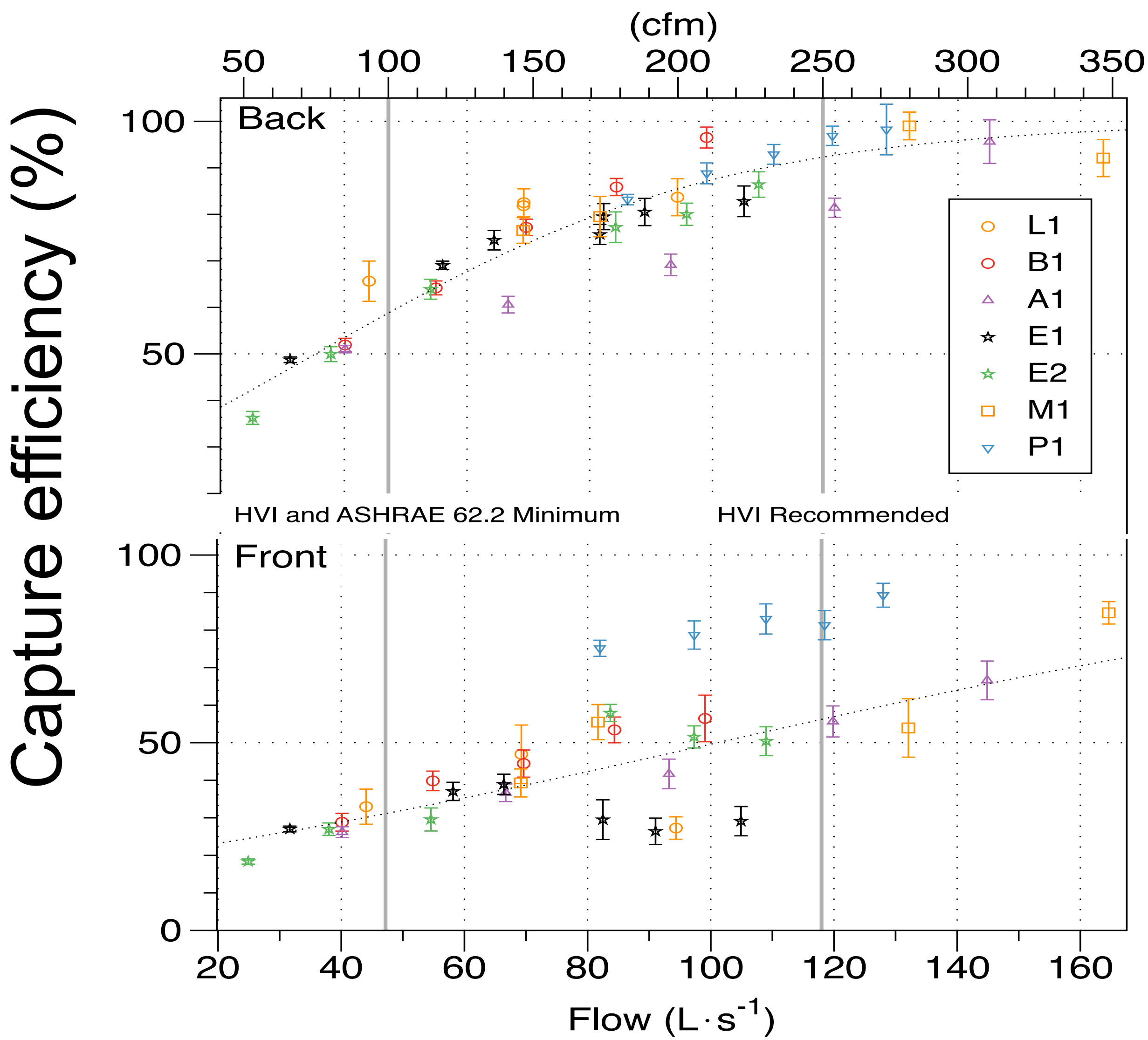
New ASTM test method.

LBNL Lab Testing

7 devices

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

Capture Efficiency—Lab Results



Reference Flows:

- 100 cfm
  - 60% back
  - 30% oven, front
- 200 cfm
  - ~80% back
  - 40-80% oven
  - 25-80% front

LBNL In-Home Performance Study

- 15 devices
- Cooktops
  - Pots with water
  - Front, back, diagonal
- Ovens
  - 425 F, door closed
  - Cool between tests




Range Hood Testing in Homes

Measure CO2 from gas burners

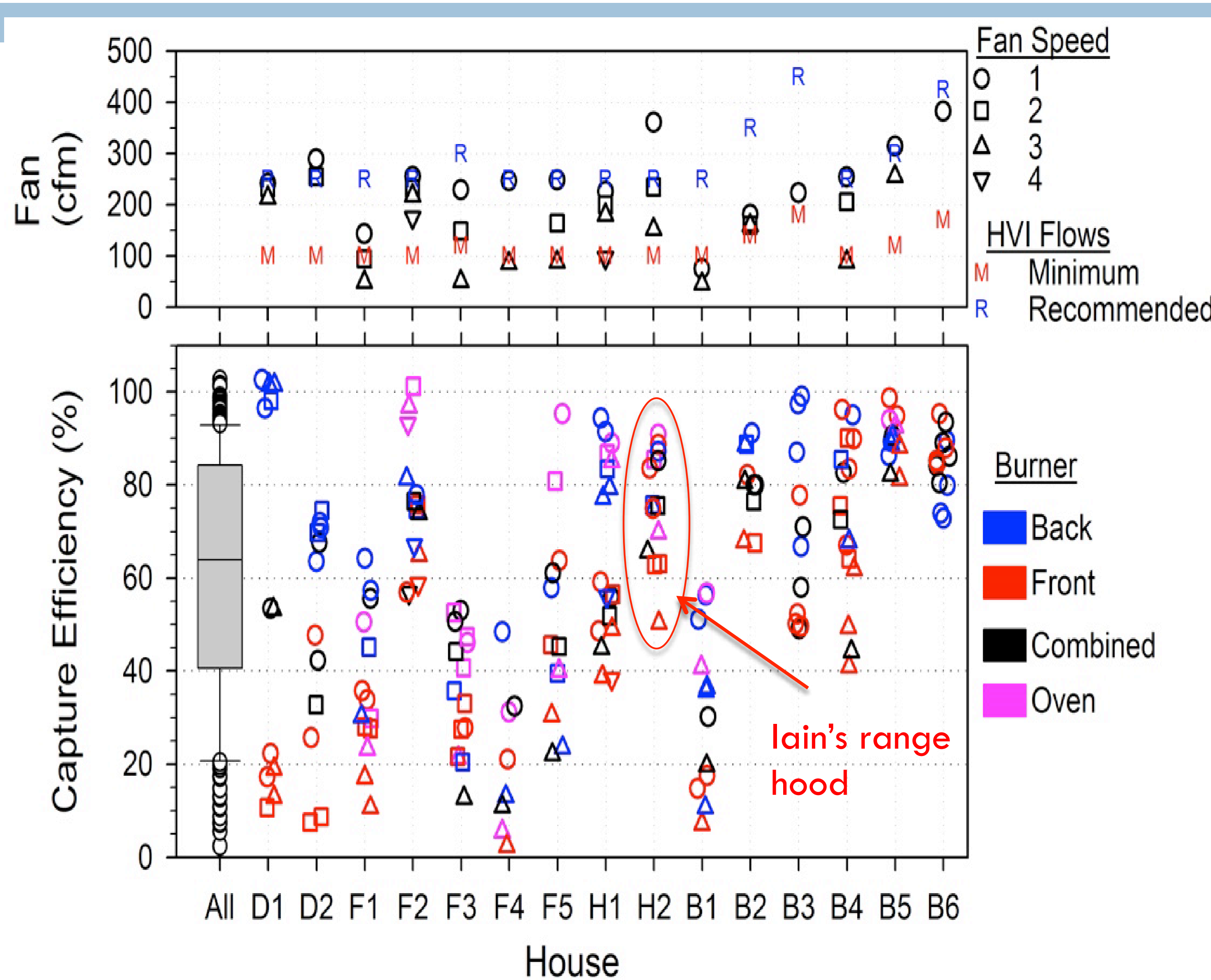
Measure ai flows with active flow hood

As installed range hood performance

Singer et al., 2012, Indoor air

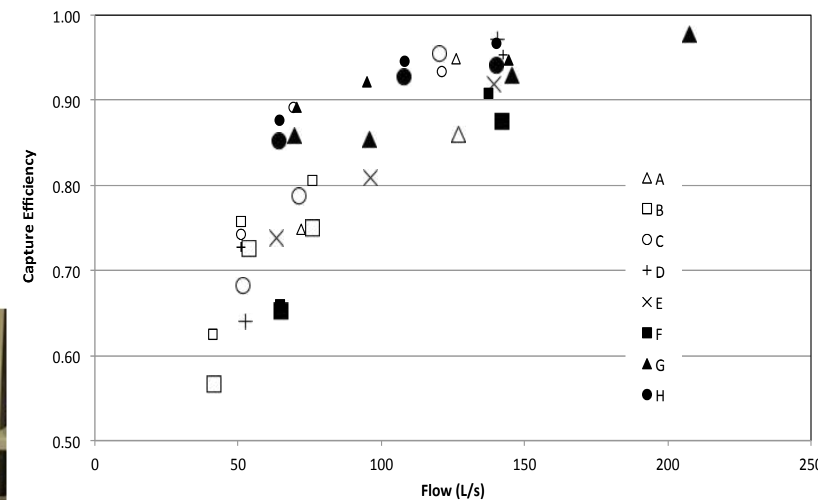
<u>Key features</u>:

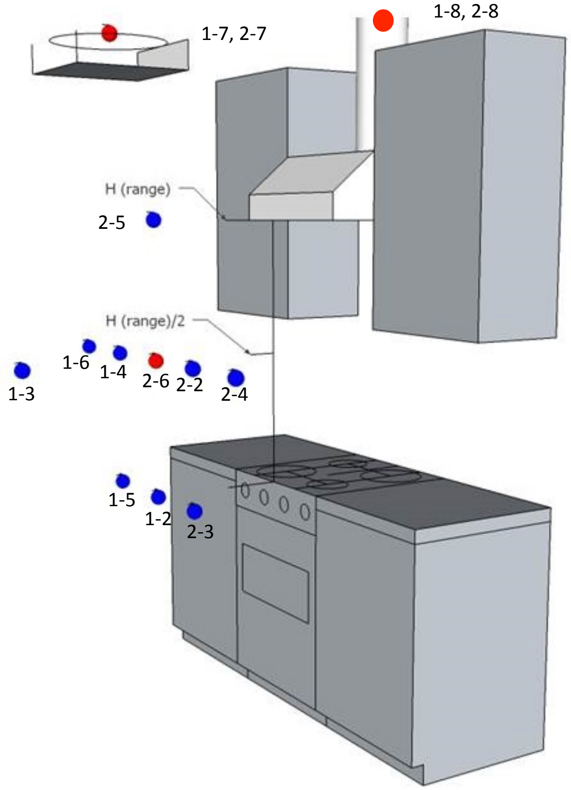
- >150 cfm
- "Sump" or hood
- Cover front burners

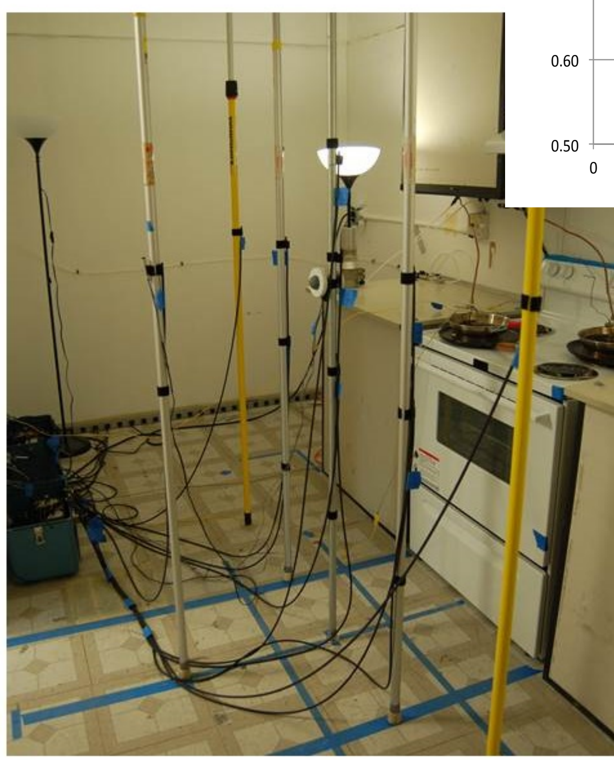


ASTM Test Method for Capture Efficiency

$$CE = \frac{c_{exhaust} - c_{chamber}}{c_{exhaust} - c_{ambient}}$$







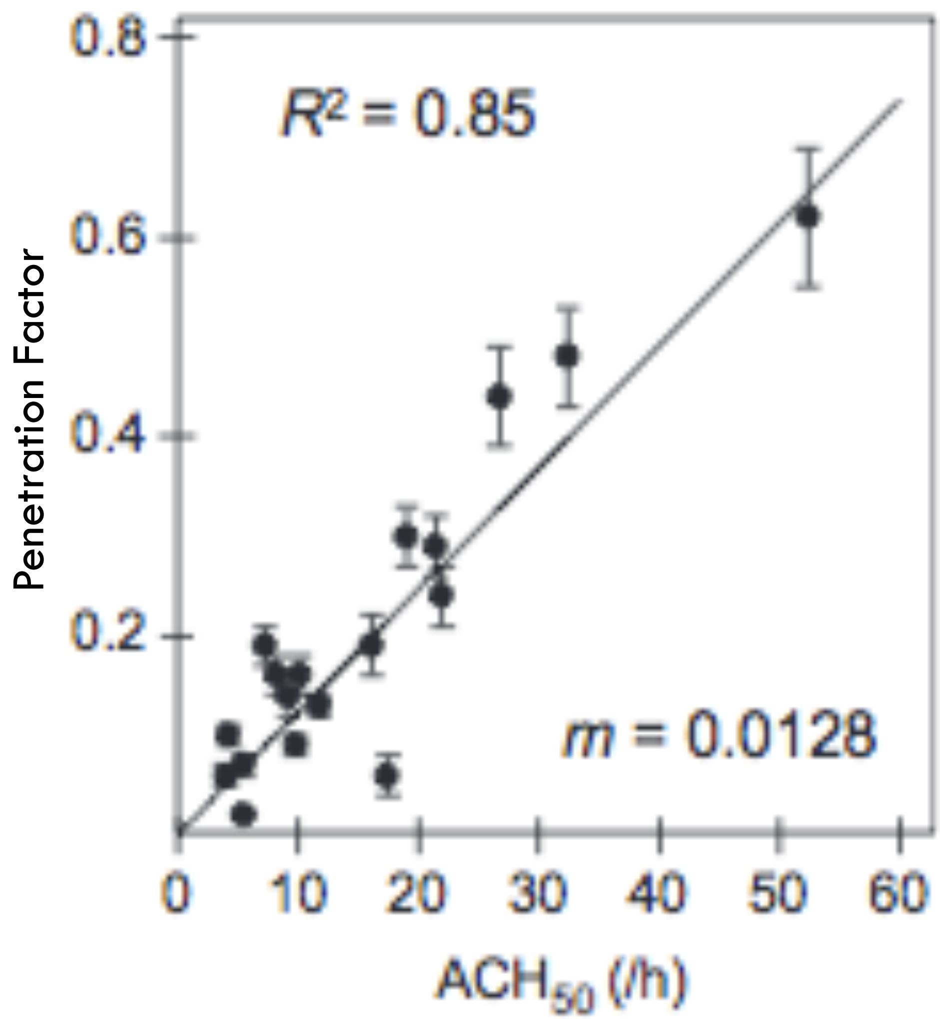
Not quite complete
Look for ratings in 2017
Major manufacturers all involved

Range Hood Recommendations

- Install range hoods vented to outside
  - Hood **covers all burners, has collection volume, & 200 cfm**
  - Or, use ASTM test method
  - **Quiet** operation, NOT just on low speed
  - **Low resistance** ducting (basis of EPA Energy Star spec)
- Provide ducted make-up air in VERY airtight homes or in systems with high flows
  - 200 cfm in 1.5 ACH50 home ~ 10 Pa – is this OK?
- Meet ASHRAE 62.2 general kitchen ventilation requirement
- Occupant Education or Automation?
  - Need to get people to use their range hoods
  - Automation is coming

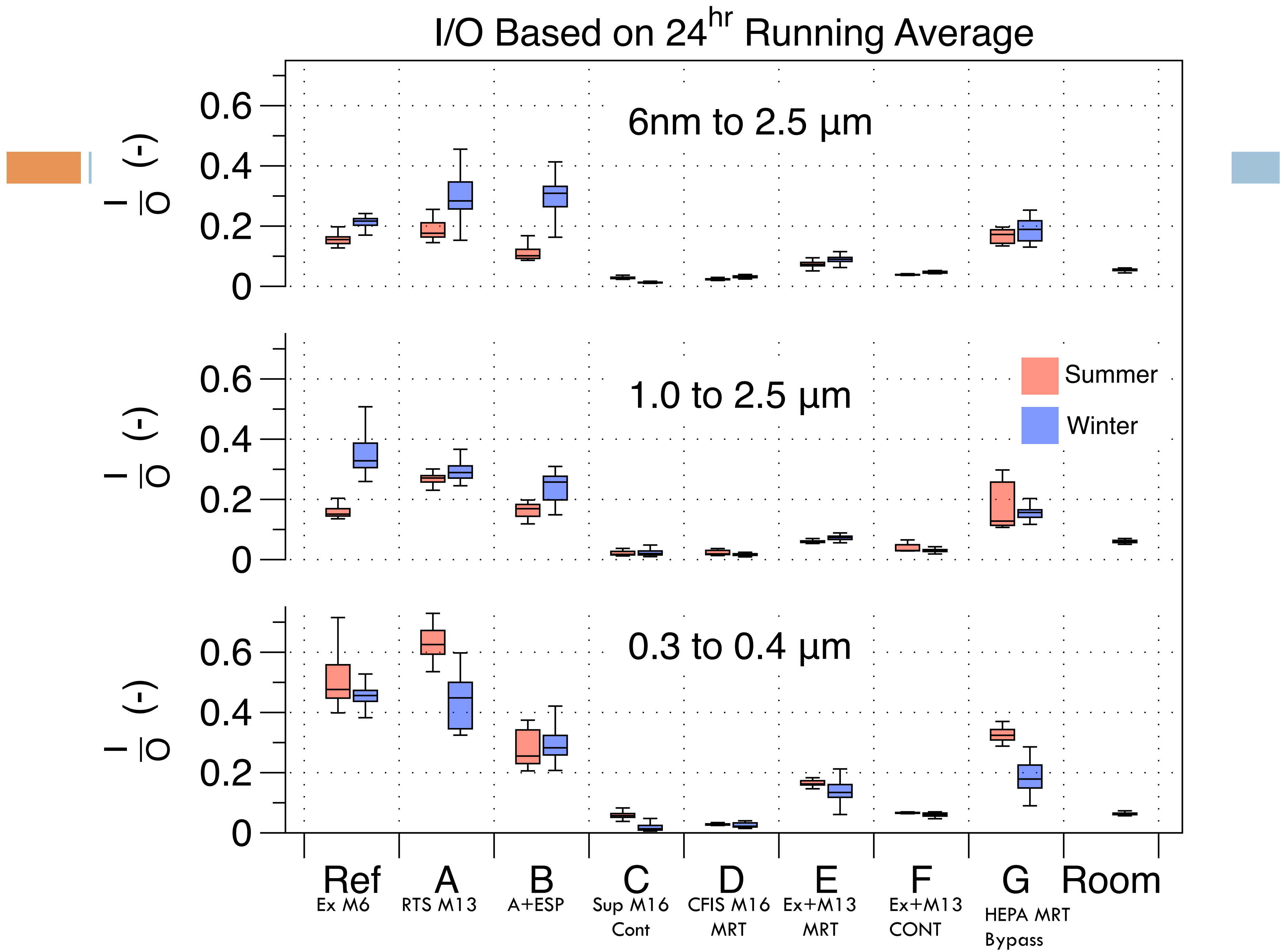
An airtight envelope filters outdoor particles

- Field testing of envelope penetration of **submicron** particles (Stephens & Siegel, 2012)
- Tight homes are good protection against outdoor particles:
  - 1.5 ACH_{50} = 2% penetration
- Need data for larger particles: PM2.5



Comparing filtration/ventilation options

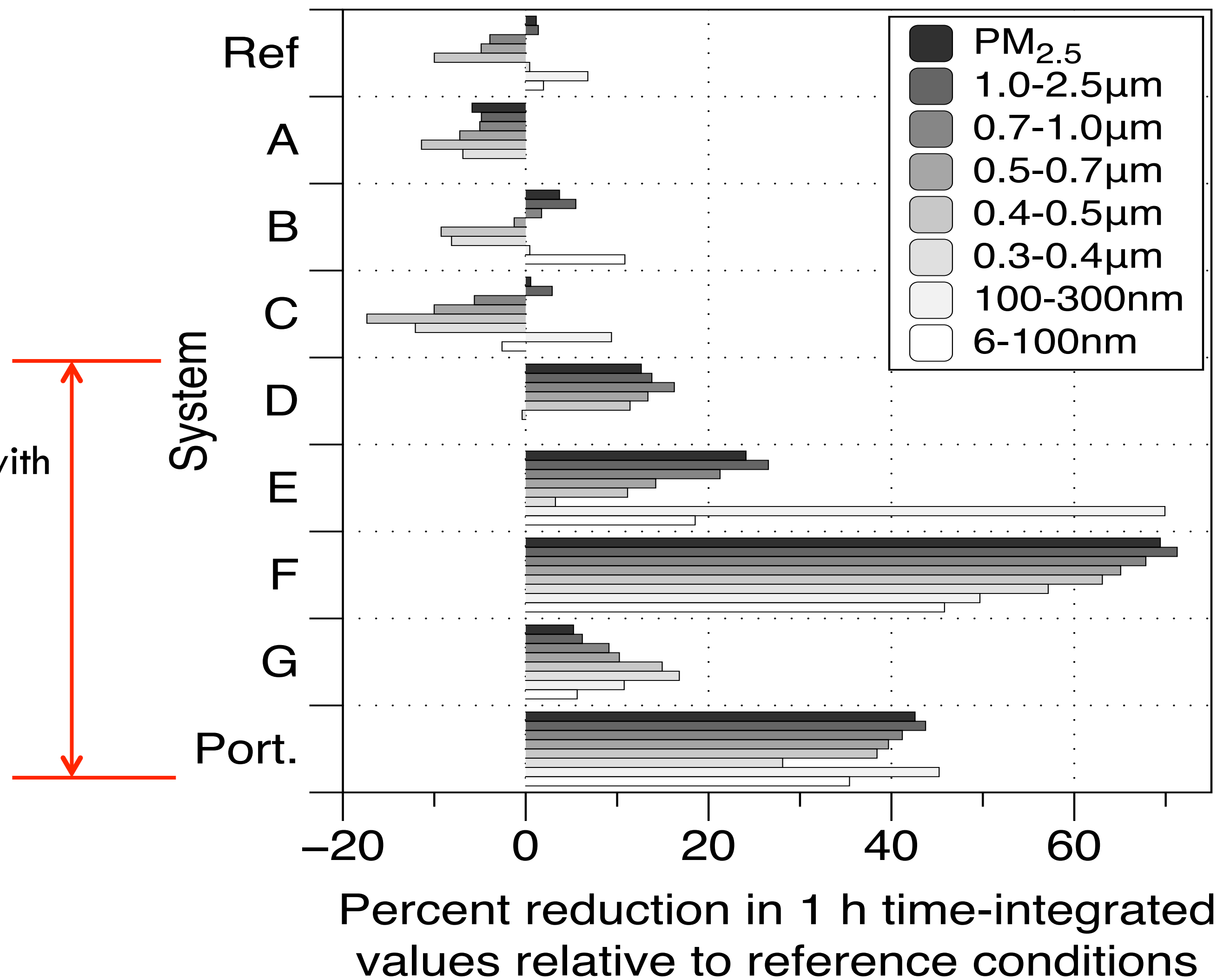
- Field Study near freeway in Sacramento, CA for California Air Resources Board
- Unoccupied – focus on outdoor particles
- Compare eight enhanced filtration systems to common, “reference” system
  - ASHRAE 62.2 Exhaust ventilation + MERV 6 on central forced air system
- Operate each system 5-7 d in summer & fall/winter
- Key metric is indoor-to-outdoor ratio (I/O)



I/O Based on 24hr Running Average
6nm to 2.5 µm
1.0 to 2.5 µm
0.3 to 0.4 µm
I/O (-)
0.6
0.4
0.2
0
Summer
Winter
Ref
Ex M6
A
RTS M13
B
A+ESP
C
Sup M16
Cont
D
CFIS M16
MRT
E
Ex+M13
MRT
F
Ex+M13
CONT
G
HEPA MRT
Bypass
Room

Indoor Particles

Recirculation with M13/M16 filters



Filtration Recommendations

- Consider the quality of your outdoor, “fresh” air
  - Highways and other major roadways, Industry, Agriculture
- **Airtight envelope provides filtration** of outdoor particles
- Supply ventilation (includes HRV/ERV) should be:
  - Minimum **MERV 13**
- Central forced air system for indoor sources
  - At least MERV 13 preferably MERV14 or greater
  - Operate central systems continuously or min run time
  - Consider stand-alone filtration in non-forced air homes or homes with inefficient FAU motors
- Gas filtration possible—but little field data to give specific recommendations

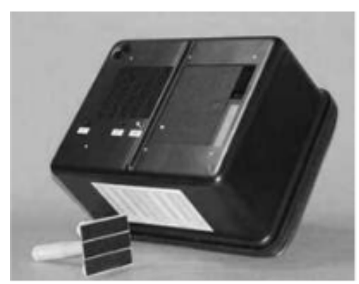
Commissioning—Why It's So Important in Airtight Homes

- If IAQ system fails, there is no natural infiltration backup
- Unfortunately, faults are more **common** in some systems

TSI/Alnor Balometer® Flow Capture Hood ABT701 (ABT701)

Observator DIFF Automatic Air Volume Flow Meter (DIFF)

TSI/Alnor Balometer® Flow Capture Hood EBT721 (EBT721)



Energy Conservatory - Exhaust Fan Flow Meter (TECEFM)

The Energy Conservatory – FlowBlaster™ (TECFB)

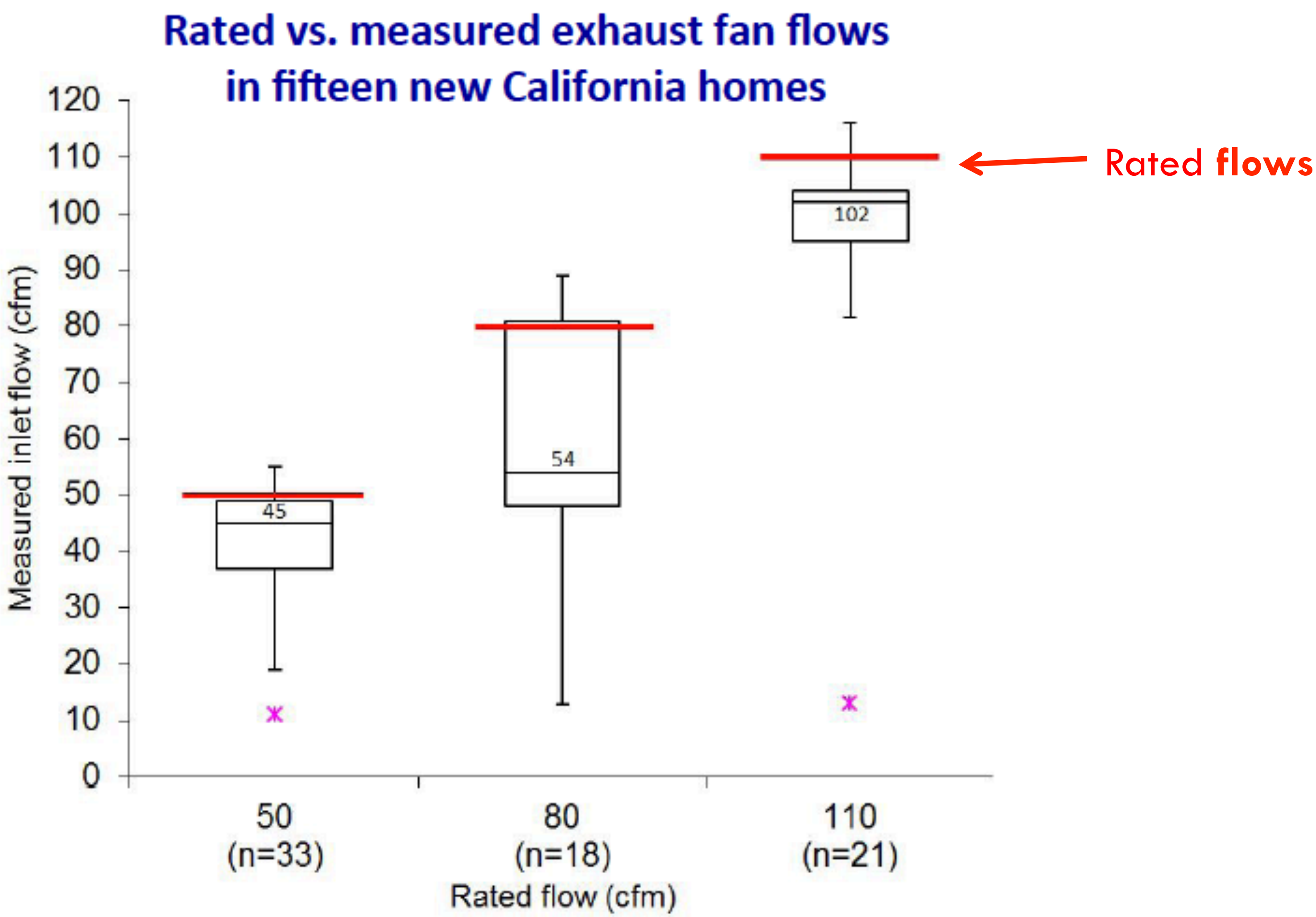
testo 417 Vane Anemometer (testo417)

Figure 1: The six commercially available flow hoods evaluated for this study

Field Survey of 60 Canadian HRVs (Hill, 1998)

- Cores and filters **“clean” in ~50%** of homes
  - <10% “clean” when five years or older
- 7 homes had **inlets clogged** with debris
- 7% of HRVs were simply **not operational** due to component failure
- 29% of systems were out of balance (supply vs. exhaust) by **>40%**
  - Excessive depressurization and back drafting concerns
- Occupant knowledge of system was largely unrelated to performance, level of maintenance, etc.

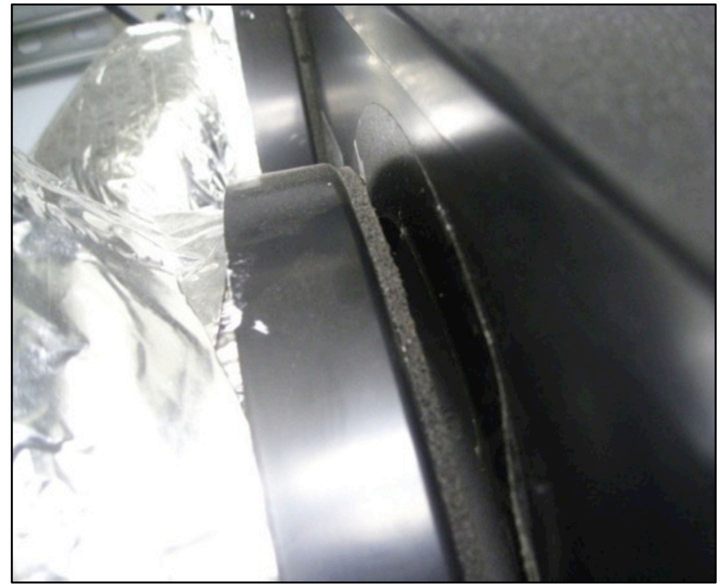
Ventilation Measurements in 15 New CA Homes (Stratton, Walker, & Wray, 2012)



The only way to know a fan's flow: MEASURE IT

Faults Observed in CA High Performance Home Ventilation Systems (Less, 2012)

- 5 of 9 ERV/HRV found to have some substantial problem
  - Low airflows
  - Failed duct connections
  - Improperly installed duct connections (recirculating ERV)
  - Erratic control of variable speed systems
  - Clogged fresh air intake on ERV
  - Not operating continuously, inactive for months



- Similar faults are found in other studies (Balvers et al., 2012; Hill, 1998; Offermann, 2009)

Recent FSEC Survey

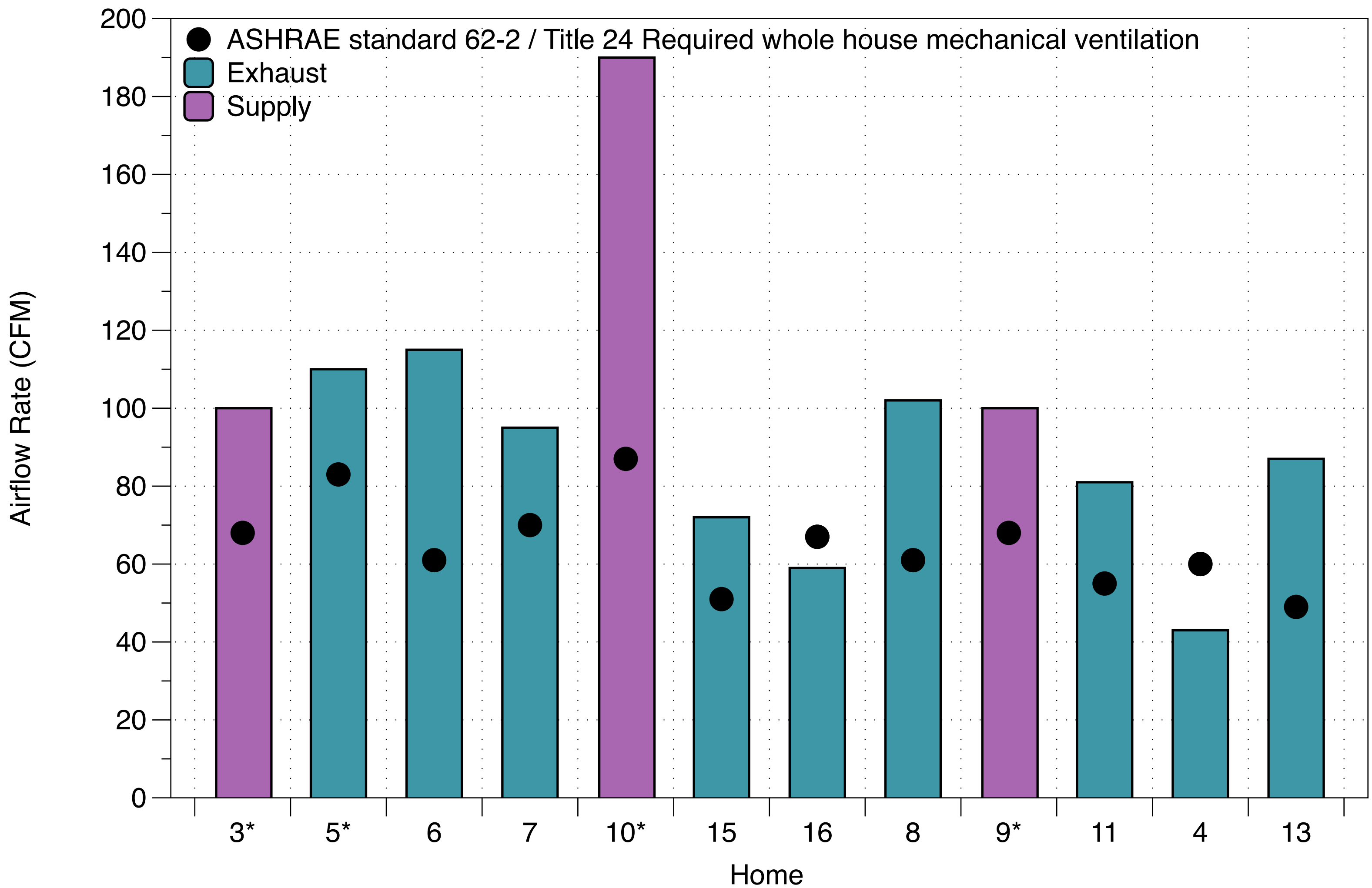
- Inspected 21 mechanical ventilation systems in Florida homes (1-9 ACH_{50})
  - Only 3 of 21 homes had airflows close to design targets
  - 2 of these 3 were disabled by occupants
  - 12 of 21 ‘capable of operating’
  - I9 of 21 were not operational

- Faults
  - Failed controllers and dampers
  - Partially disconnected or crushed ducts
  - Dirty filters
  - Outdoor air intake installed directly above outdoor unit exhaust

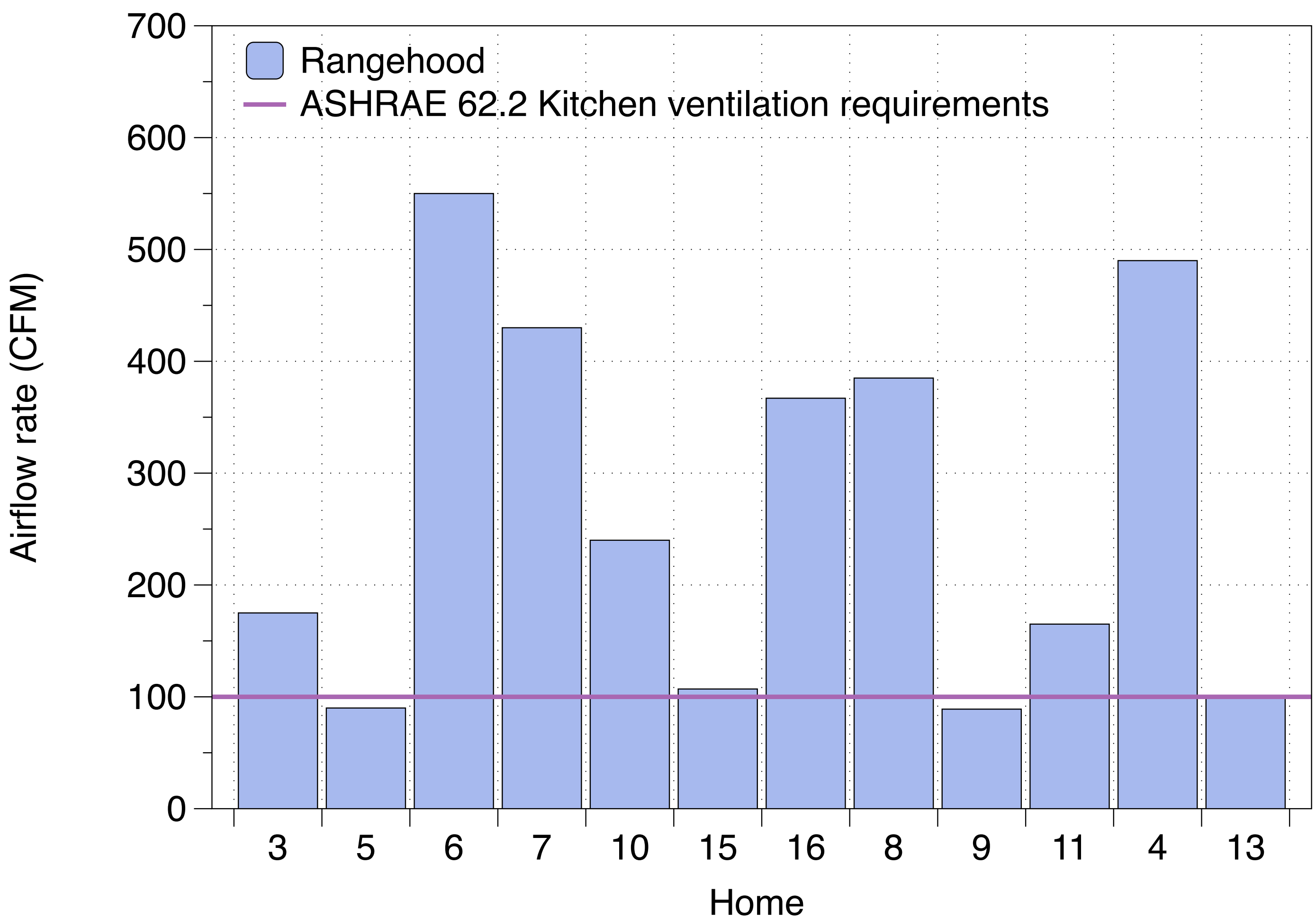
Dirty outdoor air intake.

Dirty ERV filters.

New CA study – not so bad?



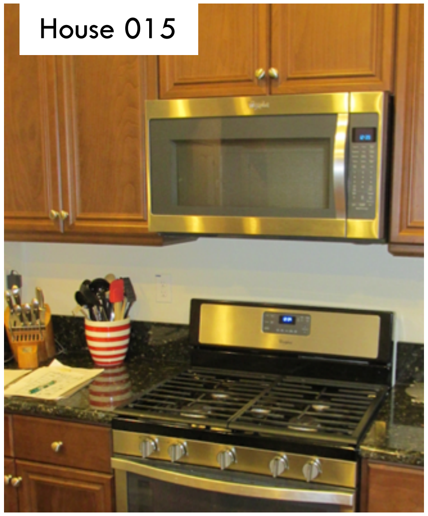
Range Hood Measured Airflow



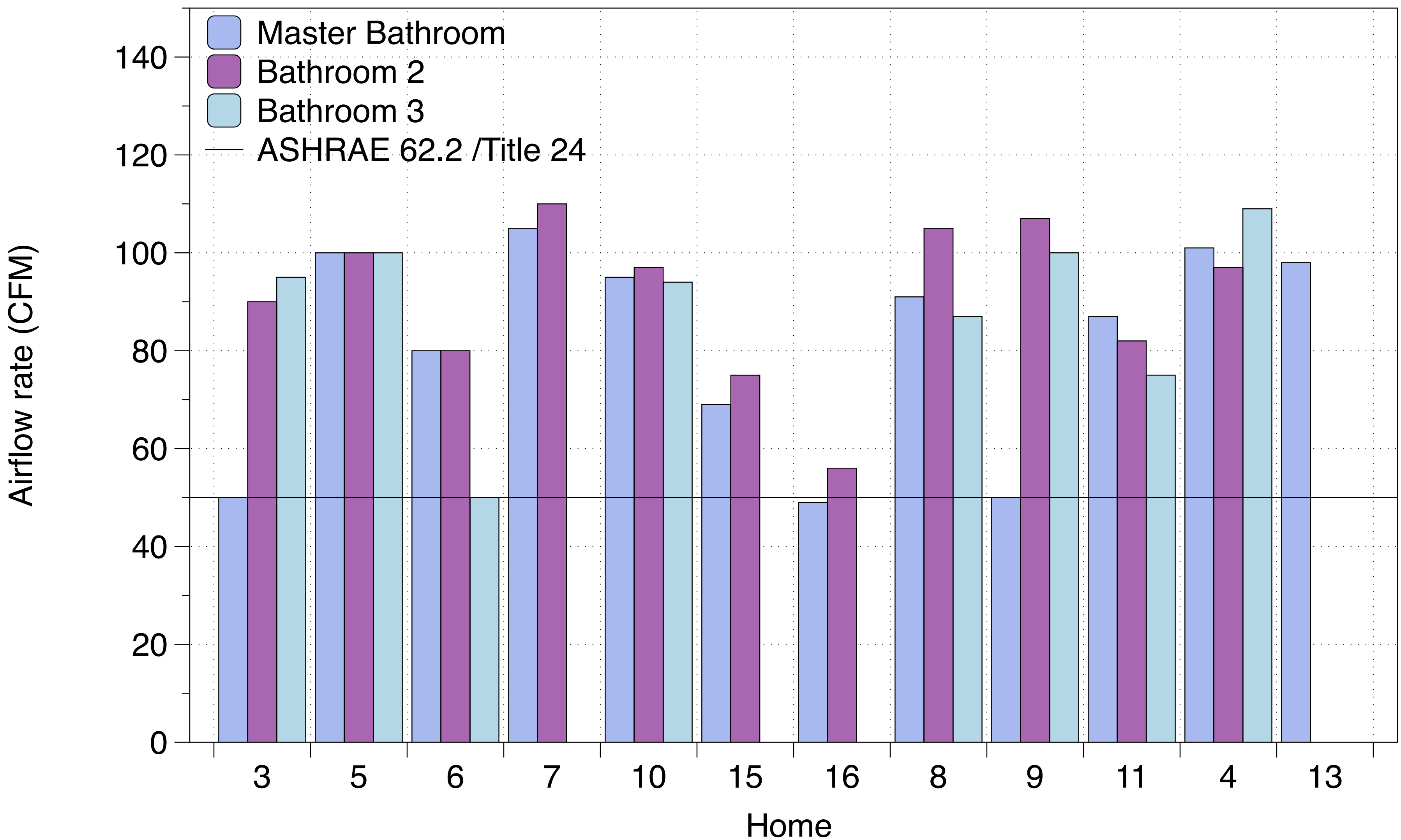
- Airflow measured at medium fan setting
- 9,11,15 are under-cabinet, microwave range hood

High-capacity range hood

Under-cabinet, microwave range hood



Bathroom Exhaust Fan Measured Airflow



Difficult to Commission Systems, I

Figure 12: None of the flow hoods would fit into the space adjacent to this bathroom ERV inlet; it went unmeasured

Figure 13: Only the smallest flow hoods could measure this ERV outlet set between floor joists

Figure 14: The refrigerator has to be pulled out to measure this kitchen ERV inlet, and even then, the uneven surface prevented measurement with most of the flow hoods

Figure 15: The ledge and uneven surface adjacent to this ERV outlet terminal made its flow difficult to measure

Difficult to Commission Systems, II

Figure 16: We located FH6's range hood outlet (circled) on its roof, but for safety reasons did not try to measure its flow

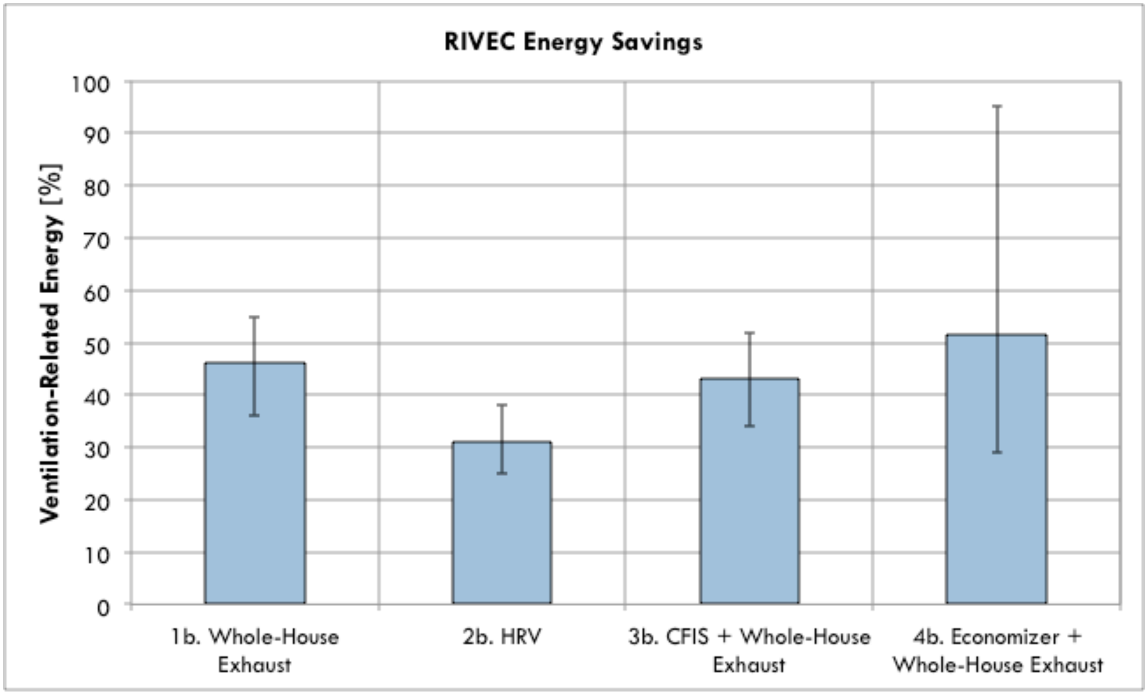
Figure 17: The dimensions and irregular surface of this typical microwave-integrated range hood in FH2 makes inlet flow measurements difficult

Commissioning Recommendations

- Carefully commission ALL ventilation equipment
  - Particularly important in airtight homes, with minimal natural air exchange
- Design and select systems with maintenance and commissioning in mind
  - Easy access to inlets and outlets
    - Particularly important for ERV/HRV, range hoods, & CFIS
  - More complex systems require much greater commissioning time and effort ($$$)

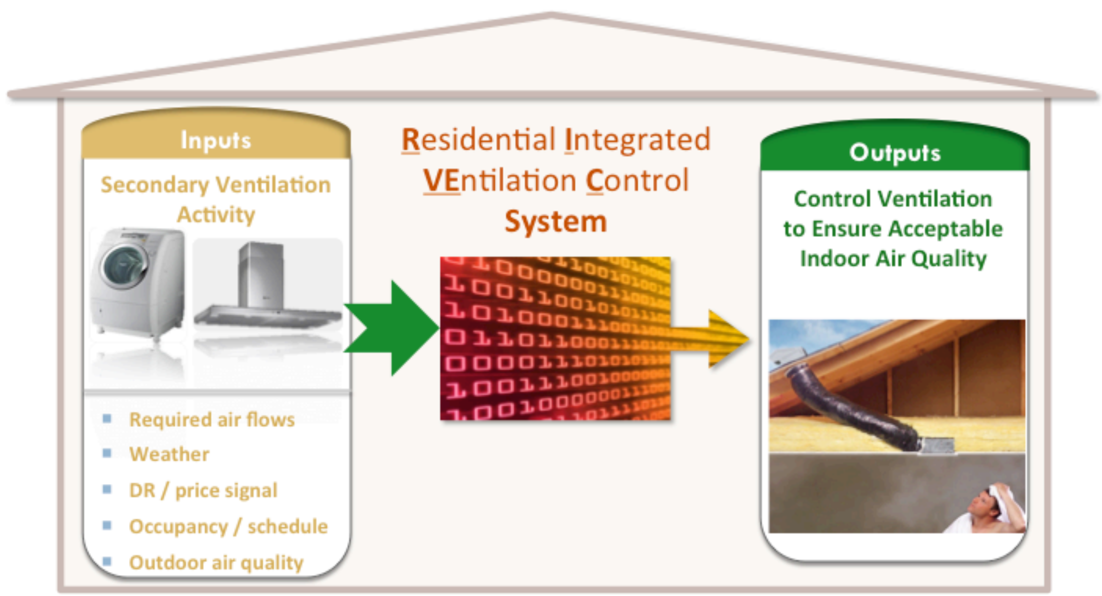
Smart Ventilation – real-time control

- Time shift ventilation + take advantage of other systems (kitchen/bath exhausts, dryers), occupancy and weather to control whole house ventilation system

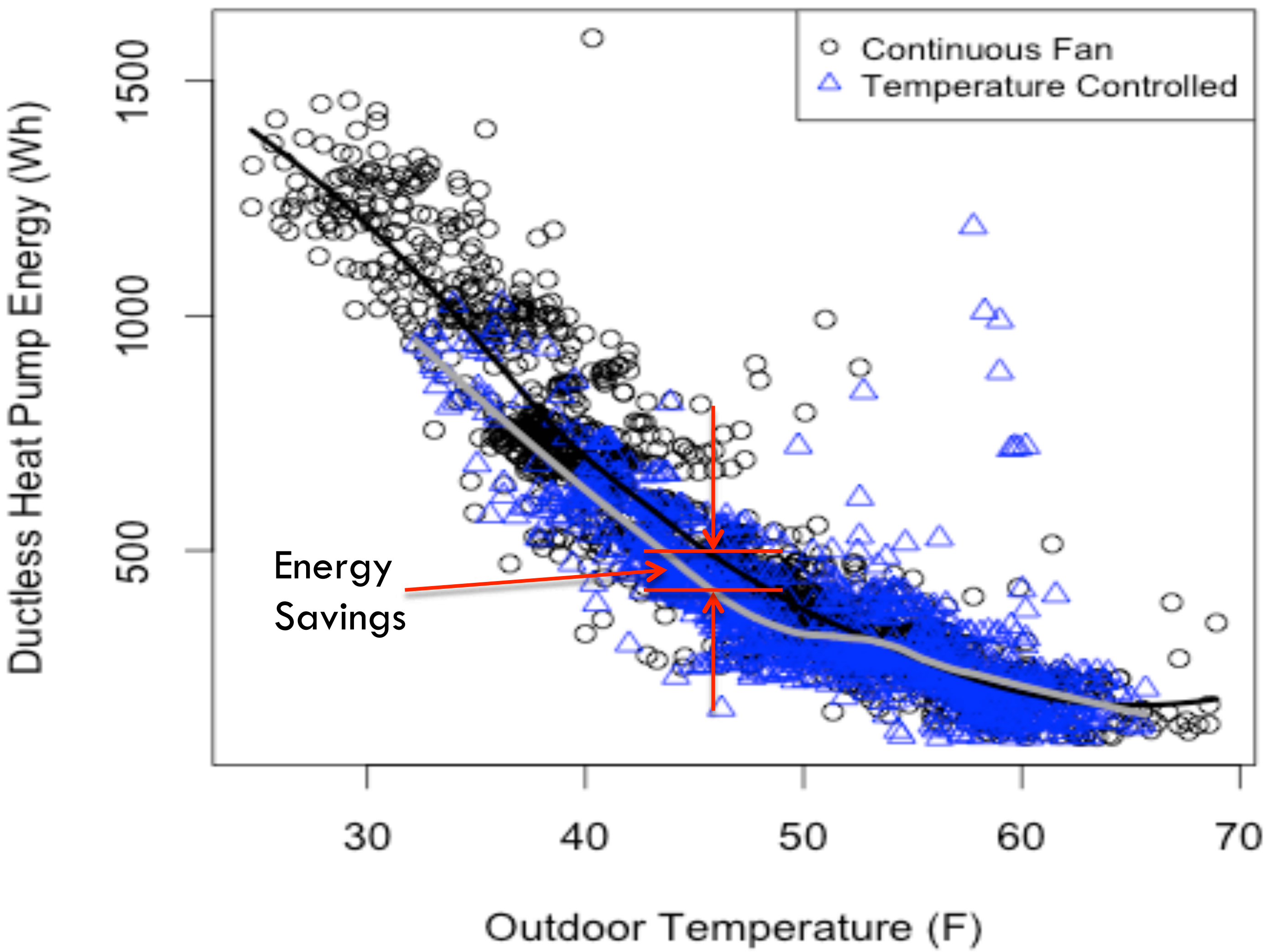


Smart Ventilation

- Use weather for natural infiltration credit
- Turn off if outdoor pollutants high (ozone/particles)
- Turn off in response to peak demand
- Operate more at other times for equivalency – i.e., same exposure to chronic pollutants as a continuous fan



Field Data from Temperature Control Building America Study



Occupants and Maintenance in Canadian HRVs—Education Only Goes So Far

- Canadian HRV (Hill, 1998) study found occupants were "educated" about their system
- **BUT** less than half comprehended:
  - Maintenance needs
  - Requirement for central fan operation with HRV
  - Location of components requiring maintenance
    - Problem was worst in tract homes, where occupants were given little or no explanation or training

Occupant Education—Link Between Design and Operation

- Occupants do not understand IAQ risks in airtight homes
  - Ventilation system operation
  - Maintenance schedule or maintenance contract
  - Use of kitchen ventilation
- Occupants DO NOT know when systems are not operating properly

Education Recommendations

- BETTER than education may be:
  - **Simple, robust systems**
  - **Requiring little to no maintenance**
  - **Have built-in automated fault detection**
  - **Service contracts for ventilation equipment**
- Provide occupants with owner's manuals, as required in LEED for Homes, EPA Indoor airPLUS, etc.
  - Including testing and commissioning results + ALL product literature, organized clearly, etc.
- Educate yourselves, so that you can better inform occupants of risks, system interactions, and life-style changes (candle/incense use, toxic cleaners, etc.)
  - Range hood use is a big opportunity

Iain's IAQ Recommendations

- Use low-emitting materials
- Encourage occupants to consider safety of consumer products
- ASHRAE 62.2-2016 is a minimum
- Pick good range hoods (will be easier in the future with capture efficiency standard))
- Commission everything
- Use at least MERV 13 filters on central forced air and supply air ventilation
- For health:
  - Focus on particles, formaldehyde, cooking and other unvented combustion
- Talk to occupants/owners –
  - Main Hazards: combustion, cleaning products, formaldehyde

Brett's IAQ Recommendations I

- Recognize that people have the biggest impact on IAQ in most homes
- Keep it dry (and mold free); dehumidify as needed
- Avoid emitting large quantities of contaminants in home. Ventilate when emitting.
  - Ventilate when cleaning, doing hobbies
  - Pay attention to chemicals in consumer and personal care products
- Provide task ventilation and use it as needed
  - Kitchen, bath, toilet exhaust;
  - Laundry and clothes closet as needed
- NO UNVENTED COMBUSTION HEATERS!!!

Brett's IAQ Recommendations II

- Use natural ventilation when outdoors is clean
- Tight envelope and ducts; close house when outdoors is polluted
- Check radon and formaldehyde using integrated samplers
- Very good FAU filter with seal (no bypass); confirm low static P
- If more filtration needed (occupant health challenges), use efficient standalone or central system with very efficient FAU motor

Further Questions?

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- Residential Building Systems Group, LBNL:
  - http://homes.lbl.gov/
- Indoor Environment Group, LBNL:
  - http://indoor.lbl.gov/

Resources

- Healthy Products
  - Environmental Working Group
    - http://www.ewg.org/
  - Healthy Building Network—Pharos Database
    - http://www.pharosproject.net/
  - Good Guide
    - http://www.goodguide.com/
  - BuildingGreen chemical avoidance guidance
    - http://www2.buildinggreen.com/guidance/Avoid-Toxic-Chemicals-in-Buildings?ip_login_no_cache=7212a98a1b9d960554b417acc51531a3
  - Health Product Declaration
    - http://hpdcollaborative.org/
- Overall Design
  - Building America
    - http://energy.gov/eere/buildings/building-america-bringing-building-innovations-market
  - Energy Star Indoor airPLUS
    - http://www.epa.gov/indoorairplus/
  - EPA Moisture Control Design Guide
    - http://www.epa.gov/iaq/pdfs/moisture-control.pdf
  - Healthy Indoor Environmental Protocols for Home Energy Upgrades
    - http://www.epa.gov/iaq/pdfs/epa_retrofit_protocols.pdf
  - HUD Healthy Homes
    - http://portal.hud.gov/hudportal/HUD?src=/program_offices/healthy_homes
    - http://www.buildingscience.com/documents/guides-and-manuals/gm-read-this-before-you-design-build-renovate
  - National Center for Healthy Housing
    - http://www.nchh.org/

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