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Ventilation and Indoor Air Quality in Recently Constructed U.S. Homes: Measured Data From Select Southeastern States

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Ventilation and Indoor Air Quality in Recently Constructed U.S. Homes: Measured Data From Select Southeastern States

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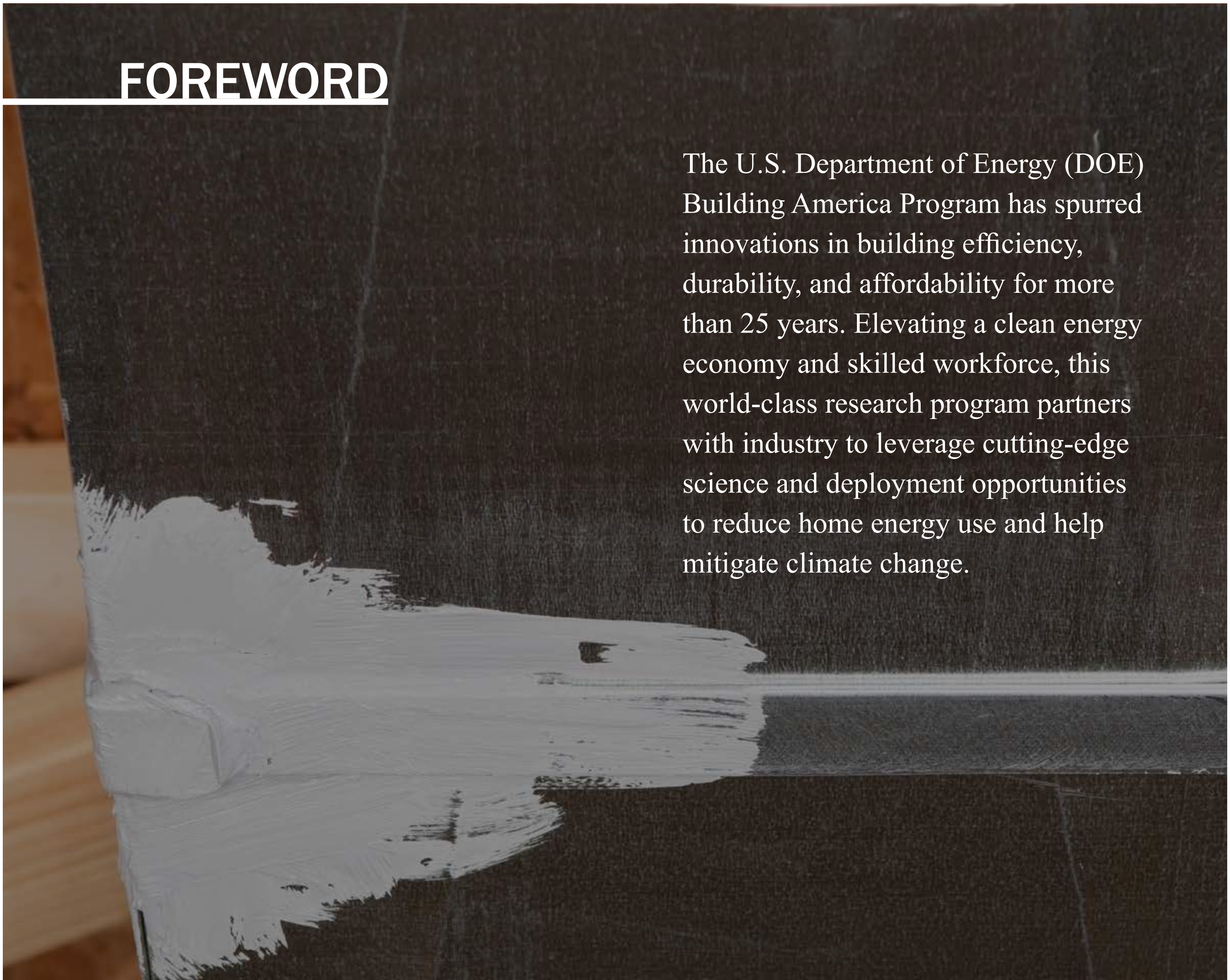
The work presented in this EERE Building America report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

FOREWORD



The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the Florida Solar Energy Center is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, *Ventilation and Indoor Air Quality in Recently Constructed U.S. Homes: Measured Data From Select Southeastern States*, presents and discusses the study protocol and high-level results obtained from data collection efforts to characterize indoor air quality in homes constructed since 2013 in Florida, Georgia, and South Carolina.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

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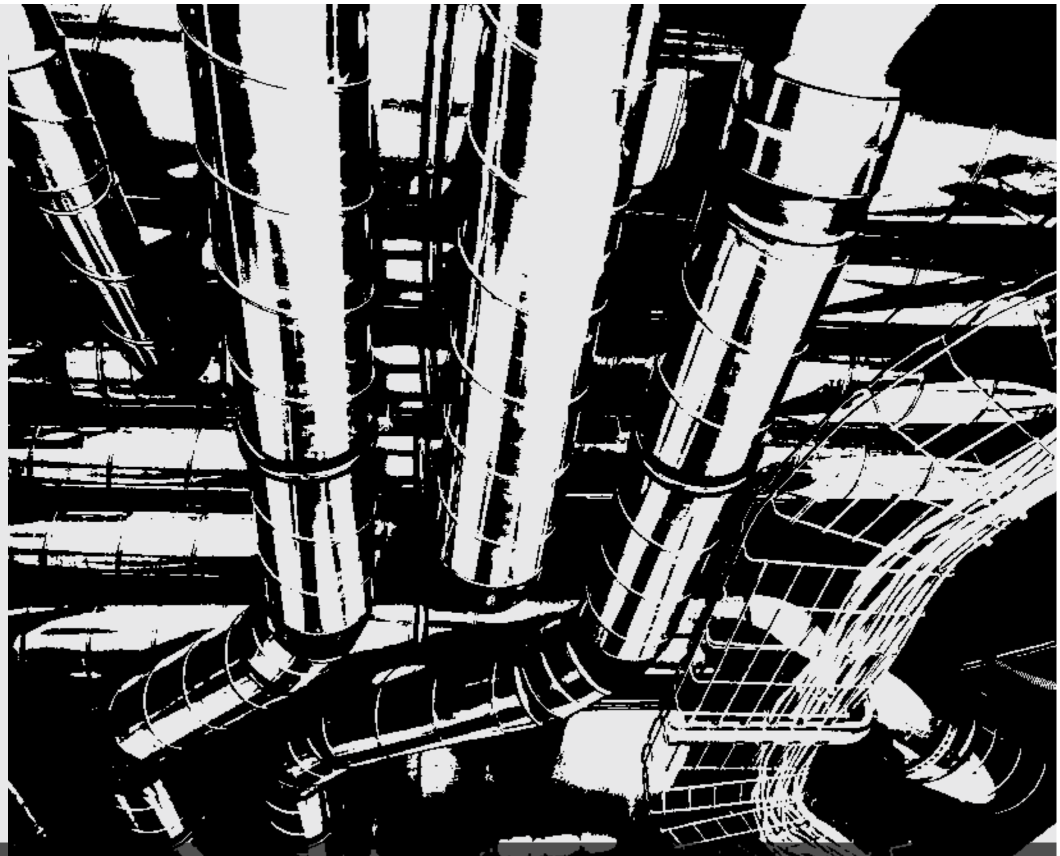

LIST OF ACRONYMS

ACH50	air changes per hour at 50 pascals
ANSI	American National Standards Institute
BAIAQ	Building America New Home Indoor Air Quality
CFIS	central-fan-integrated supply
C-CFIS	controlled central-fan-integrated supply
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
ERV	energy recovery ventilator
FSEC	Florida Solar Energy Center
HENGH	Healthy Efficiency New Gas Homes
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
ICC	International Code Council
IECC	International Energy Conservation Code
IRC	International Residential Code
LBNL	Lawrence Berkeley National Laboratory
pi/L	picocurie per liter
$PM_{2.5}$	particulate matter with diameter of 2.5 microns or less
PNNL	Pacific Northwest National Laboratory
ppb	parts per billion
ppm	parts per million
REL	reference exposure level
U-CFIS	uncontrolled central-fan-integrated supply
ug/m^3	microgram per liter
UIUC	University of Illinois Urbana-Champaign
WHMV	whole-house mechanical ventilation

EXECUTIVE SUMMARY

Whole-building air exchange is an important element to maintain healthy indoor air quality (IAQ) in residential buildings. Air exchange acts to dilute concentrations of indoor air pollutants with outdoor air.

ASHRAE Standard 62.2, “Ventilation and Indoor Air Quality in Low-Rise Buildings,” is the most commonly referenced residential ventilation standard in the United States. The 2010 version of the standard (ASHRAE 62.2-2010) is currently required by ENERGY STAR® for Homes Version 3, the U.S. Department of Energy’s (DOE’s) Zero Energy Ready Home Criteria, state weatherization programs, and other home performance programs.

Little data is available that quantifies IAQ or associates contaminant levels with air exchange in U.S. homes. To address this gap, the U.S. Department of Energy (DOE) Building America Program conducted a study to characterize IAQ in U.S. homes constructed since 2013, along with presence, functionality, and occupant use of control measures. Specific objectives of this study effort included:

- Measuring time-integrated concentrations and temporal profiles of established contaminants of concern; monitoring the use of ventilation equipment; and tracking activities that impact air pollutant emissions and removal processes in typical homes in various climate zones
- Characterizing the prevalence, type, and installed performance of mechanical ventilation equipment in new homes; exploring regional variations in system designs and performance
- Investigating associations between contaminant levels and the presence of control measures including whole-house mechanical ventilation (WHMV).

The study engaged research teams to collect data at a regional level. This report introduces the study protocol and presents and discusses high-level results obtained from Florida Solar Energy Center (FSEC) data collection efforts in the southeastern U.S. states of Florida, Georgia, and South Carolina.

FSEC developed a recruitment strategy and targeted a diverse mix of homes that reflect the general characteristics of newer housing in the target region. FSEC's energy-rated homes database served as the primary source of records to identify homes that met study requirements for recruiting purposes. A similar database maintained by the Residential Energy Services Network was used as a secondary source of records. As homes that have been built better than code are more likely to obtain an energy rating, the databases contain significantly more above-code homes than minimum-code homes. Code requirements for WHMV are relatively recent additions in Florida and Georgia and are not currently included in South Carolina. However, thanks to successful penetration of ENERGY STAR Homes and other above-code programs, a significant number of homes built since 2012 incorporate ASHRAE 62.2-2010 WHMV guidelines.

A total of 51 homes were recruited and participated in the study. Forty homes were located in Florida, six in South Carolina, and five in Georgia. All were single-family detached homes except for one townhome in South Carolina and one townhome in Georgia. Table ES-1 provides a summary of home and occupancy characteristics.

Table ES-1. Summary of Home and Occupancy Characteristics

Characteristic	Median	Range
Conditioned Area (ft^2)	2,146	1,120–3,869[a]
Year Built	2017	2013–2020
Number of Occupants	3	1–7

[a] Only homes with floor areas of less than 4,000 ft^2 and greater than 900 ft^2 were targeted.

Participants were asked to respond to a questionnaire that asked how they feel about their home environment and the factors that could affect their IAQ, and about their understanding and presence of any WHMV system. Researchers made multiple visits to each home to:

- Install instrumentation to measure indoor and outdoor concentrations of pollutants of interest—formaldehyde, carbon dioxide, particulate matter with diameter of 2.5 microns or less ($PM_{2.5}$), radon, and nitrogen dioxide

- Install instrumentation to monitor use/operation of home features and equipment that affect air quality and air exchange with the outdoors including WMHV systems

- Characterize the airflow of mechanical devices inducing air exchange with the outdoors, and quantify building envelope and duct leakage.

Most homes were monitored for one week some with an operating WHMV system, and some without. Select homes with functioning, ASHRAE 62.2-compliant ventilation systems were monitored for two weeks—one week with the WHMV system operating, and one without. Homeowners were asked to complete an activity log for each day of the monitoring period designed to capture actual occupancy as well as routine and intermittent activities that could affect IAQ.

Table ES-2. Summary of WHMV Systems Encountered

WHMV System Type	Number of Systems Encountered[a]	Able to Function On Any level	Capable of Meeting 62.2-2010 Continuous Flow Requirement	Operating As Found
Exhaust Fan	24	23	16	3
Central Fan Integrated Supply	19	5	1	3
Energy Recovery Ventilator	6	5	3[b]	5
Ventilating Dehumidifier	5	4	3	3

[a] Some homes were found with multiple WHMV systems.
[b] Two systems had rheostats which may have enabled them to deliver additional flow.

Table ES-2 summarizes the types of WHMV systems encountered, their functionality, and their operation. Similar to findings from past studies, this study encountered barriers that still need to be overcome with regard to functionality and operation of residential WHMV systems. The findings suggest that proper training of heating, ventilating, and air conditioning (HVAC) technicians, electricians, code inspectors, and home energy auditors with regard to installation and commissioning is critical to ensuring the IAQ benefits of WHMV are realized, enabling the industry to continue to build energy-efficient homes with tight building enclosures. In particular, the industry needs systems whose performance is easy to verify, including easier access to air inlets and outlets or built-in flow measurement, along with on-board fault detection systems that alert homeowners to nonfunctioning systems. Another priority is improved labeling and training on identification of controls for homeowners to overcome the issue of nonoperating systems.

The most common approach found for providing WHMV was via an exhaust fan. All such fans encountered were installed in bathrooms and also used for spot exhaust purposes. Fans were most often designed to run continuously, via a simple on/off wall switch, while a few homes had programmable fan controls. None of these switches were found to be labeled in any way in any of the homes. Among the 24 homes that had exhaust WHMV systems, 16 were found capable of meeting ASHRAE 62.2-2010 minimum requirement for WHMV. However, only three systems were operating for this purpose as found. In general, homeowners were not aware that these fans served as WHMV, and were not aware of how they should be operated as such.

The second-most common WHMV systems encountered were central-fan-integrated supply (CFIS) systems that are designed to use a home's central forced air heating and cooling system to temper and distribute outdoor air that is pulled in through a ducted connection from outside to the return side of the forced air system. Passive CFIS systems that are "uncontrolled" rely exclusively on the heating/cooling runtime of the forced air system and thus are not ASHRAE 62.2 compliant. Some manufacturers package control and damper systems that invoke additional air handler fan runtime to meet flow targets on an hourly basis. Some of these "controlled" CFIS systems also contain customizable settings that limit the introduction of outside air when outdoor temperature and/or indoor/outdoor relative humidity reach certain thresholds. This may save energy or improve comfort, but generally results in operation that is not compliant with ASHRAE 62.2. Among 19 homes that had CFIS systems, only one was capable of meeting minimum WHMV requirements for ASHRAE 62.2-2010. Only five systems were capable of operating at all, with three systems operating as found. Problems encountered included control incompatibility, disconnected wiring, and failed dampers. In general, controlled CFIS systems were labeled as to their purpose; however, in general most homeowners were not aware of the existence of CFIS systems or how they functioned.

A smaller number of homes had an energy recovery ventilator (ERV), designed to deliver quasi-balanced ventilation with capability for passive heat and moisture management; or a ventilating dehumidifier, designed to deliver supply-based ventilation with capability for active moisture removal. For 11 homes that had these types of WHMV systems, eight were found operating and six of these were capable of meeting minimum WHMV requirements of ASHRAE 62.2-2010. Only one system was not capable of operating. Homeowners with these types of WHMV systems were all generally aware of the existence of these systems, their location, and their purpose.

Spot ventilation systems that exhaust air from kitchens and bathrooms were also characterized. Nearly half of the bath fans in the home sample (46%) did not meet the minimum intermittent airflow requirements of ASHRAE 62.2-2010 (50 cfm). Three homes had fans that could not generate any measurable flow. Of all the kitchen range hoods encountered, three were recirculating type and not vented to the outdoors and two did not generate any measurable flow. Of the remaining homes, ten had kitchen range hoods that could not meet the minimum airflow requirements of ASHRAE 62.2-2010 (100 cfm).

Weekly average concentrations of carbon dioxide, formaldehyde, radon, $PM_{2.5}$, and nitrogen dioxide varied considerably among the homes, in large part due to factors not related to WHMV operation including home location, home construction materials, home contents, age of materials, and occupant activities. Several homes exceeded a weekly average carbon dioxide concentration of 1,000 ppm in the main living area and master bedroom, although most of those homes were not operated with WHMV. All homes had formaldehyde concentrations in excess of the California Environmental Protection Agency reference exposure level (REL) of 7 ppb, while six exceeded the acute REL of 44.8 ppb. Two homes in Georgia exceeded the U.S. Environmental Protection Agency (EPA) radon action level of 4 pi/L. Four homes exceeded the EPA annual REL for $PM_{2.5}$ of 12 ug/m^3, but none exceeded the 24-hour value of 35 ug/m^3. No homes exceeded the EPA yearly REL of 53 ppb for nitrogen dioxide.

To investigate WHMV as a control measure for IAQ, focus was placed on results from two-week homes for which occupant influences were somewhat normalized. Table ES-3 provides weekly average pollutant concentrations for WHMV "off" and WHMV "on" weeks for two-week homes. Table ES-4 provides differences in weekly average pollutant concentrations between WHMV "off" and WHMV "on" weeks for two-week homes.

It is evident from the carbon dioxide data that operation of the WHMV system creates additional air exchange, thereby reducing carbon dioxide concentration by a median value of 30%. WHMV operation also appears to decrease concentrations of radon and nitrogen dioxide, with

Table ES-3. Comparison of Pollutant Concentrations During "Off" and "On" Weeks in Two-Week Homes

Pollutant (n)	Median (10%–90%) Values for "Off" Week	Median (10%–90%) Values for "On" Week
Carbon Dioxide (ppm) – main (13)	899 (487–1331)	605 (497–905)
Carbon Dioxide (ppm) – master bed (12)	1000 (727–1297)	662 (541–1027)
Formaldehyde (ppb) – main (11)	28.3 (19.0–43.3)	28.0 (17.0–40.0)
Radon (pCi/L) – main (8)	1.3 (0.6–1.8)	0.7 (0.5–0.9)
$PM_{2.5}$ (ug/m^3) – main (10)	4.6 (3.5–7.9)	5.8 (3.5–11.6)
Nitrogen Dioxide (ppb) – main (4)	1.5 (1.2–2.3)	1.0 (0.6–1.5)

Table ES-4. Comparison of Pollutant Concentration Differences During "Off" and "On" Weeks in Two-Week Homes

Pollutant (n)	Median Concentration Difference Between WHMV "Off" and WHMV "On"	10% and 90% Values of Concentration Differences Between WHMV "Off" and WHMV "On"
Carbon Dioxide (ppm) – main (13)	252 (30%)	6 (0%) and 427 (36%)
Carbon Dioxide (ppm) – master bed (12)	268 (29%)	111 (12%) and 426 (40%)
Formaldehyde (ppb) – main (11)	1.8 (7%)	-6.0 (-27%) and 4.0 (13%)
Radon (pCi/L) – main (8)	0.6 (41%)	0.1 (13%) and 1.0 (54%)
$PM_{2.5}$ (ug/m^3) – main (10)	-0.1 (-11%)	-6.7 (-157%) and 2.2 (38%)
Nitrogen Dioxide (ppb) – main (4)	0.6 (43%)	0.1 (9%) and 1.2 (58%)

median reductions of 42%, although sample sizes of two-week homes with radon and nitrogen dioxide data are small due to instrument issues and a prevalence of all-electric homes. Differences in background levels between “off” and “on” weeks may also contribute to differences in indoor concentrations of nitrogen dioxide. Operation of the WHMV system appears to minimally reduce formaldehyde concentration, with a median value of 7%. This is likely due to complex indoor chemistry including an inverse relationship between concentration and emission rate. Operation of the WHMV system appeared to minimally increase $PM_{2.5}$ concentration, however additional analysis is required to rule out other confounding factors. The expectation is that spot ventilation would be more effective, especially for cooking sources. Future analysis of spatial, time-resolved $PM_{2.5}$ measurements are expected to provide additional insight.

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1 Introduction

Whole-building air exchange is an important element in maintaining healthy indoor air quality (IAQ) in residential buildings. Air exchange acts to dilute concentrations of indoor air pollutants with outdoor air. In older homes, air exchange occurs through cracks and other openings in the envelope, but in newer buildings with tighter envelopes, mechanical means of ensuring whole-building air exchange are necessary. Other components of a comprehensive IAQ strategy include limiting materials and activities that are a source of pollutants, and employing local exhaust in bathrooms and kitchens where intermittent odors and high concentrations of contaminants are likely to occur.

The U.S. Department of Energy (DOE) Building America program conducted a study to characterize IAQ in U.S. homes constructed since 2013, along with presence, functionality, and occupant use of control measures. The Building America New Home IAQ (BAIAQ) study engaged research teams to collect data regionally (Figure 1): Pacific Northwest National Laboratory (PNNL) in Oregon and Colorado, representing marine and cold dry climates, University of Illinois Urbana-Champaign (UIUC) in Illinois, representing cold climates, and Florida Solar Energy Center (FSEC) in Florida, Georgia, and South Carolina, representing warm humid climates. The data collection protocol was modeled after an earlier study called Healthy, Efficient, New Gas Homes (HENGH) (Chan et al. 2020) that was conducted by the Lawrence Berkeley National Laboratory (LBNL) and collected data in California, representing mixed dry climates.

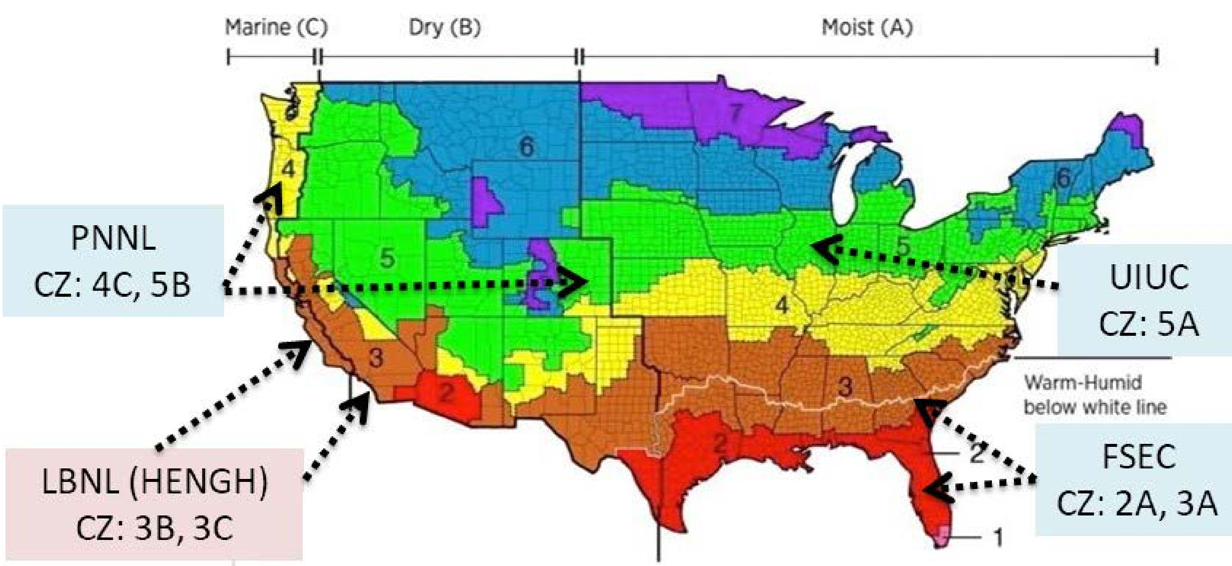

Figure 1. BAIAQ data collection teams and associated regions

Specific objectives of the BAIAQ study effort included:

- Measuring time-integrated concentrations and temporal profiles of established contaminants of concern; monitoring the use of ventilation equipment; and tracking activities that impact air pollutant emissions and removal processes in typical homes in various climate zones
- Characterizing the prevalence, type, and installed performance of mechanical ventilation equipment in new homes; exploring regional variations in system designs and performance
- Investigating associations between contaminant levels and the presence of control measures including mechanical ventilation.

This report introduces the study protocol and presents and discusses high-level results obtained from FSEC data collection efforts in the southeastern United States. Future publications will present more detailed results, combining data collected in all regions. A publicly accessible database is being constructed to make detailed data available for other analysis.

2 Background[1]

ASHRAE standard 62.2, "Ventilation and Indoor Air Quality in Low-Rise Buildings" is the most commonly referenced residential ventilation standard in the United States. The 2010 version of the standard (ASHRAE 62.2-2010) is currently required by ENERGY STAR for Homes Version 3, DOE's Zero Energy Ready Home Criteria, state weatherization programs, and other home performance programs. The current, 2019 version of the standard (ASHRAE 62.2-2019) is generally available as an alternative option, and contains several additional provisions, giving ventilation system designers more flexibility and providing more energy-efficient ventilation solutions.

Since 2012, the International Energy Conservation Code (IECC) and the International Residential Code (IRC) permit a maximum measured building air leakage of 3–5 air changes per hour at 50 Pa (ACH50), depending on climate. For homes equal to or tighter than the maximum allowable leakage, these codes require or at least define WHMV based on ASHRAE 62.2-2010. Many local jurisdictions base their local codes on these model codes. Historically, the Florida Building Code has referenced provisions for WHMV, but those provisions were not enforced, in part due to uncertainty as to how building enclosure leakage contributes to whole-house air exchange. The 6th edition of the Florida Building Code, which applied to homes permitted after July 1, 2017, instituted mandatory enclosure leakage testing, which permits a maximum enclosure leakage rate of 7 ACH50. Rather than triggering IRC requirements for WHMV for building enclosure leakage at less than 5 ACH50, the Florida code triggers WHMV in accordance with ASHRAE 62.2-2010 for enclosure leakages at less than 3 ACH50. While bathroom and kitchen ventilation is required at a minimum of 50 and 100 cfm respectively, kitchen ventilation is not required to exhaust to the outdoors, and recirculating type range hoods and over-the-range microwaves are allowed. While code requirements for WHMV in Florida are relatively recent, successful penetration of ENERGY STAR Homes and other above-code programs have resulted in a significant number of homes built since 2012 that incorporate ASHRAE 62.2-2010 guidelines. Georgia has required mandatory enclosure leakage testing since 2010, and until recently had the same state energy code since January 2011, which references IECC 2009. While that code referenced IRC 2012 requiring WHMV for homes with air exchange of less than 5 ACH50, local amendments permitted a maximum enclosure leakage of 7 ACH50. Beginning January 2020, a new code took effect that lowered the maximum allowed enclosure leakage to less than 5 ACH50, effectively triggering WHMV for all new homes. South Carolina also requires mandatory enclosure leakage testing, with a maximum permitted leakage of 7 ACH50. However, the requirements do not reference WHMV provisions of the IRC.

Little data is available that characterizes IAQ and associated contaminant levels with air exchange in homes in the southeastern United States. Indoor air pollutants including carbon dioxide, formaldehyde, acetaldehyde, volatile organic compounds, and nitrogen dioxide were

[1] Note that some of the text in this section was originally drafted by the authors for a paper submitted to the 2020 ACEEE Summer Study on Energy Efficiency in Buildings (Martin et al. 2020).

sampled in 10 homes located in Gainesville, Florida during a period from summer 2013 through summer 2014 (Widder et al. 2017). Observed concentrations of sampled contaminants were variable among the homes, suggesting the importance of occupant activities and behavior. However, with the exception of carbon dioxide, concentrations of indoor air pollutants did not show a significant dependence on the amount of mechanical air exchange. Of note, these findings contradict results from studies conducted in other states (Chan et al. 2020; Hult et al. 2015; Offerman 2009).

A survey of builders and contractors was conducted in 2015 to understand perceptions about value and costs related to WHMV requirements (Sonne et al. 2020). The overall perception of the value of WHMV was unfavorable, and included concerns about degraded IAQ and comfort due to humidity concerns. In 2014, a 21-home field study was conducted by FSEC, investigating mechanical ventilation systems installed in Florida homes since 1999 (Sonne, Withers, and Vieira 2015). More than half of the systems in the study had been installed after 2011. The researchers conducted a survey to assess homeowner ventilation system awareness and maintenance practices, and inspected and tested ventilation systems to assess operational status and level of ventilation provided, and identify performance issues. Homeowners surveyed felt ventilation was important for health, but many were unaware of how their ventilation system operated. Testing found only 3 of the 21 study homes (14.3%) had ventilation airflow close to the design level. Two of the ventilation systems were turned off by the homeowner, so only 1 of 21 homes (4.8%) was actually receiving the expected ventilation. Only 12 of the 21 homes (57.1%) were capable of operating. Issues identified included failed controllers and dampers, partially disconnected or crushed ducts, dirty filters, and poor outdoor air intake locations.

3 Recruitment and Home Characterization

3.1 Recruitment

FSEC developed a recruitment strategy and targeted a diverse mix of homes that reflect the general characteristics of newer housing in the warm humid climate region. FSEC's energy-rated homes database served as the primary source of records to identify homes that met study requirements for recruiting purposes. The database contains detailed information on homes that have undergone an energy rating for which FSEC has performed quality control and archived the results. A similar database maintained by the Residential Energy Services Network was used as a secondary source of records. In the case of the new homes that were targeted for the study, the energy ratings were typically commissioned by the home builders. The databases include the address of the home, year of construction, and detailed information on physical characteristics of the home, including WHMV system details. The databases do not contain any homeowner contact information or other personally identifiable information. As it is more common for homes that have been built better than code to obtain an energy rating, the databases contain significantly more above-code homes than minimum-code homes.

The main outreach method for recruitment was postcards that were sent to homes identified from the pre-existing databases as meeting the general criteria of being built since 2013 in the states of Florida, Georgia, and South Carolina. The postcards directed interested persons to either contact FSEC by phone or email or visit a project website to obtain more information. Homeowners were offered compensation in the form of home improvement store gift cards for their participation. A report summarizing data collected from each home was also provided.

3.2 Home Characterization

A total of 51 homes were recruited and participated in the study. Forty homes were located in Florida, six in South Carolina, and five in Georgia. Figure 2 shows a geographic distribution of the homes.

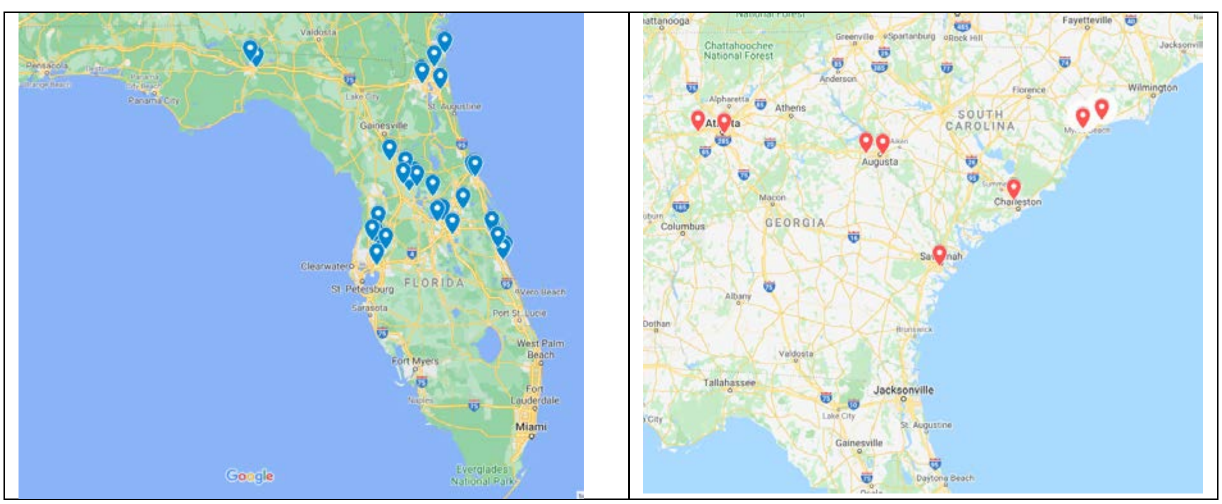

Figure 2. Geographic distribution of homes

Table 1 provides a summary of home and occupancy characteristics of the homes. All homes were single-family detached with the exception of one townhome in South Carolina and one townhome in Georgia. All foundations were slab on grade with the exception of two slab/stem wall homes in South Carolina and one walk-out basement home in Georgia. Thirty-four homes were single-story and 17 homes were two-story, one of which also had a walk out basement. Tables 1–3 provide a breakdown of conditioned area, year of construction, and full-time occupancy for the recruited homes, respectively.

Table 2. Summary of Home and Occupancy Characteristics

Characteristic	Median	Range
Conditioned Area (ft^2)	2,146	1,120–3,869[a]
Year Built	2017	2013–2020
Number of Occupants	3	1–7

[a] Only homes with floor areas of less than 4,000 ft^2 and greater than 900 ft^2 were targeted.

Table 3. Conditioned Area of Recruited Homes

Conditioned Area (ft^2)	Number of Homes
1,000–1,499	6
1,500–1,999	14
2,000–2,499	8
2,500–2,999	6
3,000–3,499	13
3,499–3,999	4

Table 4. Year of Construction for Recruited Homes

Year Built	Number of Homes
2013	1
2014	2
2015	6
2016	11
2017	11
2018	10
2019	4
2020	6

Table 5. Number of Full-Time Occupants in Recruited Homes

Number of Occupants	Number of Homes
1	5
2	19
3	15
4	5
5	4
6	2
7	1

4 Data Collection Methodology

Prior to an FSEC field team visit to the homes, participants responded to a questionnaire that asked how they feel about their home environment and about the factors that can affect their IAQ. They were also asked questions about activities and product use, as well as questions related to the home and household, including basic demographic and health-related questions. Each study home was visited by a two-person field team two to three times. On the first visit, the field team:

- Explained the study intent and requirements and obtained written consent from participants.
- Provided participants with an activity log for each day of the monitoring period designed to capture actual occupancy and routine and intermittent activities that could affect IAQ. This included prolonged opening of windows and doors, house cleaning, cooking, and burning candles. The log also had the occupant report periods of poor outdoor air quality, for example from a nearby forest fire.
- Completed house and heating, cooling, and ventilation system characterization.
- Installed air quality measurement devices indoors and outdoors, and installed devices to monitor cooking, heating/cooling system operation, and use/operation of home features and equipment that affect air exchange with the outdoors including WMHV systems, kitchen, bath, and laundry exhaust for spot ventilation, clothes dryers, and exterior doors.

Participants were asked about their understanding of, and the presence of, any WHMV system, and asked to partake in normal household activities with the exception that windows and doors should not be used for natural ventilation, and smoking of any kind should not be conducted indoors during the data collection period. Most homes—some with an operating WHMV system, some without—were monitored for one week. Select homes with functioning, ASHRAE 62.2-compliant ventilation systems were monitored for two weeks—one week with the WHMV system operating and one without. For these homes, the field team visited the home after the first week to change the WHMV system status. During the final field team visit, all data collection devices were removed, activity logs collected, and remaining tests conducted to quantify airflow of air moving equipment and to characterize building envelope and duct leakage.

4.1 Air Quality Measurements

Air pollutants of interest included formaldehyde, particulate matter with diameter of 2.5 microns or less ($PM_{2.5}$), nitrogen dioxide, radon, and carbon dioxide. Temperature and relative humidity were also measured. Table 5 lists air quality measurement equipment and sampling locations in each home. Only data collected from select measurement equipment is presented and discussed in this report. Remaining data will be presented in other publications.

Table 6. Instrumentation for Air Quality Measurements

Location	Parameter	Resolution	Measurement Device
Outdoors	$PM_{2.5}$ photometry	1 minute	MetOne ES-642
	$PM_{2.5}$ gravimetric	1 minute	Filter sample collected using Pump and PEM
	Nitrogen dioxide[a]	1 week	Ogawa passive samplers
	Formaldehyde (time-integrated)	1 week	SKC UMEx 100 passive sampler
	Temperature, relative humidity	1 minute	Onset HOBO U23 Pro v2
Central indoors	$PM_{2.5}$ photometry	1 minute	MetOne BT-645
	$PM_{2.5}$ gravimetric	1 week	Filter sample collected using Pump and PEM
	Nitrogen dioxide[a]	1 week	Ogawa passive sampler
	Formaldehyde (time-integrated)	1 week	SKC UMEx-100 passive sampler
	Formaldehyde (time-resolved)	30 minutes	GrayWolf FM-801
	$PM_{2.5}$ (optical counter), carbon dioxide temperature, relative humidity	1 minute	AirVisual Pro
Master bedroom	Formaldehyde (time-resolved)	30 minutes	GrayWolf FM-801
	$PM_{2.5}$ (optical counter), carbon dioxide temperature, relative humidity	1 minute	AirVisual Pro
Second common area	$PM_{2.5}$ (optical counter), carbon dioxide temperature, relative humidity	1 minute	AirVisual Pro
Master bathroom, second bathroom	Temperature, relative humidity	1 minute	Onset HOBO U23 Pro v2
Attic, basement, crawlspace (if sealed)	Temperature, relative humidity	1 minute	Onset HOBO UX100-003 T/RH
Lowest occupied level	Radon (short-term)	1 hour	Radstar RS300
	Radon (long-term)	6 months	Alpha Track samplers

[a] In homes with gas appliances only.

4.2 Monitoring and Measuring Airflow

Runtime of equipment that affects air exchange with the outdoors was monitored using instruments listed in Table 6. The positions (open or closed) of patio and garage-to-house door, along with the door to the master bedroom, were also monitored. Cooking events were monitored with iButton DS19222T temperature sensors placed on the cooktop, oven(s), and any other supplemental cooking equipment participants indicated may be used, such as toaster ovens.

Table 7. Instrumentation for Equipment Runtime and Door Status

Parameter	Measurement Device
WHMV system operation	Digisense anemometer WD-20250-22
	Onset plug load logger UX120-018
Master/second bathroom exhaust fan operation	Digisense anemometer WD-20250-22
Range hood operation	Digisense anemometer WD-20250-22
Clothes dryer operation	Onset motor on/off logger UX90-004 (electric)
	Onset plug load logger UX120-018 (gas)
Forced air system runtime – supply (up to two zones)	Digisense anemometer WD-20250-22
	Onset HOBO UX100-003 T/RH
Patio door, garage-to-house door status	Onset state sensor UX90-001
Master bedroom door status	Onset state sensor UX90-001

A one-time measurement to quantify airflow generated by all equipment of interest, along with building envelope and duct leakage, was conducted using devices shown in Table 7. Except in the case of a few WHMV systems integrated with multi- or variable-speed heat pumps, all fan flows deliver a constant amount of airflow during operation, and therefore a single airflow measurement was sufficient for flow characterization.

Table 8. Devices Used to Quantify Airflow

Parameter	Measurement Device
Fan forced-air flows into and out of home	Powered flow hood
	Exhaust fan flow meter
	Duct blaster
Building envelope and duct leakage air leakage	Delta Q method using blower door system with digital pressure gauge

5 Results and Discussion

5.1 Enclosure Air Leakage

Figure 3 shows the results of enclosure leakage obtained from the Delta Q tests conducted using a blower door. Median air changes per hour at 50 pascals (ACH50) was 3.8 for 37 Florida homes[2] and 5.3 for 11 Georgia and South Carolina homes. Most of the Florida homes were between 3 and 5 ACH50. The Georgia and South Carolina homes were nearly evenly divided between those with enclosure leakage between 3 and 5 ACH50 and those with enclosure leakage greater than 5 ACH50. Nine of the Florida homes fell below the recent WHMV code trigger of 3 ACH50, including two that were not built with WHMV systems. Both of those homes were built prior to institution of the WHMV code requirement. Only one of the Georgia or South Carolina homes was below 3 ACH50.

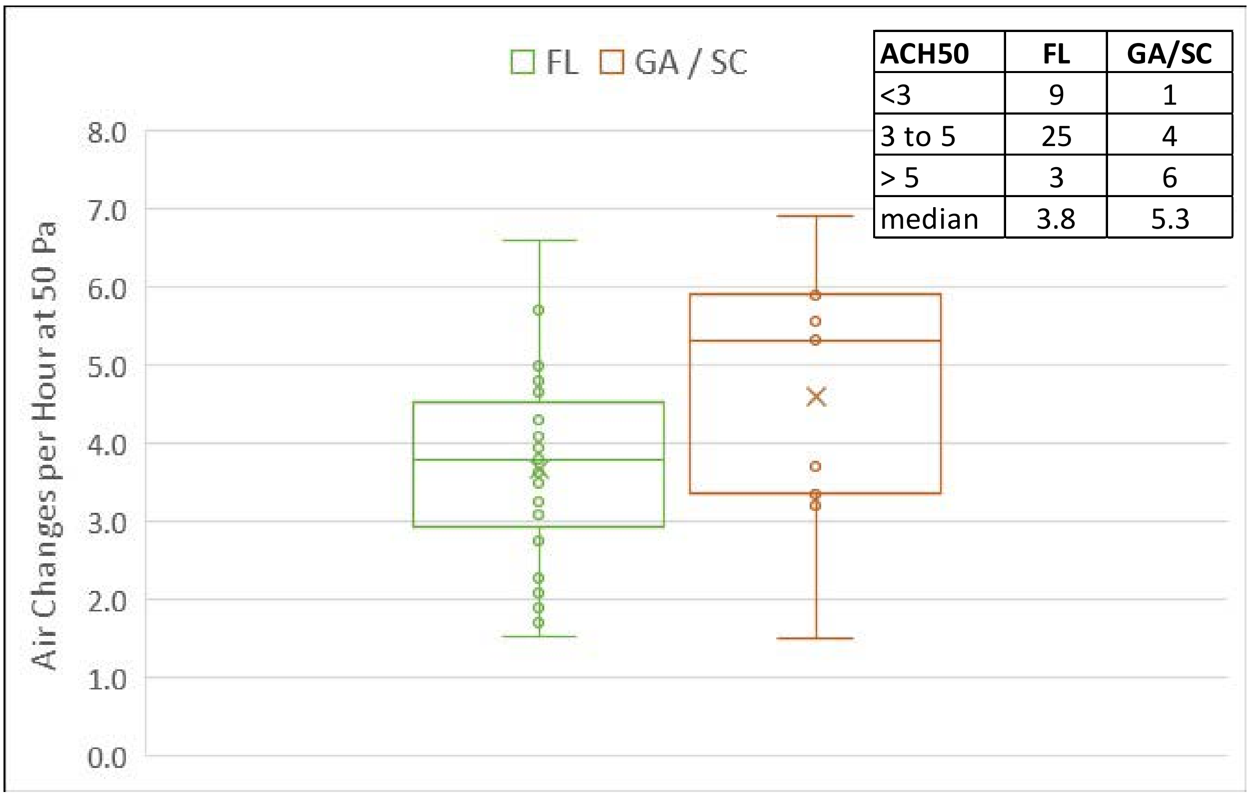

Figure 3. ACH50 of participating homes in Florida and Georgia/South Carolina

5.2 Mechanical Ventilation System Characterization

5.2.1 Whole-House Mechanical Ventilation Systems

Homes with WHMV systems which source records indicated met the minimum requirements of ASHRAE 62.2-2010 were targeted for recruitment. This version of the standard was chosen as the benchmark for this study as it is the version required by code and above-code programs for

[2] Delta Q testing was not able to be completed on three of the Florida homes.

homes in the southeastern U.S. region. Additionally, it is difficult to find a significant number of homes with systems that meet minimum requirements of more recent versions of the standard. Of the 51 homes recruited for the study, all but five homes (all in Florida) were indicated in the databases used for recruitment as having WHMV systems designed in accordance with ASHRAE 62.2-2010 requirements. Four of these five homes did not undergo an energy rating. Appendix A provides a detailed characterization of each WHMV system encountered.

5.2.1.1 Types of WHMV Systems Encountered

Exhaust Systems. The most common approach found for providing WHMV was via an exhaust fan. To comply with ASHRAE 62.2, the fan(s) must be rated for continuous duty and operate at less than 1.0 sone. Exhaust fans are the easiest WHMV system to measure air flow because the air intake is readily accessible. All exhaust WHMV fans encountered were installed in bathrooms and also designed for spot exhaust purposes. None of the switches used to operate the fans were found to be labeled in any way in any of the homes. While most exhaust fans had simple on/off switches, a small number of systems had controls located in a switch that enabled the fan to operate intermittently based on an adjustable time setting and achieve a minimum hourly runtime. Such controls often also enabled fan operation based on indoor humidity and/or occupancy, either independently from or in addition to the time setting. As discussed later, some were found to be very sensitive, resulting in significant fan runtime. While some labeling of these controls was visible after removing an access cover, adjusting and operating the control was not intuitive and required review of an operation manual. Examples of bath fan controls are shown in Figure 4.

Figure 4. Examples of exhaust fan controls. Top – runtime and relative humidity controls located on switches. Bottom left – flow controls located on fan. Bottom right – wall switches that enable standard and boost operation.

All photos by the authors, unless noted otherwise

Central Fan Integrated Supply (CFIS) Systems. The second-most common WHMV system type encountered were systems that were configured with the clear intent to use the home's central forced air heating and cooling system to temper and distribute outdoor air pulled in through a ducted connection from outside to the return side of the forced air system. This supply-based WHMV system is typically set up to pull outdoor air through the system using the negative return-side pressure generated when the forced air system fan operates. Measuring airflow of these CFIS ventilation systems is challenging when the outdoor air inlets are difficult to access, for example, when installed on roofs or in eaves of multi-story homes. Generally, outdoor air ducting is not designed to utilize other airflow quantification methods, such as those contained in ANSI/RESNET/ICC Standard 380. Characterizing airflow in CFIS systems is also challenging with variable-speed air handler fans, as such fans result in variable outdoor airflow rates; however, few such systems were found.

Passive CFIS systems that are "uncontrolled" (U-CFIS) rely exclusively on the heating/cooling runtime of the forced air system and thus are not ASHRAE 62.2 compliant. Some manufacturers package control and damper systems that invoke additional air handler fan runtime to meet flow targets on an hourly basis. These "controlled" CFIS systems (C-CFIS) may be programmed via a thermostat or a separate controller that connects to the thermostat. Generally, such controllers were located near an air handler and had some labeling as to their purpose, as ventilation controllers, and denoting system operation. CFIS systems can be configured to use a supplemental outdoor air supply fan, in which case the controls operate the supplemental fan rather than the air handler fan, outside of calls for heating and cooling, to conserve energy. Only one home was encountered that used a bathroom exhaust fan as the supplemental fan (C-CFIS/Exh) to provide ventilation when the central fan (and thus the CFIS) system was not operating. Some C-CFIS systems also contain customizable settings that limit outside air from being introduced when outdoor temperature and/or indoor/outdoor relative humidity reach certain thresholds, which may save energy or improve comfort, but generally result in operation that is not compliant with ASHRAE 62.2. Figure 5 shows photos of CFIS system components. Figure 6 shows examples of ducting issues encountered.

Figure 5. Left – common C-CFIS controller. Right – disconnected dampers prevent proper functioning

Figure 6. Left – CFIS outside air intakes high on wall are difficult to access for commissioning. Right – this return plenum ducting arrangement generates little flow through the 4-in. outside air duct.

Energy Recovery Ventilators (ERVs). ERV systems combine supply and exhaust fans that are set to operate in unison and enable both heat and moisture to be transferred between incoming and outgoing air streams to retain some of the energy used to condition the indoor air. While in general supply and exhaust flows are intended to be similar, balancing pressure between indoor and outdoors, they are sometimes (intentionally or unintentionally) designed or installed in a manner that results in imbalances. Some manufacturers institute slight imbalances by design.

Improper ducting and/or lack of maintenance can lead to flows in either direction that are much lower than design rates.

ERVs have air inlets/outlets both inside and outside the home, and supply/exhaust flows in principle could be measured at either location. However, in practice, it is often difficult to measure at all of the inlet or outlet points based on their locations or ducting connections. For example, outdoor inlets and exhaust points are sometimes inaccessible, as they are installed on roofs or in eaves/walls of multi-story homes; and the indoor terminations are sometimes connected by ducts to the home's central forced air ductwork.

Four of six ERVs encountered were designed to run continuously, with well-labeled on/off and sometimes low-/high-speed controls located on the unit or as wall switches. Two ERVs were operated intermittently via thermostat controls, and two had rheostat controls that allowed for airflow adjustment. Four ERVs were found in attics. The two systems capable of intermittent operation were ducted into the central forced air system, and two other attic-mounted ERVs operated continuously and had multiple points of supply/exhaust in different areas of the homes. In these homes, continuous ERV exhaust from bathrooms was used in lieu of bathroom exhaust fans in all but one bathroom in one home, and one of the homes had controls located in the bathrooms to boost the flow of the ERV for spot exhaust purposes. Two homes had a type of ERV with a built-in single point of supply and exhaust, mounted in the central living area of the homes (one in the ceiling, and one high on the wall). Figures 7 and 8 show examples of ERVs and associated controls.

Figure 7. Left – attic-located ERV. Right – associated thermostat control. Dirty filter hindered operation.

Figure 8. Ceiling-mounted ERV and associated wall switch controls

Ventilating Dehumidifier Systems. Five homes had ventilating dehumidifiers that delivered outside air into the return duct system of the central heating and cooling system. The systems deliver outside air via their own fixed-capacity fans, and operate independently of the central heating and cooling system, with programming that enables them to operate intermittently and deliver a target hourly ventilation rate. Most systems were not configured with capability to dehumidify the main living space, and did not have a return duct from the space. The dehumidifier compressor operated based on a customizable humidity set point, but only removed moisture from the outdoor air stream when the humidity in the main living space exceeded the set point during ventilation operation. All functions were configured via a control panel on the units, which were generally located in attics. All ventilating dehumidifiers encountered were in homes in Florida; no ventilating dehumidifiers were found in Georgia or South Carolina. Figure 9 shows examples of ventilating dehumidifiers.

Figure 9. Left – the most commonly encountered dehumidifier processed outside air only. Right – one dehumidifier also processed air from the space. Both are ducted to central heating/cooling systems.

5.2.1.2 Observed Functionality and Homeowner Knowledge of WHMV Systems

Figure 10 shows the weekly average WHMV system flow in each home that was listed in the source records as having an exhaust ventilation system. The flow is expressed as a percentage of the ASHRAE 62.2-2010 minimum continuous flow requirement for the home. The percentage takes into account both the WHMV system measured airflow and runtime. Two results are shown for each home. The "capable" results are shown with blue bars and represent the weekly average flow using the measured flow, and assuming 100% runtime. The "as found" results are shown with orange bars and represent the weekly average flow with operational time settings left as the study team found them upon arriving at the home.[3] Some homes had multiple fans with each one capable of meeting the ASHRAE 62.2-2010 requirement for the home on its own. In most cases, data for only one fan is shown, chosen based on review of fan specifications and consultation with homeowners to determine how they operate the fans.

[3] There were occasions where the field team adjusted these time settings to achieve ASHRAE 62.2-2010 compliance for the purposes of IAQ monitoring.

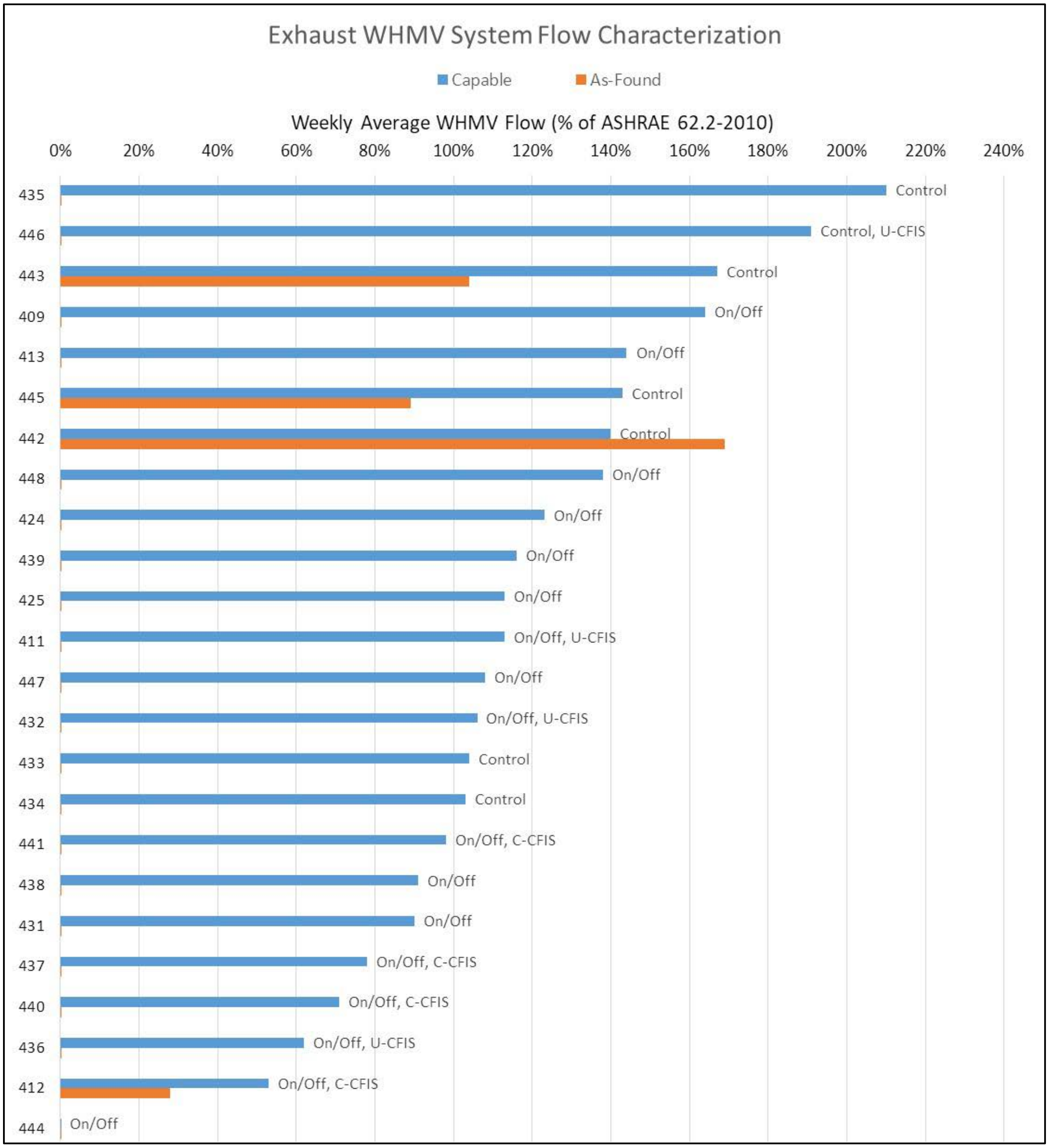

Figure 10. Airflow characterization of exhaust WHMV systems

Data labels next to the bars in Figure 10 indicate whether the exhaust fan was controlled by a simple on/off switch or a more sophisticated "control" capable of intermittent runtime or adjustable airflow. Unlike a simple on/off switch, such controls enable WHMV to be dialed in to a desired value. Homes 433, 434, and 435 were the only homes with a flow-adjustable fan, and airflow was measured at the flow setting as found, not necessarily at the highest flow setting available. The remainder of homes listed as "control" had fans with intermittent timer controls. While all homes in Figure 10 were described in source records as having an exhaust WHMV system, in certain homes, CFIS systems were also found by the field team, as indicated by data labels next to the bars. Characterization of these CFIS systems is included in Figure 11.

In all but three cases, exhaust WHMV systems were not found to be operating. In general, homeowners reported that they were not aware that these fans could provide WHMV and were not aware of why or how they should be operated for this purpose. “As-found” flow indicated for homes 442, 443, and 445 is actually the flow monitored during the testing week, driven by controls that activated fans based on a sensed rise in relative humidity. Each of these homes had two fans with such controls, and frequent runtime of each fan resulted in a combined average ventilation rate of significant magnitude. In the cases of 442 and 443, this combined, relative-humidity-activated flow exceeded the ASHRAE 62.2-2010 requirement for the homes. The “capable” flow listed for 442, 443, and 445 is based on only one fan in each home—the fan with the highest measured flow. It is assumed that only one fan was intended to provide WHMV for the home, as that was what the source records indicated. Home 444 had the same fan controls, and the owner was concerned about the frequent operation of the fans and subsequently replaced them with crank timers that did not permit continuous operation of the fans beyond 40 minutes without renewed activation of the crank timer. Therefore, that home is treated as not having capabilities for WHMV.

All fans listed as having 0% “as-found” flow were operated by homeowners for spot-ventilation purposes only, if at all. Home 412 was the only home where occupants indicated that they manually operated fans with on/off switches to achieve some level of WHMV. While they had no specific operational schedule, “as found” flow is actually the flow monitored during the testing week which indicated enough runtime to achieve more than 20% of the ASHRAE 62-2 2010 minimum requirement.

Figure 11 shows the weekly average airflows of each CFIS system. “Capable” flows are based on an assumption of continuous runtime of the home’s air handler, even though such systems are not designed to operate in that manner, in part due to the large energy consumption of the air handler fan. A label next to each bar indicates whether the system operated based on heating/cooling system runtime only (U-CFIS), or had controls capable of invoking system runtime outside of calls for heating/cooling (C-CFIS). As WHMV provided by U-CFIS systems is dependent on heating/cooling system runtime, “as-found” flows are based on runtime data collected during the data collection week, and thus vary throughout the year. No C-CFIS systems were found to operate. Labels also indicate the homes listed in the source records as having an exhaust WHMV system rather than a CFIS system. Home 421 was the only home with a CFIS system linked to another fan designed to operate outside of calls for heating/cooling—in this case, a bathroom exhaust fan. The CFIS airflow could not be measured in three homes due to inaccessible air inlets.

Of 19 homes with CFIS systems, airflows of 16 systems were measured by the field team. Only five of these 16 systems were capable of operating and generating a measurable airflow. While the system in home 406 had sufficient airflow, airflow in remaining homes with capable systems was limited by ducting that did not generate sufficient negative pressure. In the case of home 406, relative humidity control lockouts prevented the system from running during the testing week. In the case of home 436, which featured a U-CFIS system, mild outdoor conditions did not result in any heating/cooling system runtime during the week. Some heating/cooling operation generated some WHMV flow in homes 422, 423, and 430 during the testing week.

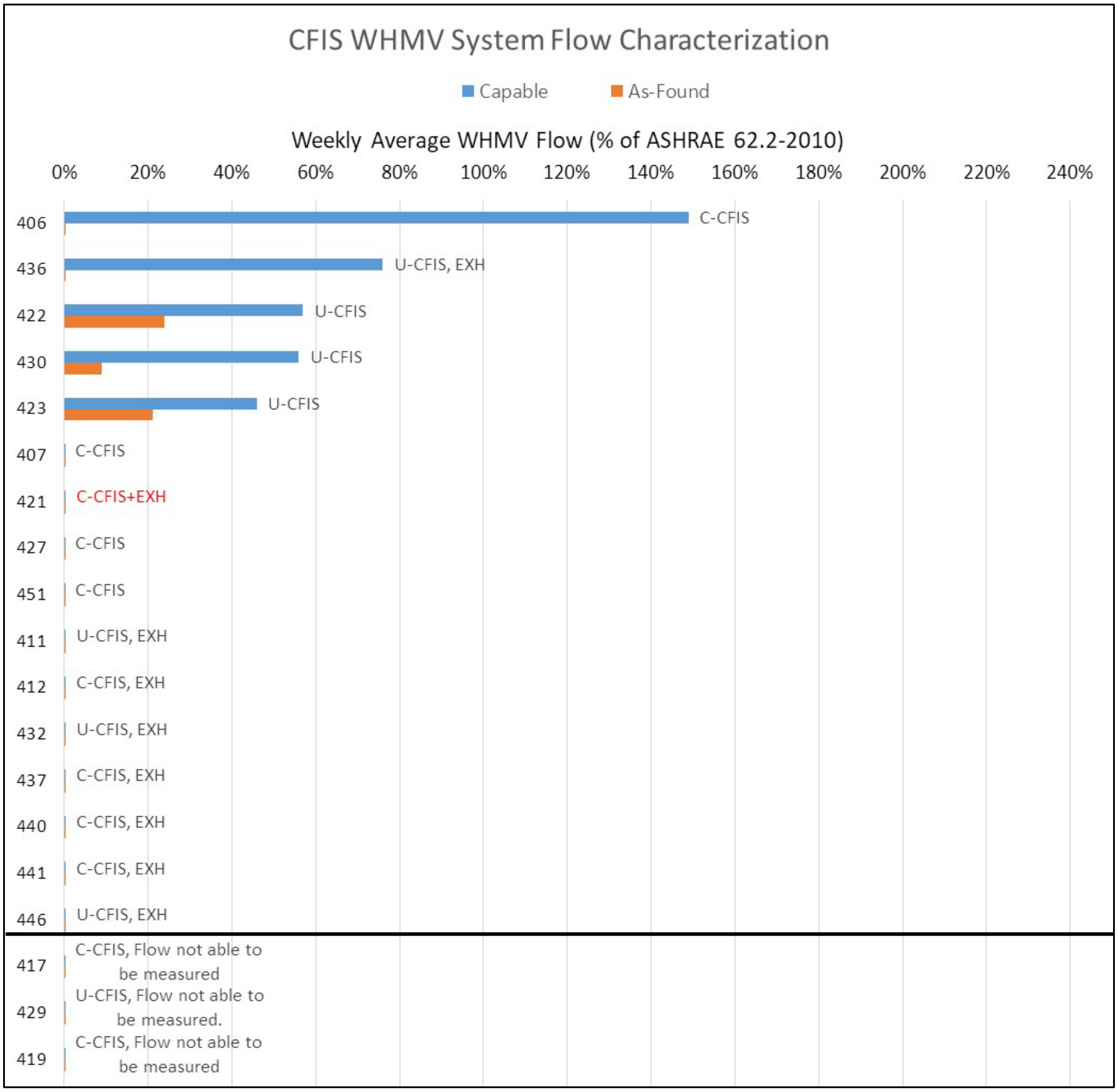

Figure 11. Airflow characterization of CFIS WHMV systems

Eleven of 16 systems were not capable of operating. Problems encountered included control incompatibility, disconnected wiring, and failed dampers. Ambient conditions did not generate any heating/cooling system runtime in home 429 during the testing week; therefore, its U-CFIS did not provide any WHMV during the testing week. The controls on the C-CFIS systems in homes 417 and 419 were set in such a way that the systems acted like U-CFIS systems. Home

419 experienced some heating/cooling runtime, generating an unknown level of WHMV flow, while home 417 did not. Due to the difficulty of finding homes with functioning CFIS systems, the study team eventually stopped intentionally recruiting homes with this type of WHMV system to participate in the study. A few owners of homes with CFIS systems were aware that their home had a system for "fresh air," but were not familiar with system operation. In general, most homeowners were not aware of the existence of their CFIS systems or how they functioned.

Figure 12 shows flow characterization results for the six homes with ERVs and five homes with ventilating dehumidifiers. Some ERV systems have adjustable flow controls, and "capable" weekly average flows are determined assuming continuous runtime and generally using the measured flow with the flow setting at the highest flow level. Weekly average "as-found" flow considers whether the system operated on a timed schedule. All dehumidifiers were fixed-flow and were able to be operated on a timed schedule.

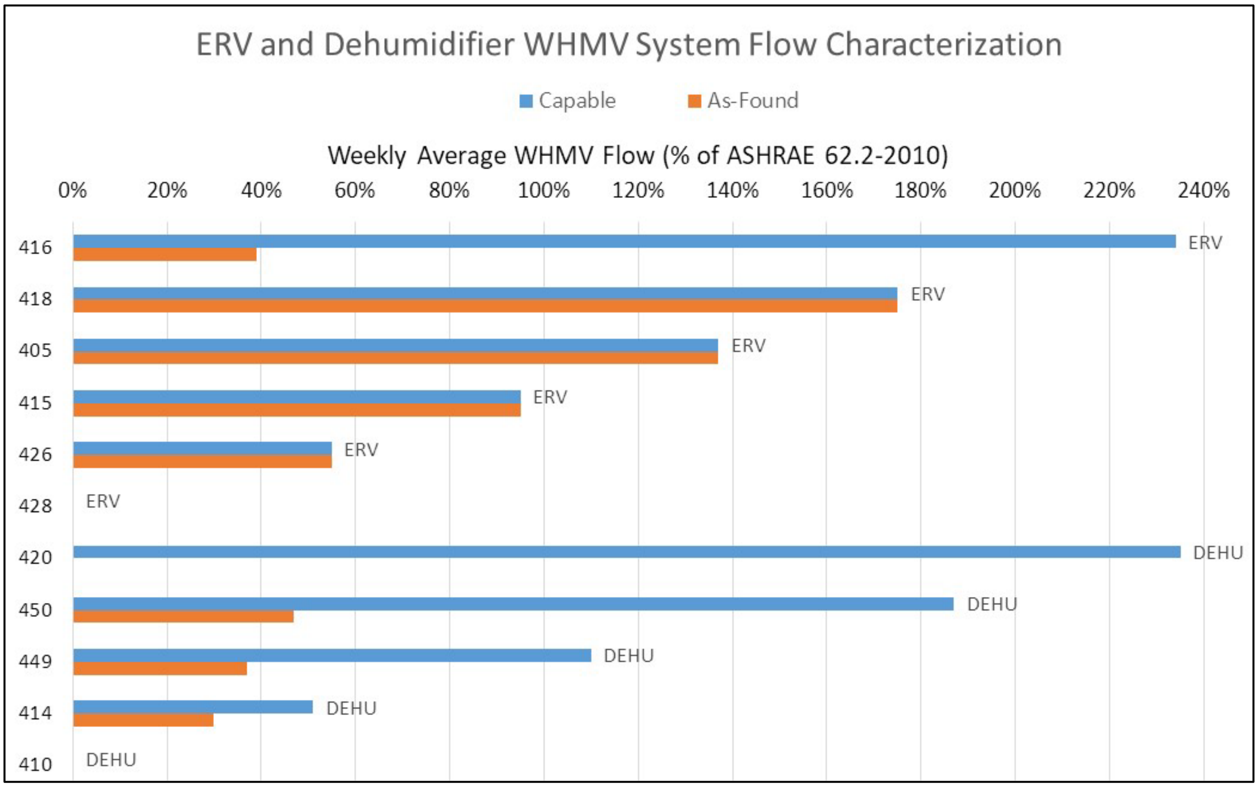

Figure 12. Airflow characterization of ERV and ventilating dehumidifier systems

ERVs and ventilating dehumidifiers were generally found to not only be more capable, but also more likely to be operating as found compared to exhaust or CFIS systems. Two of the ERVs (415 and 428) had low/high flow control, and could only be operated continuously. The field team could not measure any flow through the ERV as found in home 428 due to clogged filters. These ERVs have single points of supply and exhaust, contained in a single ceiling- or wall-mounted unit. Two ERVs (405 and 416) had low/high flow control switches on the units, and were ducted into the homes' central heating, ventilating, and air conditioning (HVAC) systems.

Intermittent operation could be programmed via the central HVAC thermostat. The ERV in home 405 was set to run continuously while the ERV in home 416 was set to run 10 min/h. The ERV in home 405 was mis-ducted so that flow was bypassing the enthalpy recovery core and the unit was only acting as a supply ventilator. ERVs in homes 418 and 426 had adjustable flow controls via a rheostat, but could only be operated continuously. Each and had multiple points of supply and exhaust, with ERV exhaust in bathrooms also serving as spot exhaust. Airflow for the dehumidifier in home 414 was limited, and its operation was hindered by control issues. The dehumidifier in home 410 was not operational for unknown reasons. Despite issues encountered, homeowners were all generally aware of the existence, location, and purpose of these WHMV systems. However, only four of the homeowners with ERVs or ventilating dehumidifiers knew how to adjust their operation.

5.2.2 Bathroom and Kitchen Exhaust Systems

Figure 13 shows measured bathroom exhaust fan airflows in each home for the master bathroom exhaust fan and the exhaust fan in the second-most-used bathroom as reported by the homeowners. Airflows of fans in toilet rooms and shower enclosures in these bathrooms were also measured but are not shown. Almost half of the bath fans in the home sample (46%) did not meet the minimum intermittent airflow requirements of ASHRAE 62.2-2010 (50 cfm). Three homes had fans that could not generate any measurable flow. As previously described, most fans were controlled with simple on/off wall switches, although a small number had controls that enabled operation based on relative humidity and/or occupancy, and another small subset of homes had programmable delay timers that operated the fan for a minimum amount of time after each activation. Home 418 had bathroom exhaust coupled with a continuously operating ERV. While standard operation of this exhaust fan did not meet the minimum continuous flow requirement of ASHRAE 62.2-2010 (20 cfm), a control in the bathroom enabled a boost mode that generated 36 cfm.

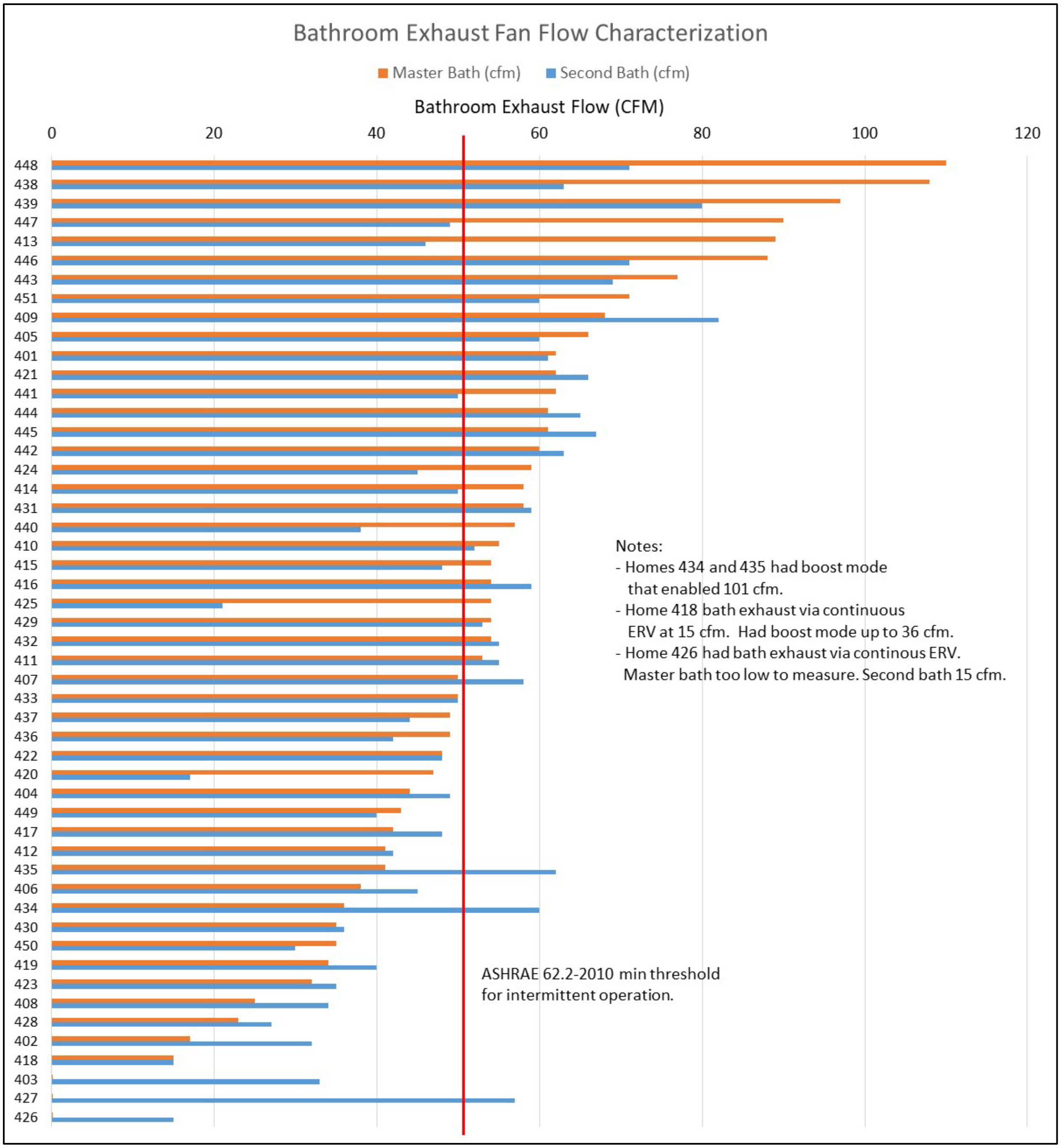

Figure 13. Airflow characterization of bathroom exhaust fans

Figure 14 shows measured kitchen range hood airflow in each home at the fans' low and high settings. Of 51 kitchen range hoods encountered, three were recirculating type and not vented to the outdoors and two did not generate any measurable flow. Of the 46 remaining homes, 10 had kitchen range hoods that could not meet the minimum airflow requirements of ASHRAE 62.2-2010 (100 cfm).

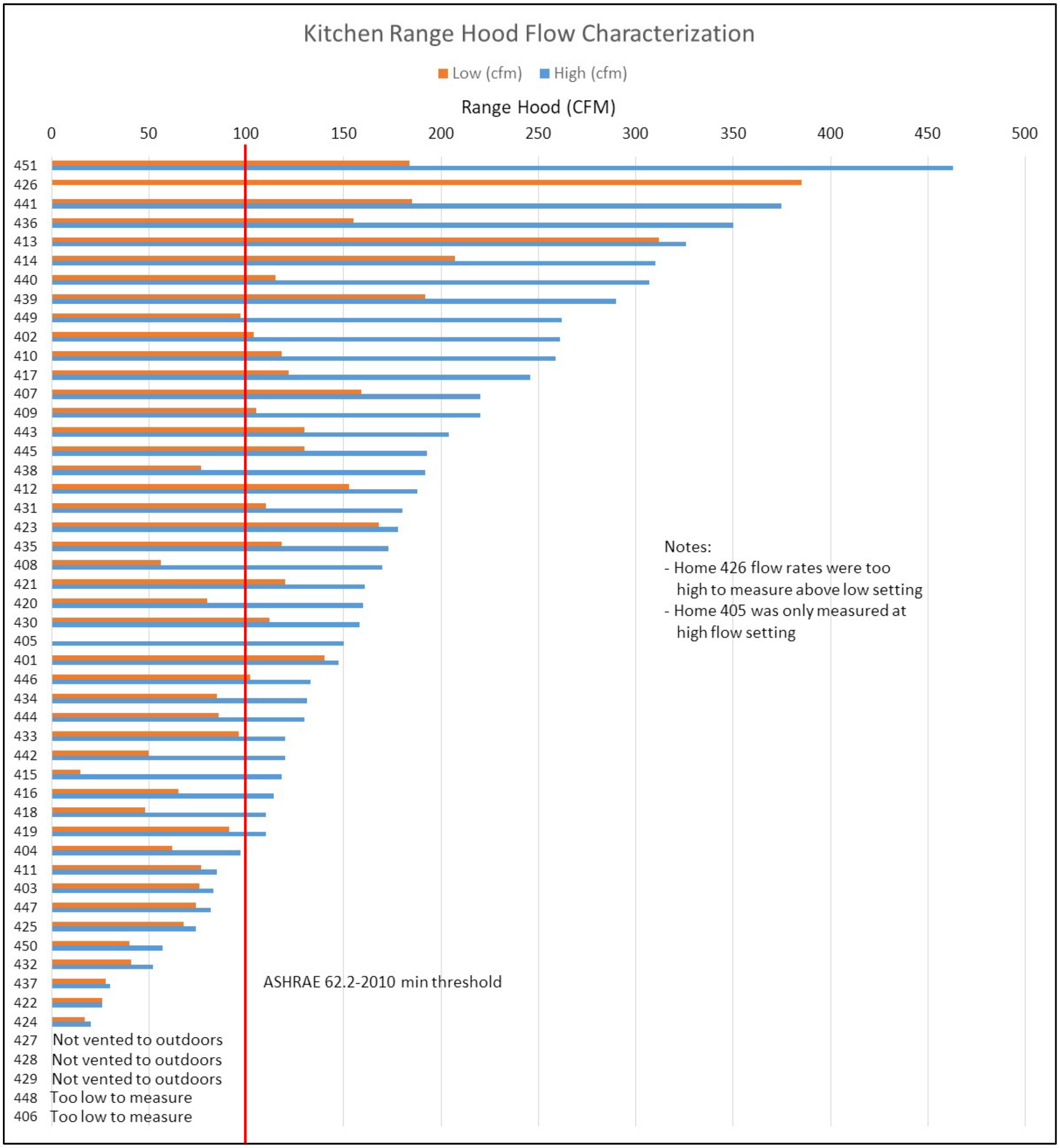

Figure 14. Airflow characterization of kitchen range hoods

5.3 Air Quality

Air quality was monitored over periods of roughly one week. The intent was to conduct monitoring in roughly equal numbers of homes with and without WHMV operating at the level required by 62.2-2010, and in about 16 homes that were operated for one week with and one week without compliant WHMV. However, due to the lack of WHMV functionality in many of the homes that were expected to have operational systems based on the source records, more sampling took place in homes operating without WHMV than in homes with WHMV operating at an airflow rate compliant with the 62.2-2010 standard. Twelve homes were monitored for only one week with a WHMV system operating. Twenty-two homes were monitored for only one week without a WHMV system operating. One home, 419, with C-CFIS, was monitored with unknown WHMV status.

Sixteen homes were monitored for two weeks. Thirteen of these homes were operated for one week with WHMV and one week without. In general, operation was configured to achieve 100% of ASHRAE 62.2-2010, but in some cases, this was not possible and the system was operated above or below this level. In one of these homes, 411, the WHMV off and WHMV on weeks were separated by three years; in all other cases, they were during consecutive weeks. In three homes, two weeks of data were collected with the WHMV system operational for both weeks. In the case of homes 442 and 443, automatic, relative-humidity-controlled activation of the bath fans could not be disabled. In the case of home 449, a mechanical contractor who visited the home reactivated the WHMV system partway through the testing week.

5.3.1 Carbon Dioxide

Figure 15 shows the weekly average carbon dioxide concentration in the main living area while the home was occupied for each week of data collected from each home, including data from one-week homes, and each week of data for the two-week homes. The y-axis denotes home number, with two-week homes labeled with “on” and “off,” or “A” and “B” in cases where the WHMV system was operated for both weeks. Data from home 411 is indicated with an asterisk to highlight the three-year gap between the off and on weeks. Bars indicating the carbon dioxide concentration in parts per million (ppm) are color coded according to the weekly average WHMV system flow expressed in terms of a percentage of the ASHRAE 62.2-2010 minimum continuous requirement for the home. This data has been grouped into three bins. Most of the data (36 weeks’ worth) was collected during weeks with the homes’ WHMV systems operating at <20% of 62.2-2010, indicated with blue colored bars. In this bin, only home 430 operated at >0%—in this case, 9%. Eight weeks of data were collected in homes with WHMV systems operating between 20% and 65% of 62.2-2010, indicated with orange bars. Twenty-three weeks of data were collected in homes with the WHMV system operating at >80% of 62.2-2010. Most of these systems operated at >100% of 62.2-2010, up to as high as 210%. Only four systems operated between 80% and 100% of the 62.2-2010 requirement. WHMV operation during data collection in home 419 is unknown, and is indicated with a white bar.

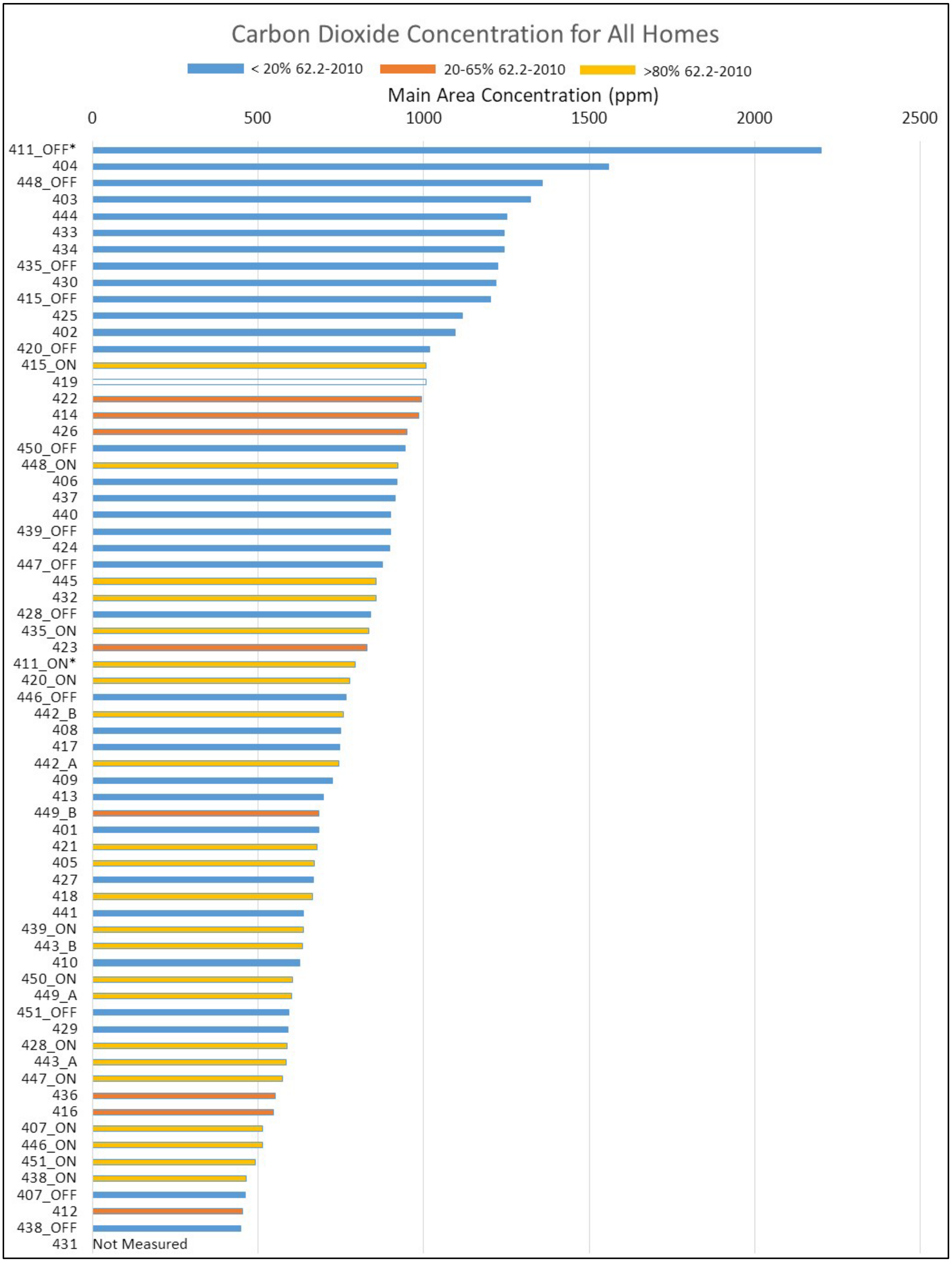

Figure 15. Main area carbon dioxide concentrations for all homes

Weekly average carbon dioxide concentration varies considerably across the sample due to a variety of factors including occupancy. However, there is an evident trend that homes with operating ventilation systems tended to have lower average carbon dioxide concentrations. Of note is that carbon dioxide concentrations >1,000 ppm were only obtained in homes without WHMV systems operating. Figure 16 shows weekly average carbon dioxide concentrations in the main living area for each two-week home. The same color coding used in Figure 15 is applied in Figure 16 to indicate WHMV system status, and data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010. In most cases, it is evident that operation of the WHMV system creates additional air exchange, thereby diluting carbon dioxide concentration by a mean value of 25%. Data from homes with bars below the horizontal black line are not included in the statistics. Figures 17 and 18 show similar data collected from the master bedroom during the period of 12 a.m.–5 a.m. Similar overall results are seen, with more homes recording carbon dioxide concentrations >1,000 ppm.

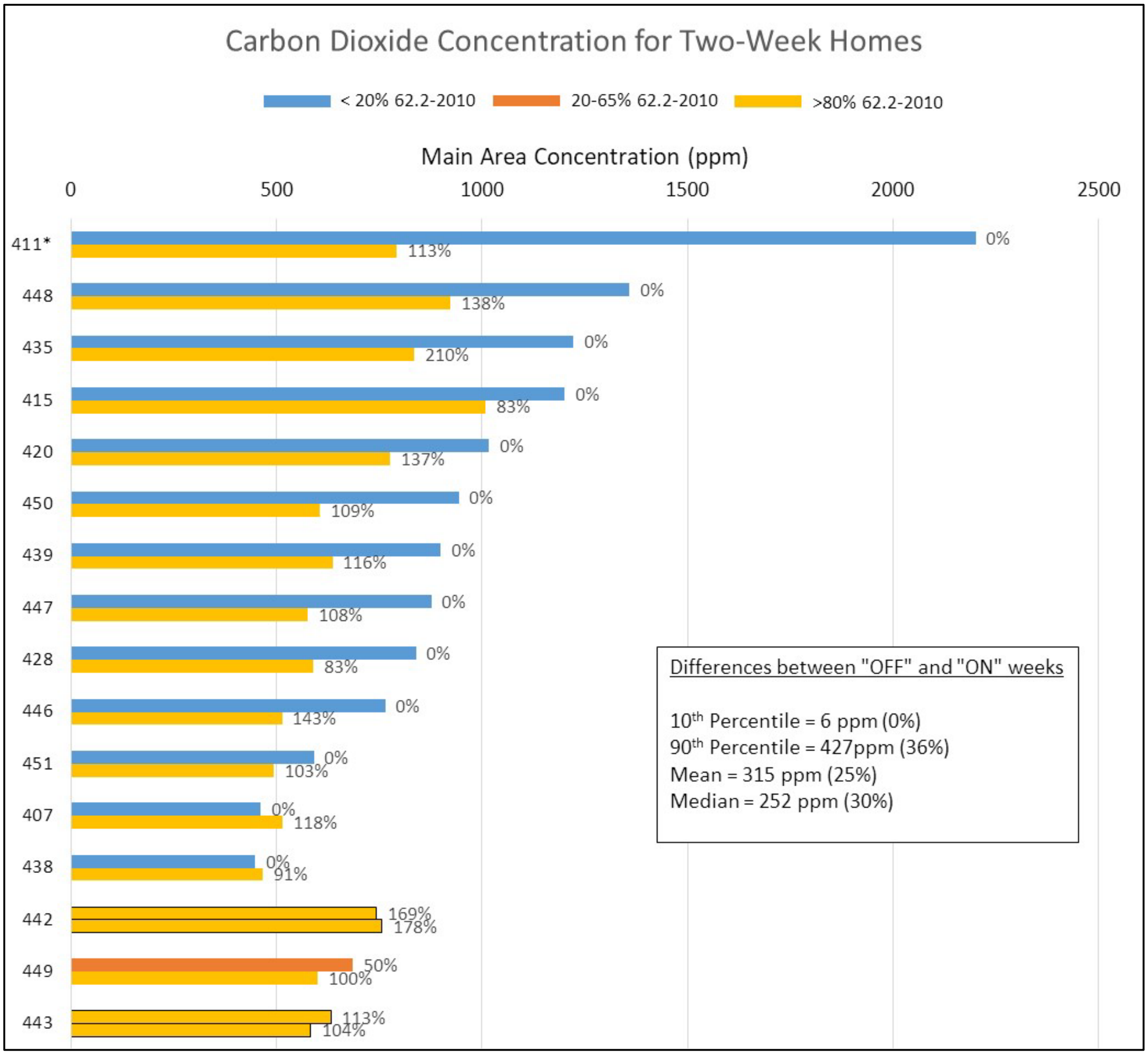

Figure 16. Main area carbon dioxide concentrations for two-week homes Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010.

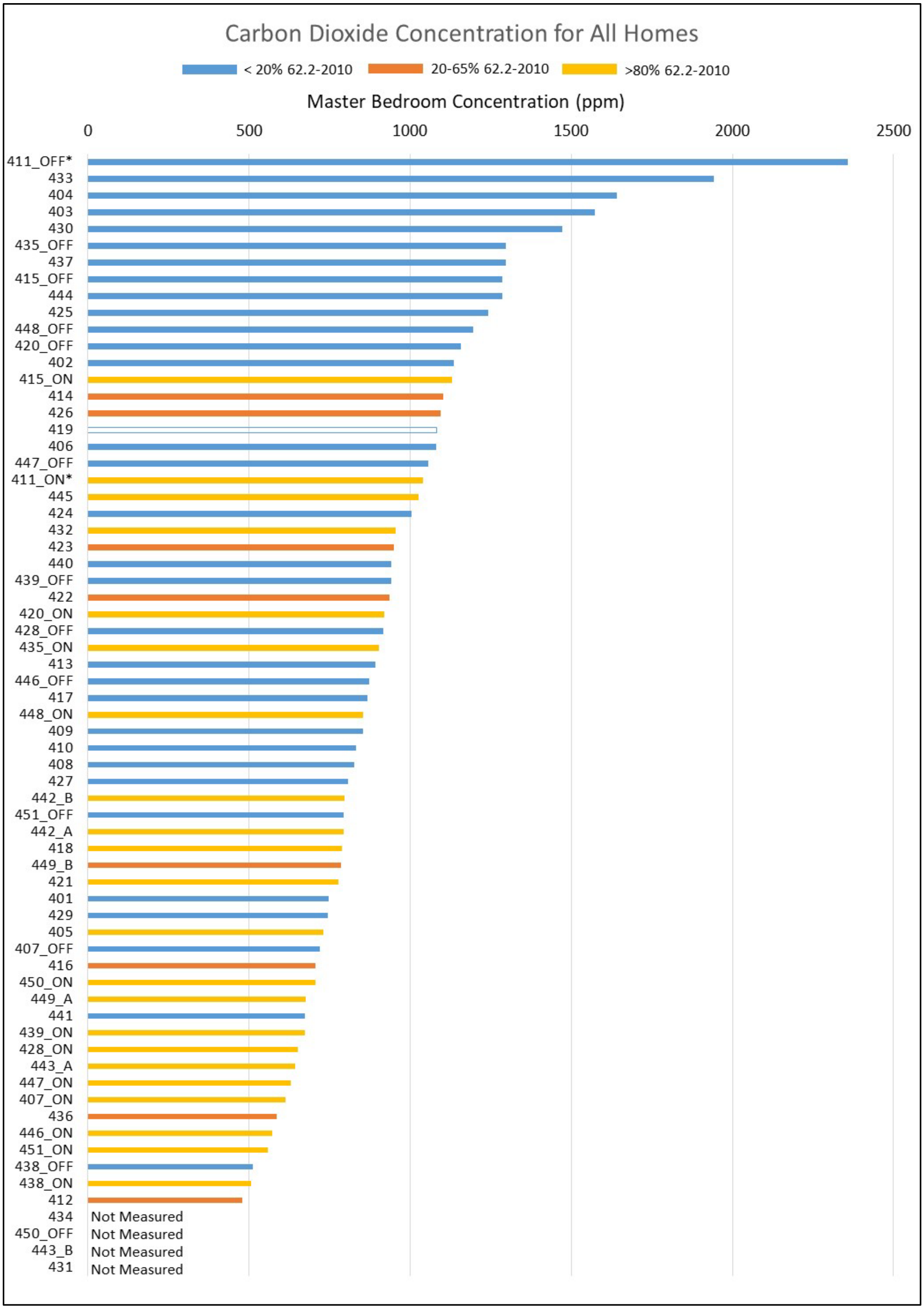

Figure 17. Master bedroom carbon dioxide concentrations for all homes

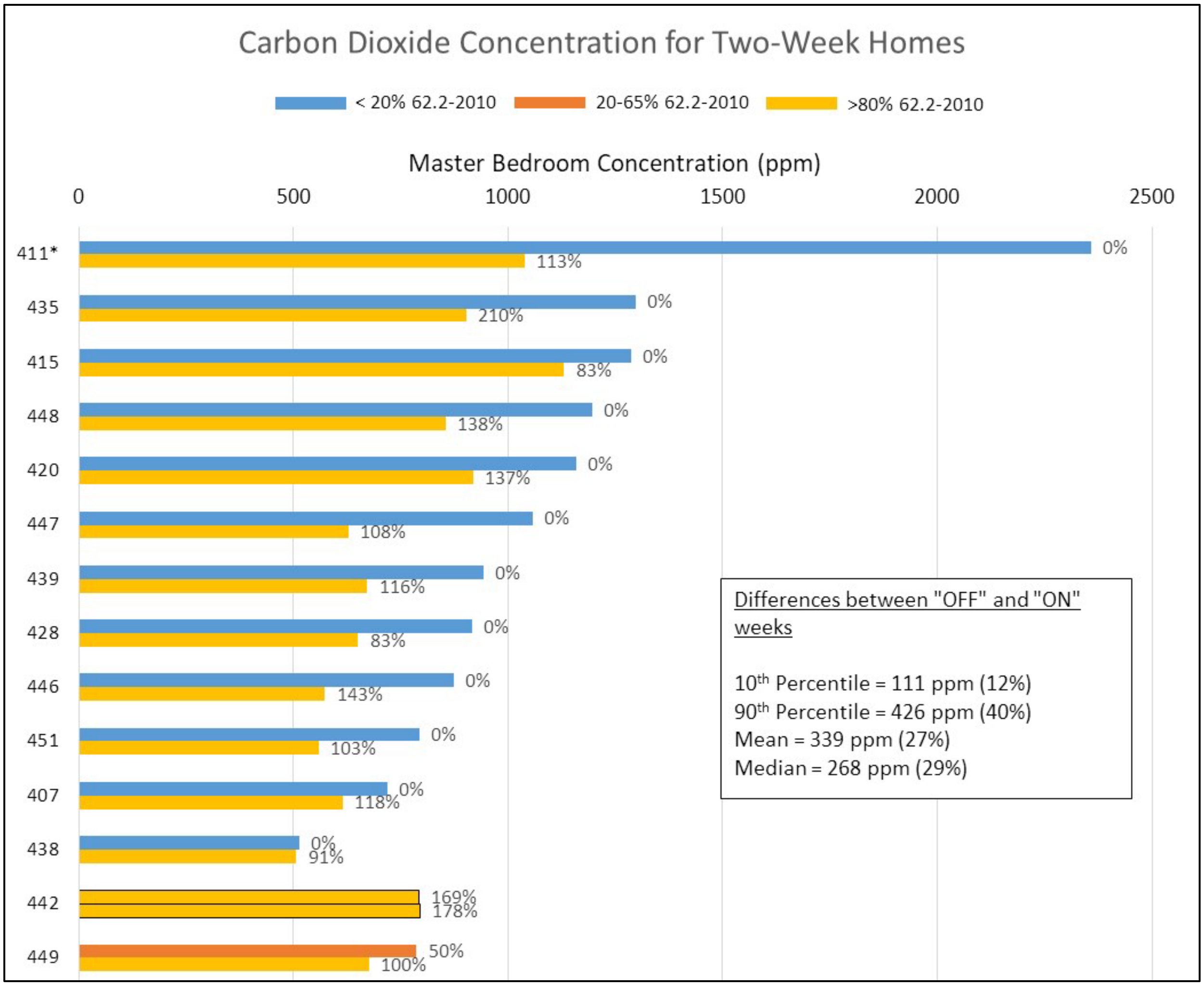

Figure 18. Master bedroom carbon dioxide concentrations for two-week homes Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010.

5.3.2 Formaldehyde

Weekly average formaldehyde concentrations in parts per billion (ppb) are presented in Figures 19 and 20 in an identical format as used for reporting carbon dioxide concentrations. This data was collected using passive, UMEx-100 samplers in the main living area. As with carbon dioxide, concentrations vary considerably across the sample due to variability in home construction materials, home contents, age of materials, and occupant activities. No homes were below the California Environmental Protection Agency's chronic (lifetime) reference exposure limit (REL) of 7 ppb, and six homes were above the 1-hour acute REL of 44.8 ppb. The World Health Organization has set a general REL of 80 ppb.[4] In contrast to the case of carbon dioxide, formaldehyde concentrations do not appear to be consistently reduced with additional air exchange.

[4] Nielsen, G.D., Larsen, S.T. and Wolkoff, P. 2017. "Re-evaluation of the WHO (2010) formaldehyde indoor air quality guideline for cancer risk assessment." *Arch Toxicol* **91**. https://doi.org/10.1007%2Fs00204-016-1733-8

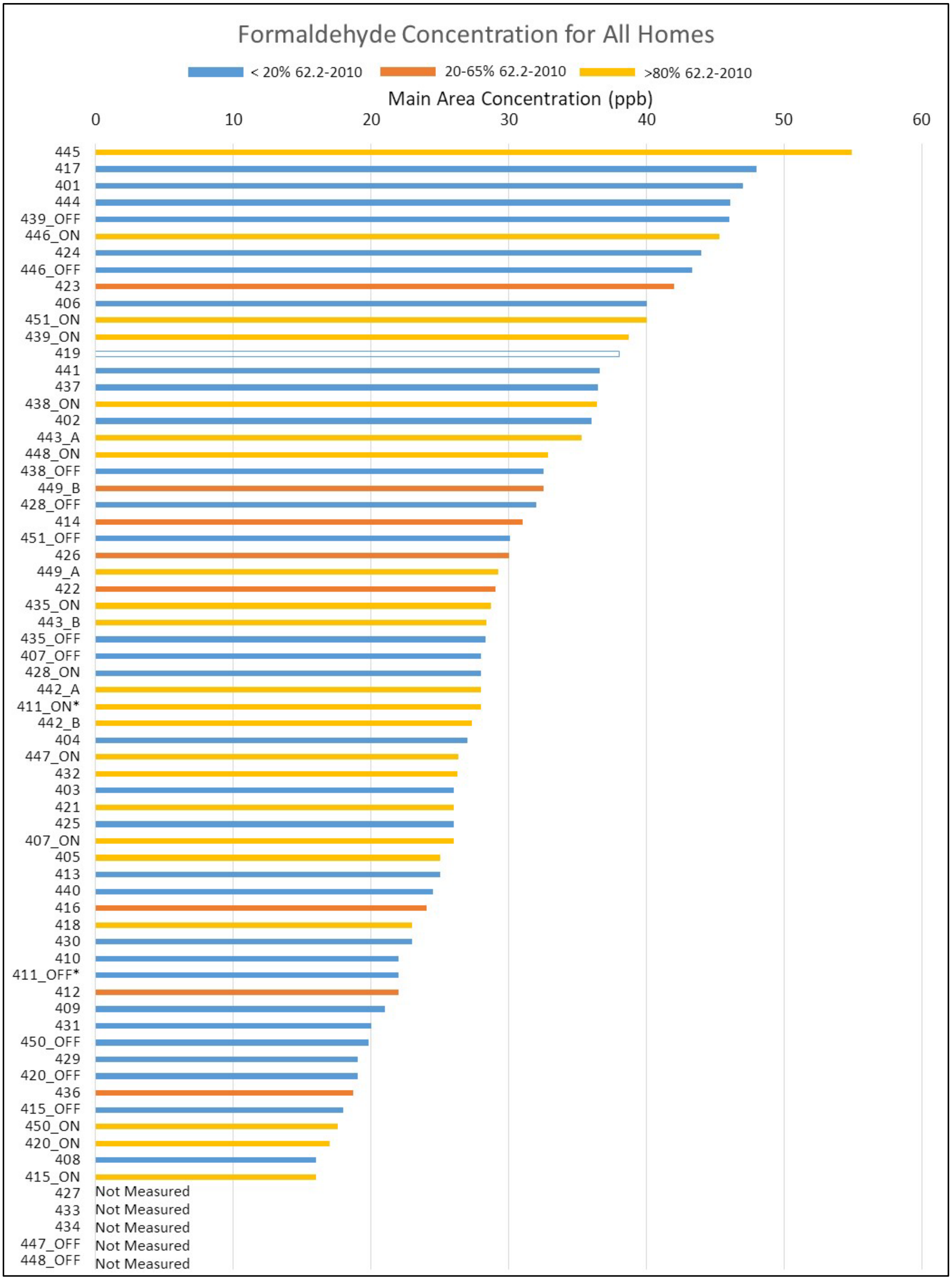

Figure 19. Main area formaldehyde concentrations for all homes

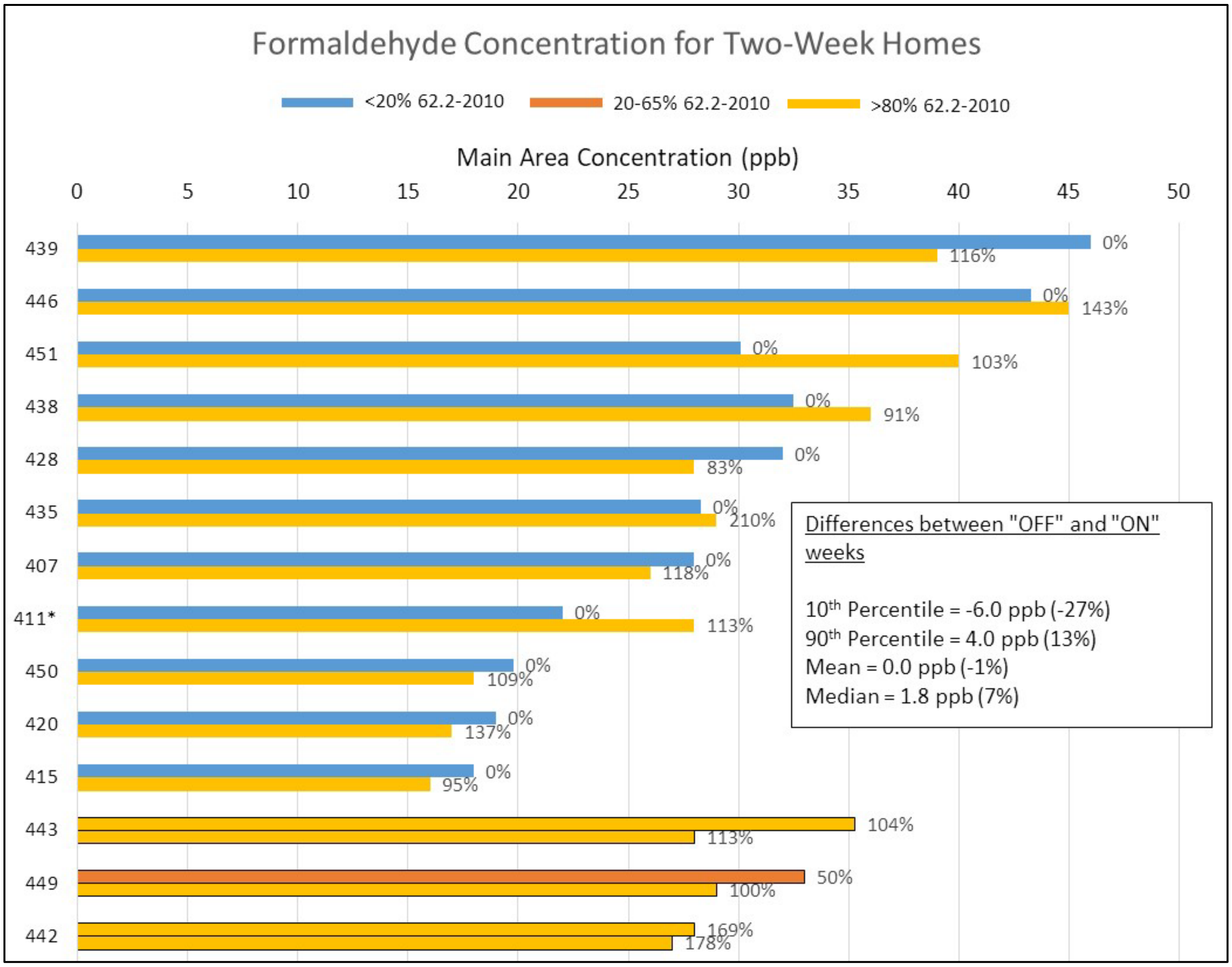

Figure 20. Main area formaldehyde concentrations for two-week homes Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010.

5.3.3 Radon

Weekly average radon concentrations collected from the lowest occupied level of each home using the Radstar RS300 are shown in Figures 21 and 22 in picocuries per liter (pCi/L). All homes were slab on grade except for home 426, which had a walk-out basement. Concentrations were not measured in several homes due to instrument failure. While concentrations across the sample vary widely, primarily due to home proximity to naturally occurring radon sources, only one home exceeded the EPA action level of 4 pi/L. The two homes with the highest recorded one-week radon concentrations were located in Georgia. Long-term, six-month average concentrations measured with the Alpha Track sensors confirmed results significantly higher than the EPA action level in each of these homes. In general, there is an evident trend that homes with operating WHMV systems tended to have lower radon levels. Data from two-week homes shows that WHMV decreases radon concentration by a mean value of 35%, although none of the two-week homes had radon concentrations above the EPA action level.

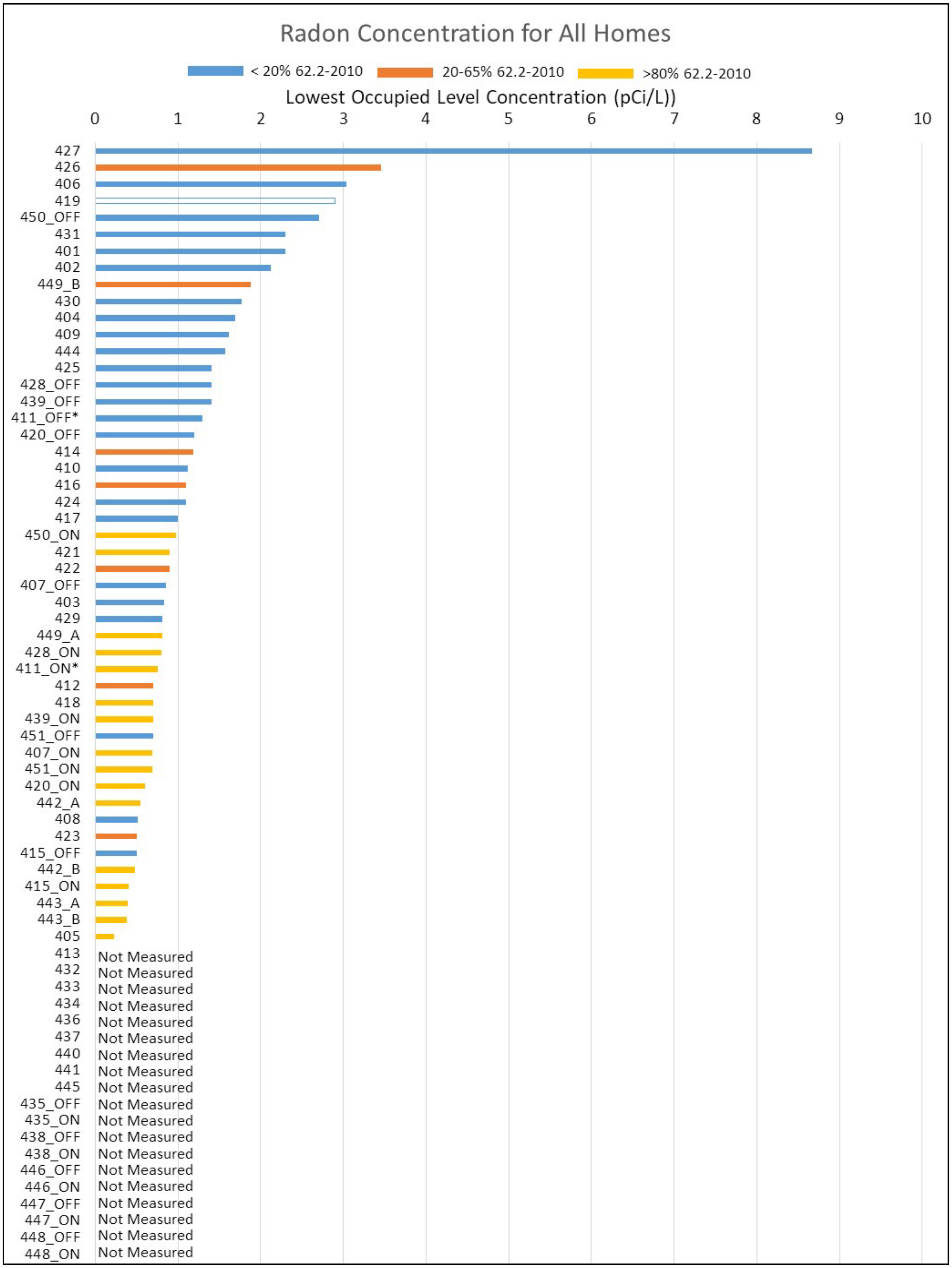

Figure 21. Lowest occupied level radon concentrations for all homes

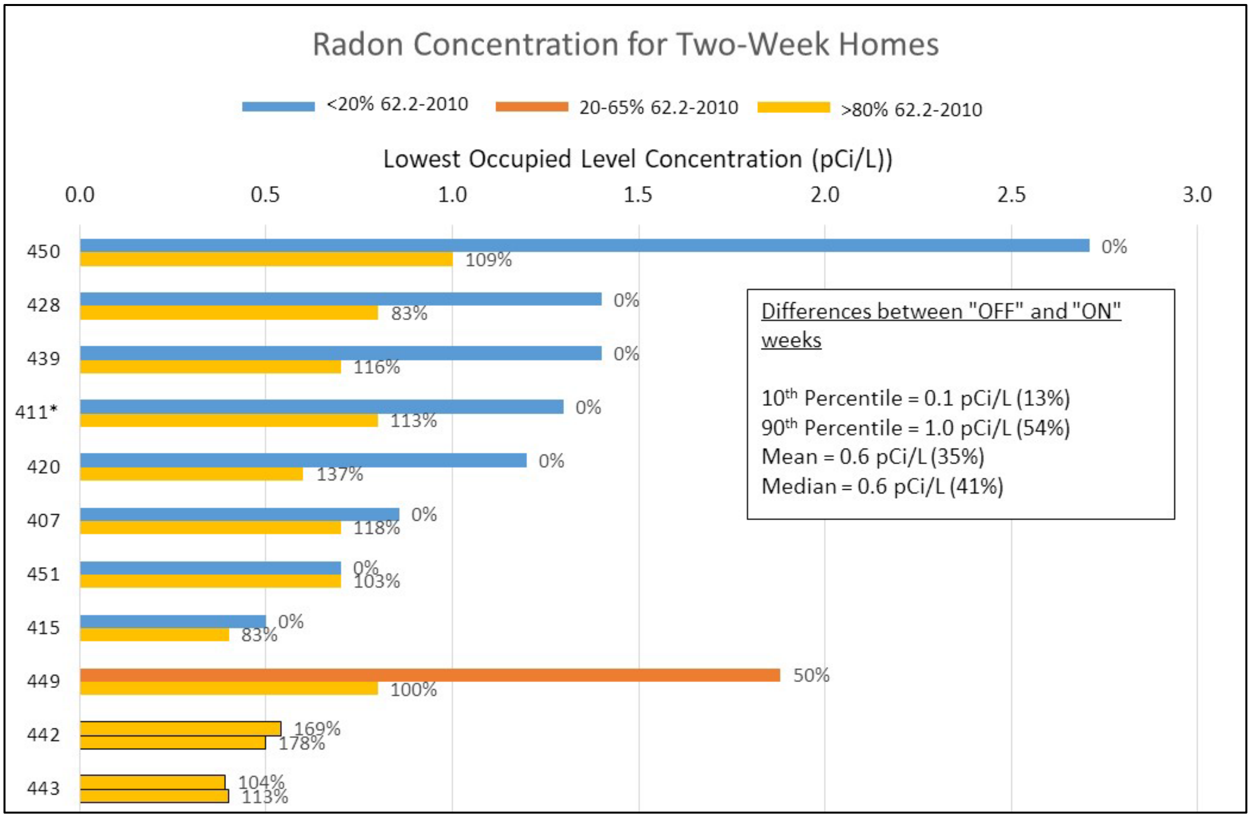

Figure 22. Lowest occupied level radon concentrations for two-week homes Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010.

5.3.4 $PM_{2.5}$

Weekly average $PM_{2.5}$ concentrations in micrograms per cubic meter (ug/m^3) are shown in Figures 23 and 24. Data was collected using a gravimetric filter technique. Similar to results for other indoor air pollutants of interest, results show that concentrations vary widely across the sample, presumably due to differences in occupant activities, outdoor particulate matter entry, and removal processes including filtration. Four homes exceeded the EPA annual REL of 12 ug/m^3, but none exceeded the 24-hour value of 35 ug/m^3. $PM_{2.5}$ is best mitigated via filtration and spot ventilation, especially in the case of cooking-based sources, and $PM_{2.5}$ concentrations are not well correlated to WHMV system operation. While operation of the WHMV system appeared to minimally increase $PM_{2.5}$ concentration, additional research is necessary to confirm causation rather than unrelated correlation. Future analysis of spatial, time-resolved $PM_{2.5}$ measurements are expected to provide additional insight. Data labels in Figure 24 also indicate weekly average outdoor $PM_{2.5}$ concentrations for two-week homes, for unlike other pollutants, variable outdoor $PM_{2.5}$ concentrations from week to week may influence indoor concentrations in a few homes, including homes 415, 407, and 406.

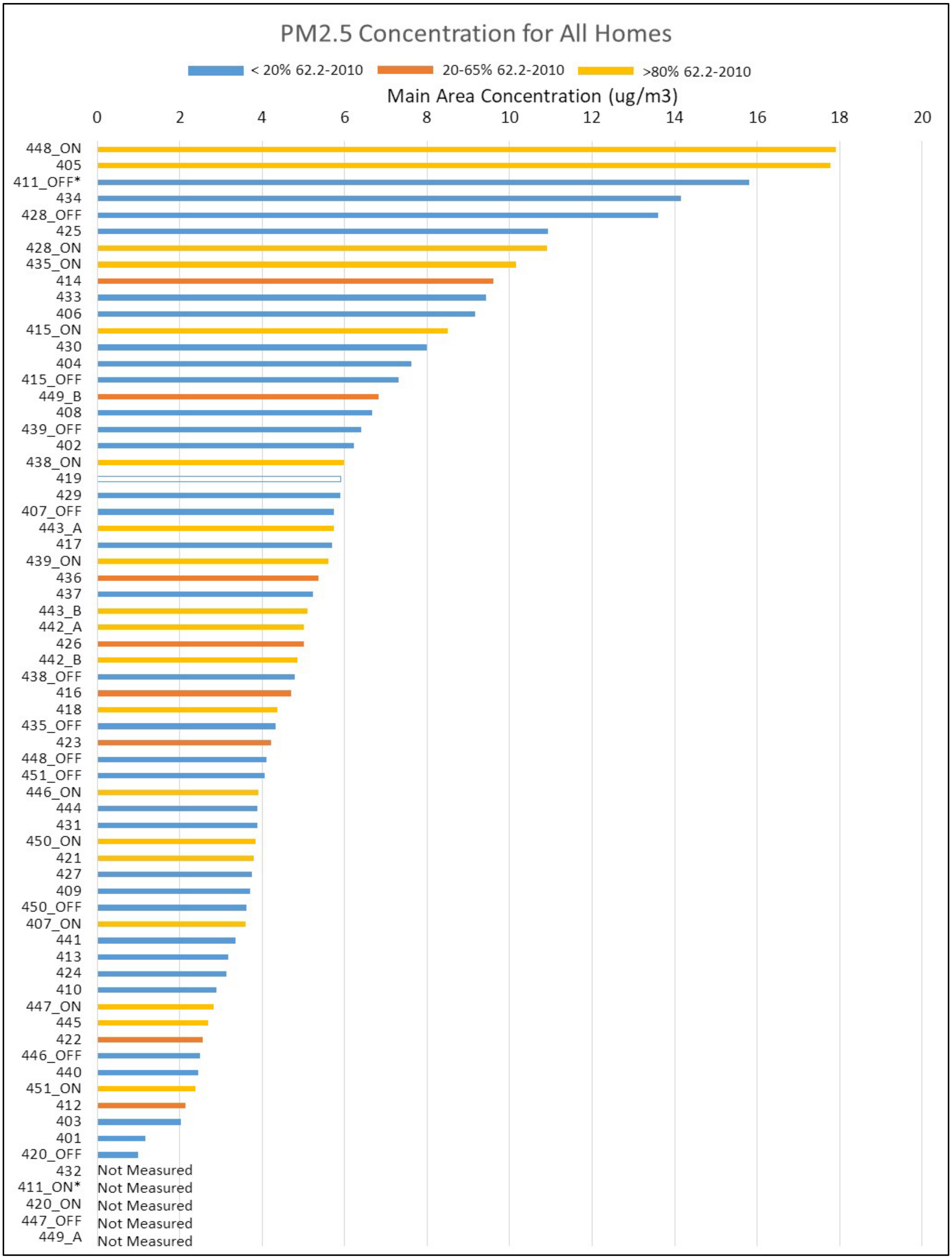

Figure 23. Main area $PM_{2.5}$ concentrations for all homes

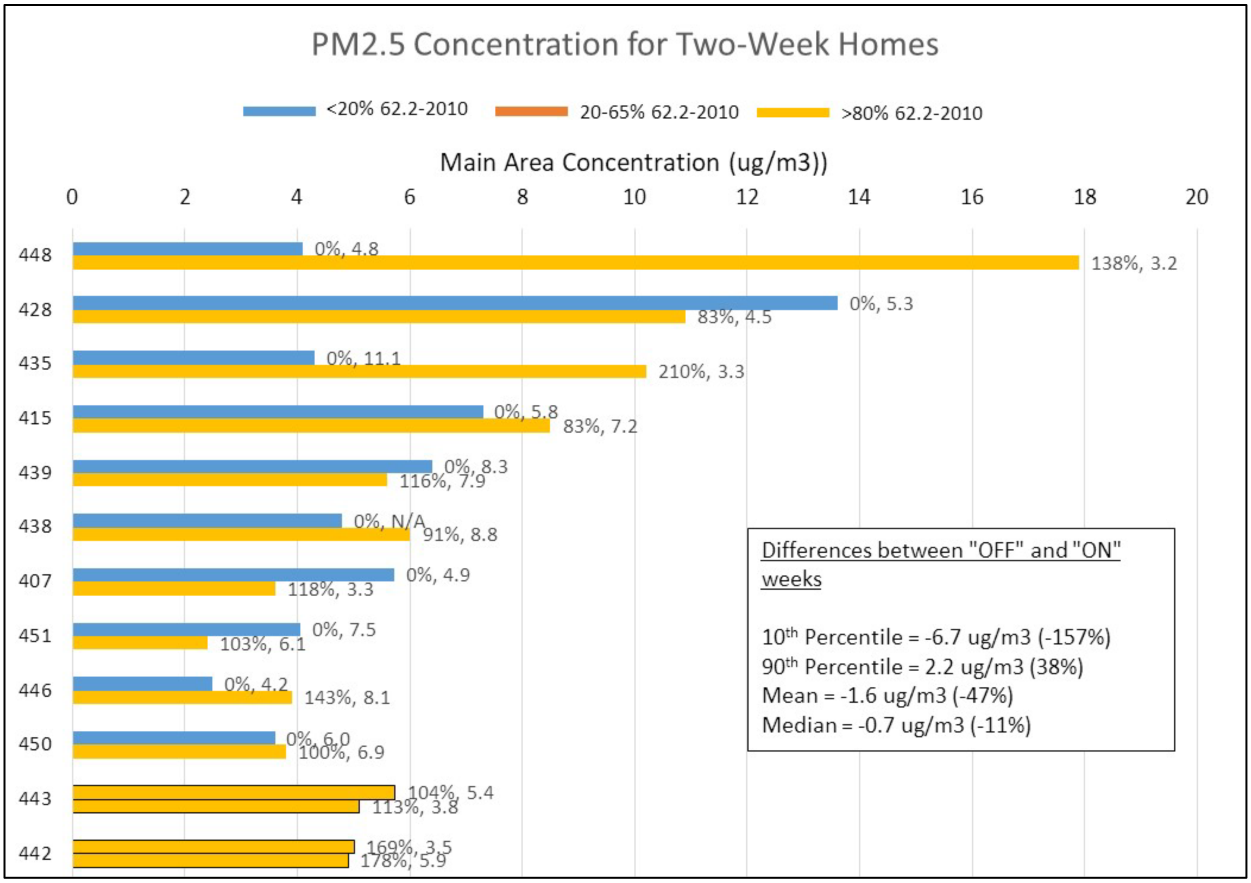

Figure 24. Main area $PM_{2.5}$ concentrations for two-week homes Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010, and weekly average outdoor $PM_{2.5}$ conentration.

5.3.5 Nitrogen Dioxide

Figures 25 and 26 show weekly average nitrogen dioxide concentrations in ppb. Most homes that used natural gas or propane for at least one end use (space heating, water heating, clothes drying, cooking) were sampled for nitrogen dioxide. While use of gas for various end uses varied among the homes sampled for nitrogen dioxide, all but two homes (425 and 436) had a gas cooktop. No homes exceeded the EPA yearly REL of 53 ppb. While it appears that operating WHMV systems reduce nitrogen dioxide concentrations, the magnitude of nitrogen dioxide concentrations measured in two-week homes is on the lower end of the overall sample's concentration range, and very close to background levels measured outdoors, which are shown with data labels. Differences in background levels between "off" and "on" weeks may also contribute to differences in indoor concentrations.

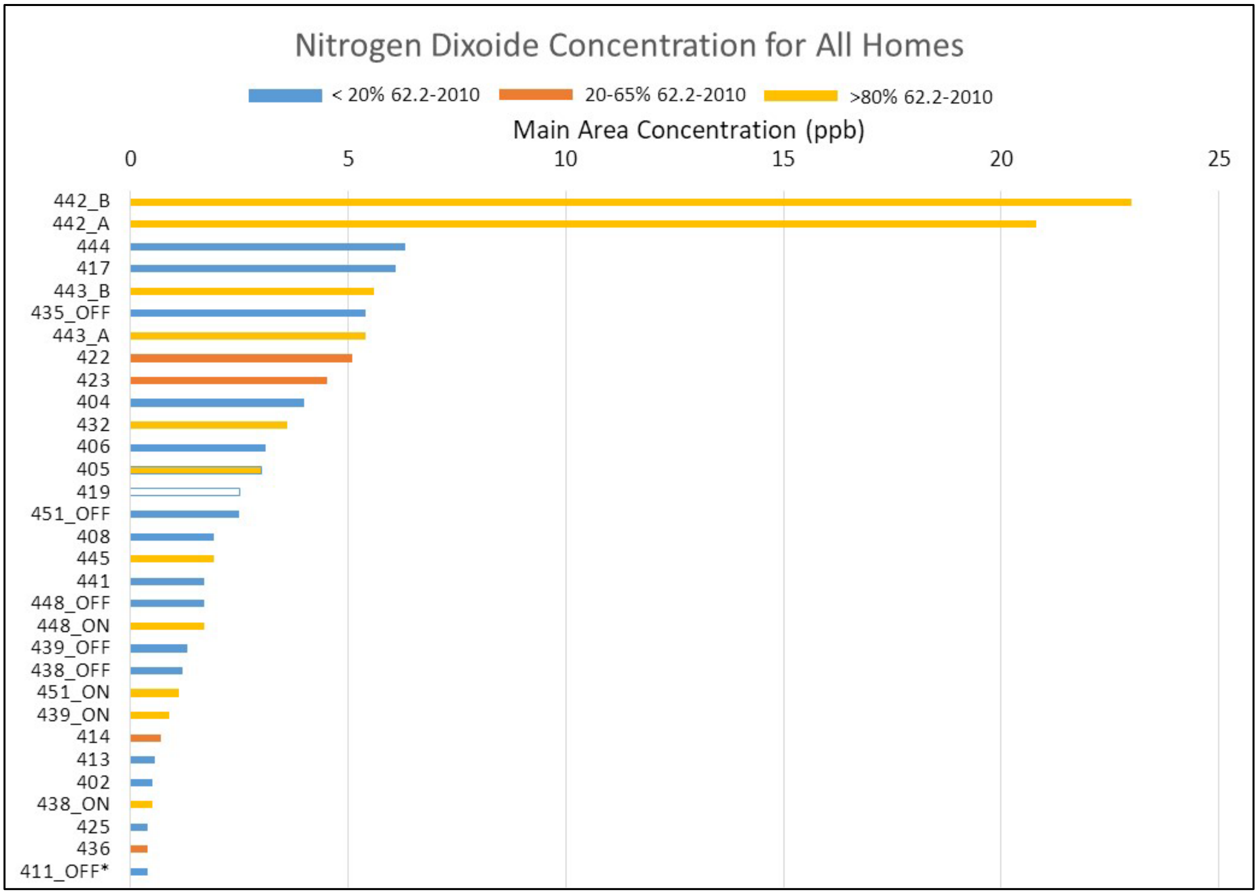

Figure 25. Main area nitrogen dioxide concentrations for all homes with at least one gas appliance

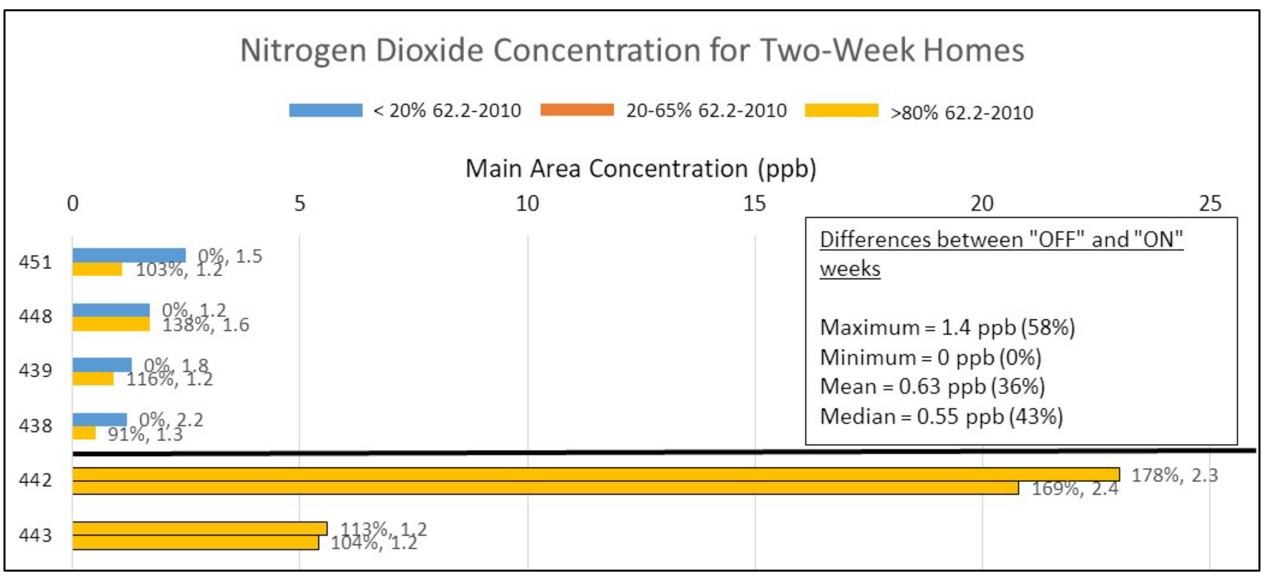

Figure 26. Main area nitrogen dioxide concentrations for two-week homes with at least one gas appliance Data labels indicate the WHMV system flow as a percent of ASHRAE 62.2-2010, and weekly average outdoor nitrogen dioxide concentration.

6 Conclusions

FSEC conducted a study to characterize IAQ in southeastern U.S. homes constructed since 2013, along with presence, functionality, and occupant use of WHMV. A total of 51 homes were recruited and participated in the study. Forty homes were located in Florida, six in South Carolina, and five in Georgia. All homes were single-family detached with the exception of one townhome in South Carolina and one townhome in Georgia. Field teams instrumented the homes to measure concentrations of indoor air pollutants for one to two weeks, monitored operation of equipment influencing air exchange between the house and the outdoors, and quantified associated airflows.

Table 8 summarizes the types of WHMV systems encountered, their functionality, and their operation. Similar to findings from past studies, this study encountered barriers that still need to be overcome with regard to functionality and operation of residential WHMV systems. The findings suggest that proper training of HVAC technicians, electricians, code inspectors, and home energy auditors around installation and commissioning is critical to ensuring the IAQ benefits of WHMV are realized, enabling the industry to continue to build energy-efficient homes with tight building enclosures. In particular, the industry needs systems with performance that is easy to verify, including easier access to air inlets and outlets or built-in flow measurement, along with on-board fault detection systems that alert homeowners to nonfunctioning systems. Another priority is improved labeling and training on identification of controls for homeowners to overcome the issue of nonoperating systems.

Table 8. Summary of WHMV Systems Encountered

WHMV System Type	Number of Systems Encountered[a]	Able to Function On Any level	Capable of Meeting 62.2-2010 Continuous Flow Requirement	Operating As Found
Exhaust Fan	24	23	16	3
CFIS	19	5	1	3
ERV	6	5	3[b]	5
Ventilating Dehumidifier	5	4	3	3

[a] Some homes were found with multiple WHMV systems.
[b] Two systems had rheostats that may have enabled them to deliver additional flow.

The most common approach found for providing WHMV was via a bathroom exhaust fan. For 24 homes with exhaust WHMV systems, 16 were found capable of meeting the ASHRAE 62.2-2010 minimum requirement for WHMV. However, only three systems were operating for this purpose as found. In general, homeowners were not aware that these fans could be used as WHMV, and were not aware of why or how they should be operated as such. The second-most common WHMV system type encountered were CFIS systems that are designed to use a home's central forced air heating and cooling system to temper and distribute outdoor air that is pulled in through a ducted connection from outside to the return side of the forced air system. For 19 homes that had CFIS systems, only one was capable of meeting minimum WHMV requirements for ASHRAE 62.2-2010. Only five systems were capable of operating at all and only three were operating as found. The observed problems included control incompatibility, disconnected wiring, and failed dampers. In general, most homeowners were not aware of the existence of CFIS systems or how they functioned. Six homes had an ERV, designed to deliver quasi-balanced ventilation and passive enthalpy recovery, and five homes had a ventilating dehumidifier, designed to deliver supply-based ventilation and active moisture removal. For 11 homes that had these types of WHMV systems, eight were found to be operating and six of these were capable of meeting minimum WHMV requirements of ASHRAE 62.2-2010. Only one system was not capable of operating. All homeowners with these types of WHMV systems were generally aware of their existence, location, and purpose.

Spot ventilation systems that exhaust air from kitchens and bathrooms were also characterized. Nearly half of the bath fans in the home sample (46%) did not meet the minimum intermittent airflow requirements of ASHRAE 62.2-2010 (50 cfm). Three homes had fans that could not generate any measurable flow. Of all the kitchen range hoods encountered, three were recirculating type and not vented to the outdoors, and two did not generate any measurable flow. Of the remaining homes, ten had kitchen range hoods that could not meet the minimum airflow requirements of ASHRAE 62.2-2010 (100 cfm).

Weekly average concentrations of carbon dioxide, formaldehyde, radon, $PM_{2.5}$, and nitrogen dioxide varied considerably among the homes, in large part due to factors not related to WHMV operation including home location, occupancy, and occupant activities. Several homes exceeded a weekly average carbon dioxide concentration of 1,000 ppm in the main living area and master bedroom, although most of those homes were not operated with WHMV. All homes exceeded the California Environmental Protection Agency REL for formaldehyde of 7 ppb, while six exceeded the acute REL of 44.8 ppb. Two homes in Georgia exceeded the EPA radon action level of 4 pi/L. Four homes exceeded the EPA annual REL for $PM_{2.5}$ of 12 ug/m^3, but none exceeded the 24-hour value of 35 ug/m^3. No homes exceeded the EPA yearly average REL of 53 ppb for nitrogen dioxide.

To investigate WHMV as a control measure for IAQ, focus was placed on results for two-week homes for which occupant influences were somewhat normalized. Table 9 provides weekly average pollutant concentrations for WHMV “off” and WHMV “on weeks for two-week homes. Table 10 provides weekly average pollutant concentration differences between WHMV “off” and WHMV “on” weeks for two-week homes.

Table 9. Comparison of Pollutant Concentrations in Two-Week Homes

Pollutant (n)	Median (10%–90%) Values for "Off" Week	Median (10%–90%) Values for "On" Week
Carbon Dioxide (ppm) – main (13)	899 (487–1331)	605 (497–905)
Carbon Dioxide (ppm) – master bed (12)	1000 (727–1297)	662 (541–1027)
Formaldehyde (ppb) – main (11)	28.3 (19.0–43.3)	28.0 (17.0–40.0)
Radon (pCi/L) – main (8)	1.3 (0.6–1.8)	0.7 (0.5–0.9)
$PM_{2.5}$ (ug/m^3) – main (10)	4.6 (3.5–7.9)	5.8 (3.5–11.6)
Nitrogen Dioxide (ppb) – main (4)	1.5 (1.2–2.3)	1.0 (0.6–1.5)

Table 10. Comparison of Pollutant Concentration Differences During "Off" and "On" Weeks in Two-Week Homes

Pollutant (n)	Median Concentration Difference Between WHMV "Off" and WHMV "On"	10% and 90% Values of Concentration Differences Between WHMV "Off" and WHMV "On"
Carbon Dioxide (ppm) – main (13)	252 (30%)	6 (0%) and 427 (36%)
Carbon Dioxide (ppm) – master bed (12)	268 (29%)	111 (12%) and 426 (40%)
Formaldehyde (ppb) – main (11)	1.8 (7%)	-6.0 (-27%) and 4.0 (13%)
Radon (pCi/L) – main (8)	0.6 (41%)	0.1 (13%) and 1.0 (54%)
$PM_{2.5}$ (ug/m^3) – main (10)	-0.1 (-11%)	-6.7 (-157%) and 2.2 (38%)
Nitrogen Dioxide (ppb) – main (4)	0.6 (43%)	0.1 (9%) and 1.2 (58%)

It is evident from the carbon dioxide data that operation of the WHMV system creates additional air exchange, thereby reducing carbon dioxide concentration by 30%. Homes measured with and without WHMV operating had radon and nitrogen dioxide concentrations that were 42% lower with WHMV, although sample sizes of two-week homes with radon and nitrogen dioxide data are small due to instrument issues and a prevalence of all-electric homes. Differences in background levels between "off" and "on" weeks may also contribute to differences in indoor concentrations of nitrogen dioxide. Operation of the WHMV system appears to minimally reduce formaldehyde concentration. This is likely due to complex indoor chemistry including an inverse relationship between concentration and emission rate. Operation of the WHMV system appeared to minimally increase $PM_{2.5}$ concentration, however additional analysis is required to rule out other confounding factors. Future analysis of spatial, time-resolved $PM_{2.5}$ measurements are expected to provide additional insight. The expectation is that spot ventilation would be more effective, especially for cooking sources.

Next steps are to combine the results from homes in the southeastern United States with results from other regions sampled as part of the overall BAIAQ study. The resulting analysis will generate recommendations for codes, standards, equipment manufacturers, and contractors to address design, installation, labeling, and homeowner education related to WHMV systems as an effective control measure for IAQ in new homes.

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Appendix A. WHMV System Characterization Details

State	Home Number	WHMV System Type	Control Type	Label at Controller?	WHMV system operated first arrival?	62.2-2010 min airflow (cfm)*	Measured airflow (cfm)	WHMV runtime (min/h) as found	WHMV runtime (min/h) sample week	Calculated WHMV airflow (cfm)	Ratio: sample week ventilation rate 62.2 ventilation rate	Notes
FL	401	none	NA									
FL	402	none	NA									
FL	403	none	NA									
FL	404	none	NA									
FL	405	ERV	Settings in Thermostat. Capable of timed operation	Settings screens in tstat. Label at on/off and low/high switch on ERV itself	Yes	51	70	60	60	70	137%	ERV has good flow but misducted, no enthalpy exchange.
FL	406	C-CFIS (tstat)	Settings in Thermostat. Allows system to turn off when T/RH outside of acceptable band.	No overt label. Settings screens in tstat	Yes	51	76	with temp/rh lockouts	0	0	0%	Functioning with good flow but flow largely locked out at Tstat with temp/RH settings. Soffit OA intake.
FL	407	C-CFIS (tstat)	Settings in thermostat	No overt label. Settings screens in tstat	not functioning	57	67	1	60	67	118%	CFIS system set to operate 1 min/hr on arrival, but flow not functioning. Able to force flow on but only 45 cfm. Homeowner had thermostat replaced for second week. System functions but flow was still too low. Masked off return to increase flow, set to run 60 mins/hr for testing week. 6" duct, soffit mounted air intake
FL	408	none	NA									
FL	409	EXH	on/off switch	no	no	50	82	0	0	0	0%	Simple on/off switch. Did not run.
FL	410	Ventilating Dehu	control pad at unit allows for continuous or intermittent operation	yes	not functioning	84	0	0	0	0	0%	Turned off on arrival. Tried to turn on but outside air damper would not open and no flow.
FL	411	EXH + U-CFIS	On/off switch + Uncontrolled CFIS	Exh, no. U-CFIS, no	no + not functioning	53	53 + 0	0 + runtime	0 + 16	0+0	0%	Energy rating file indicates exhaust system. Exhaust fan has simple on/off switch. Team did not run but annemometer shows 20% runtime during week. House also has CFIS that field team could not get to function. Manual damper next to air handler. 4" metal duct to plenum under air handler, Gooseneck on roof has damper for exhaust thus blocking flow, could not measure any flow. Cooling runtime estimated at 26% of time from annemometer.

State	Home Number	WHMV System Type	Control Type	Label at Controller?	WHMV system operated first arrival?	62.2-2010 min airflow (cfm)*	Measured airflow (cfm)	WHMV runtime (min/h) as found	WHMV runtime (min/h) sample week	Calculated WHMV airflow (cfm)	Ratio: sample week ventilation rate 62.2 ventilation rate	Notes
FL	412	EXH + C-CFIS	On/off switch Controlled CFIS	Exh, no. C-CFIS, yes	EXH no but was run by homeowner during week. C-CFIS did not operate.	79	42+ 0	undetermined	32 + 0	22+0	28%	Energy rating file indicates exhaust system. Exhaust fan has simple on/off switch, but homeowner indicated they do run for extended periods from time to time. Field team did not run but annemometer shows 53% runtime. House also has CFIS that field team could not get to function. 6" duct in hall return plenum. Could not locate damper.
FL	413	EXH	on/off switch	no	no	62	89	0	0	0	0%	Energy rating file indicates exhaust system. Exhaust fan has simple on/off switch. Did not run. House had a mystery switch that might have controlled a damper, but could not be located.
FL	414	Ventilating Dehu	ventilation control unknown; humidistat near thermostat	no	yes	67	34	36	36	20	30%	Outside air damper appears to be miswired as the damper only opens when dehu senses high indoor relative humidity. Humidistat allows humidity set point but controls for ventilation unknown. House also has aircycler smart exhaust switch for master bath fan but homeowner indicates fan only used for on/off spot ventilation.
FL	415	ERV	Continuous and high/low	yes	yes	42	40	60	60	40	95%	Ceiling mounted ERV.
FL	416	ERV	Settings in Thermostat. Capable of timed operation	Settings screens in tstat. Label at on/off and low/high switch on ERV itself	yes	47	110	10	10	18	39%	Same community as 405. ERV ducted to central heating/cooling system return to return Set to run 10 min/hr and team left it that way.
FL	417	C-CFIS	Controlled CFIS	yes	runtime?	64	unknown	runtime?	runtime?	unknown	unknown	Found to be switched "off" on arrival acting like U-CFIS. 4" duct from eave to plenum under air handler. Unknown whether Intake at wall or soffit. CFIS flow not tested, no system runtime during week.
FL	418	ERV	continuous. Rheostat flow control at air handler, boost controlls in bathrooms	yes	yes	76	133	60	60	133	175%	ERV that exhausts from kitchen and bath. 105 cfm normal with bath/kitchen boost up to 210 cfm.
FL	419	C-CFIS	Controlled CFIS	yes	runtime?	69	unknown	runtime?	runtime?	unknown	unknown	Controller found in the "off" position acting like U-CFIS. Duct runs from soffit to plenum in attic. CFIS Flow not tested, runtime during week.

State	Home Number	WHMV System Type	Control Type	Label at Controller?	WHMV system operated first arrival?	62.2-2010 min airflow (cfm)*	Measured airflow (cfm)	WHMV runtime (min/h) as found	WHMV runtime (min/h) sample week	Calculated WHMV airflow (cfm)	Ratio: sample week ventilation rate 62.2 ventilation rate	Notes
FL	420	Ventilating Dehu	allows for continuous or intermittent operation	yes	no	68	160	0	35	93	137%	System was off upon arrival. Team set to run 35 mins/hour for testing week.
FL	421	CFIS + Exhaust	air cycler controller at air handler, fan connect switch for bath fan	yes	not functioning	43	47+66	0	complicated	12+38	116%	CFIS integrated with smart bath fan switch. Defeated by both closed manual damper and always closed electric damper. Team able to get system to function after calling manufacturer and resetting, but only at the default inputs that did not match house.
SC	422	U-CFIS	Uncontrolled CFIS	n/a	yes	42	24	25	25	10	24%	Discovered CFIS on second visit. Measured 24 cfm. 4" duct to hallway ceiling return. Annemometer estimates runtime of 25 min/hr.
SC	423	U-CFIS	Uncontrolled CFIS	n/a	yes	52	24	27	27	11	21%	No controller. Could not access fresh air intake but tracer gas testing indicates 60 cfm with AHU on, which is what was found in 422 with same system measured at 24 cfm . 4" duct to hallway ceiling return. Annemometer estimates runtime of 27 min/hr.
SC	424	EXH	on/off switch	no	no	48	59	0	0	0	0%	Simple on/off switch. Did not run.
SC	425	EXH	on/off switch	no	no	48	54	0	0	0	0%	Simple on/off switch. Did not run.
GA	426	ERV	continuous, rheostat flow control in attic	yes	yes	64	35	60	60	35	55%	Fully ducted ERV.
GA	427	C-CFIS (tstat)	Thermostat controlled CFIS	yes	not fuctioning	49	0	0	0	0	0%	Found "off" on arrival. Field team could not activate CFIS. Gable intake to return plenum in closet. Could not measure any flow.
GA	428	ERV	continuous and high/low	yes	yes	41	34	60	60	34	83%	ERV filters were clogged on arrival and little flow measured. Field team cleaned filters.
GA	429	U-CFIS	Uncontrolled CFIS	n/a	U-CFIS maybe working but couldn't access intake, very little ahu runtime during week	44	0	1	1	0.00	0%	roof mounted intake to return plenum. Could not access intake. Dirty inline filter, but damper indicated as closed. Did not open. Put annemometer on filter but no flow recorded. Only 1% runtime during testing week.
GA	430	U-CFIS	uncontrolled CFIS	n/a	unknown	48	unknown	unknown	10	0	0%	No signs of any ventilation components, but attic not accessible. Little system runtime during week.

State	Home Number	WHMV System Type	Control Type	Label at Controller?	WHMV system operated first arrival?	62.2-2010 min airflow (cfm)*	Measured airflow (cfm)	WHMV runtime (min/h) as found	WHMV runtime (min/h) sample week	Calculated WHMV airflow (cfm)	Ratio: sample week ventilation rate 62.2 ventilation rate	Notes
SC	431	EXH	on/off switch	no	no	67	60	0	0	0	0%	simple on/off switches. Rating file indicated "balanced"
SC	432	EXH + U-CFIS	On/off switch + Uncontrolled	no + no	no + unknown	52	55+0	0+runtime	60+6	55+0	106%	bath fan forced "on". 4" eave CFIS intake to master ceiling return plenum. CFIS damper likely remained closed. Little runtime during testing week.
FL	433	EXH	flow selectable fan. Continuous operation. On/off switch and boost switch	no	no	48	50	0	0	0	0%	
FL	434	EXH	flow selectable fan. Continuous operation. On/off switch and boost switch	no	no	58	60	0	0	0	0%	
FL	435	EXH	flow selectable fan. Continuous operation. On/off switch and boost switch	no	no	48	101	0	60	101	210%	Flow high because both master and mode switch left "on"
FL	436	EXH + U-CFIS	On/off switch + Uncontrolled	no	U-CFIS likely working but could not access intake. very little AHU runtime.	68	42 + 52	0+runtime	60+2	42+0	62%	Team ran 42 cfm bath fan. Could not measure cfis flow due to roof. Very little AHU runtime during testing week. Eave mounted intake with 6" duct to air handler.
FL	437	EXH + C-CFIS	On/off switch + Controlled CFIS	yes	no+not functioning	63	49	0	0	0	0%	no cfis flow measured . Did not run exhaust fan.
FL	438	EXH	on/off switch	no	no	69	63	0	60	63	91%	second floor bath
FL	439	EXH	on/off switch	no	no	69	80	0	60	80	116%	first floor hall bath
FL	440	EXH + C-CFIS	On/off switch + Controlled CFIS	no+ yes	no+unknown	80	57+0	0+ 30	0	0	0%	6" cfis duct from 2nd story roof inlet to return jumction box. Controller left "off" as found, assume to mean runtime only. Did not try and measure flow. Did not run any fans.
FL	441	EXH + C-CFIS	On/off switch + Controlled CFIS	no+ yes	no+not functioning	63	62 + 0	0	0	0	0%	oa intake at front porch with two ducts connected (8 and 6"). Wires to dampers disconnected. Could not meausre any flow.
FL	442	EXH	RH controled/timer	no	RH control mode	45	60+63	RH control mode	35+39 week 1, 29+49 week 2	35+41 week 1, 29+51 week 2	169% week 1; 178% week 2	Fans with overactive RH switch. first week fans ran in humidity mode. Second week ran both fans in runtime mode.time Both fans set from 10 to 22 min/hr. Mode changed from auto to cycle; sensitivity changed from 'low to medium' to 'low'.

State	Home Number	WHMV System Type	Control Type	Label at Controller?	WHMV system operated first arrival?	62.2-2010 min airflow (cfm)*	Measured airflow (cfm)	WHMV runtime (min/h) as found	WHMV runtime (min/h) sample week	Calculated WHMV airflow (cfm)	Ratio: sample week ventilation rate 62.2 ventilation rate	Notes
SC	431	EXH	on/off switch	no	no	67	60	0	0	0	0%	simple on/off switches. Rating file indicated "balanced"
FL	443	EXH	RH controled/timer	no	RH control mode	46	77+69	RH control mode	32+5 week 1; 28+14 week 2	42+6 week 1; 36+16 week 2	104% week 1; 113% week 2	Fans with overactive RH switch. first week fans ran in humidity mode. Second week ran both fans in runtime mode. Both fans set from 10 to 20 and 18 min/hr respectivley. Mode changed from auto to cycle; sensitivity changed from 'low to medium' to 'low'.
FL	444	EXH	dial, non-programmable Timer control that is used to activate fan on each occasion	no	no	47	55	0	0	0	0%	Original RH switch replaced by homeowner with simple timer switch that could not be left "on"
FL	445	EXH	RH controled	no	RH control mode	47	61+67	RH control mode	12+27	12+30	89%	All fans operated with RH switches, which were left as found in humidity mode.
FL	446	EXH + U-CFIS	timer/humidity + on/off	no + yes	delay timer mode+not functioning	46	88+0	delay timer mode	45+19	66+0	143%	CFIS damper functioning but no flow measured. Switch at AH. Long 4" flex with sharp bend. AS1 shows 32% runtime. Homeowner installed advanced controllers in all bathrooms.
FL	447	EXH	on/off switch	no	no	60	65	0	60	65	108%	Left switch on
FL	448	EXH	on/off switch	no	no	80	110	0	60	110	138%	Left switch on
FL	449	Ventilating Dehu	control pad at unit allows for continuous or intermittent operation	yes	yes	82	90	20	55	83 week 1, 40 week 2	100% week 1, 50% week 2	Dehumidifier "on" as found at 20 mins/hr. Set to 55 mins/hour for first week. Turned off for second week but contractor turned it back on about half way into the week.
FL	450	Ventilating Dehu	control pad at unit allows for continuous or intermittent operation	yes	yes	68	127	15	35	74	109%	Dehumidifier "on" as found at 15 min/hr. Set to 35 min/hour for first week.
FL	451	EXH + C-CFIS	On/off switch + Controlled CFIS	no + yes	no	69	71	0	60 + 0	71	103%	Team ran exhaust fan. Second floor CFIS damper wiring was not connected and no control seen at AHU. First floor CFIS damper is wired to controller at AHU but all attempts to trigger the damper open were unsuccessful. No flow was ever recorded at outdoor air inlet on porch.

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