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U.S. DEPARTMENT OF ENERGY

Evidence-Based Best Practices for IAQ in High Performance Homes

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Energy & Environmental Building Alliance

High Performance Home Summit 2017

Atlanta GA

Learning Objectives

- Best practices to reduce IAQ risk
  -> IAQ Scoring Tool
- Interim findings IAQ study in new, California homes
- Building America study of IAQ in new US homes
- Low-cost IAQ monitors for residential $PM_{2.5}$
- Florida Solar Energy Center demonstration of smart ventilation for energy savings and comfort

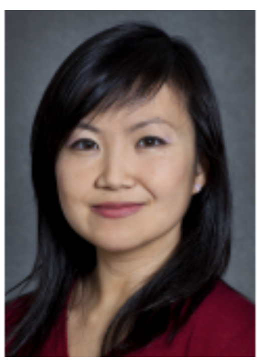
Acknowledgements

U.S. Department of Energy

EPA
Indoor Environments
Division

CEC
Public Interest
Research Programs

HUD
Office of Healthy Homes
and Lead Hazard Control



Rengie Chan

Woody Delp

Yang-Seon Kim

Brennan Less

Vi Rapp

Max Sherman

Iain Walker

What is good indoor air quality?

- Pollutant concentrations at <u>safe</u> levels
- No dampness & mold issues
- Allergens minimized
- No unpleasant odors
- Comfortable temperature and humidity
- Air seems "fresh" and pleasant

Best practices to minimize IAQ risk

- Start with Indoor airPLUS / Energy Star
  - Water tight, robust drainage
  - Robust ventilation for kitchen, bath, laundry, dwelling
  - Low-emitting materials
  - Commissioning and pre-ventilation
- Moisture and comfort managed; dehumidification and humidification as needed
- Airtight and well-insulated envelope
- Filtration for fine and ultrafine particles (≥MERV13)
- Minimize potentially hazardous SVOC*
- Build for changing climate: resilient to storms & floods

*www.sixclasses.org

Best practices for IAQ performance

Occupants aware, educated, and empowered

- Aware of indoor pollutant sources and controls
- Manuals describing equipment, use, required maintenance

Robust control equipment:

- Minimal maintenance and/or service contracts
- Automated fault detection

Sensors:

- Aid awareness
- Closed loop control
- Fault detection

NOT Best Practices

- Unvented gas heater / fireplace
- Built on a flood plane, former wetland, etc.
- Inattention to radon risk
- Inadequate kitchen exhaust / recirc range hood
- Build tight and leave ventilation to the occupant

IAQ Score – Example New Home

IAQ hazards | **Sources** | **Controls**

Indoor Pollutants
- Allergens
- $PM_{2.5}$
- UFP
- Form.
- VOC
- SVOC
- NO_2
- CO

Outdoor Pollutants
- $PM_{2.5}$
- UFP
- Ozone
- NO_2
- VOC
- Radon

Moisture & humidity
- Indoor moisture
- Outdoor moisture

Odors

IAQ Score Framework

- Rates the home as found
- Considers typical IAQ hazards and risks
  - Includes typical occupant activities
- Adds house-specific risks
  - Nearby outdoor source, mold contamination, etc.
- Quantifies severity of hazard and effectiveness of control
- Value of each control depends on severity of hazard
- Considers control robustness, ease of use, durability, etc.

Concerns about IAQ in California New Homes

- **2004-5: Surveyed ~1500 new homeowners by mail[1]**
  - Few opened windows in winter; many did not ventilate all year
  - Kitchen and bath ventilation not used regularly
- **2007-8: Measured pollutants & ventilation in 108 new homes[2]**
  - 9 of 16 homes with ducted mechanical ventilation had grossly insufficient flow
  - Many homes did not use windows for ventilation; 67% below code requirement
  - Majority of homes exceeded formaldehyde health guidelines
- **2008: California Building Code requires mech. ventilation**
- **2014: Healthy Efficient New Gas Homes study begins**
  - Funded by Public Interest Natural Gas Research program

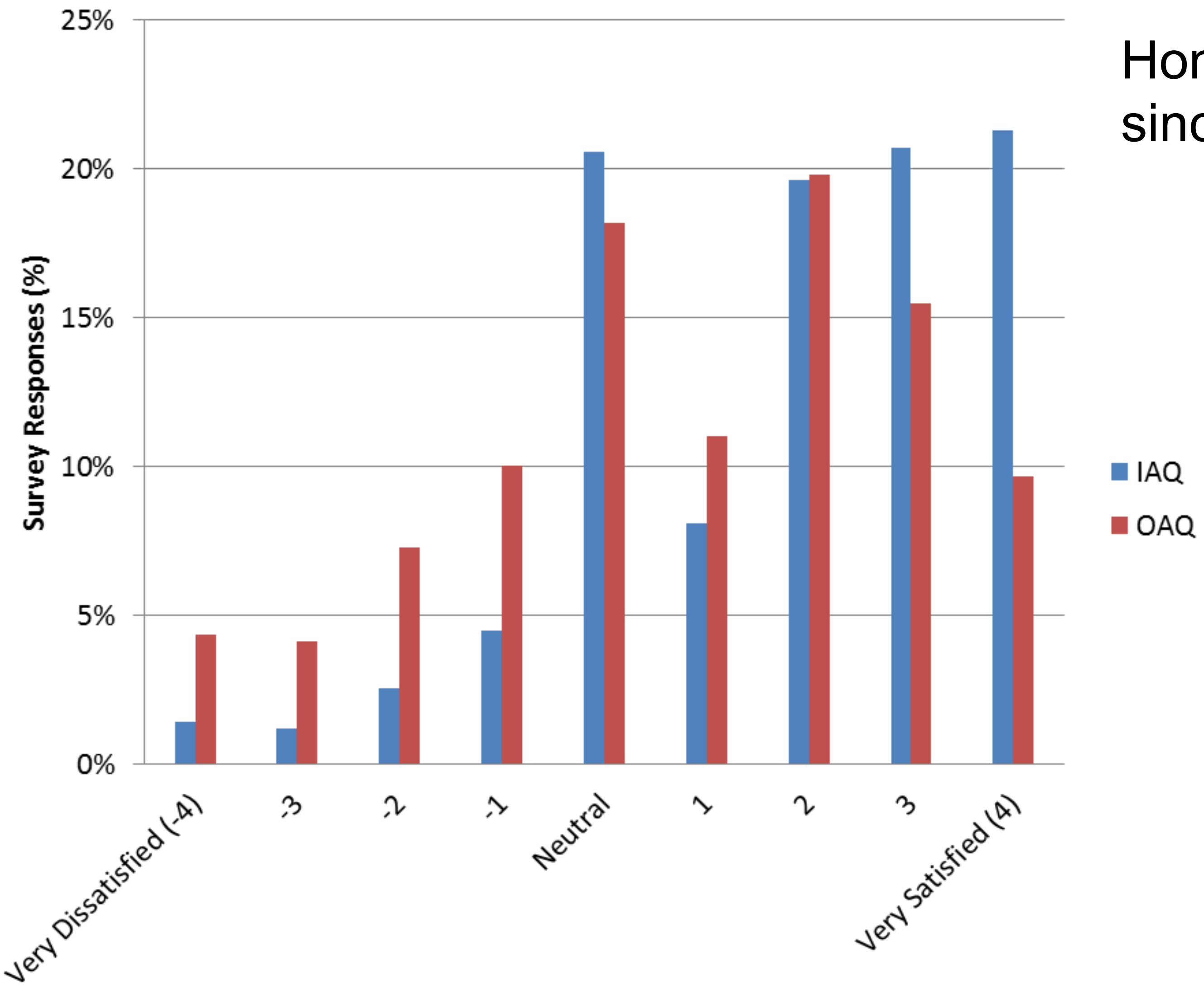
[1]Price and Sherman, 2006; [2] Offermann, 2009;
[3] hengh.lbl.gov

California New Home Study

Goal: Characterize ventilation equipment and IAQ in homes built to 2008 code, which required mechanical ventilation per ASHRAE 62.2

- Web-based survey to update knowledge about ventilation practices and IAQ perceptions
- Field study in occupied homes:
  - Characterize ventilation equipment, measure flows
  - One-week monitoring of ventilation and indoor air quality; occupants log activities that impact IAQ
  - LBNL designed protocols and analyzing data
  - GTI collecting data with help from PG&E and SoCalGas

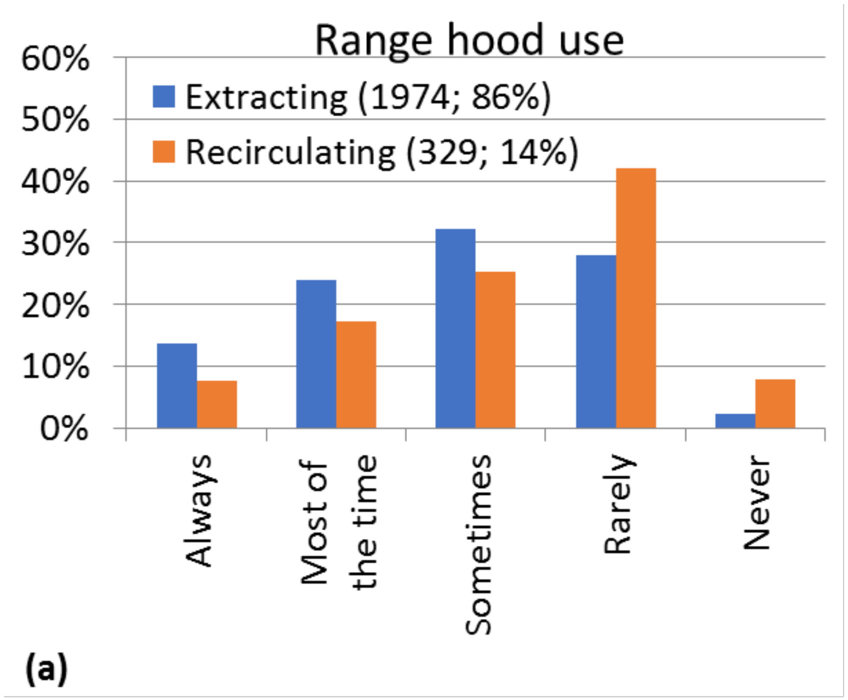
Californians* in more satisfied with IAQ than outdoor air quality

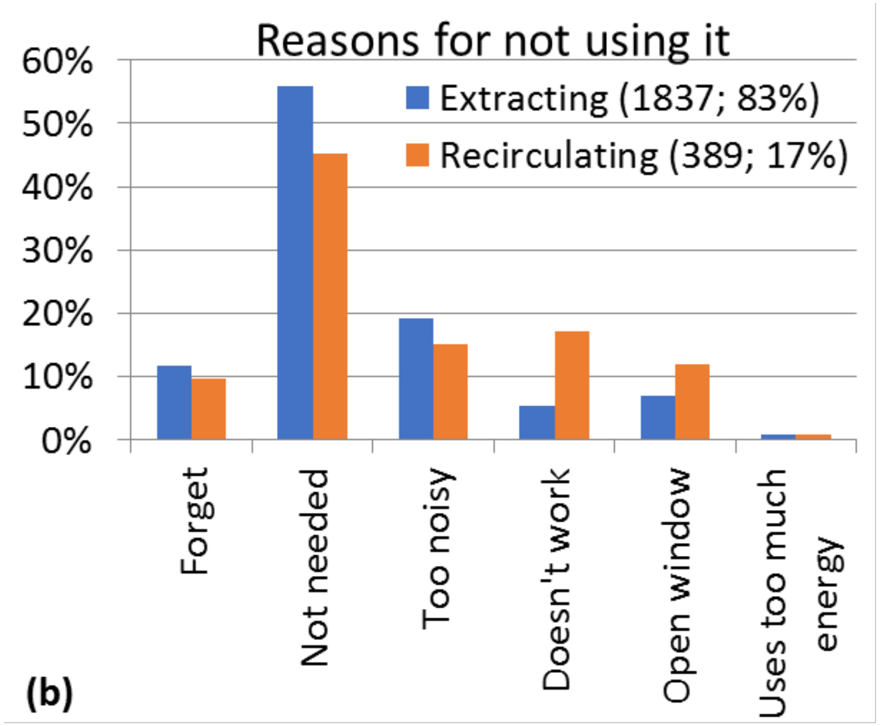


Homes built since 2002

IAQ n=2765
OAQ n=2766

Californians recognize that recirculating range hoods not as effective as venting hoods

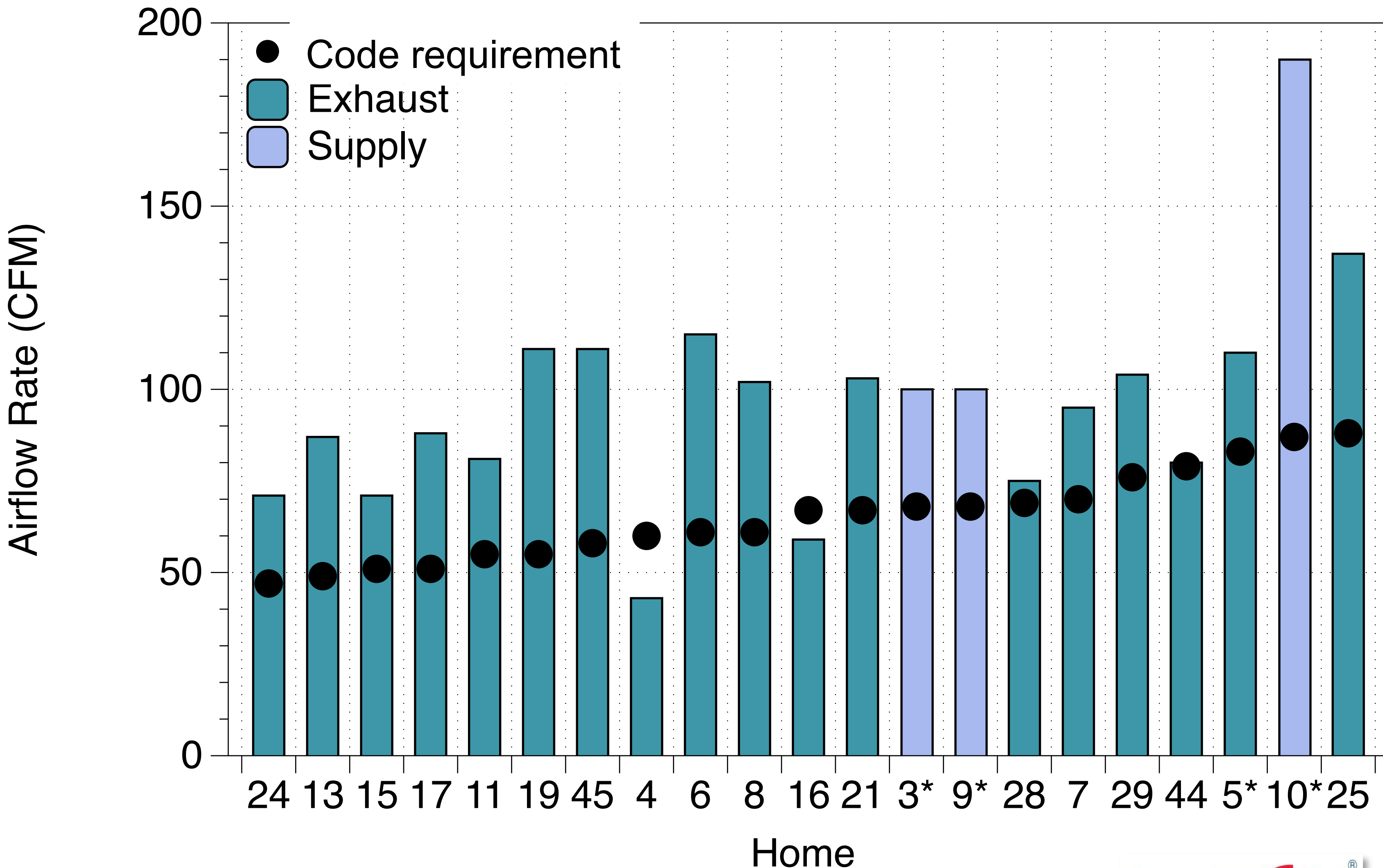




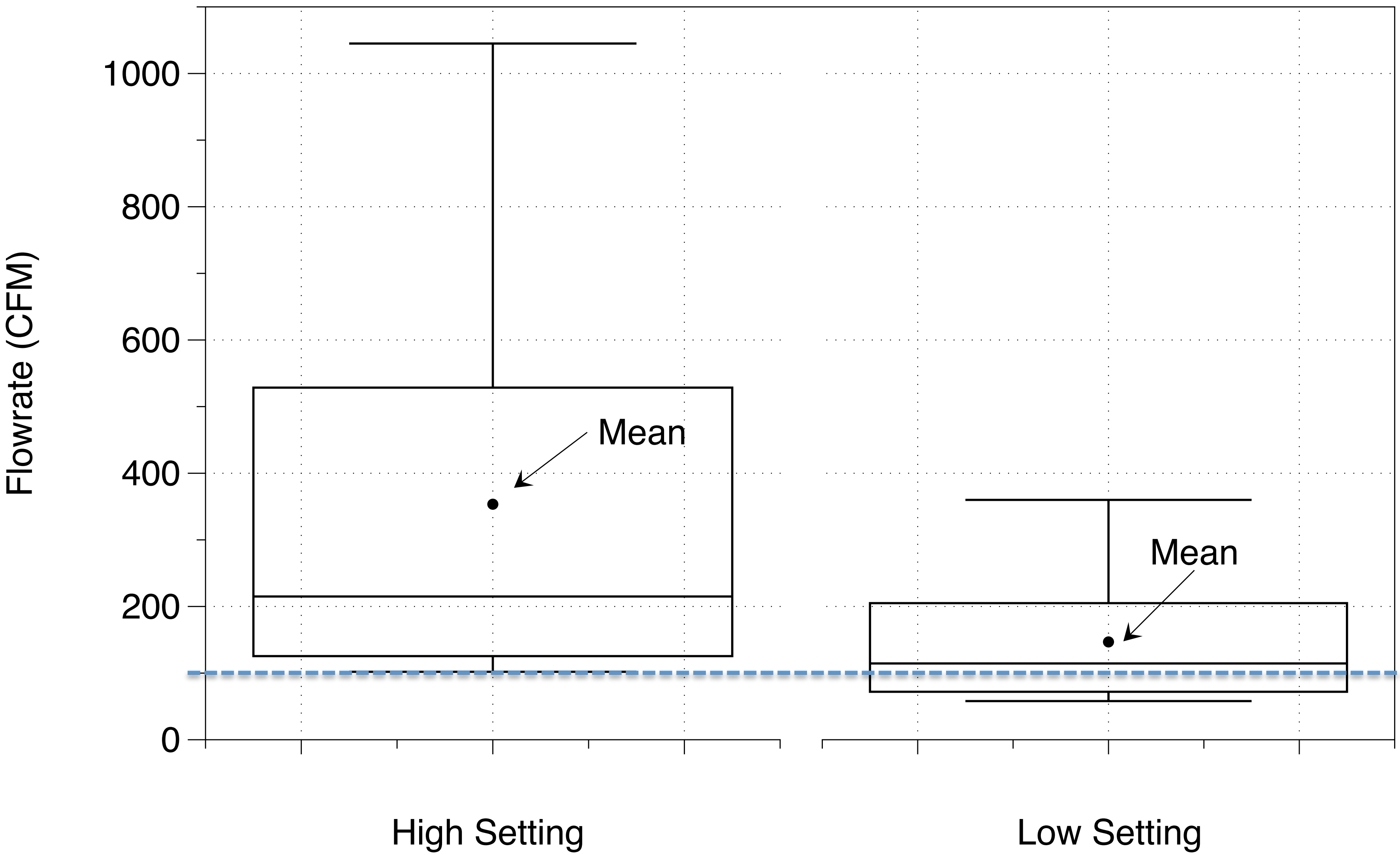
California New Home Study

Data from first 21 homes	Mean	Range
Size (ft^2)	2818	1363 – 4975
# of Bedrooms	3.8	3 – 5
# of Full Bathrooms	3.0	2 - 5
Year Built	2014	2011- 2015
Number of Occupants	3.1	1 - 8
Density (ft^2 / occupant)	1149	387 - 2127

Dwelling unit mechanical ventilation meets code in most homes, exceeds in many

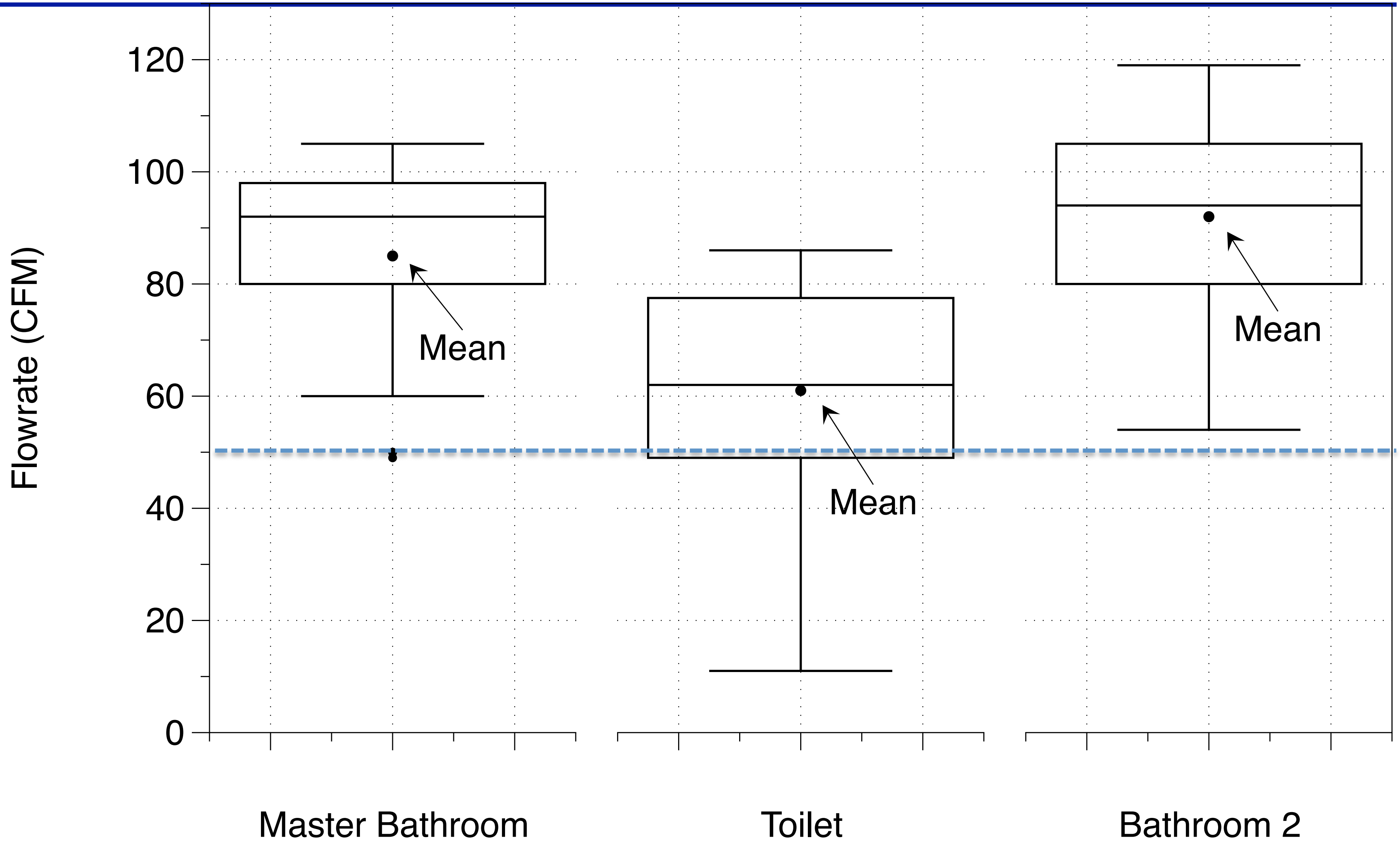


Range hood exhaust flows have sufficient flow*



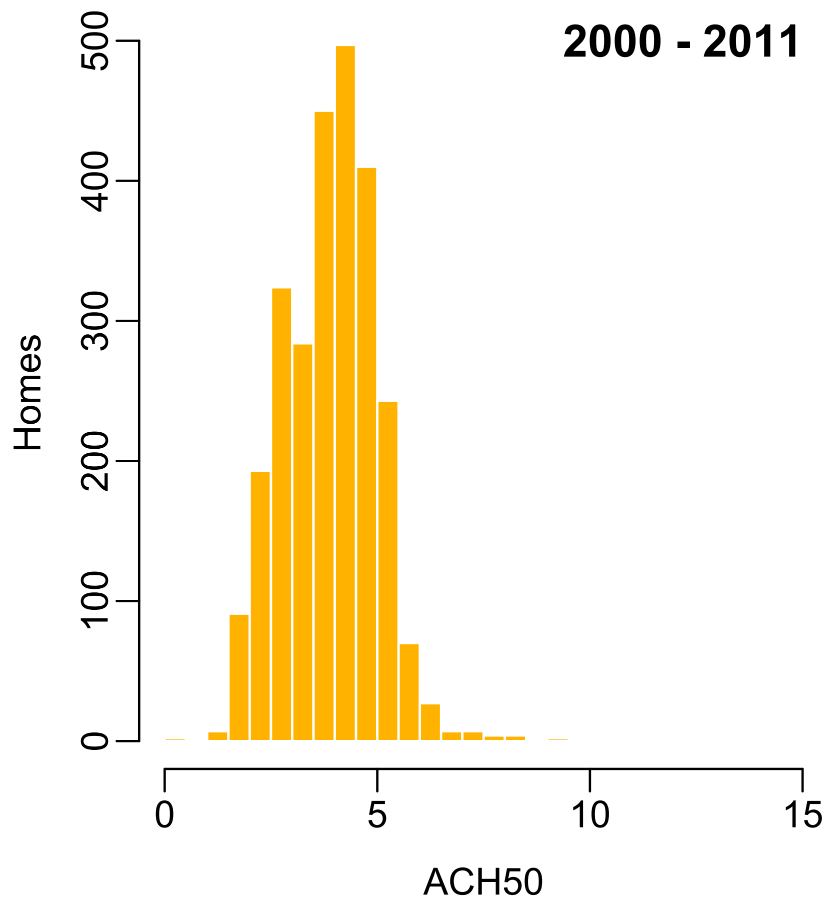
*Also code requirement for sound

Measured bath & toilet exhaust fans meet code



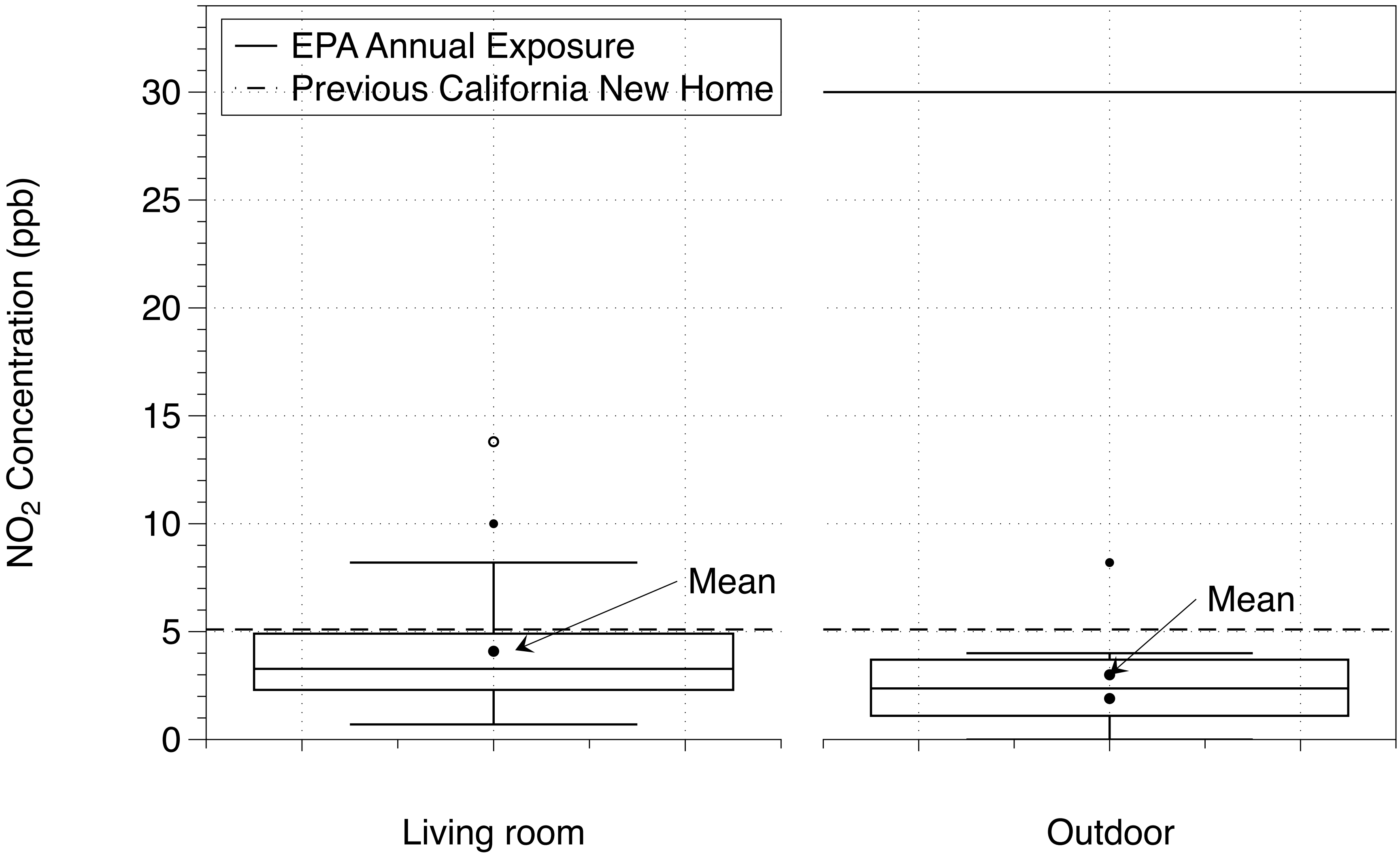
Envelope air tightness

Mean of first 17 homes (5 ACH50) is slightly higher than homes in LBNL Air Leakage Database (resdb.lbl.gov)*



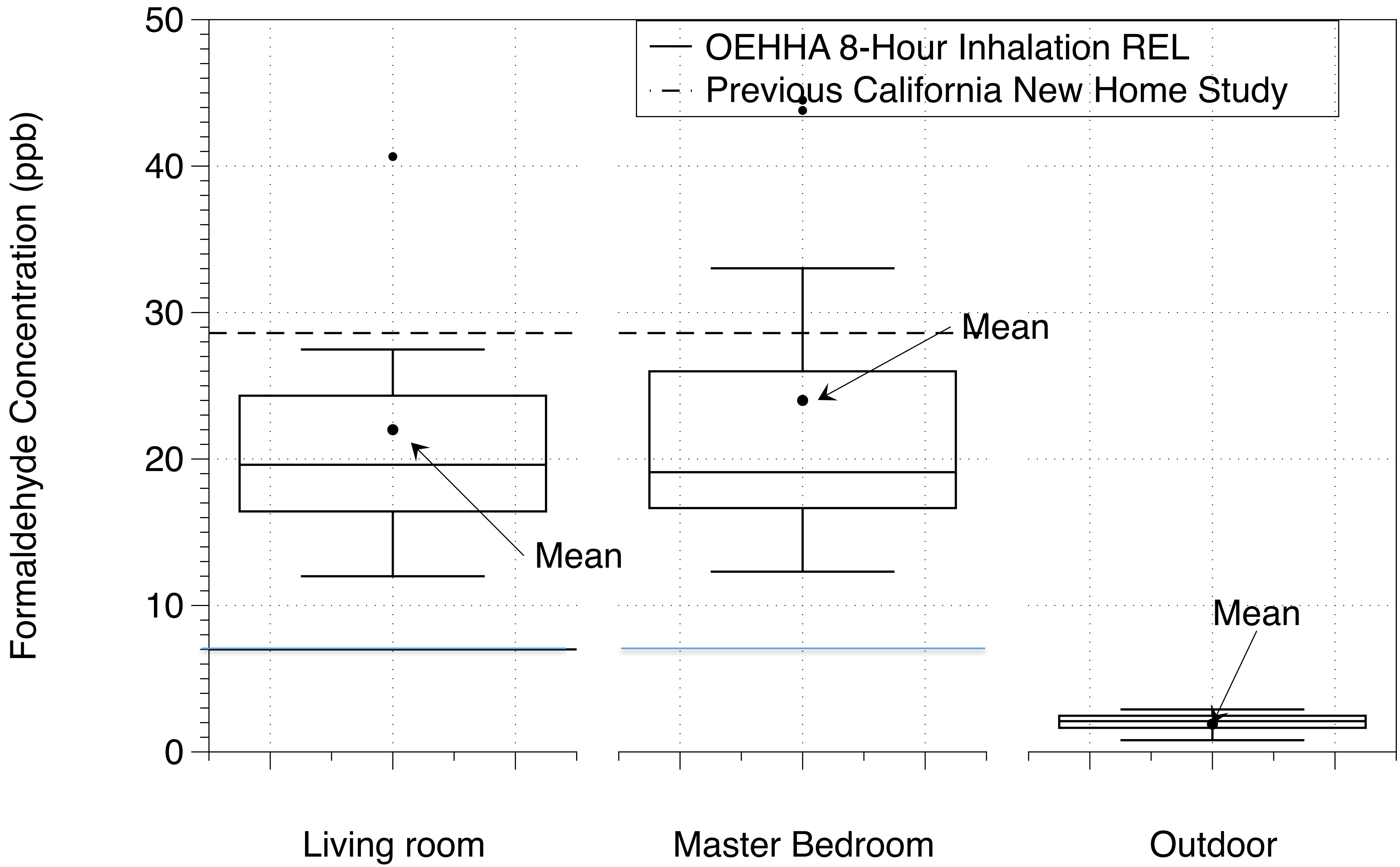
*Reported in Chan et al., LBNL-5967E

Nitrogen dioxide very low in first 21 homes

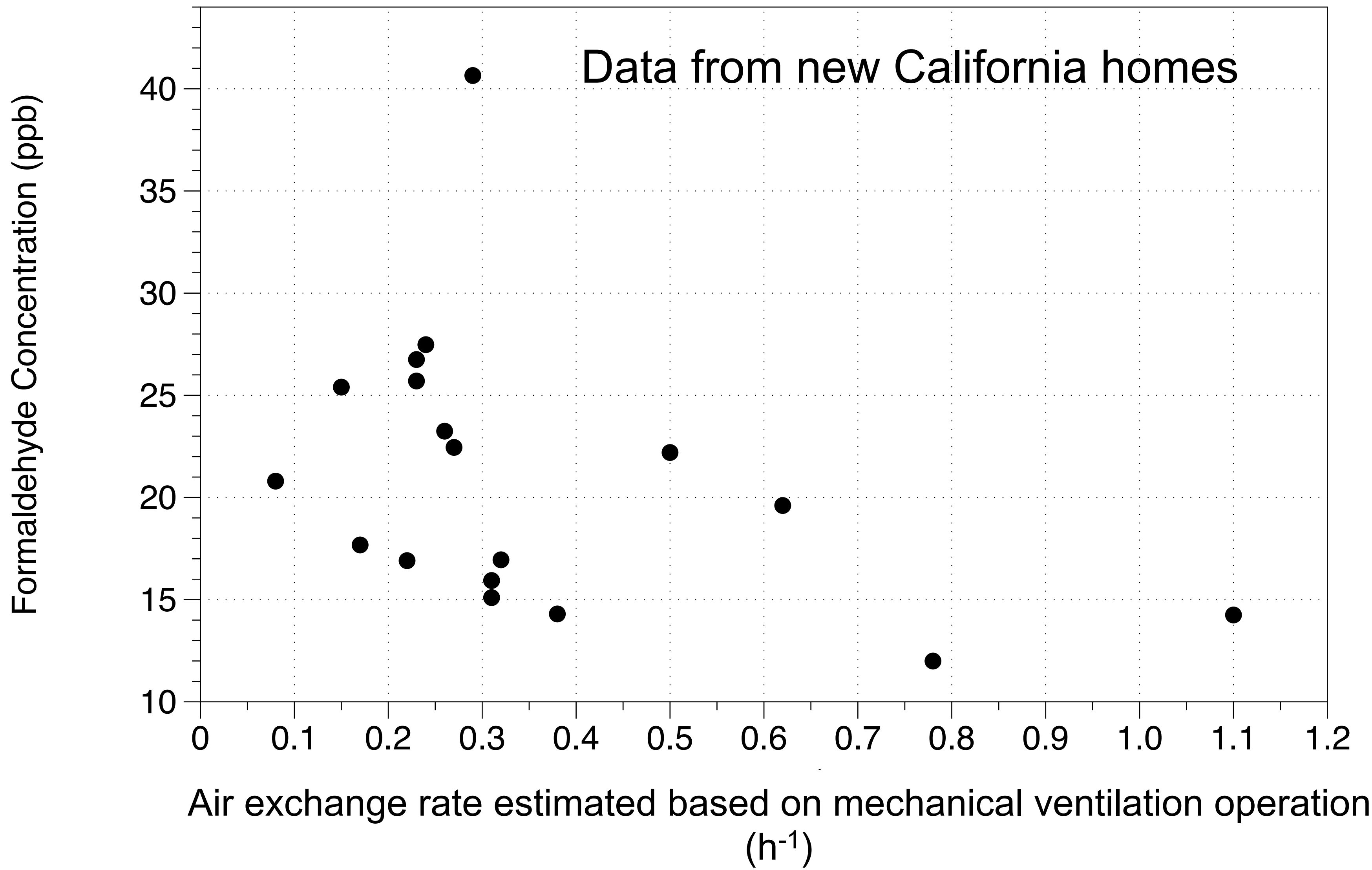


Mullen et al. 2016
Mean outdoor = 17
Mean Kitchen = 23

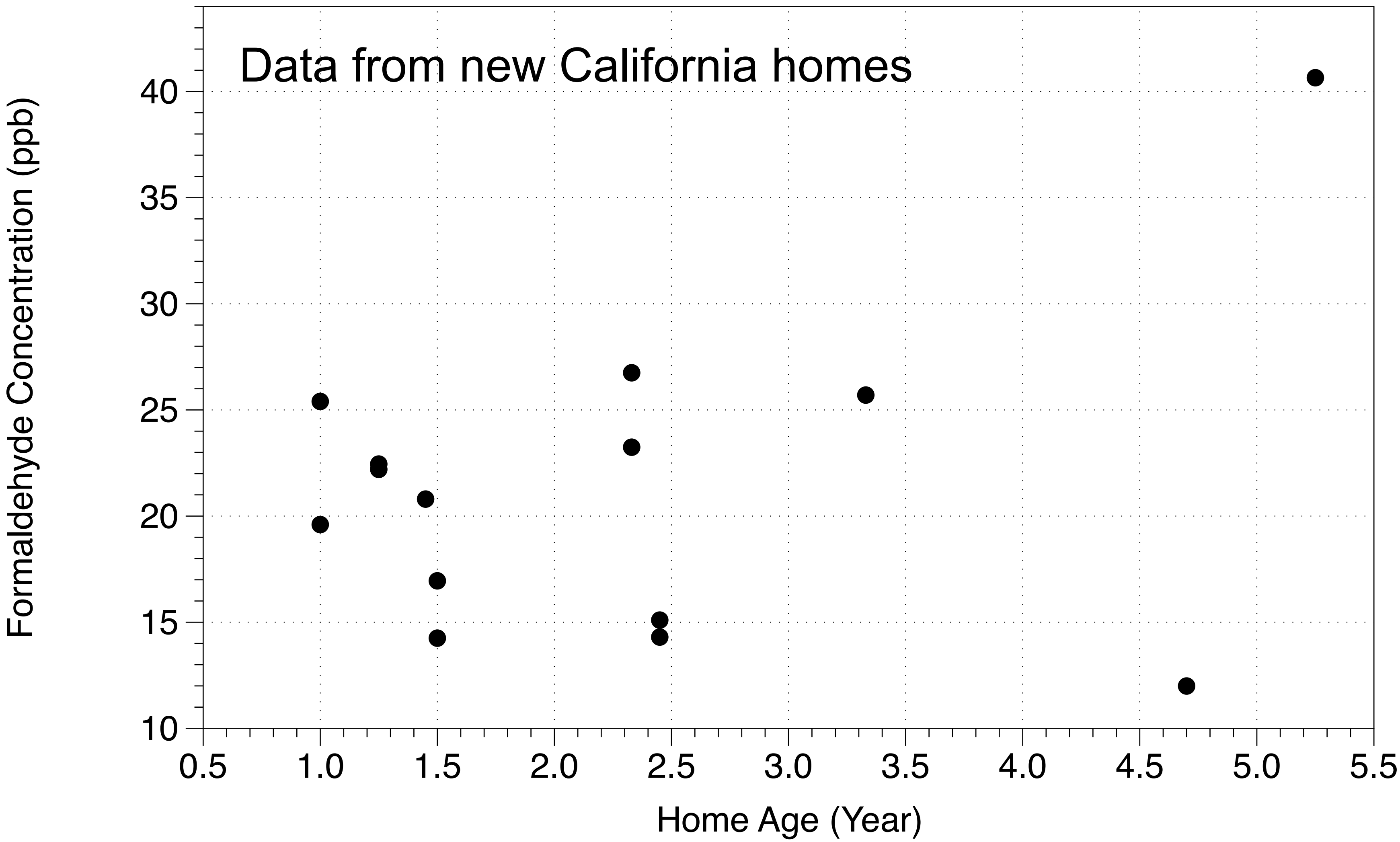
Formaldehyde lower than in prior CA study



Formaldehyde decreases with air exchange rate



Formaldehyde may not decrease over time

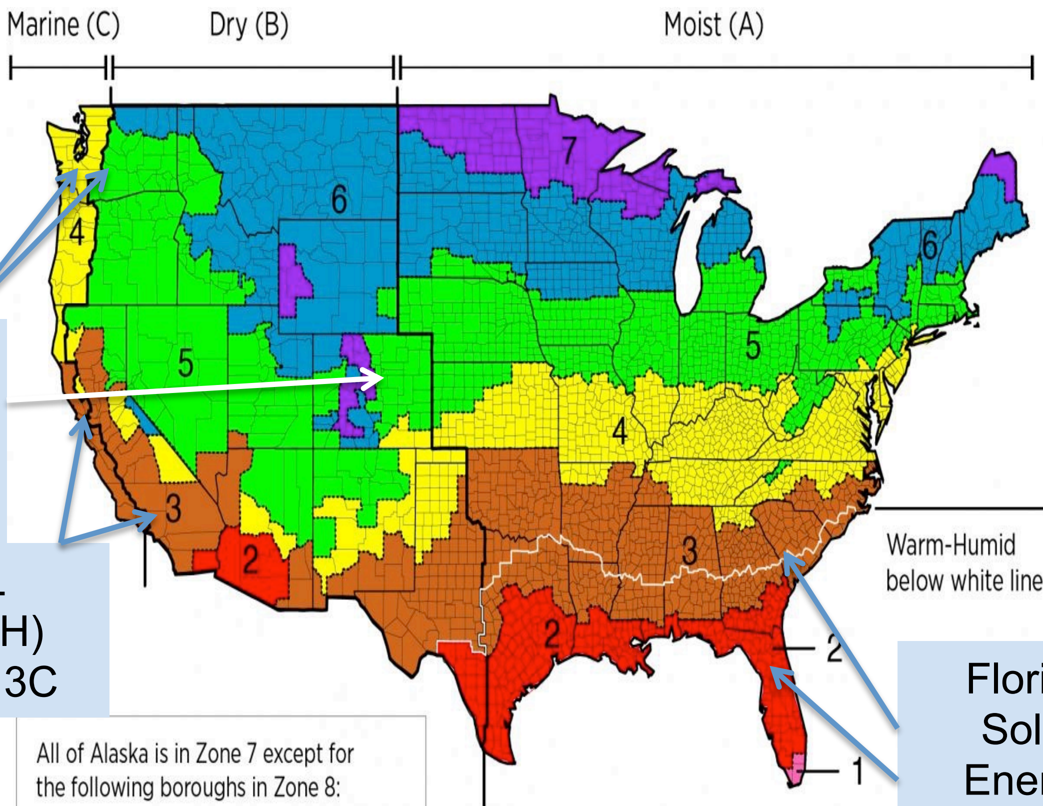


Building America New Home IAQ Study Goals

- **Collect baseline data**
  - Measure indoor air pollutants and humidity, characterize mechanical system designs and performance in a diverse sample of new homes (2013 or later) and climates.
- **Inform standards and technology development**
  - Analyze data to assess impacts of current building practices, codes and standards on IAQ, to inform future standards and technology development needed to ensure acceptable IAQ in new homes.

Study Scope

- Target 32 homes per CZ:
  - ~50% with 62.2-compliant mechanical ventilation (MV)



Pacific NW National Lab

LBNL (HENGH) CZ: 3B, 3C

Florida Solar Energy Center CZ: 2A, 3A

- Characterize home, mechanical equipment
- Survey occupants about activities, satisfaction
- Monitor ventilation, IAQ, activities for 1 week; repeat for 2nd week in 8 homes / CZ
- Repeat monitoring in 8

Project Team

- **DOE Building America**
  - Project direction and management for impact
- **Lawrence Berkeley National Lab**
  - Design field study procedures
  - Create & manage database
  - Analyze data to inform standards & technology development
- **Florida Solar Energy Center (FSEC), Pacific NW National Lab (PNNL)**
  - Recruit and collect field data
  - Quality assurance and upload data
  - Analysis by climate zone
  - Enhancements

Measurements

- Diagnostic testing
  - Envelope & duct airtightness
  - Mechanical ventilation equipment rated and measured flows
- One-week monitoring
  - Use of ventilation equipment and activities
  - Pollutants & environment

    (<u>**O**</u>utdoor, <u>**I**</u>ndoor, <u>**B**</u>edroom)
    - $PM_{2.5}$: O, I*, B*
    - CO_2: I, B
    - NO_2, NO_X: O, I, B
    - Formaldehyde: O, I, B
    - T, RH: O, I, B, baths

- Dwelling unit ventilation system
- Most frequently used bath fans
- Kitchen exhaust
- Clothes dryer
- Water heater in conditioned space
- Heating/cooling equipment
- Standalone (de)humidification equipment
- Standalone air cleaner
- Cooktop, oven, and toaster oven use
- Fireplace use

*Low-cost monitor used in this location

Low-Cost / Consumer Grade Indoor Air Quality Monitors

What's available to measure PM?

Packaged devices ~$200

- A pleasing box that may have a display or glow according to the perceived IAQ
- May have additional sensors (CO_2, VOC, …)
- Cloud storage

Download on the App Store   GET IT ON Google Play

- Possibility of controlling things

amazon echo   ecobee   Honeywell

IFTTT   works with nest   LUX™

Low Cost Devices Evaluated ~ $200-300

AirBeam

PM, T, RH

AirVisual Node

PM2.5, PM10,
T, RH, CO2

AirQualityEgg V2

PM, T, RH

AWAIR

PM, T, RH,
CO2, VOC

Dylos DC1700

Counts (Small,
Large)

Foobot

PM, T, RH,
CO2, VOC

PurpleAir V2

PM1, PM2.5,
PM10, T, RH

Speck V2

Count, PM, T,
RH

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For what do we need IAQ monitors?

- Measure things we can't see or smell

- Hazard identification
- Closed loop control

- Assess benefits of controls or retrofits
- Track performance over time
- Quantify IAQ

For what do we need IAQ monitors?

- Measure things we can't see or smell

- Hazard identification
- Closed loop control

Reliable: see every important event

Some "false positives" OK.

Reversible: recovers after a spike

Quantitative not essential

Drift okay if relating rise to recent

For what do we need IAQ monitors?

- Measure things we can’t see or smell

- Assess benefits of controls or retrofits
- Track performance over time
- Quantify IAQ

Quantitative; Limited drift

Not varying with environmental conditions

What do we want to measure?

	Parameter	Identify hazard	Activate controls	Evaluate benefits	Track over time
Satisfaction	T/RH/CO_2				
Smell it	Odors				
Smell or see it	Dampness and mold				
Misleading	TVOC				
Mostly indoor sources	Formaldehyde, Radon				
	Carbon Monoxide (CO)				
	Acrolein, NO_2				
Indoor and outdoor sources	$PM_{2.5}$, PM_{10}				
	Ultrafine particles				
	Irritants / Allergens				
Mostly outdoor sources	Diesel PM / Black carbon				
	Ozone				

What do we want to measure?

	Parameter	Identify hazard	Activate controls	Evaluate benefits	Track over time
Satisfaction	T/RH/CO_2		✔	✔	✔
Smell it	Odors		✔	✔	✔
Smell or see it	Dampness and mold	✔		✔	✔
Misleading	TVOC	✔	✔	✔	✔
Mostly indoor sources	Formaldehyde, Radon	✔	✔	✔	✔
	Carbon Monoxide (CO)	✔	✔	✔	✔
	~~Acrolein~~, NO_2 ($$)	✔	✔	✔	✔
Indoor and outdoor sources	$PM_{2.5}$, PM_{10}	✔	✔	✔	✔
	~~Ultrafine particles~~	~~✔~~	~~✔~~	~~✔~~	~~✔~~
	~~Irritants / Allergens~~	~~✔~~	~~✔~~	~~✔~~	~~✔~~
Mostly outdoor sources	Diesel PM ($$)	✔	✔	✔	✔
	Ozone ($$)	✔	✔	✔	✔

Some information on the web

- **EPA: mostly focusing on outdoors**

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

- **South Coast AQMD: outdoor and chamber tests**

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

- Carnegie Mellon (chambers)

  https://explorables.cmucreatelab.org/explorables/air-quality-monitor-tests/

- Air quality in China (outdoors)

  http://aqicn.org/sensor/

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Low-cost IAQ monitors for residential $PM_{2.5}$

- Most of the existing evaluations of low-cost particle monitors done outdoors or with ideal aerosols
- Particles emitted in homes vary with the source, and may differ greatly from outdoor aerosols

Question:

Do any of the available low-cost IAQ monitors provide quantitative data or reliably track reference monitors?

Study:

In lab, generate particles from typical indoor activities and compare low-cost to research and reference monitors.

Evaluation of low-cost particle monitors

Experiments conducted in a 120-m^3 room

Sources to evaluate low-cost particle monitors

Sources to evaluate low-cost particle monitors

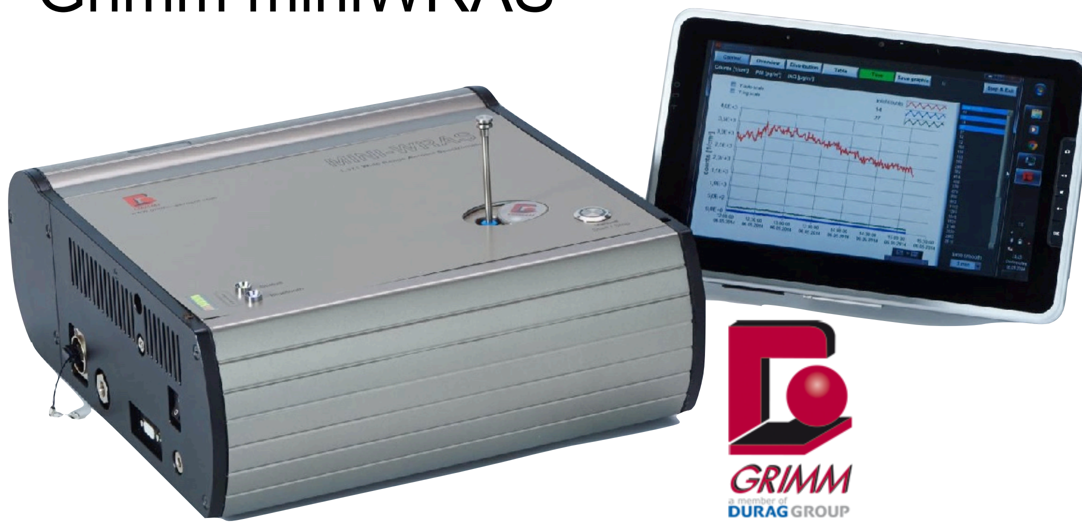
Reference Instruments ~ $35000 each

Thermo-Scientific
TEOM-1405DF

ThermoFisher
SCIENTIFIC

Direct Mass readings
$PM_{2.5}$, PM_{Coarse}

Grimm miniWRAS



GRIMM
a member of DURAG GROUP

Aerosol Spectrometer
Particle size distribution in 41 channels from 10nm up to 35μm

Research Instruments ~ $4000-7000

Light scattering devices

$PM_{2.5}$ ~$1 \mu g \cdot m^{-3}$ to $100+ \ mg \cdot m^{-3}$

BT-645

Met One Instruments, Inc.

ThermoFisher SCIENTIFIC pDR-1500

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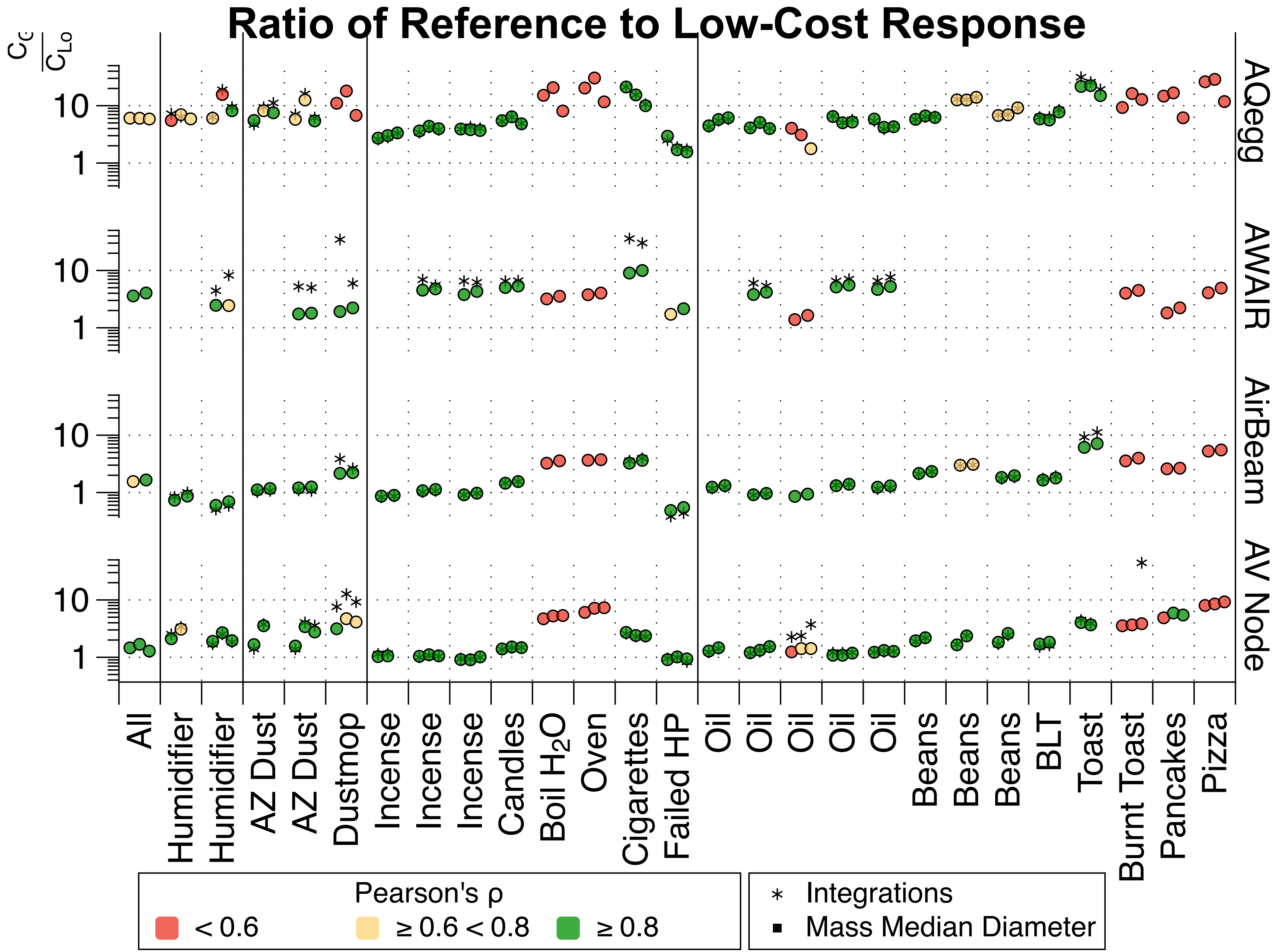
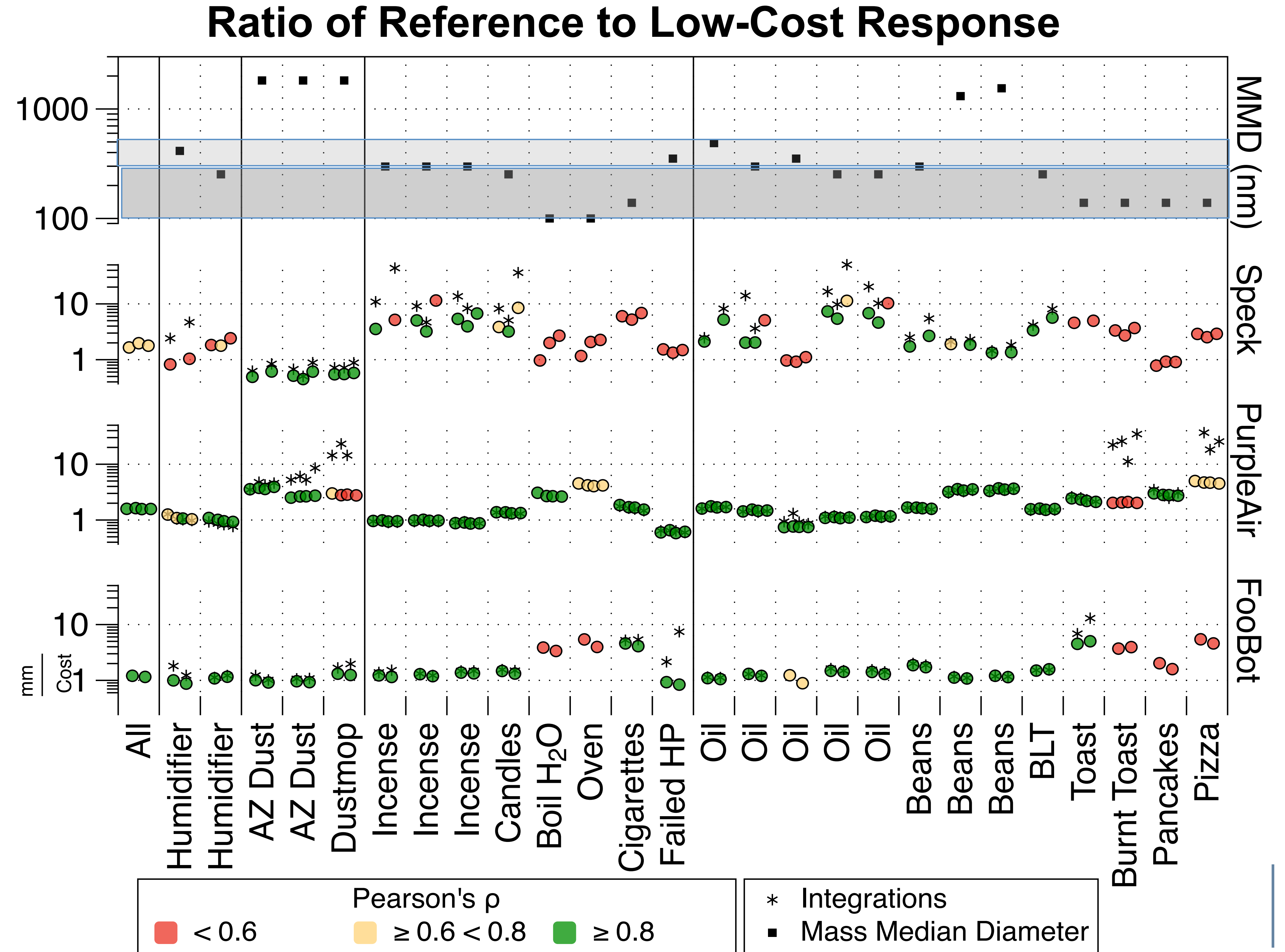


Ratio of Reference to Low-Cost Response
$\frac{C_C}{C_{Lo}}$
10
1
AQegg
AWAIR
AirBeam
AV Node
All
Humidifier
Humidifier
AZ Dust
AZ Dust
Dustmop
Incense
Incense
Incense
Candles
Boil H_2O
Oven
Cigarettes
Failed HP
Oil
Oil
Oil
Oil
Oil
Beans
Beans
Beans
BLT
Toast
Burnt Toast
Pancakes
Pizza
Pearson's ρ
< 0.6
≥ 0.6 < 0.8
≥ 0.8
Integrations
Mass Median Diameter



Ratio of Reference to Low-Cost Response
1000
100
10
1
MMD (nm)
Speck
PurpleAir
FooBot
mm / Cost
All
Humidifier
Humidifier
AZ Dust
AZ Dust
Dustmop
Incense
Incense
Incense
Candles
Boil H2O
Oven
Cigarettes
Failed HP
Oil
Oil
Oil
Oil
Oil
Beans
Beans
Beans
BLT
Toast
Burnt Toast
Pancakes
Pizza
Pearson's ρ
< 0.6
≥ 0.6 < 0.8
≥ 0.8
Integrations
Mass Median Diameter

Low-cost particle monitors for indoor PM

- None of the devices were quantitative across all or even most of the sources.
  - If sources vary, cannot use low-cost monitors to quantify pollutant exposures.
- Several “saw” most of the sources; could be used to control filtration and ventilation to reduce in-home exposures.
- All of the low-cost devices failed to see sources dominated by ultrafine particles.
  - Need another way to detect UFP for control.
  - VOC sensors *could* partially fill this gap.

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FSEC

Variable Capacity Comfort Systems and Smart Ventilation Systems in High-Performance Homes

Panelists

Eric Martin, Chuck Withers, Danny Parker, and Karen Fenaughty – Florida Solar Energy Center

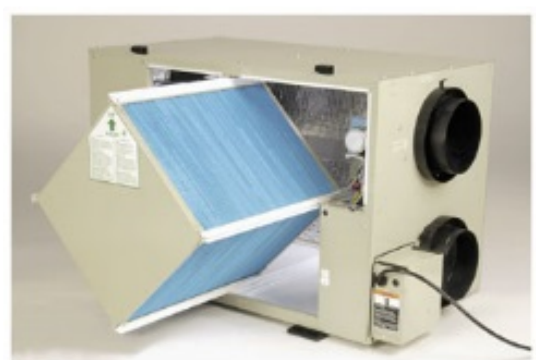
October 3, 2017

Building America
U.S. Department of Energy

FSEC

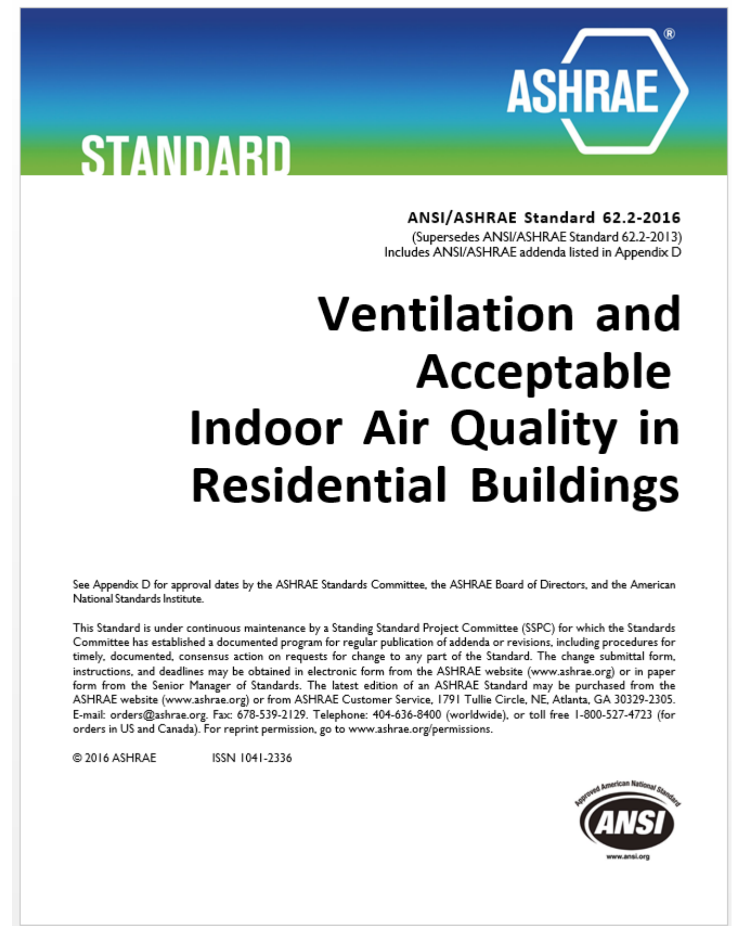
Smart Mechanical Ventilation Systems

- Systems optimize energy consumption and comfort while maintaining IAQ by varying fan operation.
- Systems ventilate more during periods that provide energy, comfort, and/or IAQ advantages and less during periods that provide a disadvantage.
- System operation controlled in response to differing control variables, such as outdoor temperature, outdoor moisture, occupancy, etc.



ASHRAE 62.2-2016 Appendix C

- Procedures for evaluation of time-varying ventilation
- Occupant exposure to pollutants relative to continuous ventilation
- Average (annual) relative exposure = 1 (chronic exposure)
- Peak exposure < 5 for any time step (acute exposure)
- No existing system varies flow rate while maintaining relative exposure


STANDARD

ASHRAE®

ANSI/ASHRAE Standard 62.2-2016
(Supersedes ANSI/ASHRAE Standard 62.2-2013)
Includes ANSI/ASHRAE addenda listed in Appendix D

Ventilation and Acceptable Indoor Air Quality in Residential Buildings

See Appendix D for approval dates by the ASHRAE Standards Committee, the ASHRAE Board of Directors, and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE website (www.ashrae.org) or in paper form from the Senior Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

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Approved American National Standard
ANSI
www.ansi.org

Real-Time Weather-Based Smart Ventilation

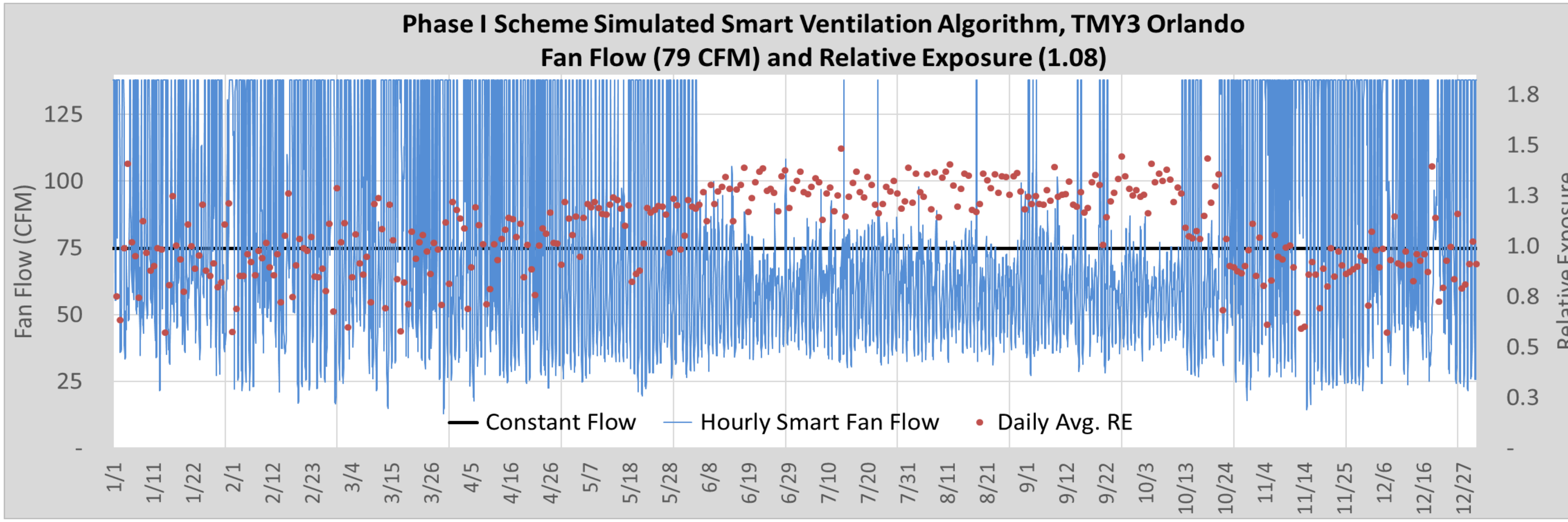
Vary mechanical ventilation airflow with an algorithm that interprets measurements of current and 24-hour historical outdoor temperature and moisture.

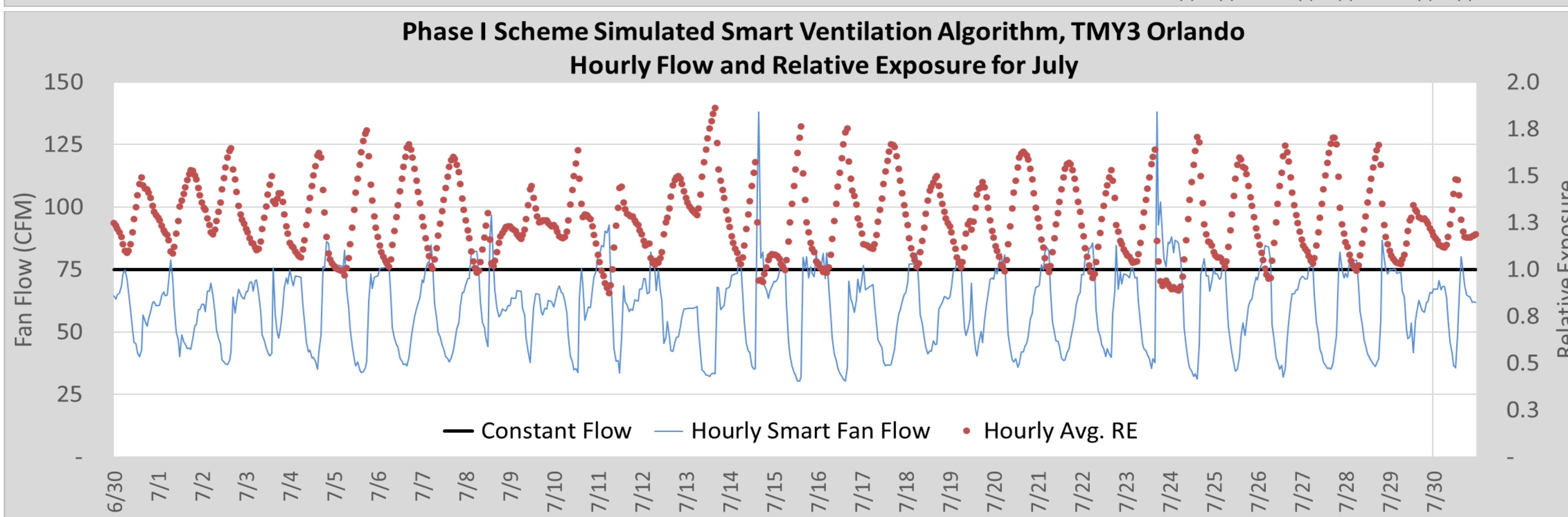
$$RSS=\sqrt{(\Delta T * X_T)^2 + (\Delta W * X_W)^2}$$

Hourly Fan Flow = (Target Fan Flow * (Average RSS_1:RSS_{23}/RSS_{24})

Period (defined by hourly outdoor T)	**Parameter**	**Phase I Scheme Values**
Cooling	Outdoor temp range for cooling period target Cooling period target fan flow	> 71.5°F 55 cfm
Heating	Outdoor temp range for heating period target Heating period target fan flow	< 60°F 75 cfm
Floating	Outdoor temp range for floating period target Floating period target fan flow	<= 71.5°F; >= 60°F 138 cfm (fan limit)
All	Indoor temperature Delta-temperature weight (X_T) Indoor moisture (W) Delta-moisture weight (W_W)	64.4°F 2 12g/m^3 1

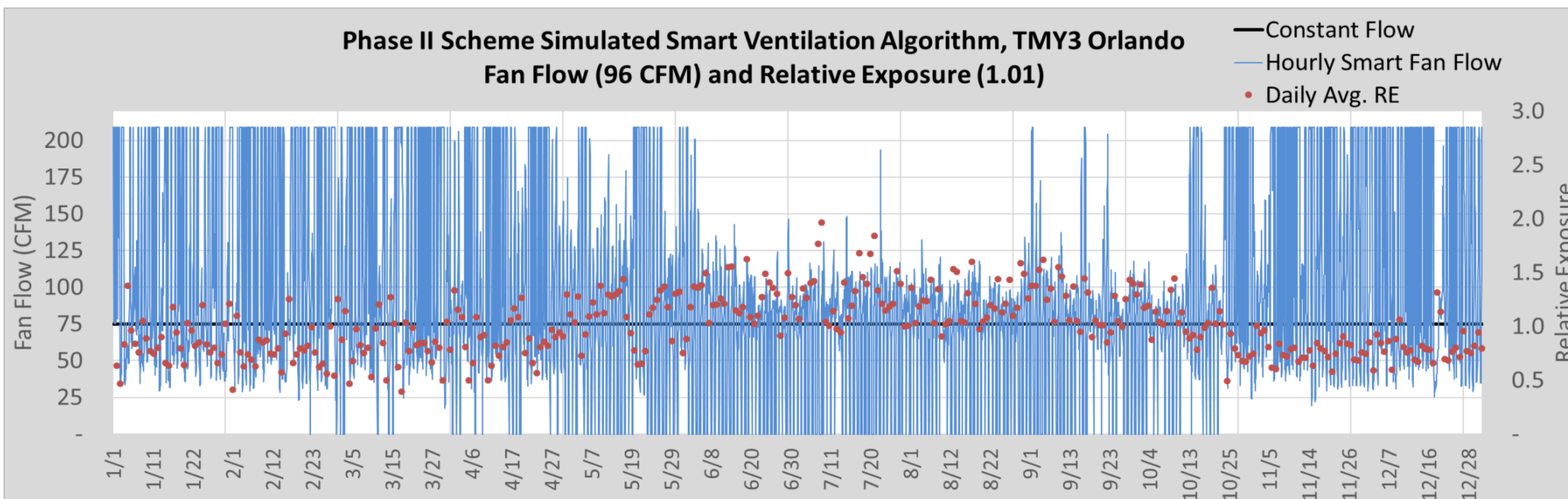
Phase I Simulated Results





Phase II

Period	Parameter	Phase I Scheme Values	Phase II Scheme Values
Cooling	Outdoor temp for cooling period target	> 71.5°F	> 71.5°F
	Cooling period target fan flow	55 cfm	75 cfm
	Outdoor temperature for fan override	n/a	>= 88°F
Heating	Outdoor temp for heating period target	< 60°F	< 50°F
	Heating period target fan flow	75 cfm	75 cfm
Floating	Outdoor temp for floating period target	<= 71.5°F; >= 60°F	<= 71.5°F; >=50°F
	Floating period target fan flow	138 cfm (fan limit)	209 cfm (fan limit)
	Outdoor W to adjust floating period target	n/a	>= 15g/m3
	Floating period target adjusted for W	n/a	75 cfm
All	Indoor temperature (T)	64.4°F	64.4°F
	Delta-temperature weight (X_T)	2	2
	Indoor moisture (W)	12g/m3	12g/m3
	Delta-moisture weight (X_W)	1	1



Laboratory Evaluation

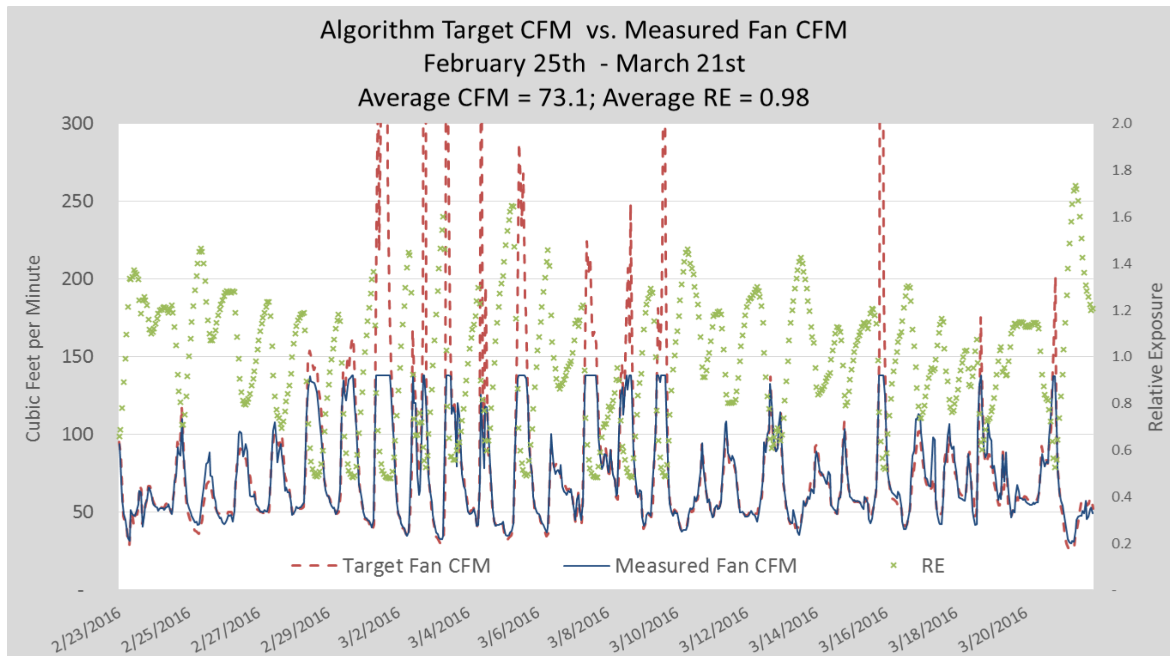
FSEC FRTF Labs

- 1,536 ft^2, 2.2 ACH50
- Supply ventilation
- ASHRAE 62.2-2016

$Q_{total} = Q_{fan} + \phi Q_{inf} = 76.1$ cfm

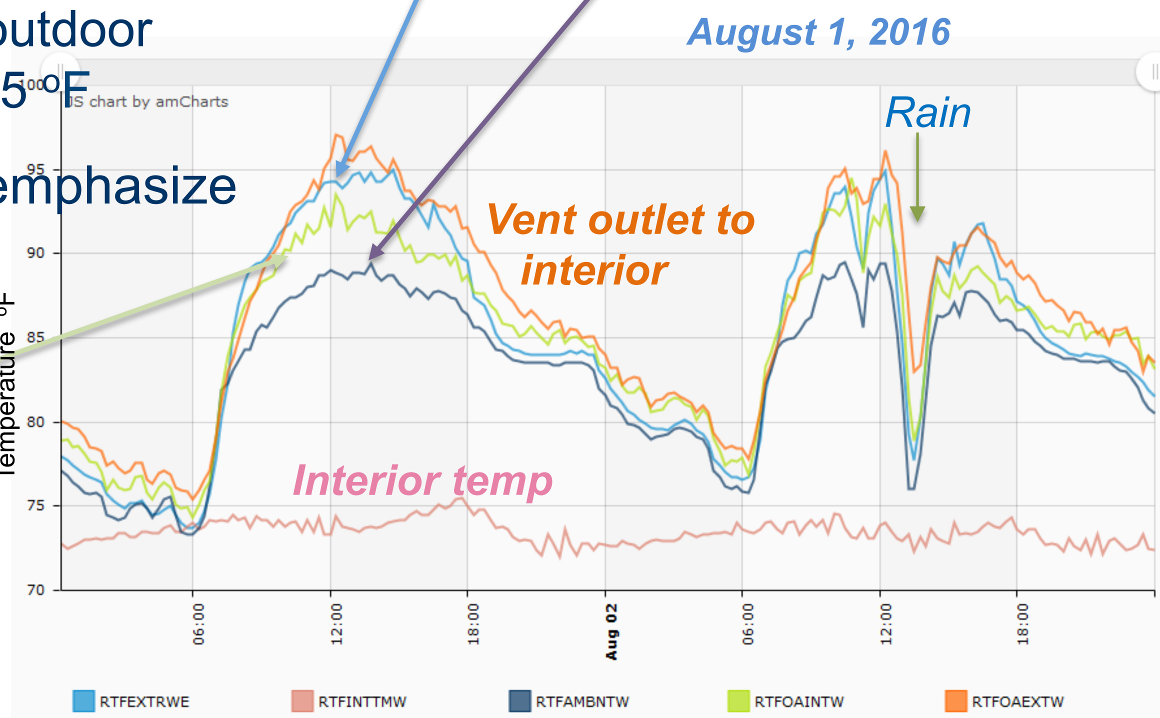
$\phi = 1$, $Q_{fan} = 66$ cfm

$\phi \neq 1$, $Q_{fan} = 75$ cfm



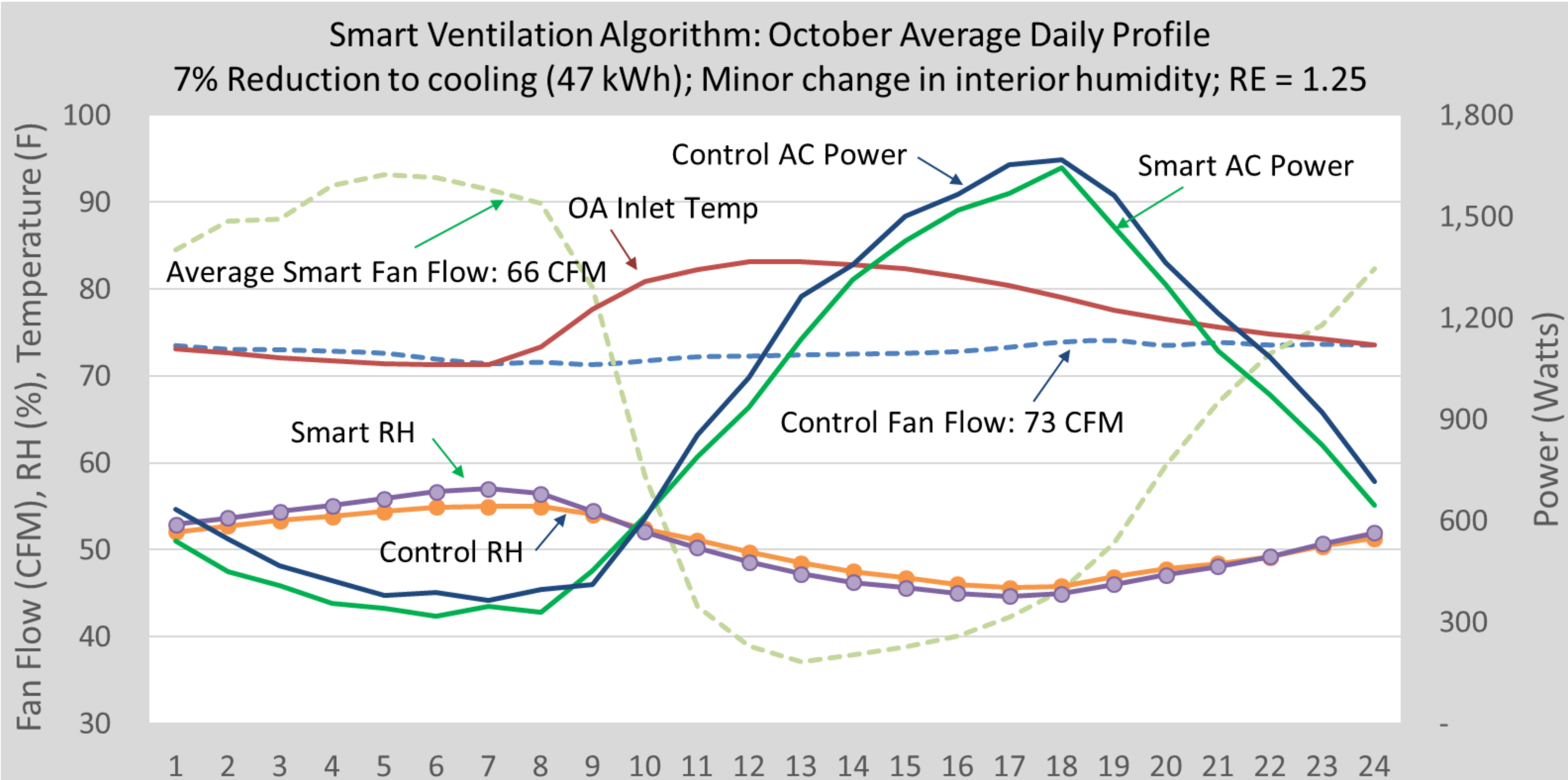
Key findings

- Potential to use broadband weather to drive Smart Vent.
- Accurate sensing of local outdoor temperature is
  - Air temperature higher near ground & varies w/ time of day
  - Ideal summer ventilation outdoor target temp not 75, but ~65 °F
- Hi-outlet to interior temps emphasize SV comfort potential



Air temp @ 1m

Phase I Experimental Results



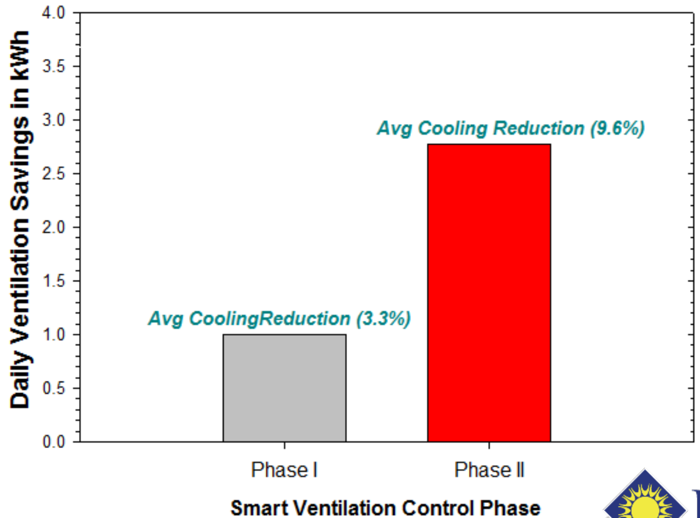
Phase I vs. Phase II Experimental Results

Phase I: Summer

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total (kWh)			
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
Aug	1,312	1,295	16	29	18	11	1,340	1,313	27	2%
Sep	1,011	1,013	(2)	29	18	10	1,039	1,031	8	1%
Oct	671	624	47	29	21	8	700	645	55	8%

Phase II: Summer

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total Energy (kWh)			
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
May	719	630	89	29	36	(7)	748	666	82	11%
Jun	822	749	73	29	20	8	851	770	81	9.5%
Jul	1,011	924	87	29	26	2	1,040	950	89	8.6%



Smart Ventilation (SV) Conclusions

- ***10% summer cooling energy savings can be achieved***
  - *Potential for greater savings with enthalpy heat recovery and optimization of fan energy* (var. speed motor)
  - Certainty of improved comfort & likely acceptability
  - Reduction in fan power critical to positive ann. savings
  - Need evaluation of SV control method across climates

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