Ventilation Effectiveness Study Final Report

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A key component of any field research is recruitment. This project, which required specific types of ventilation systems located in homes ranging from low to very low air leakage, was particularly challenging. In addition, the homeowners were expected to be active participants in the field experiments with weekly changes in the setup continuing over two seasons. Marla Hacklander was the main recruiter, relationship manager, and schedule reminder with able assistance from Tanya Beavers.

Luke Howard and Luke Mattheis were the WSU Energy Program staff who joined Messrs. Prill and Hales in the field research. Because Prill and Hales were based in Spokane, Mr. Howard and Mr. Mattheis did most of the field research in Western Washington once they were trained in the detailed characterization tests and monitoring installation and commissioning.

Analysis was a guiding principle in the data organization as soon as it started to flow. Luke Mattheis organized data with guidance of Rick Kunkle, the project's lead analyst. Mr. Kunkle performed quality assurance on the data, resulting in detailed characterization sheets for every home in the study.

As soon as data became available, Mr. Kunkle, Josiah Narog, and Adria Banks began working on what ultimately became a database of over 400,000 data points. After Mr. Narog left the employ of WSU, the analysis became the responsibility of Mr. Kunkle, Ms. Banks, and Mr. Hales.

Assisting the project was Mike Lubliner, who served as a project consultant with strong ties to the American Society of Heating, Refrigerating, and Air Conditioning Engineers and its Standard 62.2 Committee. Two outside consultants, Terry Brennan of Camroden Associates, and Dr. Jeffrey Siegel, Professor of Mechanical Engineering at the University of Toronto, provided insights into data analysis. Mr. Brennan also provided the key analytical tool for the short-term test data.

The project was managed by Ken Eklund, the WSU Energy Program Building and Standards Team Lead. Mr. Eklund coordinated and supported field research, data analysis, and reporting efforts. He conducted the analysis of the home occupant knowledge and ventilation system issues.

Organizing, drafting, editing, and integrating the multiple reports of which this is the final stage was the work of the entire analytical team, with the assistance of Melinda Spencer, our technical editor.

The last key component of the team was the home occupants, who performed experiments and trusted WSU Energy Program staff to measure and monitor their homes. Working together, this entire team made great strides in confirming the importance of ventilation in America's increasingly tight homes, identifying issues that must be dealt with, and pointing out directions for future research.

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Acronyms

AC	alternating current
ACH_{50}	air changes per hour at 50 Pascals
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CFA	central forced air
CFM	cubic feet per meter, cubic feet per minute
CO_2	carbon dioxide
DC	direct current
EO	exhaust only
ERV	energy recovery ventilation
RH	relative humidity
HRV	heat recovery ventilation
NEEA	Northwest Energy Efficiency Alliance
WSU	Washington State University

Executive Summary

This report presents the findings and conclusions of a ventilation effectiveness study in houses with low air leakage. A total of 29 houses with five different types of ventilation systems were included in the study. Exhaust ventilation (exhaust only (EO) and exhaust with inlet vents) and heat recovery ventilation (HRV)/energy recovery ventilation (ERV) systems made up the largest share of the ventilation systems that were studied.

Data was collected in short-term and long-term field experiments using a standard set of test conditions (ventilation systems on and off, bedroom doors open or closed). Monitoring also included normal periods when no experiments were being conducted and occupants were free to operate ventilation systems and doors as they liked. Data collected included:

- CO_2[1], temperature, and humidity measurements in the main living area and two bedrooms;
- Bedroom door closure status;
- Ventilation system fan operation;
- A journal maintained by occupants; and
- House characteristics including automated, multi-point blower door tests, exhaust fan flows, house pressure mapping, and physical measurements and layout. (Excerpted house characteristics are provided in **Table 2.**)

Five research questions are considered in this report:

1. Characterization of estimated direct electrical energy use by the ventilation system,
2. The relative effectiveness of the ventilation system types during the test periods,
3. The ability of each system studied to provide effective ventilation in bedrooms and main living areas during normal home occupancy and use.
4. Factors that contribute to ventilation effectiveness, and
5. House occupant satisfaction with and knowledge of their ventilation system.

The key results summarize the research findings for each of these questions.

Before presenting the summary of the short-term, long-term, and normal period study results, it is useful to consider one measure of ventilation – how delivered air volumes compared to ASHRAE 62.2-2010 requirements. The houses provided, on average, 137% of the minimum ventilation air required by Standard 62.2, with a range of just under 100% to over 200% of this minimum volume. These are the ventilation levels that existed during the tests. Three houses had ventilation under 100% (only one was below 90%) and 9 houses had levels at or over 150%. Cases with higher levels of ventilation were fairly evenly distributed across ventilation system types. It is, however, a finding of this study that total ventilation is not a determining factor in ventilation effectiveness. The study demonstrates that a key factor is the ventilation delivered to each occupied space coupled with a number of other influencing factors such as house size, occupant density, airtightness, and the presence of a whole house air circulation system such as central forced air.

[1] CO_2 was used as a trace gas for evaluating ventilation effectiveness.

Key Results

Characterization of Direct Electrical Energy Use

The energy use of ventilation systems is an important factor to consider when evaluating performance. The direct energy use of each ventilation system type was estimated based on the operation of the ventilation system during the tests and on a one-time amperage measurement under normal (low flow) conditions. The analysis does not include any energy to heat ventilation air.

The configurations of the systems were confirmed to comply with the nominal ventilation flow requirements of 2010 ASHRAE Standard 62.2 though three systems were slightly below the standard. Modification of existing settings was necessary for approximately one-third of the houses.

There is a fairly wide variation of fan energy use both within and across ventilation system types. The exhaust systems have the lowest fan energy use (34 to 547 kWh/year), followed by the HRV/ERV systems (193 to 765 kWh/year). On average, the integrated with CFA systems have the highest energy use (515 to 1,564 kWh/year), with the qualification that with a very efficient variable speed air handler the energy use can be much lower—as it was for one of the systems in this category.

In addition to the direct energy use of the ventilation systems, some other factors should be considered that influence overall ventilation energy use, including ventilation air energy loads (HRV/ERV systems have heat recovery), contributions of ventilation system energy use to household internal gains, duct and distribution system energy losses, system control and run time, and maintenance issues. These issues remain for further analysis and study.

Relative Effectiveness of Ventilation Systems Studied During Test Periods

The "effectiveness" of a ventilation system is the degree to which it is successful in removing or diluting indoor pollutants and providing fresh air for occupants. To compare the effectiveness of the systems studied, the performance metric of measured CO_2 levels[2] in the houses during different test conditions was evaluated. The test condition status and the different types of ventilation systems were the primary variables considered. Ventilation effectiveness was evaluated using two approaches:

- For the short-term tests, researchers spent six to eight hours at each house (the houses were un-occupied). A known amount of CO_2 was injected into the air and mixed evenly, and the decay was measured under different test conditions.
- In long-term tests (houses were occupied), CO_2 levels were measured at 15-minute intervals in the main living area, the master bedroom, and a second bedroom. Household occupants changed the status of ventilation operation and bedroom door closure for weekly periods to conform to the different test conditions. Data analysis focused on the occupied bedrooms at night (midnight to 6 a.m.), when measured CO_2 levels were highest.

[2] In the short-term and long-term studies, ventilation rates above 0.35 ACH or CO_2 levels below 1,000 ppm were used as indicators of adequate ventilation.

The key findings from the ventilation effectiveness analysis include:

- Measurements with the ventilation system off during the short- and long-term tests indicated that natural ventilation in these houses was inadequate.
- The data demonstrate that operating ventilation systems provided a clear benefit. In the short-term test, ventilation improved from less than 0.1 ACH to 0.3 ACH, on average. For the master bedroom in the long-term test with the ventilation system on, CO_2 levels clearly shifted below 1,000 ppm in most cases. When bedroom doors were open, 75% of the measurements were below 1,000 ppm. When doors were closed, 55% were below 1,000 ppm.
- In general, ventilation systems that provided ventilation air to each space (CFA integrated and HRV) provided more effective ventilation than exhaust-type systems. This is particularly true for the bedrooms when the doors were closed.
  - The HRV systems provided higher levels of ventilation than the other systems in the short-term test, particularly in the bedrooms when the doors were closed. In the long-term test, the HRV systems were more effective for the second bedroom, but this advantage was less clear for the master bedroom. This may be due to the many complicating factors introduced in the long-term data that did not exist in the short-term test, which was a controlled experiment without the influence of human behavior and occupancy.
  - The houses with CFA integrated and CFA integrated with ERV ventilation systems had the lowest CO_2 levels in the long-term study, but only five houses had these systems. The two CFA integrated systems included in the short-term test did not perform quite as well relative to the other systems, but this may be due to the short-term test not accounting for the mixing and dilution that a CFA system provides.[3]
- The CO_2 levels measured across houses varied greatly, even within ventilation system types. For example, while the HRV systems in the short-term test generally had higher ventilation levels, some HRV systems performed worse than many of the exhaust systems. The HRV systems were more likely to have ACH levels well above 0.35 ACH (suggesting a few cases of over-ventilation, particularly in the second bedroom). The HRV systems tended to have the greatest variation in ventilation rates across rooms, particularly when bedroom doors were shut (suggesting balancing issues). The highest CO_2 levels were concentrated in a relatively small number of houses. The houses that had the highest CO_2 levels when the ventilation system was off also tended to have the highest levels when the ventilation system was on. These results indicate that other factors besides ventilation system type also influence ventilation effectiveness.

The research also considered relative humidity (RH) as a measure of ventilation effectiveness. The following points summarize key conclusions from the WSU Energy Program analysis of RH data:

- Ventilation reduces RH in houses, but the impact is less significant than for CO_2.
- The RH for west-side houses is higher than for east-side houses, which reflects the colder and dryer east-side climate.

[3] A CFA system can reduce CO_2 levels in the bedrooms by mixing air from the living space, which has lower CO_2 levels. In the short-term test, all the rooms were seeded with CO_2 and then the decay rate was measured. Because all spaces have high levels of CO_2, the dilution from mixing could not occur.

- Ventilation can contribute to low RH levels. Low humidity seems to be more of an issue than high humidity in these houses.
- On average, there is a correlation between CO_2 and RH levels (houses with higher CO_2 levels also have higher RH), suggesting that factors that contribute to higher CO_2 also contribute to higher RH.
- RH is not as good an indicator of ventilation system effectiveness, given the very different ways RH and CO_2 are generated and dissipated (e.g., door closure and occupancy do not seem to affect RH). Outdoor ventilation air reduces indoor CO_2 at consistent rates, but does not affect RH consistently because the outdoor moisture level varies significantly with outdoor temperature and other factors. Likewise, indoor RH varies with temperature: reducing the temperature raises RH.

Ability of Each System Studied to Provide Effective Ventilation During Normal Occupancy and Use

This part of the study considered ventilation system performance during normal home occupancy and use. During this “normal period,” home occupants were free to operate ventilation systems and open or close doors as they liked. Data were collected before and after the long-term study test week periods. A significant amount of data was collected; in fact, 18 of the 29 houses produced more data for the normal period than for the test week period.

Key conclusions from this analysis of the normal period data include:

- CO_2 levels were similar for the bedrooms at night during the normal and test week periods. The results for the normal period indicate that most of the houses had adequate ventilation. CO_2 levels in the second bedrooms tended to be slightly higher than levels in the master bedroom during the normal period (consistent with the test week period results).
- Doors being closed or ventilation systems being off contributed to higher CO_2 levels, consistent with the long-term study test week period results.
- During the normal period, the most common bedroom door and ventilation operation status condition (when data was available) was bedroom doors open and ventilation system on. This is the condition during the short- and long-term tests when the ventilation systems were most effective and measured CO_2 levels were lowest. The ventilation system was on most of the time for most houses during the normal period, but in seven houses the ventilation system was off more than 33% of the time (because of measurement issues, the ventilation status was unknown for 11 houses). At night, doors were left open 62% of the time for the master bedroom and 52% of the time for the second bedroom (the lower value for the second bedroom is partly due to a larger number of cases where the door status was unknown because of measurement issues).
- Houses with CFA integrated (including with ERV) ventilation systems tended to have the lowest measured CO_2 levels when they operated (and in some cases when the ventilation system was off most of the time). The houses with HRV systems generally had relatively low and consistent CO_2 levels. The results for the exhaust systems were mixed; some houses had relatively low CO_2 levels and others had high levels. These results are consistent with the long-term study.

Effectiveness of Inlet Vents

Six exhaust system houses with inlet vents were studied in the short- and long-term tests.[4] The results are inconclusive – a clear benefit from inlet vents is not evident. In one case, when the bedroom doors were closed in the short-term test, the inlet vents provided a modest benefit in the bedrooms: the mean improvement in the second bedroom was 0.05 ACH and in the master bedroom was 0.09 ACH. The improvement varied, and in two cases for the second bedroom, the change was negative.

For the long-term study, it is difficult to draw any conclusions about the benefit of inlet vents due to the small sample size (only three of the six houses complied with the closed-door test condition) and uncertainty about whether the vents were open or closed. It appears that the benefit of inlet vents in the long-term is small enough to be lost in the noise of all the other factors influencing CO_2 levels in these houses. In addition, the field interviews showed that at least 67% of the vents were normally closed.

In the normal period, the exhaust system with inlet vent houses tended to have the highest CO_2 levels. The status of inlet vents was unknown; occupants were free to open or close them as they normally would (observations from the field visits suggest they were normally closed for four of six cases). The researchers did not note advantages for exhaust systems with inlet vents houses compared to those without inlet vents.

Factors Contributing to Ventilation System Effectiveness

While the type of ventilation system is important, the wide variation in ventilation effectiveness across houses with the same ventilation system suggests other factors have an important influence. The researchers considered a variety of characteristics for each house to identify factors that contribute to the effectiveness or lack of effectiveness of each ventilation system type studied. Factors included house size, airtightness, heating system type, number of occupants, internal air paths, and ventilation rates. While the small sample and number of factors makes it difficult to assign significance to specific factors, the following observations can be made:

- Heating system type was a key factor influencing ventilation effectiveness. Houses with CFA heating systems tended to have lower CO_2 levels. This finding is consistent with the ventilation effectiveness analysis results that suggest ventilation systems that provided ventilation air to each space (CFA integrated and HRV) were more effective. A CFA heating system also distributes air to each space, providing air mixing that can reduce CO_2 levels in spaces with higher concentrations.
- Another key factor influencing ventilation effectiveness was the amount of ventilation provided to the space. Ventilation systems that were less effective in reducing CO_2 levels tended to provide lower ventilation flows to the space. This explains some of the variation in performance across the same type of ventilation system in different houses. Related to this is ventilation operation. During the normal period, some ventilation systems were operated much less frequently, resulting in less ventilation to the space.

[4] The houses were not the same in each test. There were a total of eight houses with inlet vents. Two houses with inlet vents in the short-term study analysis functioned as exhaust only systems in the long-term test (the vents were closed). Two other houses with inlet vents in the long-term study did not participate in the short-term study.

- Houses with relatively high master bedroom CO_2 levels tended to be smaller, tighter, have more occupants, or did not have a ventilation return air path. Houses with lower CO_2 levels tended to be larger, leakier, and have lower occupancy.
- There were outliers in the analysis where the factors considered by the research team did not explain the measured CO_2 levels. Other household behaviors that could influence CO_2 levels were not considered in this analysis. These behaviors included opening windows, operating spot ventilation, and operating a clothes dryer. Some of this information was recorded by households in journals, but this information was inconsistent and was not used in the analysis.

Home Occupant Satisfaction with Different Types of Ventilation Systems

The WSU Energy Program researchers examined home occupant knowledge of ventilation systems, system operation and maintenance, and the degree of occupant satisfaction with the system. All but two of the participating households expressed general satisfaction with the performance of their ventilation systems. This may suggest that satisfaction is not a good indicator of ventilation system performance.

- The home occupants' knowledge of their ventilation systems ranged from very limited to very knowledgeable. Fewer than 50% had a good understanding of how to maintain and control their systems and almost 33% had no effective knowledge about system function, control, or maintenance.
- WSU Energy Program researchers identified a number of ventilation system issues during site visits to the participating homes. None of the ventilation systems had labels as required by Washington state law. Many systems had control issues such as not being set to meet ASHRAE Standard 62.2-2010 requirements and inaccessible controls. In over 25% of the houses, fans and ducts needed to be cleaned or repaired in order for the systems to operate properly.
- There was a substantial relationship between lack of knowledge and higher numbers of ventilation system issues (except the requirement for labeling, which was universally ignored). This indicates that, without effective home occupant education, it is highly unlikely that these systems will be operated or maintained as intended. Over time, this could result in significant deterioration in system performance.
- Almost all of the home occupants were very interested in CO_2 levels, which prompted their interest in learning about their ventilation systems. This fact may be useful in improving long-term ventilation effectiveness in homes because system maintenance is key to long-term effective and energy-efficient system operation.

Recommendations

The results of this ventilation effectiveness study have implications for policy and building codes as well as future research.

Policy Areas and Code Changes

Public policy should focus on ventilation effectiveness. The results of this study apply to any gaseous pollutant, including carbon monoxide, radon, nitrogen oxide, and formaldehyde, as well as CO_2 and water vapor. This is particularly important as houses become tighter like those in this study, which show the shape of the future.

The study revealed key areas that clearly require policy and code changes:

- The existing legal requirement that ventilation controls be labeled needs to be enforced.
- Builders should be required to brief home buyers on ventilation system operation and maintenance, and system instructions and a schematic should be left with the home.
- Systems should be designed for easy operation and maintenance. Controls should be in a convenient location and filters should be accessible. Screens that can clog with lint and require cleaning should not be located at roof level or be otherwise difficult to access; they should be located where the home occupant can easily access and clean them.
- All ventilation systems should be commissioned for proper flow and control settings.
- The requirement for inlet vents should be reviewed. While the results from this study are not definitive, they questions whether inlet vents are widely used or provide any clear benefit.
- Air handlers integrated into ventilation systems should have variable speed ECM motors.
- Ventilation systems need to provide adequate ventilation for all occupied spaces. This is particularly true for bedrooms where doors can be closed. Each space needs to have a supply and/or return path to the ventilation system.

Potential Areas for Future Research

This study did not address the following topics, which should be considered for future research:

- Research the exhaust penalty of each system and actual heat recovery of HRV and ERV systems.
- Research the impact of air leakage, conductive heat loss, and duct static pressure on ventilation system energy use and performance.
- Account for the impact of exhaust appliances other than the ventilation system, window opening, and other related behavior on ventilation effectiveness.
- Explore the impact of outdoor temperature and wind speed on ventilation effectiveness using site-specific measurements.
- Consider whether ventilation effectiveness declines due to operation and maintenance issues.
- Consider if gaseous pollutants such as radon are mitigated by effective ventilation.
- Consider ventilation flow rates that are not at or above the minimum ventilation rates required by ASHRAE 62.2-2010 to learn the *lowest* ventilation rates at which effective ventilation can be provided by each system type.

Insights about Conducting Future Research

Another important result of this study is the experience gained from evaluating the performance of ventilation systems. Some of the challenges experienced by the researchers include small sample size, limited amounts of data for some houses due to test condition compliance issues, and problems with ventilation operation status measurements. Insights gleaned from this effort that could help guide future research include:

- Developing consistent field data collection and ventilation system set-up protocols,
- Establishing real-time data management and quality control procedures,
- Identifying ways to simplify the experimental design,
- Recruiting more participants, and
- Collecting data for longer periods.

Introduction

The Pacific Northwest Ventilation Effectiveness Study is a Washington State University (WSU) Energy Program research project commissioned and funded by the Northwest Energy Efficiency Alliance (NEEA). This paper reports the findings based on analysis of the data collected in the field study and conclusions by the WSU Energy Program research team.

The unique feature of this study is that the test sites represent the top tier of house airtightness in any sample of new houses. Air leakage ranged from just over three air changes per hour at 50 Pascals (ACH_{50}) to less than one.

The other main feature is that five different types of ventilation systems were tested and assessed in a range of house airtightness configurations. The ventilation systems studied were:

1. **Exhaust Only** (EO)
2. **Exhaust – Inlet**: exhaust with window or inlet vents
3. **CFA Integrated**: ventilation integrated with central forced air (CFA)
4. **HRV** and **ERV**: heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs)
5. **CFA Integrated with ERV**: ERVs integrated with CFA

This study focused narrowly on ventilation system performance. All references to ventilation system energy use do not include the induced space conditioning load component.

Study Team

The WSU Energy Program marshaled a multi-disciplinary team to conduct the study. The field phase of the study effort focused on recruitment, field characterization and monitoring. In practice, WSU Energy Program researchers added extensive time and expertise for data management and display of data in floor plans and charts. The analysis phase of the study included extensive data quality assurance and analysis. The project team included:

Project PI and Manager	Ken Eklund
Field Scientific Leads	David Hales, Rich Prill
Field Scientific Researchers	Luke Howard, Luke Mattheis
Participant Relations	Marla Hacklander, Tanya Beavers
In-House Consultant	Mike Lubliner
Data Organization & Management	Rick Kunkle, Luke Mattheis
Data QA & Analysis	Rick Kunkle, Adria Banks, David Hales, Josiah Narog, Ken Eklund
Floor Plan Creation	Andrew Gordon
Report Editing	Melinda Spencer
Outside Consultants	Terry Brennan, Dr. Jeff Siegel

Research Objectives

Five research objects were addressed in this report. They include all of those which were supported by quantifiable data, and are listed here. Each of these objectives is addressed in detail later in this report.

1. Characterize the air flow performance and estimated direct energy use of each ventilation system type studied. This was done for the configuration of the systems as studied, each of which was confirmed to comply with ASHRAE Standard 62.2-2010 during the measured experiments.
2. Assess the relative effectiveness of each ventilation system type studied, including advantages and disadvantages associated with each relative to the others.
3. To the extent possible, assess the factors that contribute most strongly to the effectiveness or lack of effectiveness of each ventilation system type studied, focusing on the degree to which the level of air-airtightness of the house influences system performance.
4. Assess the ability of each system studied to produce air change in bedrooms and main living areas during normal home occupancy and use.
5. Assess home occupants' knowledge of the ventilation system and its operation and maintenance, and their degree of satisfaction or dissatisfaction with the system.

Experimental Setup

Once a house was selected for the study based on its tested air leakage rate and ventilation system type, the ventilation system was inspected, cleaned and repaired if necessary, and tested. The basic guideline for the experiment was that all systems would be set to provide at least the minimum ventilation required by the Washington State Ventilation and Indoor Air Quality Code 2010 Edition (Chapter 51-13 of the Washington Administrative Code). This code has been interpreted to be met by compliance with the ASHRAE Standard 62.2-2010 (State Building Code Council Interpretation 10-05).

As found, ten of the study houses (34%) did not meet the ventilation requirements defined by ASHRAE 62.2-2010. In most cases, this was due to controls not being set to provide sufficient operation time. The controls were reset to provide this minimum required ventilation rate as close as possible throughout the study and were left in this configuration after the experiments were finished.

Only one of the systems, an integrated CFA ventilation system, was left as an intermittent system. All other systems operated continuously. Some of the HRV/ERV systems provided more than the required minimum air flow. This was adjusted to default to a lower compliance setting if available, but was left alone where this was not possible. Three of the systems provided slightly less than the required flow.

The data collected in this study reflects the best-case levels as mandated by the Washington State Ventilation Code as interpreted by the State Building Code Council. If 30% of the systems were below code standards and operated that way normally, the occupants were likely experiencing higher CO_2 levels than those recorded during this study. Where the flows of some HRV and ERV systems were reduced but still met minimum requirements, the energy used by the systems was less but the CO_2 levels may have increased.

This report contains a lot of references to CO_2, which was used as a trace gas for determining ventilation rates in the short-term study and as an indicator of ventilation effectiveness in the long-term study. The research is not concerned with what constitutes indoor air quality; rather, this project focuses on the effectiveness of ventilation systems in houses and how they are operated.

Ventilation System Treatment and Operation

Each ventilation system was examined for controls and tested for flow as found and inspected. This data was used to determine the next action. In some cases, the system needed to be repaired or cleaned. Many of the systems had controls set to operate for a period of time that was insufficient to meet ventilation requirements given the measured flow. These controls were reset.

Repairs included moving a screw or bent duct that blocked a damper in the closed or open position. In one case, an HRV had the exhaust connected to the supply fan and the supply connected to the exhaust, which had to be reversed. Ducts were found to be disconnected from the system or to terminate in a wall cavity, which required action by the builder.

Cleaning was required for filters, fan housings, ducts, and screens. In some cases, these components were inaccessible, requiring the researcher to climb to the roof and remove a roof cap or enter an attic. In most cases, this cleaning was critical to ventilation system performance.

Controls were most often reset from intermittent to continuous operation. In some cases, the high-speed setting for an HRV was reset to continuous operation at a lower speed. Only one system, a ventilation system integrated with a CFA heating system, was found to have sufficient flow so intermittent operation was sufficient to meet requirement standards.

Once the systems were operating according to specification and providing ventilation at required rates, they were left in that condition for all testing and monitoring so this study could examine the ventilation provided by systems operating as they were designed to work.

Methodology

The research methodology is briefly described here, with an emphasis on the elements most relevant for this report: field experiments, data collection and management, and analytical methodology.

Field Experiments

The analyzed data came from two sets of field experiments: long-term experiments conducted over many weeks by homeowners and short-term (partial-day) experiments conducted by WSU Energy Program researchers. It also came from normal periods when home occupants were free to operate their ventilation systems as they wished without conducting an experiment, but the monitoring continued.

Experiments were conducted with ventilation systems on and off, doors open and closed, and inlet vents open and closed for those houses with inlet vents. **Table 1** shows the combination of test conditions used for each test week in the study and the naming convention used to report the results. Note that houses with inlet vents had twice as many test weeks so that tests could be conducted with inlet vents opened or closed. The long-term test consisted of two phases—heating season and shoulder season—in which the entire experimental protocol was repeated.

Table 1. Test status conditions

Test Condition	A	B	C	D
Ventilation system	On	On	Off	Off
Bedroom doors	Open	Closed	Open	Closed
Inlet vents	Open or Closed	Open or Closed	Open or Closed	Open or Closed

A total of 29 houses were included in the study. **Table 2** summarizes the basic characteristics of the houses. Information about the ventilation systems can be found in **Appendix A**.

Data Collection and Management

Long-Term Field Study

The long-term field study produced over 400,000 data points. Each type of data (**Table 3**) was managed according to its characteristics to ensure consistent reporting, data security, quality assurance, and redundant storage. Multiple copies of each data set were kept at all times.

Table 2. House characteristics

Site #	Ventilation System Type	ACH_{50}	Year Built	Area	Floors	Occupants	Bedrooms	Baths
E01	Exhaust Only	1.94	2011	1,656	1	2	3	2
E03	HRV	0.89	2012	1,876	2	2	2	2
E05	Exhaust - Inlet	3.18	2010	1,310	2	4	3	1
E09	CFA Int.	3.20	2008	2,843	2	3	3	3
E10	HRV	2.00	2011	1,896	1	2	1	2
E11	Exhaust Only	2.76	2012	2,364	2	4	4	3
E13	Exhaust Only	1.82	2011	1,352	1	1	2	2
E16	CFA Int.	2.39	2009	2,805	2	2	3	2.5
E18	Exhaust Only	1.44	2009	3,150	2	2	3	2
E19	CFA Int. - ERV	3.10	2012	1,700	2	1	3	2.5
E22	ERV	0.36	2011	2,115	2	2	2	2.5
E23	CFA Int. - ERV	3.10	2010	2,843	1	2	3	3.5
E25	HRV	1.08	2012	1,496	1	2	3	2
E26	Exhaust - Inlet	3.50	2011	1,199	1	2	3	2
W02	HRV	1.02	2011	3,675	3	7	4	4
W04	HRV	2.65	2012	3,024	2	2	3	2.5
W06	HRV	1.42	2011	1,881	2	3	3	3
W07	Exhaust - Inlet	2.93	2012	2,080	2	2	3	3
W08	Exhaust - Inlet	3.31	2012	1,080	1	6	3	1
W12	HRV	0.57	2011	1,904	2	4	3	3
W14	Exhaust Only	2.60	2004	3,300	2	4	3	3
W15	Exhaust - Inlet	2.30	2012	1,176	1	2	3	2
W17	Exhaust Only	2.11	2012	1,240	2	2	3	3
W20	HRV	1.94	2012	1,832	2	4	3	2
W21	Exhaust Only	2.26	2008	1,971	2	2	3	2
W24	Exhaust Only	0.71	2011	1,900	2	2	3	2
W27	Exhaust - Inlet	2.87	2012	1,216	2	3	3	2
W28	CFA Int. - ERV	0.29	2011	1,970	1	4	4	2
W29	HRV/Exhaust Only[5]	0.26	2012	1,764	2	2	3	2

[5] This is an HRV system that was operated as an HRV in the short-term study tracer gas test, but was operated in exhaust only mode in the long-term study. For the normal period analysis, the system in this house is classified as exhaust only, but occupants may have operated it in HRV mode (supply and exhaust) some or most of the time.

Table 3. Types of data collected

House Characterization Data Measurements included house occupancy, house size, room size, volume, air leakage rate at 50 Pascals (ACH_{50}), ventilation system type, flow rates, amperage draw at the standard setting, other exhaust system flows, cumulative pressure with reference to outside from staggered operation of exhaust devices, and the pressure of the main and secondary bedroom with reference to the main living area with the ventilation system on. The data was recorded in separate field notebooks for each house and transferred to a master template spreadsheet for that house.
Carbon Dioxide, Temperature, and Relative Humidity Measurement Measurements were recorded throughout the long-term study using Veris CWLS CO_2, temperature, and relative humidity (RH) meters located in the master bedroom, a secondary bedroom,[6] and the main living area. Before placement, the meters were checked with known CO_2 levels and set to record in 15-minute intervals.[7] The meters were downloaded after each long-term phase (heating and shoulder seasons); stored on a field computer under a unique file name showing test site, location, and test phase; and copied into a unique page on the house master template.
Bedroom Door Open and Closed Status Digital loggers were placed on the bedroom doors that recorded whether the door was open or closed and the time. Readings (percent of time closed) were reported at 15-minute intervals. The data download, storage, and processing was the same as for the CO_2, temperature, and RH data.
Ventilation Fan On and Off Status Small current transformers installed to read the ventilation "on" status were placed on the electric supply line to the ventilation fan.[8] Readings were taken at 15-minute intervals. The data download, storage, and processing were the same as for the CO_2, temperature, RH, and door status data.
Home Occupant Journals At each test site, the home occupants were asked to keep a journal that recorded: • The start and end dates of each week-long experiment in the long-term study, • Status of the ventilation system during the experiment, • Status of doors during each test week, • Reading of CO_2 level at the beginning of each test, • Minutes that exhaust appliances (other than the whole house ventilation system) were used each day, and • Comments on each experiment and day, if any. These journals were collected at the end of each long-term field phase and recorded in the master template for each house. Journal compliance varied widely among test sites.
Home Occupant Knowledge The WSU Energy Program field staff met with the home occupants and assessed their knowledge of the ventilation system in their home and mastery of the system controls and settings. These observations were recorded in field notes.

[6] Two houses did not record second bedroom data because there was not a second bedroom or the room was not used.
[7] Two houses recorded data at 30-minute intervals for the heating season.
[8] Ventilation fan data was not recorded for seven houses due to failure of the current transformers to collect data for hard-wired ventilation fans.

Short-Term Field Study

The short-term field study required that the researchers spend six to eight hours at each test site. Houses were unoccupied during testing. Tests were done from mid-April to mid-June for 26 of the houses. CO_2 readings were taken with highly accurate WMA-4 CO_2 analyzers from PP Systems, which were backed up by Veris meters in the same location. The performance of the tests on three of the houses resulted in data that prevented inclusion in the analysis, which focuses on 23 houses.

The test protocols paralleled the test structure of the long-term tests—with ventilation system on and off, doors opened and closed, and inlet vents open and closed. However, for the short-term tests, a known amount of CO_2 was injected into the air and mixed evenly, and the decay was measured as the test conditions were changed. Master files of short-term data were set up for each site containing one-minute CO_2 concentration logs for three primary zones in each house: main living area, master bedroom, and secondary bedroom. This data was downloaded, stored on a field computer file name showing the test site, and loaded onto a specific matrix for the short-term test. The field researchers kept a journal during the test that documented experimental conditions, including exterior temperature and the exact time and sequence of tests. This data was also merged into the specific test matrix.

Analytical Methodology

The analysis of the data was an iterative process that involved organizing it into data sets, examining the data quality, analyzing and making comparisons of ventilation effectiveness for particular houses and across houses, and further refining the analysis to provide additional insights and address issues found in the analysis. This report presents basic results that focus on comparative CO_2 levels.

Estimated Energy Use

Fan run time and power measurements were used to estimate the annual electric energy use from operating different types of ventilation systems. All measurements were taken in alternating current (AC) prior to any conversion to direct current (DC). The control settings were recorded, and energy use was estimated based on operation during the tests, which in most cases was continuous.. Power factor was not measured on site. For purposes of this analysis, the power factor was assumed to be 0.8, based on a review of manufacturers' specifications.

Short-Term Field Study

The short-term results indicate ventilation performance under controlled, unoccupied conditions. To establish air changes per hour (ACH), the data was processed by a calculator provided by Terry Brennan, a consultant to the WSU Energy Program, which calculated a curve fit for the exponential decay of CO_2. The slope of the curve fit plotted exponentially is the ACH. The ACH values for each of the 23 sites analyzed and the R^2 values for the data fit are reported in **Appendix B**: Table of Short-Term Study Calculated ACH Rates by Test .

The test data from each house was summarized in a single file along with test characterization data. The unified data table for the short-term study data was much smaller than the one for the long-term tests, given that for each tracer decay test, a curve fit analysis provided a single ventilation value (in ACH) observed for each test run and zone. A comparative analysis of the performance of different system types was conducted.

Long-Term Field Study

Data for the long-term field study was organized in a master template for each test site in order to bring data from various sources together in one place, maintain its identity, and conduct initial quality assurance checks. The master template for each site contains house characterization data, floor plans with key data, journal data, the field data measurements, and graphs of CO_2 concentrations and door status over time. This allowed the data to be managed and discrepancies or errors in the data to be observed and, if possible, corrected.

The quality assurance, compliance, and major analysis required to answer the key research questions for the long-term tests were done using the statistical software R.[9] R was used in a multi-step process to create the unified data set for analysis:

- **Documenting data issues**: Data in the master templates was reviewed and errors in data entry and coding (primarily for journal dates and test week status coding) were corrected. Data issues were documented, including situations where data was missing or faulty, periods when occupants were out of town, tracer gas (short-term) test periods and ventilation, test week coding, and data confidence flags. This information was recorded in order to exclude or categorize certain data for analysis. See **Appendix E**: Data Quality Issues and Data Compliance Approach for details about data quality issues and how they were addressed.
- **Compiling data tables for analysis**: A table of house characteristics was created using data from the master templates for each house along with flags from the data documentation. Time series data for temperature, relative humidity (RH), CO_2, doors, and ventilation fans from the master templates was copied into CSV files for each test site.
- **Assessing compliance with test conditions**: This was one of the more challenging and time-consuming issues. The long-term test was designed to examine and compare the measured conditions (particularly CO_2 levels) in the houses under different test conditions (see **Table 1**). When the data was copied into the master template and compiled into a data file for each season, test conditions were manually coded based on measured data and journal entries. The same test condition code was entered for an entire week, even if there were periods within a week that did not match all of the test status conditions.
- **Reviewing data**: Initial review of the data showed that compliance with test conditions was generally good, but was an issue that needed to be addressed in the analysis. Households did not always follow the expected test conditions. This was most evident for door closure. To address this compliance issue, protocols were established.
- **Determining long-term compliance**: Because conditions at any particular moment are dependent on the previous hours, this is not simply a matter of determining compliance for each 15-minute data point; it was necessary to determine compliance for more extended periods of time. The threshold for compliance was set at 80%, meaning that ventilation system operation status and

[9] R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

door closure status had to comply with a given test condition 80% of the time for a given period. Compliance was determined separately for the master bedroom and second bedroom. (This is a simplified description of the compliance approach; see **Appendix E**: Data Quality Issues and Data Compliance Approach for more detail.)

- **Creating the unified data set**: R was used to compile all data from the data tables into one unified data set, as well as to manage the data and calculate variables used for analysis.

Normal Period Field Study

The normal period was those portions of the field study when the monitoring equipment was operating and data was collected, but no long-term experiment was being conducted. This provided an opportunity to analyze how the ventilation systems were operated normally by the home occupants.

The analysis of this data focused on a broader range of questions concerning the status of items that were the subject of control in the long-term study. These included whether ventilation systems were on or off, and whether bedroom doors were closed or open, as well as resulting CO_2 levels.

Analysis of Long-Term Test Data

Analyzing the long-term data set focused on data from the master bedroom and second bedroom, when occupied, at night (midnight to 6 a.m.). It was assumed that the master bedroom was occupied during this period. It was also assumed that this is the most challenging situation for the ventilation system, and that differences between the systems would likely be most evident under these conditions.

The long-term analysis focused on the absolute measured CO_2 concentration in the room and comparing the median concentration across test conditions and ventilation types to provide insight into a given ventilation system's ability to maintain *adequate* ventilation under a variety of conditions. Statistical analysis and data visualization were also used to reveal houses with higher relative CO_2 concentrations and to explore possible explanations for these higher CO_2 levels.

For these tests, the research hypothesis was that the median CO_2 concentration for the bedroom zones would be different for each of the ventilation types, with exhaust only (EO) systems showing the highest median CO_2 levels in the bedroom, particularly under "door closed" test conditions.

A secondary research hypothesis was that, for houses equipped with inlet vents, there would be evidence of lower average CO_2 concentrations in peripheral zones in the same houses with inlet vents open or when compared to houses with EO systems with no inlet vents. It was also hypothesized that some other factors, such as house airtightness, house size, occupancy, and a return path for air from the master bedroom to the main living area, may influence CO_2 concentrations in the test houses.

Research Findings

Research findings are presented for each of the research topics:

1. Ventilation effectiveness
2. Factors influencing ventilation effectiveness
3. Relative humidity analysis
4. Estimated energy use analysis
5. Home occupant knowledge and satisfaction with ventilation systems

The study was designed to test and compare the effectiveness of five different ventilation systems:

1. **Exhaust Only** (EO)
2. **Exhaust – Inlet**: exhaust with inlet vents
3. **CFA Integrated**: ventilation integrated with central forced air (CFA)
4. **HRV** and **ERV:** heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs)
5. **CFA Integrated – ERV**: ERV integrated with CFA

The ease of finding houses that met study criteria varied:

- Finding houses that had low air leakage and HRV/ERV systems was not difficult. On average, the tightest houses have this ventilation technology.
- Surprisingly, it was also relatively easy to find houses with three or fewer ACH_{50} with EO or exhaust with inlet vent ventilation (although the inlet vent houses tended to be leakier).
- It was very difficult to find houses with three or fewer ACH_{50} with CFA integrated ventilation systems. Only three houses with CFA integrated systems that were standard type and produced consistent, useful data were recruited. These were included in the long-term study analysis but not in the short-term study due to limited data.

In all, three types of ventilation systems included in the analysis were located in six or more houses: EO, exhaust-inlet, and HRV/ERV. The CFA integrated and CFA integrated-ERV systems were provided in only two or three houses, respectively. The small sample size needs to be considered when making performance comparisons with these system types.

1. Ventilation Effectiveness

The "effectiveness" of a ventilation system is the degree to which it is successful in removing or diluting indoor pollutants and providing fresh air for occupants. This study primarily focused on each system's ability to remove or dilute CO_2 rather than on the sources and quantity of fresh air. To compare the effectiveness of the systems studied, the performance metric of measured CO_2 levels in the houses during different test conditions was evaluated. The test condition status and the different types of ventilation systems were the primary variables considered.

Data from the short-term, long-term, and normal period studies provided insight for this analysis. Each study followed a different approach:

- The short-term study used CO_2 as a trace gas, introduced a known quantity, and observed its decay over a period of time while manipulating ventilation, door, and inlet vent status.

- The long-term study measured the impact of key variables on natural CO_2 levels, such as ventilation system on or off with bedroom doors open or closed and window (inlet) vents open or closed.
- The normal period study measured natural CO_2 levels before and after the long-term study test weeks when occupants were free to open and close bedroom doors and operate their ventilation systems as they wished.

The remainder of this section evaluates the ventilation effectiveness of the CFA integrated, CFA integrated-ERV, exhaust, and HRV ventilation systems. For this analysis, the exhaust only and exhaust-inlet systems are combined. The impact of inlet vents is considered in a sub-section at the end of this ventilation effectiveness section.

Short-Term Study

The short-term study measured decay rates of known concentrations of CO_2 for most of the test houses using very accurate monitors while changing key factors such as ventilation system "on" status, bedroom door status, and inlet vent status. Ventilation air changes per hour were calculated from the decay rates. The same questions were posed for the short-term study as for the long-term study, but the answers are given in the calculated air changes produced by the ventilation systems under various conditions. The algorithm for this calculation was provided by Terry Brennan, a consultant to the project. Note that the ACH calculated with this method represents ventilation rate – not to be confused with the ACH_{50}, which is used as the benchmark pressurization rate for air leakage testing.

To most accurately represent the ACH of multiple individual zones, a unique tracer would be required for each zone, which was not done in this study. ACH values are reported for the multi-zone configurations when interior doors were closed, but these values will not provide the certainty that would result from using unique tracers for each zone. The reason we can have confidence in the data from the door-closed test is that the concentrations were within the same range at door closure for all the tests, and the results make sense – they are not unexpected. And in this analysis, the absolute ACH in different rooms is not the key focus; instead, the research focus was the relative performance of different types of ventilation systems under the same set of typical occupancy conditions.

Exterior ambient conditions were measured at each site. These tests were all conducted from mid-April to mid-June to avoid high wind and temperature differences. The wind speed and outside air temperature were recorded at each short-term test site at the test start, and extreme conditions that could impact the tests were specifically avoided.

The short-term tests were run with two different protocols, depending on whether the house had exhaust with inlet vents or not.

- If the house had inlet vents, the inlet vents were closed for the ventilation system off test, but they were tested in both the open and closed status for all of the ventilation tests. This increased the number of EO cases, making it the largest sample in the short-term study.
- If the house did not have inlet vents, the protocol included performing tests with the ventilation system off and doors open, and with the ventilation system on and doors both open and closed.

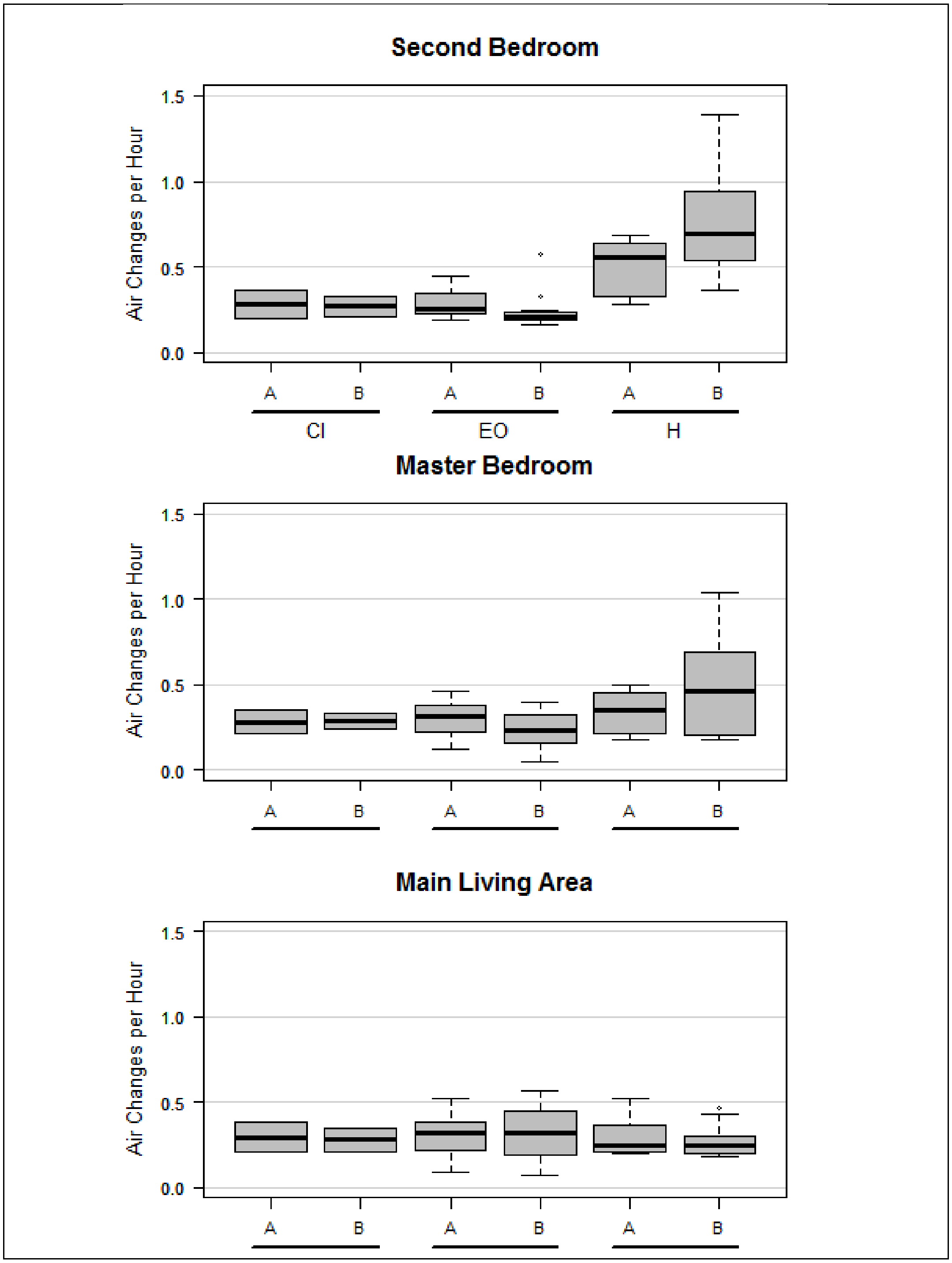
EO ventilation systems (including inlet vent cases with the vents closed) were compared with HRV systems and the two CFA integrated systems. Note that the three CFA integrated with ERV systems are not included in this analysis because there was not adequate data. The EO systems with inlet vents open and closed are compared separately.

The tests with the ventilation system off provide a baseline for this analysis of ventilation system performance. When the ventilation system was off, the mean air changes per hour (ACH) values for the three rooms generally ranged from 0.03 to 0.09. For most houses, ACH values were similar for all three rooms, with the master bedroom tending to have slightly lower mean ACH values. The mean ACH value was below 0.10 ACH in most cases. These levels clearly demonstrate the need for ventilation in houses with low air leakage.

Figure 1 shows the calculated ACH for the three rooms when the ventilation system was on and the door was open (test A) or closed (test B). For the **CFA integrated systems** (two cases), there was little difference in the ACH values for the different rooms or when the door was open or closed. The ACH values were approximately 0.2 in one house and 0.35 in the other. In cases where there are only two houses in the analysis, the top of the box is the median for one house and the bottom is the median for the other; the line in the box is the average of these two values.

When the **EO ventilation systems** bedroom doors were closed (12 cases), the mean ACH value declined from 0.29 to 0.25 for the second bedroom and from 0.30 to 0.24 for the master bedroom. There was little change in the mean ACH value of 0.31 for the EO systems in the main living area for the open and closed door cases. While the mean ACH values for the EO systems were similar across the rooms and door closures (0.24 to 0.32), there was greater variation among the individual houses. For example, in the second bedroom in one house, the ACH increased when the doors were closed; in two other cases, the ACH decreased by more than 30% when the doors were closed. In three cases, the second bedroom ACH value was below 0.2 when the door was closed; in two cases, the ACH was greater than 0.30 under the same test conditions. Some houses have very low ACH values in the master bedroom and main living area.

Figure 1. Short-term test ACH with ventilation system on and doors open (A) or closed (B) by system type



Ventilation systems shown are CFA integrated (CI), Exhaust Only (EO), and heat recovery ventilation (H).

What is notable for the HRV systems is the very wide range in ACH values in the bedrooms for the door closed case. When the doors were closed, the mean ACH for the second bedroom ranged from 0.36 to 1.39, and for the master bedroom it ranged from 0.20 to 1.04. Some HRV systems had large changes in ACH when the bedroom door was closed while a few others were less significant (in six cases, the ACH decreased or remained constant for the bedrooms when the door was closed). Generally, the HRV systems provided more ventilation air to the bedrooms than the other systems, particularly with the doors closed; however, there are three exceptions for the master bedroom where ACH was around 0.2 and there was little difference between the door open and closed cases.

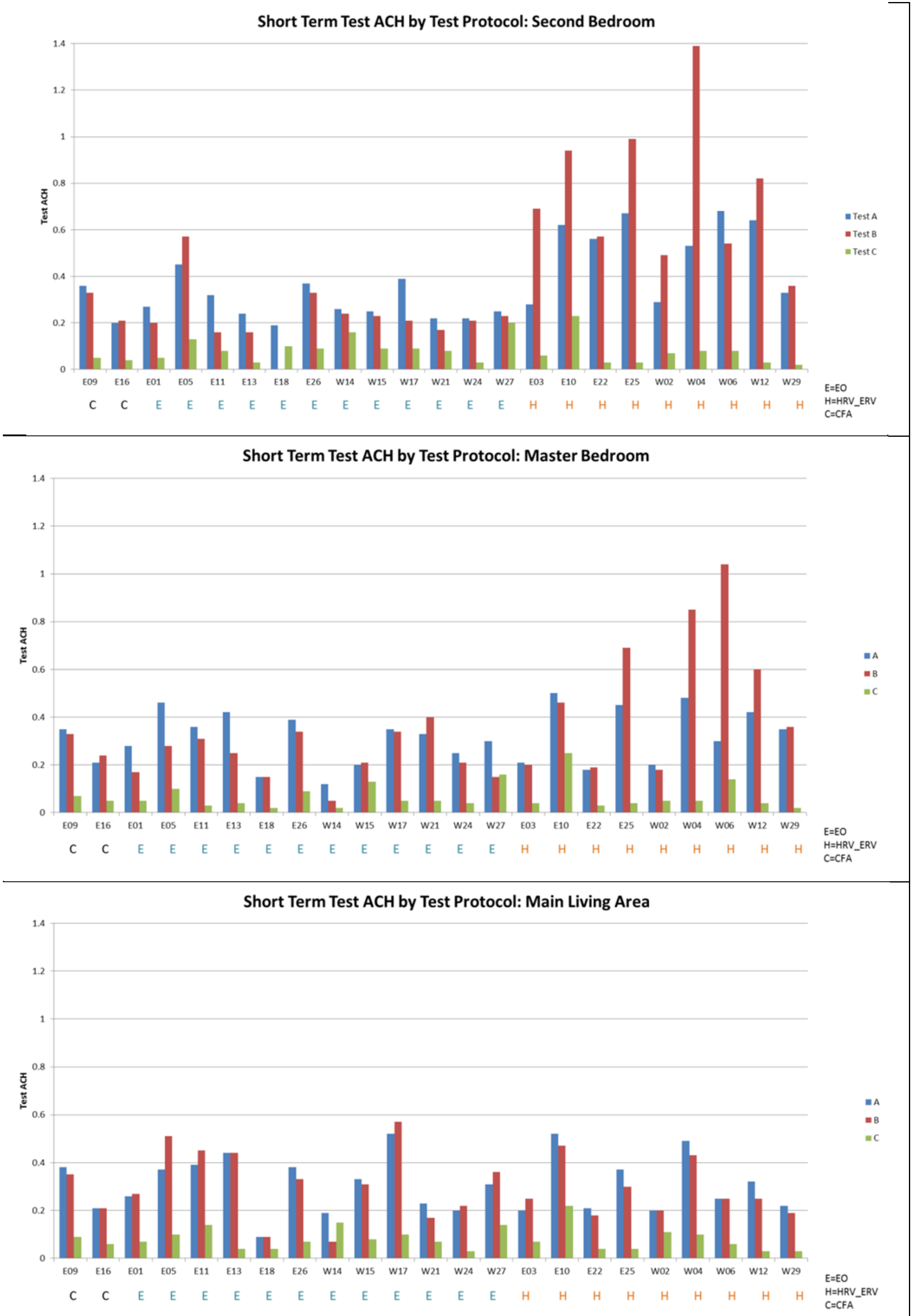
To illustrate the variation in the ACH values in the houses, **Figure 2** shows the ACH for each house for each test condition (the C test condition is for the ventilation system off and doors open) and for each room. The HRV systems tend to provide higher levels of ventilation in the second bedroom and, in some cases, in the master bedroom. The wide variation in values, even within the same system type, is one of the key findings from this study.

The HRV systems did the best, with 57% of the measured values for all three rooms greater than or equal to 0.35 ACH in the ventilation on tests with doors open or closed. An hourly air change rate of 0.35 can be viewed as a benchmark which should be close to 15 cfm/occupant for an average size house with average occupancy, and roughly corresponds to 1000 ppm CO_2. The HRV systems performed best in the second bedroom, where 67% of the houses exceeded this benchmark when the doors were open and 100% exceeded it when the doors were closed.

The EO systems did the worst, with only 28% of the measurements for all three rooms greater than or equal to 0.35 ACH for the doors open or closed with ventilation on. In both main and second bedrooms with the doors closed, only 9% of the EO cases were greater than or equal to 0.35 ACH. For the CFA systems, one house exceeded this benchmark most of the time while the other had measured values that were significantly below it.

The short-term test data were further analyzed to consider the induced ACH by the ventilation system for each house. The induced ventilation is the ventilation provided by the ventilation system. It is calculated by subtracting the ACH values calculated for short term test C (doors open, ventilation system off) from the values for test A (doors open, ventilation system on) for each zone (see **Appendix B**: Table of Short-Term Study Calculated ACH Rates by Test for the original values). **Table 4** shows the results. When the doors were open, the house was essentially one zone. For this case, if the ventilation system was balanced, the ACH values for each room (columns 2-4) should be similar. For many of the houses this is true. A few of the more extreme outliers are highlighted in yellow in the table.

Figure 2. Short-term test ACH with ventilation system on by test condition sorted by ventilation type



Note: E18 second bedroom is an office with no door

Table 4. Induced ACH by ventilation system (Test A minus Test C) compared to measured CFM

1	2	3	4	5	6	7	8	9	10	11
	ACH 2B (A-C)	ACH MB (A-C)	ACH ML (A-C)	Weighted Average (A-C)	Measured CFM	Area CF	Volume CF	Measured ACH	Difference	Ventilation Type
E01	0.22	0.23	0.19	0.21	60	1,656	15,499	0.23	0.03	Exhaust
E03	0.22	0.17	0.13	0.16	51	1,876	21,404	0.14	-0.02	HRV
E05	0.32	0.36	0.27	0.30	59	1,310	11,135	0.32	0.01	Exhaust
E09	0.31	0.28	0.29	0.29	135	2,843	27,008	0.30	0.01	CFA
E10	0.39	0.25	0.30	0.31	76	1,896	17,770	0.26	-0.05	HRV
E11	0.24	0.33	0.25	0.27	90	2,364	20,094	0.27	0.00	Exhaust
E13	0.21	0.38	0.40	0.36	55	1,352	12,649	0.26	-0.09	Exhaust
E16	0.16	0.16	0.15	0.15	64	2,805	26,026	0.15	-0.01	CFA
E18	0.09	0.13	0.05	0.08	62	3,150	39,525	0.09	0.01	Exhaust
E22	0.53	0.15	0.17	0.24	80	2,115	21,439	0.22	-0.02	HRV
E25	0.64	0.41	0.33	0.42	67	1,496	14,178	0.28	-0.13	HRV
E26	0.28	0.30	0.31	0.30	45	1,199	9,588	0.28	-0.02	Exhaust
W02	0.22	0.15	0.09	0.13	80	3,675	35,415	0.14	0.00	HRV
W04	0.45	0.43	0.39	0.41	75	3,024	25,422	0.18	-0.24	HRV
W06	0.60	0.16	0.19	0.27	63	1,881	16,928	0.22	-0.04	HRV
W12	0.61	0.38	0.29	0.38	78	1,904	22,000	0.21	-0.17	HRV
W14	0.10	0.10	0.04	0.07	60	3,300	30,825	0.12	0.05	Exhaust
W15	0.16	0.07	0.25	0.18	39	1,176	9,408	0.25	0.07	Exhaust
W17	0.30	0.30	0.42	0.36	50	1,240	9,920	0.30	-0.06	Exhaust
W21	0.14	0.28	0.16	0.19	61	1,971	18,819	0.19	0.01	Exhaust
W24	0.19	0.21	0.17	0.19	60	1,900	20,378	0.18	-0.01	Exhaust
W27	0.05	0.14	0.17	0.14	80	1,216	10,944	0.44	0.30	Exhaust
W29	0.31	0.33	0.19	0.25	38	1,764	19,839	0.11	-0.14	HRV

Notes: In columns 2, 3, and 4, 2B indicates second bedroom, MB indicates master bedroom, and ML indicates main living area. Some values in column 10 may not directly follow from the values in column 5 and 9 due to rounding.

Column 5 (highlighted in darker blue) is a weighted average of the three ACH measurements for each house. The weighted average ACH weights the second bedroom, master bedroom, and main living area ACH values by 1, 1.3, and 2.5, respectively, to estimate an overall ACH for the house based on the relative areas of the three spaces.

The induced ventilation from the short-term test can be compared to the measured CFM of the ventilation system taken on-site. The measured CFM is shown in column 6. Using the house volume, this is converted to the measured ACH shown in column 9 (lighter blue). Ideally, the weighted average ACH values (column 5) from the short-term test would be the same as the measured ACH values (column 9) from measured ventilation system CFM. Column 10 shows the difference in these values. Cells highlighted in green show differences less than ± 0.05 ACH and cells in yellow differ by more than ± 0.10. Most cells are green, suggesting reasonable agreement between the two measurements of ventilation system performance.

Key conclusions from this analysis of the short-term study data include:

- When the ventilation system was off, the mean ACH value was below 0.10 ACH in most cases. These levels clearly demonstrate the need for ventilation in houses with low air leakage.

- The ventilation systems significantly reduced CO_2 levels compared to no ventilation. Ventilation improved from less than 0.1 ACH to 0.3 ACH, on average.
- There is a great deal of variation in ventilation performance among the houses. The wide variation in values, even within the same system type, is one of the key findings from this study.
- The HRV systems provided higher levels of ventilation than the exhaust or CFA integrated ventilation systems, particularly when the bedroom doors were closed. However, the HRV systems also had greater variation in ventilation levels with the doors closed (suggesting some balancing issues).
- The results of the short-term test ACH estimates and a calculation of induced ventilation compare favorably to the measured ventilation flows taken on-site during the field visits.

Long-Term Study

The long-term study analyzed CO_2 levels under different test conditions to evaluate the ventilation system effectiveness. It is critical to understand the cycle of test weeks when each test site participated.

Table 5 shows these weeks and the name given to each test condition, which can be referenced.

Table 5. Test conditions

	Test Conditions			
	A	B	C	D
Ventilation System	On	On	Off	Off
Bedroom Doors	Open	Closed	Open	Closed
Inlet Vents	Open or Closed	Open or Closed	Open or Closed	Open or Closed

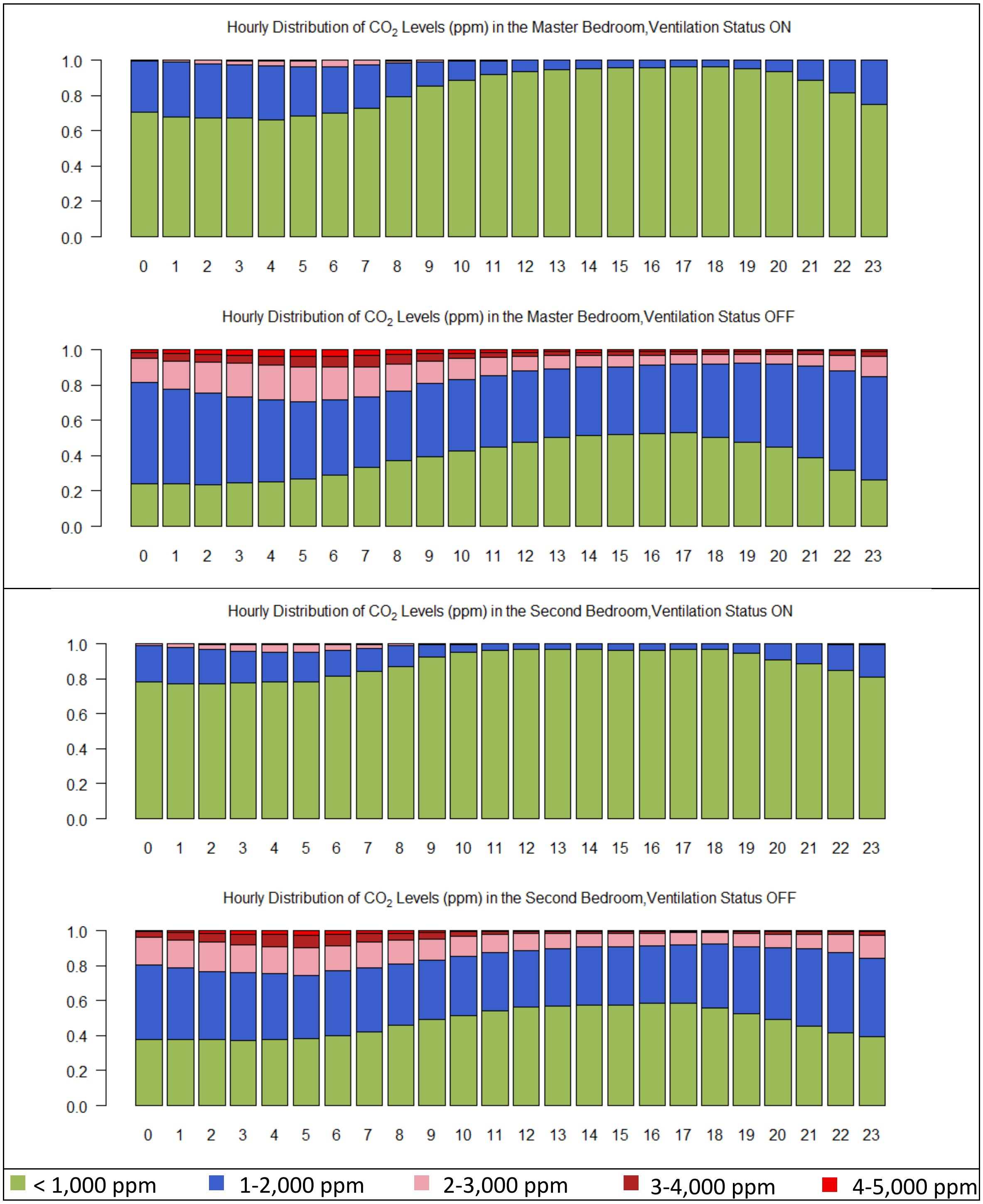
As in the short-term study, CO_2 was used as a trace gas. However, rather than introducing a known concentration of CO_2, household occupants generated the CO_2. For the purposes of this study, the researchers used increments of 1,000 ppm of CO_2 to report the level of CO_2 with a focus on levels above and below 1,000 ppm.

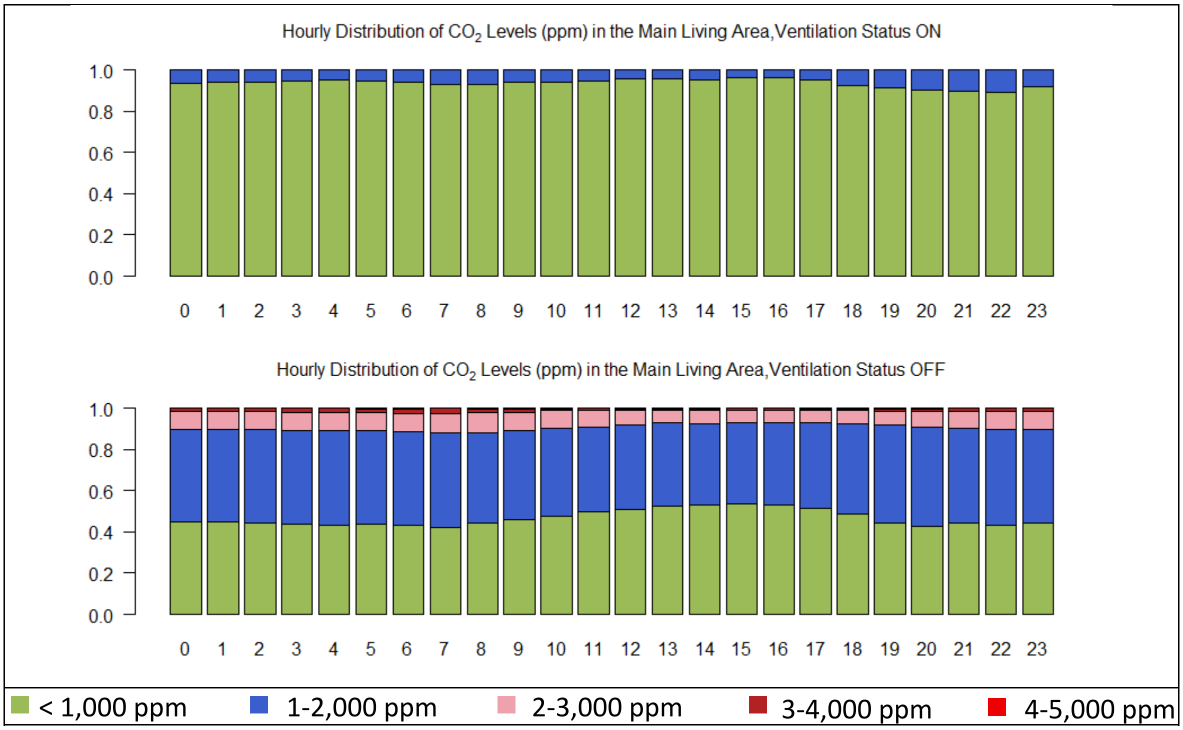
For the analysis to be relevant, it was important to analyze data collected when the houses were occupied and CO_2 was being generated. The stacked-bar plot in **Figure 3** shows that in the bedrooms, the highest CO_2 levels occurred early in the morning, declined during mid-day, and rose in the evening. There was not much variation in the overall CO_2 levels in the main living area throughout the day. Looking closely at the plot, levels were highest late in the evening, declined slightly at night, showed a modest bump in the morning, declined until mid-afternoon, and then started rising.

When the ventilation systems were on, the majority of CO_2 measurements for all hours were below 1,000 ppm. Even in the master bedroom in the early morning (the worst-case period), two-thirds of the readings were less than 1,000 ppm and very few readings were over 2,000 ppm. The main living area had very few readings above 1,000 ppm, even in the evening, when this area should have its highest occupancy.

The hourly plots confirm that most of the hours when CO_2 levels were greater than 1,000 ppm during the early-morning periods in the bedrooms. These locations and times are of most interest for this research into the comparison of different ventilation types and the factors impacting performance.

Figure 3. Hourly CO_2 level distribution with ventilation on or off





The results in **Figure 3** suggest the long-term study analysis should consider the early morning period in the bedrooms. The researchers initially focused on the master bedroom at night (between midnight and 6 a.m.) because that room was most likely to be occupied during that period. To help target the long-term study analysis in the other rooms and inform the analysis, the occupancy in the houses was examined.

Of the 29 houses in the study, 11 have 3 or more occupants, 16 have 2 occupants, and 2 have 1 occupant. The following categories classify occupancy:

- Retired at home (6): one or two adults that are likely to be home much of the day.
- Mixed adult (9): a two-adult household where one adult has a typical work schedule and the other adult is home some of the time.
- Work and/or school schedule (8): All household members are away during the day at school or work.
- Mixed family (6): Some family members are at home during the day and others are at work or school.

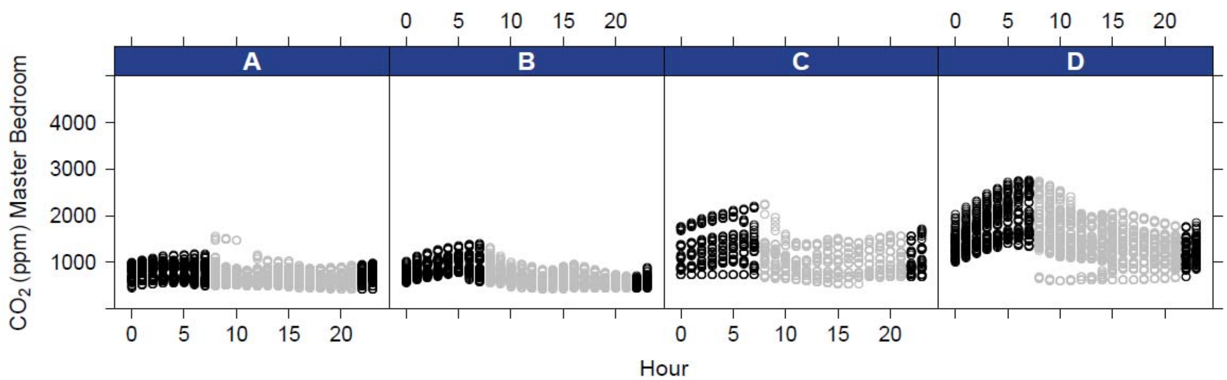
To determine the occupancy/use of the second bedroom, it was assumed that if a household had children, the second bedroom was used. Of the 29 houses in the study, 11 households were assumed to have an occupied second bedroom.[10] The results of the long-term study analysis of the data at night for all master bedrooms and the 11 occupied second bedrooms are presented in the remainder of this section.

[10] A twelfth household had an infant, but this child did not consistently occupy the second bedroom.

Master Bedroom Results

The analysis of long-term study data focused on the master bedroom between midnight and 6 a.m., when it was likely to be occupied and the need for ventilation was most significant. It is under these conditions when the differences between the ventilation systems are most apparent. This is illustrated in **Figure 4**, which shows all the measured CO_2 data for the master bedroom[11] for a house with EO ventilation (E01). The highest CO_2 levels tended to occur during the early morning hours. CO_2 levels tended to be lowest with the ventilation system on and doors open (test A), increased when the doors were closed (test B), increased more with the ventilation system off and doors open (test C), and were highest when the ventilation system was off and doors closed (test D).

Figure 4. CO_2 levels for E01 master bedroom by the hour of day and test condition



Not all of the test houses followed this expected pattern of CO_2 levels. Some had a relatively flat profile across all the test conditions. Some CO_2 levels did not increase smoothly from test A to D. Some had missing data or did not comply with certain test conditions. CO_2 levels tended to be lower in the main living space, which is expected because this space tends to be larger and with less concentrated occupancy. Second bedrooms sometimes had high CO_2 levels like the master bedroom, but because many houses have only two occupants, this space is not consistently used in all houses. **Appendix D**: Figures of Long-Term Study Hourly CO2 Values by House shows this data for all of the houses with ventilation on and off (regardless of door status).

What is the range of CO_2 levels in the master bedroom?

The research team considered the range of CO_2 levels at night in the master bedroom for different test conditions to provide a context for the analysis of the ventilation effectiveness of different types of systems. **Figure 5** shows a histogram of master bedroom CO_2 levels at night with the ventilation system on (tests A and B) or off (tests C and D) and bedroom doors open (tests A and C) and closed (tests B and D). The data in the figure has been normalized so houses with different amounts of data are treated equally.

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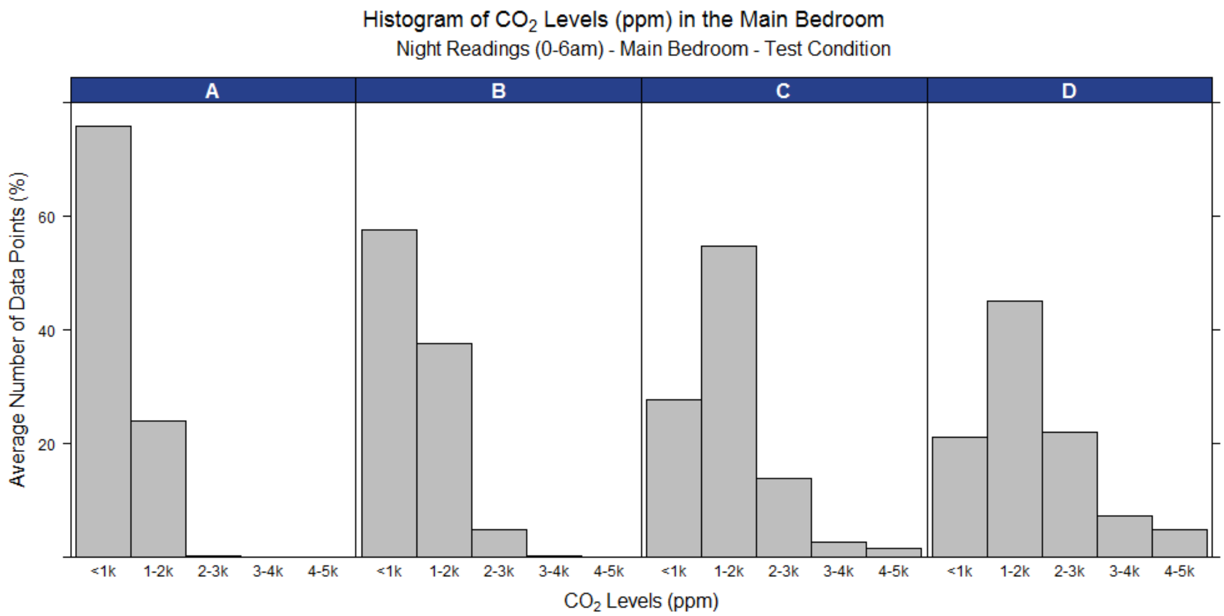
[11] The figure shows all data and does not exclude data that may not comply with the test conditions. Note that there can be apparent jumps in the data due to the start of a test period being different than the rest of the test period data.

The higher CO_2 levels shown in panels C and D of **Figure 5** were found in a number of houses.

- Test condition C (ventilation off, bedroom doors open): In five houses, more than half of the master bedroom night CO_2 levels were above 2,000 ppm. Many master bedrooms did not have any CO_2 levels above 2,000 ppm. Fewer than 30% of the measurements were below 1,000 ppm.
- Test condition D (ventilation off, bedroom doors closed): Most master bedrooms had CO_2 levels above 2,000 ppm. In eight houses, more than half of the CO_2 levels were above 2,000 ppm. About 21% of the measurements were below 1,000 ppm.

Figure 5. CO_2 levels in master bedroom with ventilation on (A, B) or off (C, D), doors open (A, C) or closed (B, D)



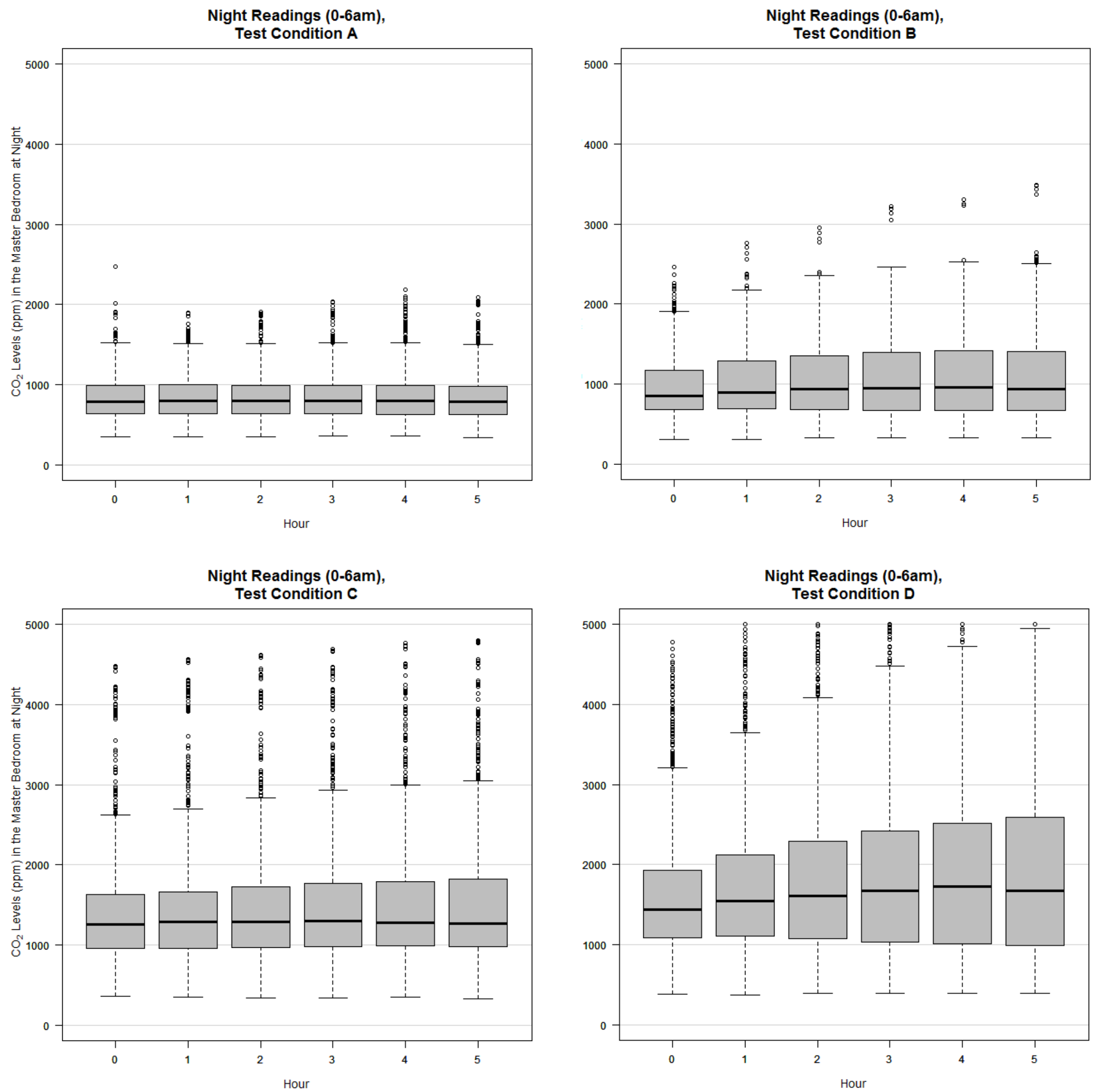
When the ventilation system was turned on (panels A and B of **Figure 5)**, the CO_2 levels shifted below 1,000 ppm a majority of the time.

- For test condition A (doors open, ventilation on), 76% of the measurements were below 1,000 ppm. Less than 2% of the measurements were over 2,000 ppm for test condition A.
- For test condition B (doors closed, ventilation on), 58% of the measurements were below 1,000 ppm. Less than 5% of the measurements were over 2,000 ppm for test condition B.

These results demonstrate that the ventilation systems effectively removed CO_2 much better than no ventilation, but a significant number of CO_2 readings were between 1,000 and 2,000 ppm even with the ventilation system on.

The impact of the ventilation systems on hourly CO_2 levels at night is shown in **Figure 6**. When the ventilation systems were on (tests A and B), the median CO_2 levels as well as the variation and extremes were lower than when the ventilation systems were off (tests C and D). However, in test condition B (doors closed), the 75th percentile values were above 1,000 ppm, particularly in the early morning hours. The data show that higher levels occurred in 10 houses, where more than half of the recorded CO_2 levels were over 1,000 ppm. See the next section for more discussion of individual houses and factors that influence ventilation effectiveness.

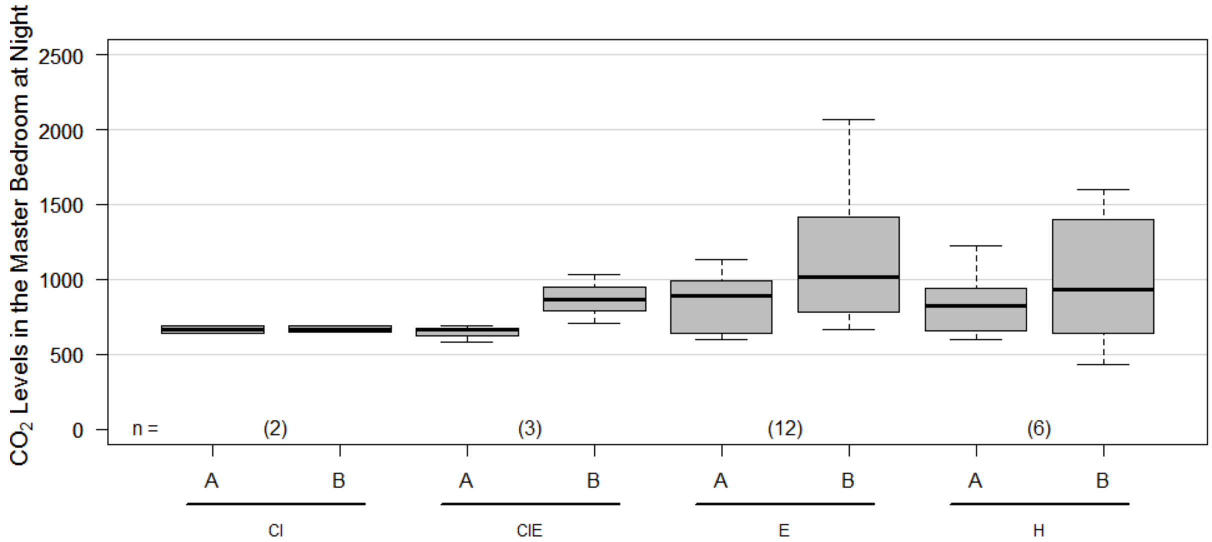
Figure 6. Hourly CO_2 levels in master bedroom by test condition



Do some types of ventilation systems perform better than others?

This question is considered in several ways, and the results from the master bedroom analysis in the long-term study are mixed. In **Figure 7,** the median nighttime CO_2 levels in the master bedroom are compared for the four primary ventilation systems when the systems are operating and with the doors closed or opened. To account for differences in the size of the data set for each house, the box plot is based on the median CO_2 level for each house.

Figure 7. Median CO_2 levels in master bedroom at night with doors open (A) or closed (B) with ventilation on for four ventilation system types



Ventilation systems shown are CFA integrated (CI), CFA integrated with ERV (CIE), Exhaust (E), and HRV (H).

The data analysis includes only houses that complied with both test conditions A and B so comparisons can be made among the same set of houses. The sample is very small for some types of ventilation systems. There are:

- Six HRV houses,
- Twelve exhaust houses (including exhaust only and exhaust with inlet vents),
- Two CFA integrated and three CFA integrated with ERV houses.

Additionally, four houses are included that had only two or three nights of data that complied with one of the test conditions. This small number of data points makes it more difficult to meaningfully compare these systems, but the data is presented for illustrative purposes.

Figure 7 shows the median CO_2 levels for the houses with different ventilation system types. The median is the value where half the data is higher or lower than this level.

- For test condition A (doors open), half the houses had median CO_2 levels well under 1,000 ppm for all ventilation system types. The 75^{th} percentile (top of the box) shows that for all system types, 75% of the houses had median CO_2 levels at or below 1,000 ppm. This means that there are some houses where half the CO_2 readings were over 1,000 ppm for this test condition. The plots show results similar to those of the short-term tests, but differences seen in this analysis may be less meaningful because of the smaller sample size resulting from compliance screening of the data.
- For test condition B (doors closed), the median CO_2 levels tended to shift up for most of the ventilation systems and the variation in values increased.

The ventilation systems in some houses performed better than others with the door closed.

- The HRV systems had a lower median and a lower maximum CO_2 concentration than the exhaust systems, but not as great as the difference shown in the short-term test analysis. Both exhaust and HRV systems showed increased variability when the bedroom doors were closed.
- The lowest CO_2 levels in the long-term study were found with the CFA integrated and ERV integrated with CFA systems. This is inconsistent with the short-term study results, where the CFA integrated systems tended to have lower ACH levels (which would imply higher CO_2 levels). This difference between the two studies apparently resulted from differences in the test approaches. In the long-term study, the CFA systems diluted CO_2 levels in rooms with high concentrations by mixing air from rooms with lower concentrations of CO_2. This did not occur in the short-term study because all the rooms were seeded with high levels of CO_2. The short-term study may underestimate the mixing benefit from CFA systems.

These results suggest the need to look more closely at individual houses where higher CO_2 levels indicate the ventilation system is working less effectively.[12]

Figure 8 shows the distribution of CO_2 levels for each house for each test condition, and identifies which test sites had adequate ventilation for the different test conditions. The stacked bars for each house reflect the percent of measured CO_2 levels that fall into certain bins. Green reflects CO_2 levels below 1,000 ppm. Houses that show up as mostly green for a certain test condition seem to have adequate ventilation. Red shades indicate higher levels of CO_2 and suggest that ventilation is not adequate.

Several general observations can be made from the results shown in **Figure 8**:

- Data from 28 houses are included in the figure out of the 29 houses that were tested. Data from one house was excluded because it did not comply with any of the test conditions (W12). Missing bars in the figure indicate where a house had no data that complied with the test condition displayed.
- CO_2 levels were lowest for test A (ventilation on, bedroom doors open) and highest for test D (ventilation off, doors closed).
- Many of the houses seemed to have adequate ventilation for test A (green), but some houses had CO_2 levels between 1,000 and 2,000 ppm most of the time (blue). All of these houses are among the Western Washington participants (denoted by a W in the identifier). The houses in Eastern Washington (denoted by an E in the identifier) seemed to have better overall ventilation.
- When the doors were closed in test B, fewer houses had ventilation in the mostly green range.
- The houses that had the highest CO_2 levels when the ventilation system was off (tests C and D) also tended to have the highest CO_2 levels when the ventilation system was on.
- A few houses had relatively low CO_2 levels across all the tests.

[12] **Appendix C**: Figures of Long-Term Study CO2 Values by Ventilation System Type provides additional figures illustrating CO_2 values by ventilation system type for individual houses under specific test conditions.

Figure 8. CO_2 level distribution in individual houses by test condition and ventilation system type

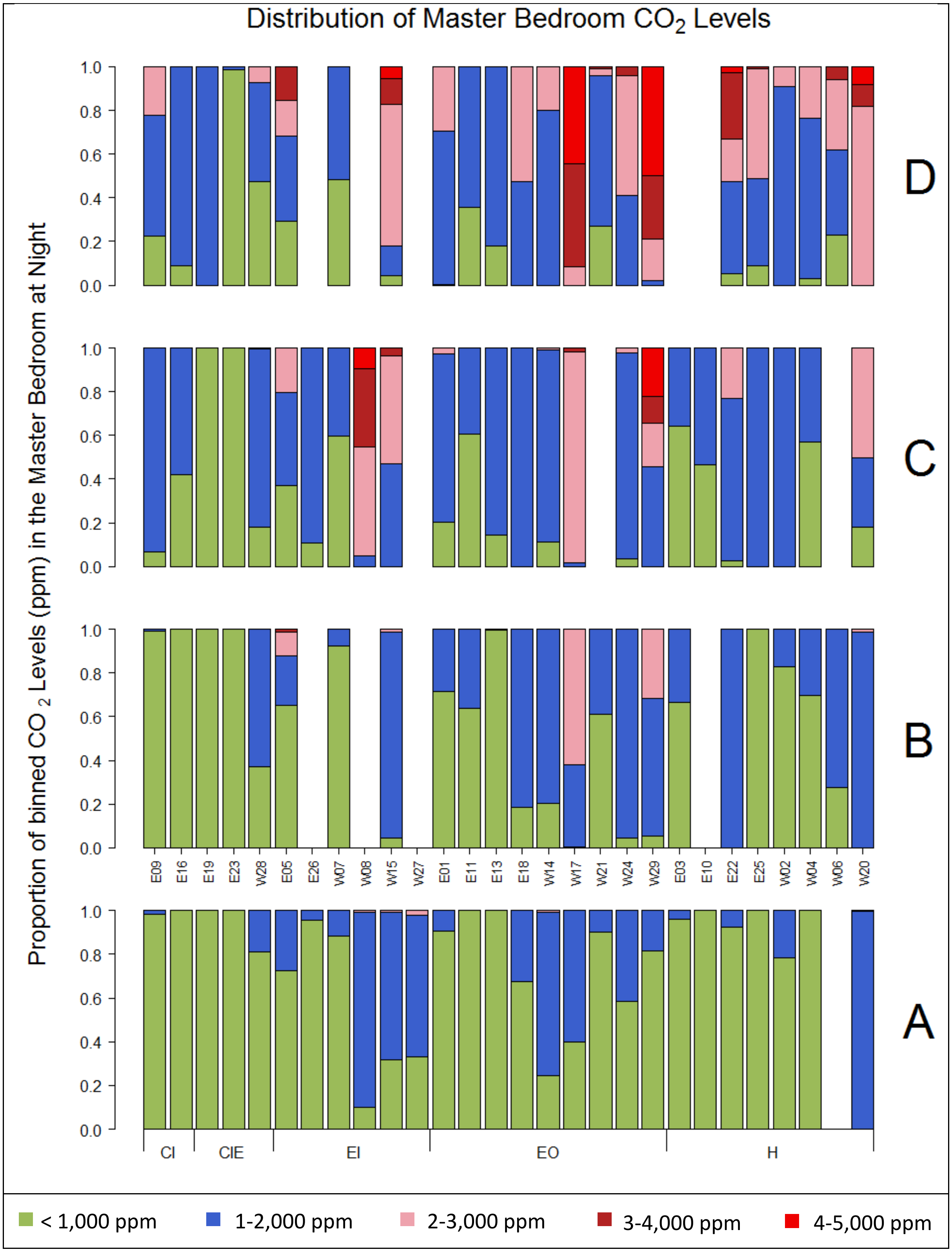


Figure is organized by the following ventilation system types: CFA integrated (CI), CFA integrated with ERV (CIE), Exhaust with inlet vents (EI), Exhaust only (EO), and HRV (H).

Second Bedroom Results

The analysis used for the master bedroom was repeated just for the second bedrooms that were occupied. All of the houses with children had occupied second bedrooms (with one exception where the child was an infant who did not sleep in the second bedroom). Eleven houses had occupied second bedrooms: E05, E11, W02, W06, W08, W12, W14, W15, W20, W27 and 28. Four of these houses had HRV ventilation, one had CFA integrated-ERV, and the other six had exhaust systems.

Like the master bedroom analysis, the analysis of long-term study data for the second bedroom focused on the midnight to 6 a.m. period, when the room was likely to be occupied and the need for ventilation was most significant. The analysis showed CO_2 levels (a proxy for occupancy) were highest during this period. The same compliance tests for the different test conditions used for the master bedroom analysis were also used for the second bedroom analysis. In some cases, houses did not comply with certain test conditions, which limited the number of houses included in different parts of this analysis. Because the sample of houses is much smaller, it is difficult to draw strong conclusions about the performance of the different types of ventilation systems. The research team considered the ventilation performance in the houses and made comparisons with the master bedroom results.

What is the range of CO_2 levels in the second bedroom?

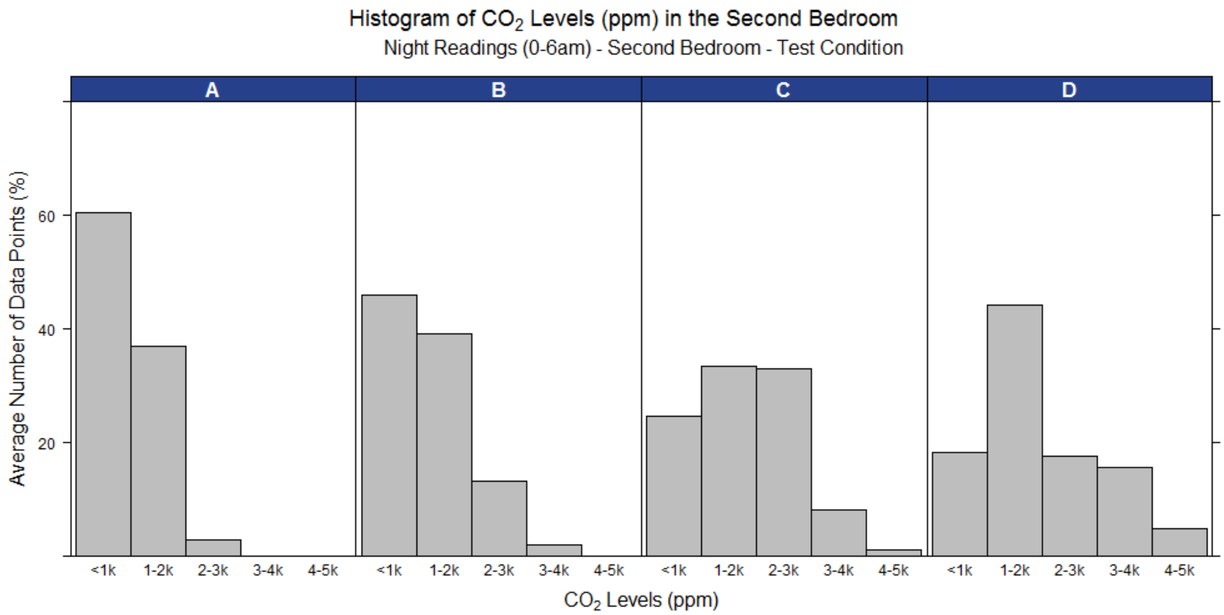
The research team considered the CO_2 levels in the second bedrooms during the nighttime period when the rooms were very likely to be occupied. **Figure 9** shows a histogram of second bedroom CO_2 levels at night with the ventilation system on (tests A and B) or off (tests C and D) and bedroom doors open (tests A and C) and closed (tests B and D). The data in the figure has been normalized so houses with different amounts of data are treated equally.

CO_2 levels tended to be higher when the door was closed (test D) and the ventilation system off. About 20% to 25% of the “no ventilation” levels were below 1,000 ppm when the doors were open or closed. Approximately half of the levels exceeded 2,000 ppm, which is higher than for the master bedroom.

The higher CO_2 levels, shown in **Figure 9**, tend to be concentrated in some houses.

- Test condition C: For the eight houses that complied with test condition C, three houses had CO_2 levels above 2,000 ppm in more than half of the readings. Three houses did not have any CO_2 levels above 2,000 ppm.
- Test condition D: For the nine houses that complied with test condition D, five had CO_2 levels that were mostly above 2,000 ppm. Two houses had some CO_2 levels over 4,000 ppm.

Figure 9. CO_2 levels in second bedroom with ventilation on (A, B) or off (C, D), doors open (A, C) or closed (B, D)



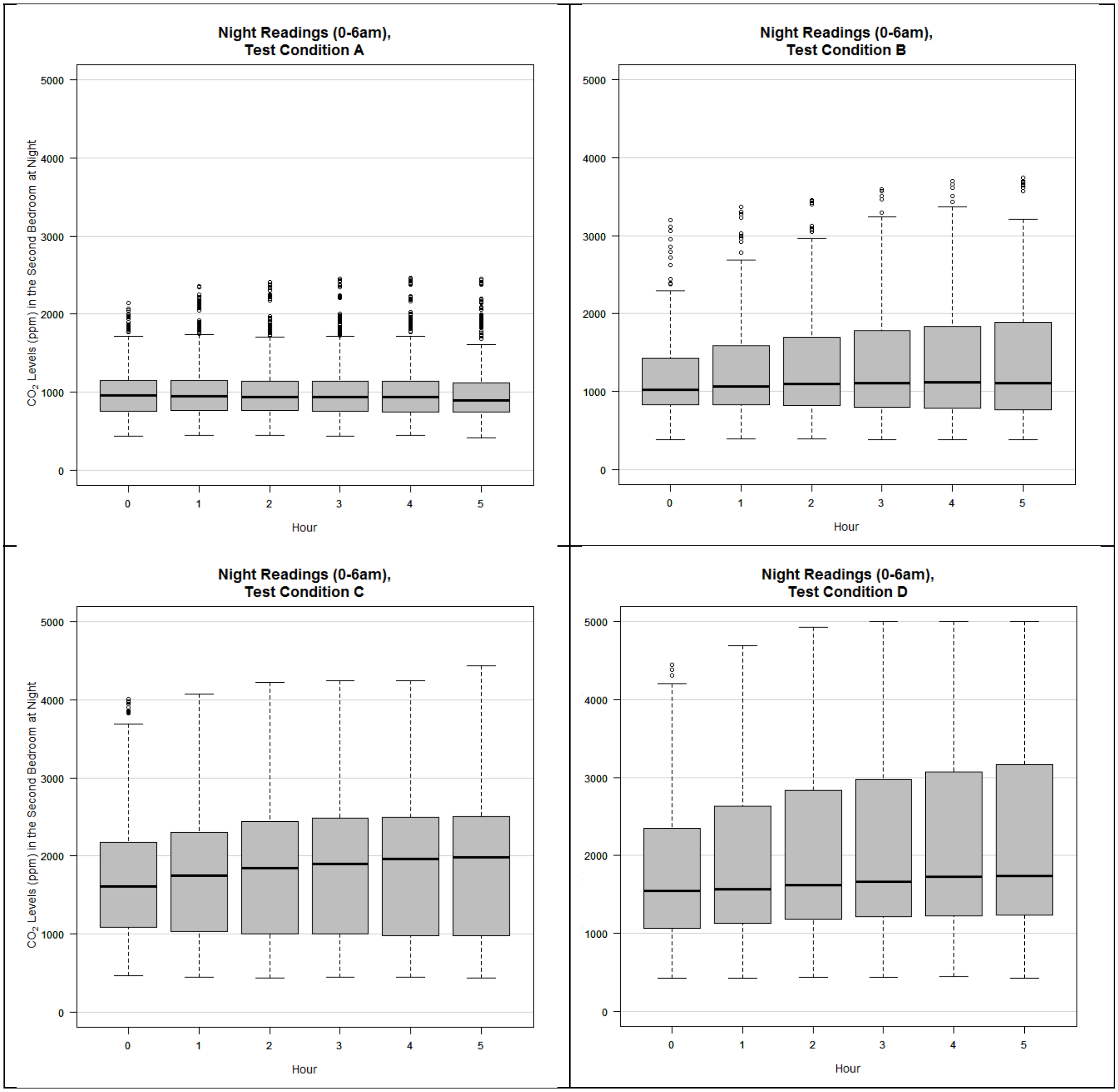
CO_2 levels declined significantly when the ventilation system was turned on:

- For test condition A (doors open, ventilation on), 60% of the measurements were below 1,000 ppm. Six houses had levels above 1,000 ppm some of the time and only one house had levels over 2,000 ppm.
- For test condition B (doors closed, ventilation on), 46% of the measurements were below 1,000 ppm. Eight of the nine houses that complied with this test condition had CO_2 levels over 1,000 ppm part of the time, and three had levels over 2,000 ppm.

These results demonstrate that the ventilation systems provided much better air quality in the second bedroom at night than no ventilation. However, a significant number of CO_2 readings were between 1,000 and 2,000 ppm even with the ventilation system on, particularly when the door was closed. Compared to the master bedroom, CO_2 levels in occupied second bedrooms were over 1,000 ppm more of the time during the nighttime period.

The impact of the ventilation systems on hourly CO_2 levels is shown in **Figure 10**. When the ventilation systems were on (tests A and B), the median CO_2 levels, and the variation and extremes, were lower than when the ventilation systems were off (tests C and D). When the doors were open (test A), the ventilation systems maintained consistent CO_2 levels throughout the night that were below 1,000 ppm most of the time. However, in test condition B (doors closed), the median values were above 1,000 ppm and the CO_2 levels tended to rise during the night.

Figure 10. Hourly CO_2 levels in second bedroom by test condition



Do some ventilation systems perform better than others?

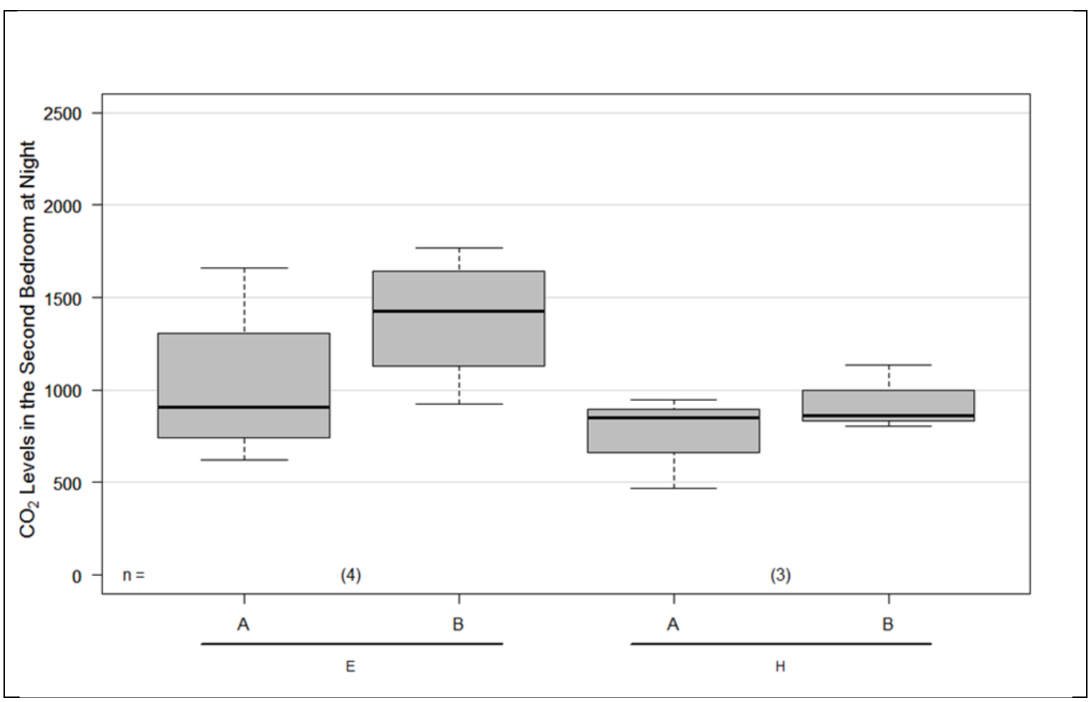
Like the master bedroom analysis, the research team considered several ways to address this question for the second bedroom. **Figure 11** shows the median nighttime CO_2 levels in the second bedroom for the three different ventilation systems when the systems were operating and with the doors open and closed. To account for differences in the size of the data set for each house, the box plot is based on the median CO_2 level for each house.

The data analysis includes only houses that complied with both test conditions A and B so comparisons can be made between the same set of houses. Of the eleven houses with occupied second bedrooms, three houses (two exhaust and one HRV) never complied with at least one of the test conditions. The single CFA integrated with ERV house with an occupied second bedroom was not included in this comparison because its ventilation on and doors open data was limited to a single night's sample, which could not be considered representative of the house, the test condition, nor the ventilation system. The remaining sample is very small for each of the ventilation systems.

Additionally, two houses are included that had only two nights of data that complied with one of the test conditions. The small sample and limited data for some houses made it difficult to meaningfully compare the exhaust and HRV systems, but the data is presented for illustrative purposes. The research team made the following observations:

- The exhaust houses had higher CO_2 levels when the bedroom doors were closed (test B) than when they were open (test B). The difference between test condition A and B was less significant for the HRV houses.
- Generally, the three HRV system houses had lower CO_2 levels than the exhaust systems for both test A and test B, but the difference was more significant when the doors were closed (test B). These results are consistent with the short-term test results.
- The difference between the HRV and exhaust systems was more significant in the long-term test for the second bedroom than it was for the master bedroom analysis, where the difference was less pronounced. This is also consistent with the short-term test results, which showed a much bigger difference for the second bedroom analysis than the master bedroom analysis.

Figure 11. Median CO_2 levels in second bedroom at night with doors open (A) or closed (B) with ventilation on for two ventilation system types



Ventilation systems shown are Exhaust (E) and heat recovery ventilation (H).

Figure 12 shows the distribution of CO_2 levels for each house for each test condition, and identifies which test sites had adequate ventilation for the different test conditions. The stacked bars for each house reflect the percent of measured CO_2 that falls into certain bins. As with the master bedroom analysis, green reflects CO_2 levels in the second bedroom below 1,000 ppm. Houses that show up as mostly green for a certain test condition seem to have adequate ventilation. Red shades indicate higher levels of CO_2 and suggest that ventilation is not adequate in the second bedroom.

Several general observations can be made from the results shown:

- Data from 11 houses with occupied second bedrooms are included. Missing bars in the figure indicate where a house had no data that complied with the test condition.
- CO_2 levels are lowest for test A (ventilation on, doors open) and highest for test D (ventilation off, doors closed).
- Many of the houses seem to have adequate ventilation for tests A and B (green), but one house for test A and five houses for test B had CO_2 levels that exceed 1,000 ppm more than half the time. All but one of these five houses with levels above 1,000 ppm had exhaust systems.
- For the master bedroom analysis, houses with the highest CO_2 levels when the ventilation system was off (tests C and D) also tended to have the highest CO_2 levels when the ventilation system was on. This is less clear for the second bedroom. Two houses with HRV systems that had high CO_2 levels with ventilation off had fairly low levels with ventilation on (W02 and W20). Two EO systems (E11 and W14) showed little change when the ventilation system was on.
- Compared to the master bedroom analysis, the sample is much smaller so overall trends are less clear.

Key conclusions from this analysis of the long-term study period data include:

- Natural ventilation was inadequate.
- The ventilation systems significantly reduced CO_2 levels in the bedrooms at night compared to no ventilation.
- There was a great deal of variation in ventilation performance among the houses, both within and across ventilation systems.
- The advantage of HRV systems compared to exhaust systems, particularly for the closed door case, was less significant for the long-term test than the short-term test. In the long-term test the difference was more pronounced for the second bedroom than the master bedroom.
- The CFA integrated and CFA integrated with ERV systems showed the best performance for the long-term test for the master bedroom. This is inconsistent with the short-term test results. The small sample for these systems and differences in the test approaches contribute to this inconsistency.

Figure 12. CO_2 level distribution in individual houses by test condition and ventilation system type

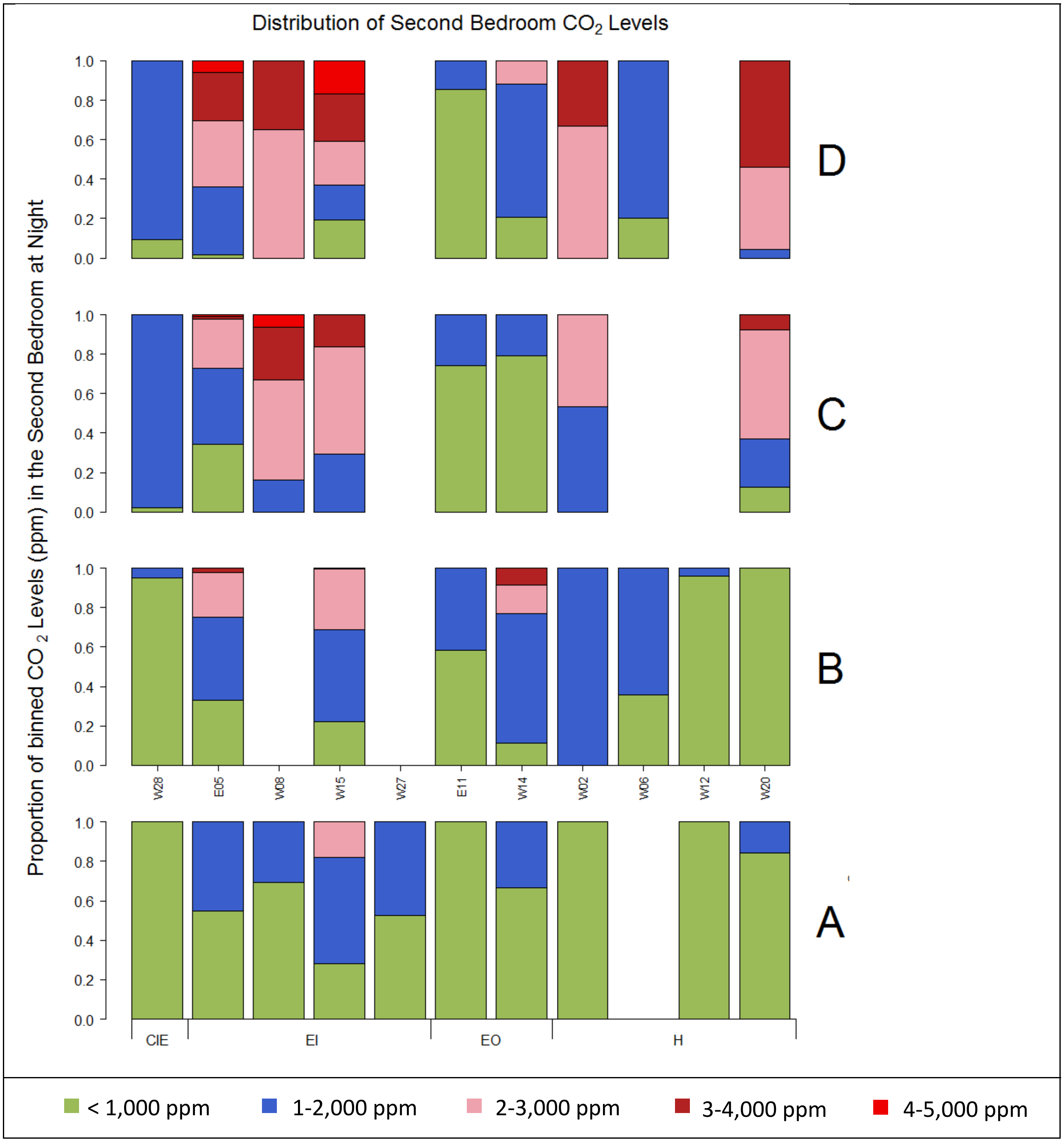


Figure is organized by the following ventilation system types: CFA integrated with ERV (CIE), Exhaust with inlet vents (EI), Exhaust only (EO), and HRV (H).

Normal Period Study

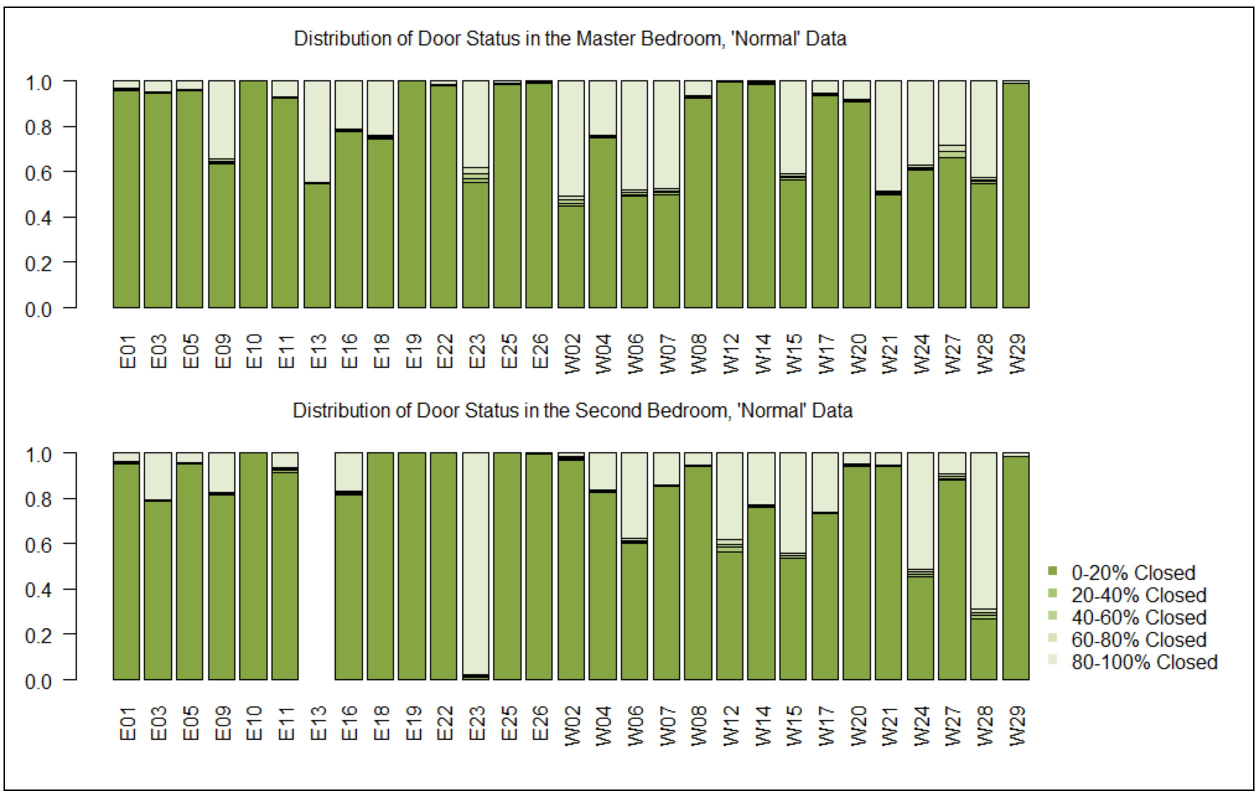
Data were collected before and after the long-term study period. During this "normal period," home occupants were free to operate ventilation systems and open or close doors as they liked. A significant amount of data was collected; in fact, 18 of the 29 houses produced more data for the normal period than for the test week period. The research team used this data to:

- Analyze door closure and ventilation system operation behavior to compare to reported and observed field data collection, and
- Analyze CO_2 data for the master bedroom and second bedroom at night to consider ventilation effectiveness and if results reinforce or differ from the long-term study period (test week analysis).

Door Closure and Ventilation Operation Behavior

The results for door closure status conditions in the master and second bedrooms are shown in **Figure 13**. The data was sorted into bins depending on the percentage of time the door was closed during a 15-minute interval. Most of the data falls into the "doors open" bin (dark green, 0-20% closure) or "doors closed" bin if the doors were closed most of the time (light green, 80-100% closure). The doors were open most of the time. For more than half (15) of the houses, the master bedroom doors were open more than 90% of the time.[13] Likewise half of the 28 reported second bedroom doors, whether occupied or not, were open 90% of the time.

Figure 13. Bedroom door closure status – normal period



[13] Door closure data was available for the master bedroom in 28 houses. One house, E10, did not have a master bedroom door and is shown as "open" in **Figure 13**.

Figure 14 presents the hourly distribution of door closures (normalized to account for differences in the amount of data between houses). During the day, occupants in a small portion of houses (~10%) closed their bedroom doors. The proportion of door closure increased in the evening. Information reported from the field visits indicated that occupants in half the houses closed their bedroom doors at night, but results from normal period monitoring suggest that a smaller share of occupants closed their doors at night. Although bedroom doors were more likely to be closed at night than during the day, measured normal period data indicates this occurred about a third of the time. The long-term study analysis shows that CO_2 levels were highest at night in the bedrooms with the doors closed. Normal period results indicate that households typically had the highest rates of door closure during the nighttime analysis period (outlined in red in **Figure 14**).

Figure 14. Hourly distribution of bedroom door closure status – normal period

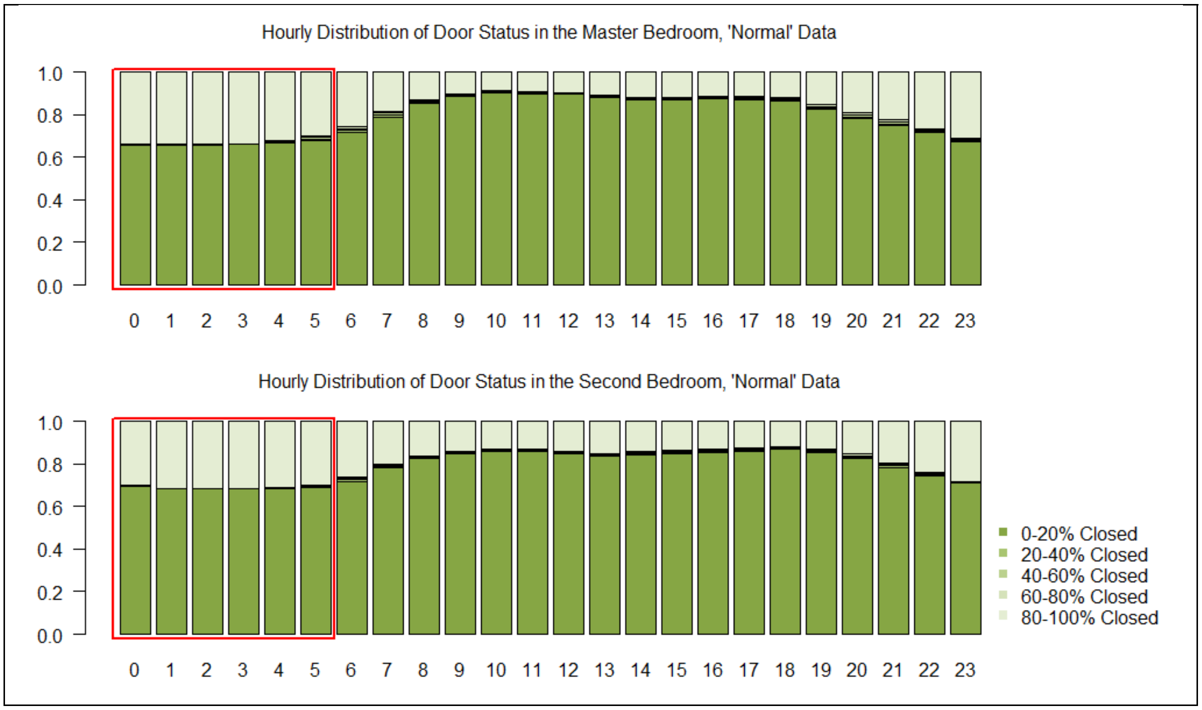
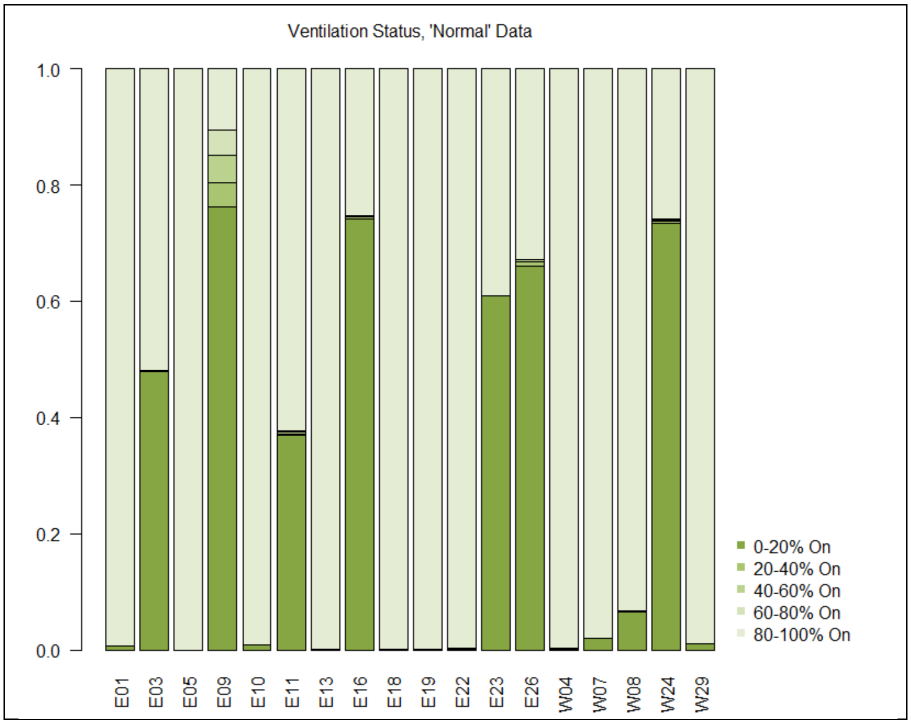


Figure 15 shows the ventilation system operation status for the 18 houses with measured ventilation system operation data.[14] These data were sorted into bins based on the percentage of time the ventilation system was on during a 15-minute period. Dark green in the figure indicates when the ventilation system was mostly off (0-20% on) and light green indicates when the system was mostly on (80-100% on). The ventilation system was on most of the time for 11 of the houses, but in seven houses the ventilation system was off more than a third of the time—in some cases significantly more than a third. Three of these houses had CFA integrated systems, three had exhaust only systems, and one had

[14] There were some problems with the ventilation system operation measurements (see **Appendix E**: Data Quality Issues and Data Compliance Approach) and the data was faulty for some houses, particularly the west-side houses. During the test week periods, the research team relied on journal data to determine ventilation system operation status, but in the normal period, the researchers could only rely on the measured operation status data.

an HRV. In four of these houses, the "as-found"[15] set up for the systems was less than continuous. In the other three houses, as-found operation was continuous according to the field notes.

Figure 15. Ventilation system operation status – normal period



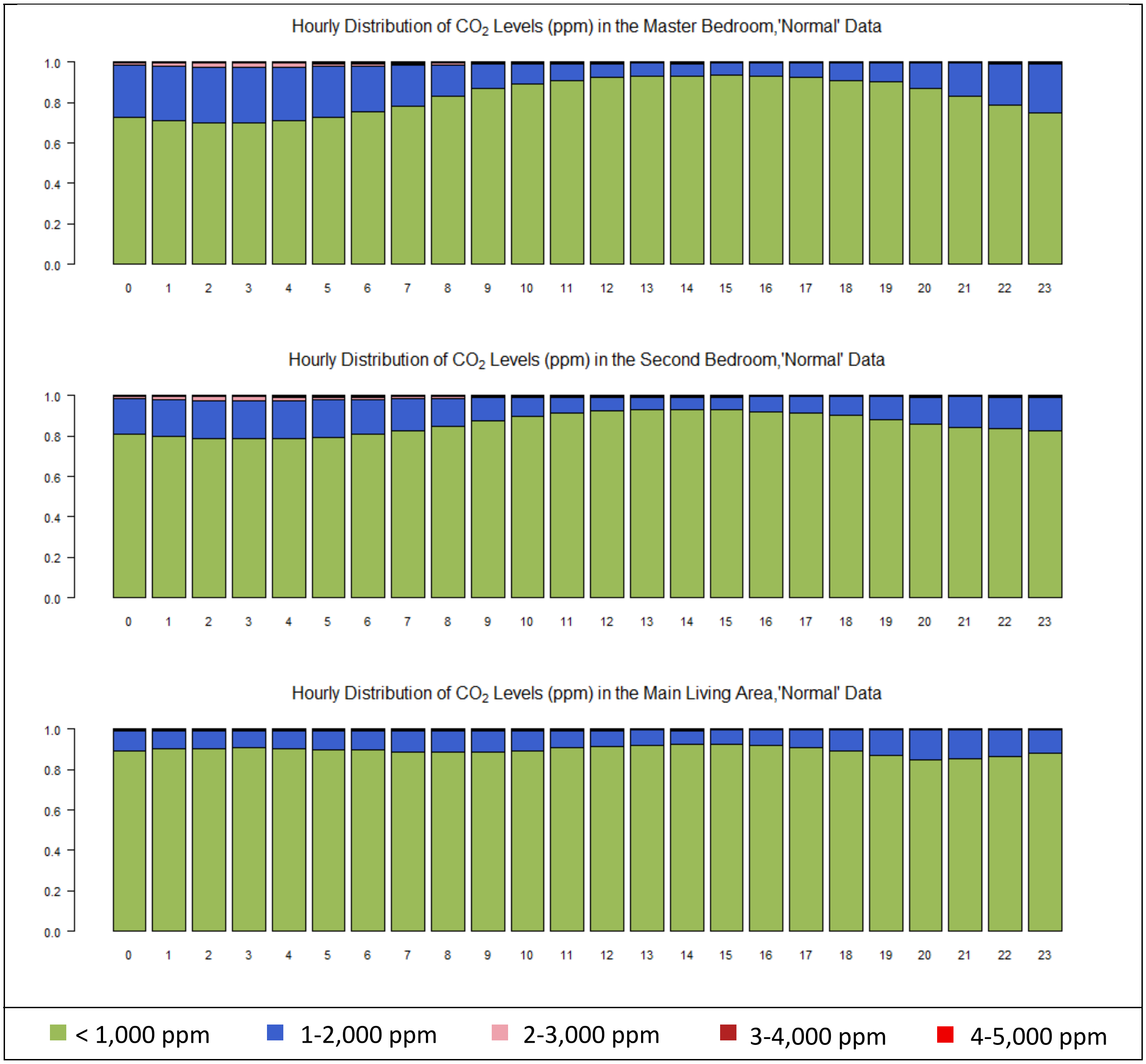
For the seven ventilation systems that were off more than a third of the time, the team analyzed the average hourly distribution of ventilation system operation data. For each house, the amount of time the ventilation system was on or off during each hour was similar to the percentage of time shown in **Figure 15** (in a few cases, there was a little more daytime operation). This led the researchers to assume that the ventilation systems operated for a certain amount of time each hour (semi-continuous operation). However, looking more closely at the time series ventilation data suggests that, for many of these houses, the ventilation systems were turned on and off for large blocks of time. On average, the data suggests semi-continuous operation, but in actuality the systems tended to be on or off.

Normal Period CO_2 Levels

The hourly distribution of CO_2 levels for each room and for all of the houses during the normal period is shown in **Figure 16**. At night, CO_2 levels were highest in the master bedroom and second bedroom. These results – similar to observations made during the test week period analysis – confirmed the need to focus analysis on the bedrooms between midnight and 6 a.m., when the rooms were most likely to be occupied and the need for ventilation was greatest.

[15] The operation status found and noted during the first field visit to the house to install the monitoring equipment and set up the ventilation system for testing.

Figure 16. Hourly Distribution of CO_2 levels for the normal period



The analysis of the bedroom CO_2 data for the normal period builds on the approach used for the long-term study test week data analysis, except in this case the researchers did not determine compliance with specified test conditions (ventilation system on or off and bedroom doors open or closed). Instead, the researchers used measured ventilation system operation and door open/closed data to classify the status for each nighttime period.

Door status for each nighttime period for each house was determined as follows:

- Open: measured data shows the doors open more than 80% of the time
- Closed: measured data shows the doors closed more than 80% of the time
- Mixed: measured data shows the doors are neither open nor closed more than 80% of the time
- Unknown: there is no measured data or it is faulty

Likewise, for ventilation status:

- On: measured data shows the ventilation system on more than 80% of the time
- Off: measured data shows the ventilation system off more than 80% of the time
- Mixed: measured data shows the ventilation system is neither on nor off more than 80% of the time
- Unknown: there is no measured data or it is faulty

The combination of the four door conditions and four ventilation status conditions results in 16 possible door/ventilation system status conditions.

Master Bedroom Results

Status results for the master bedroom are shown in **Figure 17** for the six most common conditions (the other ten conditions are combined as "other" in the figure). The normal period status matched the test conditions for the test weeks (A, B, C, and D) for slightly more than half the cases (normalized to account for differences in the amount of data between houses). Door open and ventilation system on (test A) is most common. This is the situation where CO_2 levels were lowest in the long-term study tests. CO_2 levels were higher in the long-term study tests when the doors were closed or the ventilation system was off, but these status conditions occurred less often in the normal period and tended to be localized in a few houses. Besides the four test conditions, the other two common status conditions shown in **Figure 17** are when the ventilation system status is unknown and the doors are open or closed. This occurs for a significant number of cases as noted earlier (see **footnote 8**).

The distribution of CO_2 levels for the master bedroom at night for each house in the normal period is shown in **Figure 18**. This repeats the analysis of the master bedroom at night, but in this case the door and ventilation system operation status reflects the occupants' preferences (as shown by the label in the figure) rather than a specified test status. For more than 80% of the time, 16 of the 29 houses had CO_2 levels below 1,000 ppm. For at least 50% of the time, nine of the houses had CO_2 levels over 1,000 ppm (one of these, W27, had data for only two nights). For more than 10% of the time, two houses, W15 and W24, had CO_2 levels over 2,000 ppm. Generally, these results indicate that the majority of the houses had adequate ventilation under normal operation conditions.

Figure 17. Master bedroom nighttime door and ventilation system status – normal period

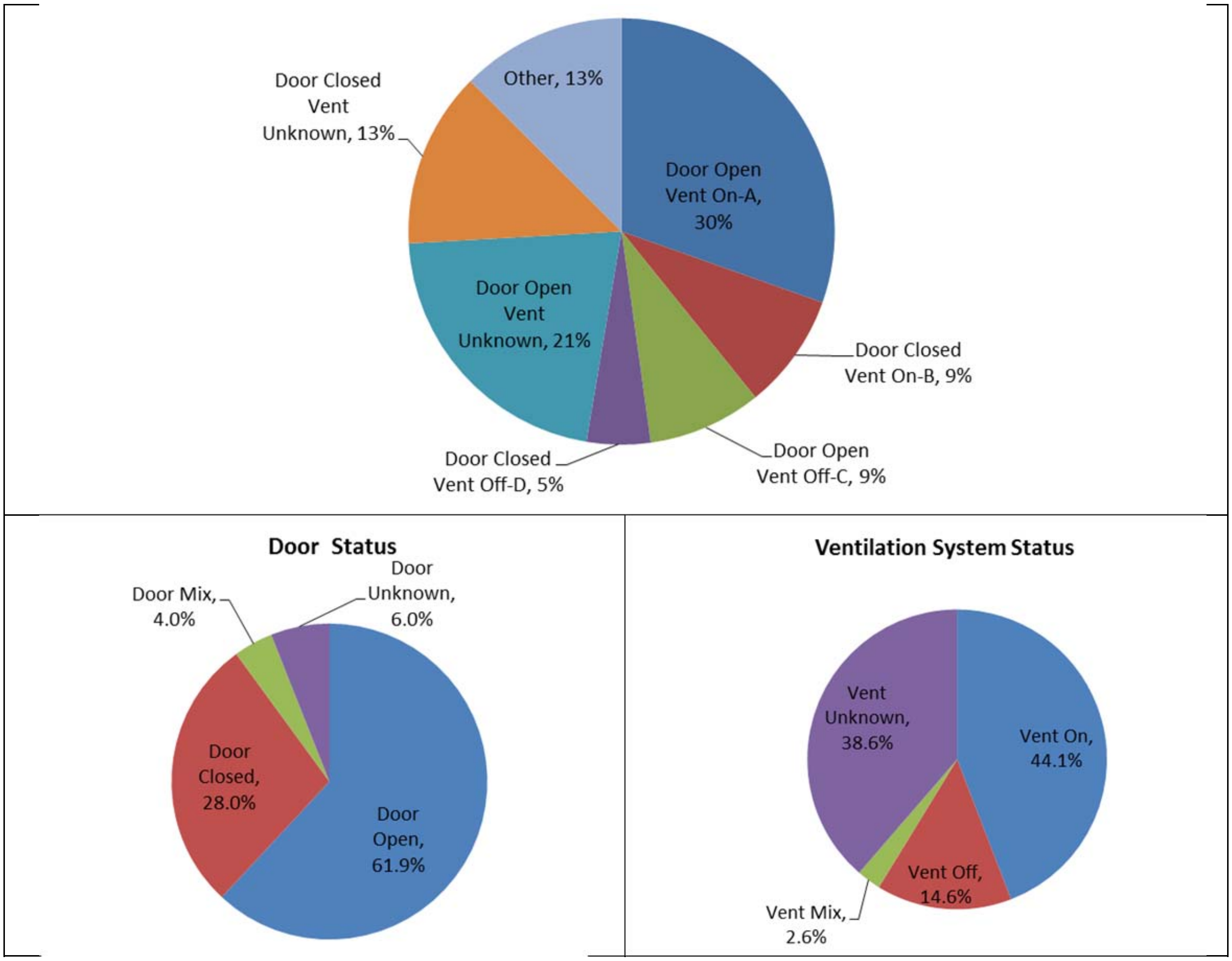
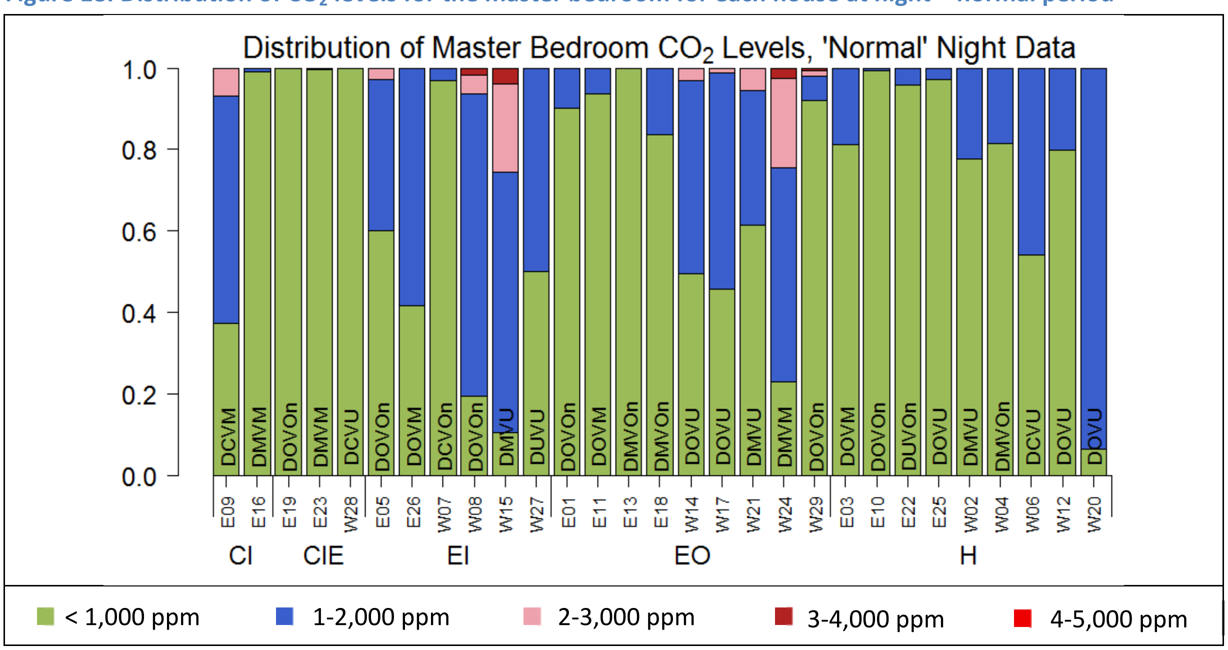


Figure 18. Distribution of CO_2 levels for the master bedroom for each house at night – normal period



The findings for each ventilation system type shown in **Figure 18** include:

- **CFA Integrated (including with ERV; CI and CIE)**: These CFA systems tended to have the lowest measured CO_2 levels, even though the ventilation system was off most of the time for three of the cases (the exception is E09). Examining the results for E09 more closely, the researchers found that when the ventilation system was on at night (it operated in a ventilation mixed mode), CO_2 levels were below 1,000 ppm almost 100% of the time, and the highest level was 1,088 ppm. Thus, the ventilation system was effective in this house when it operated. For the other two houses where the ventilation system was off a significant amount of time, the CFA furnace may have operated enough of the time to provide adequate air mixing to maintain low CO_2 levels.
- **Exhaust with Inlet Vents (EI)**: Four of the six houses with these systems had average CO_2 levels above 1,000 ppm. This is more than the other three ventilation system types, which had one house each with CO_2 levels over 1,000 ppm.
- **Exhaust Only (EO)**: Five exhaust only houses (out of nine) had relatively low CO_2 levels and share several characteristics. Generally, the doors are open and ventilation systems are on in these houses. The house in this ventilation category with the highest CO_2 levels (W24) had the ventilation system off 74% of the time and the doors closed 38% of the time. The other three houses with higher CO_2 levels included one case where the doors were closed most of the time and in all three houses the operation status of the ventilation system was unknown.
- **HRV (H)**: Generally, the nine HRV system houses had relatively low and consistent CO_2 levels. Of those cases with measured data, all but three kept their doors open and operated their ventilation system most of the time.

The results for the normal period appear to be comparable to the results presented for the long-term study. To confirm this,

Table 6 presents the average CO_2 levels for each house during the two test periods under the primary door and ventilation status conditions (tests A, B, C, and D). The values for the two periods are generally close (when there is valid data for both).

The highlighted cells in the table indicate where the normal and test week period average CO_2 level is greater than 200 ppm. The difference is greater than 200 ppm in 10 of the 44 cases with comparable data:

- In four of these cases (as noted in the last column), this result may be attributable to the low amount of data (data was available for three or fewer nights for either the normal or test period).
- For four other cases, the houses had CFA heating systems. Differences in the operation of the CFA system between periods could influence the results, particularly for cases when the ventilation system was off.
- For the remaining two cases, the CO_2 level was very low (E13), suggesting that the occupants were not at home or the data was faulty (this house has one retired occupant), or the difference was less than 15% because the CO_2 level was very high (W08).

Table 6. Average CO_2 level by ventilation and door status for the normal and test periods – master bedroom

	A-Vent On Door Open		B-Vent On Door Closed		C-Vent Off Door Open		D-Vent Off Door Closed		Vent Unknown Normal Period		Explanation
House	Normal	Test	Normal	Test	Normal	Test	Normal	Test	Door Open	Door Closed	
E01	718	814	873	881	1,452	1,352	-	1,755	-	-	
E03	837	729	1,189	702	721	875	-	-	-	-	Low Data
E05	920	836	2,431	1,037	-	1,329	-	1,737	-	-	Low Data
E09	-	677	-	707	873	1,243	1,458	1,533	-	-	CFA
E10	694	693	-	-	1,056	1,091	-	-	-	-	
E11	619	620	909	836	1,011	974	-	1,127	-	-	
E13	523	591	463	796	-	1,117	-	1,298	-	-	Very low reading
E16	545	607	528	652	635	1,037	685	1,306	-	-	CFA
E18	841	945	892	1,312	-	1,416	-	1,940	621	612	CFA
E19	642	666	-	885	-	743	-	1,332	-	-	
E22	781	859	-	1,385	-	1,697	-	2,216	-	-	
E23	688	683	698	692	761	769	708	797	-	-	
E25	-	527	-	633	-	1,429	-	1,984	586	-	
E26	652	714	-	-	1,259	1,218	-	-	-	-	
W02	-	931	-	957	-	1,506	-	1,768	946	979	
W04	745	643	928	899	-	985	-	1,694	-	-	
W06	-	-	-	1,176	-	-	-	1,764	625	933	
W07	636	753	654	736	-	984	1,031	1,021	-	-	
W08	1,137	1,233	-	-	2,525	2,968	-	-	-	-	15% difference
W12	-	-	-	-	-	-	-	-	785	-	
W14	-	1,136	-	1,131	-	1,415	-	1,543	907	1,208	
W15	-	1,181	-	1,365	-	2,035	-	2,535	1,499	1,854	
W17	-	1,039	-	2,042	-	2,435	-	3,854	1,003	788	
W20	-	1,250	-	1,589	-	1,801	-	2,801	1,225	1,386	
W21	-	716	-	960	-	-	-	1,331	410	1,215	Very low reading
W24	979	973	910	1,338	1,476	1,528	2,129	2,141	-	-	Low Data
W27	-	1,229	-	-	-	-	-	-	1,365	-	
W28	-		-		-		-		-	637	
W29	729	902	-	1,751	-	2,623	2,408	3,878	-	-	Low Data

Cells are highlighted to indicate where the difference between the normal and test period value is greater than 200 ppm or where values are lower than expected.

The other two highlighted cells are for W17 and W21 during the normal period when the ventilation status was unknown. In both of these cases, the measured CO_2 levels were lower than expected and the amount of data was limited (five and four nights, respectively). For W21, the unusually low readings suggest either faulty data or no occupancy.

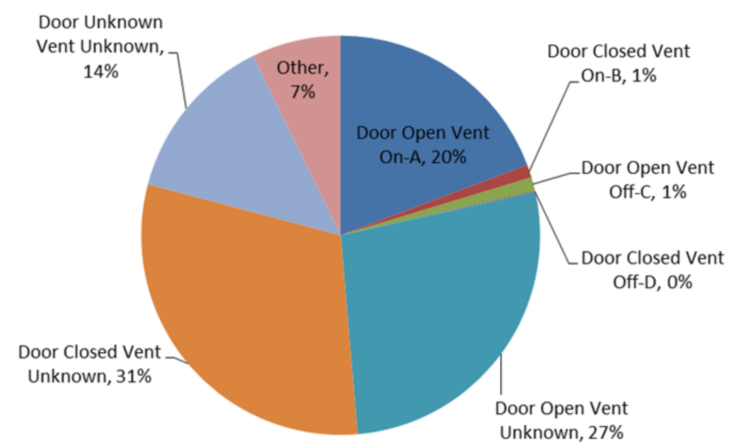
For test A (ventilation on, doors open), 17 of the 29 houses have data for both the normal period and the test week period. The results were similar for all of the houses for both periods. The largest difference between the periods is 173 ppm for W29[16] and less than 100 ppm for most houses (less than 12% in all but four cases).

Assuming that the ventilation system was on for the cases in the normal period when the ventilation status was unknown, the average CO_2 level for the door open condition was comparable to the test A values for those houses. Applying this assumption also allowed the researchers to compare the houses with the highest average CO_2 levels for the normal and test week periods. The ten houses with the highest CO_2 levels are the same, with two exceptions: E05 has the eighth highest CO_2 levels in the normal period and W29[16] has the tenth highest CO_2 levels for the test week period.

Second Bedroom Results

The researchers repeated the normal period analysis for the 11 houses with second bedrooms that were occupied at night. Status condition results are shown in **Figure 19**. The normal period status matches the test conditions (A, B, C, and D) for approximately 22% of the cases (normalized to account for differences in the amount of data between houses). The ventilation system status is unknown for many of these houses, comprising the majority of status conditions (door open or closed, ventilation unknown – see **footnote 12**). Assuming the ventilation system is on in many of these cases, test condition A (door open and ventilation system on) would be most common. This is the situation where CO_2 levels were lowest in the long-term study tests.

Figure 19. Second Bedroom Nighttime Door and Ventilation System Status – Normal Period



[16] W29 has an HRV that was operated in exhaust-only mode during the long-term test period. During the normal period, occupants may have operated the system as an HRV (exhaust and supply mode). This may explain the lower CO_2 levels during the normal period.

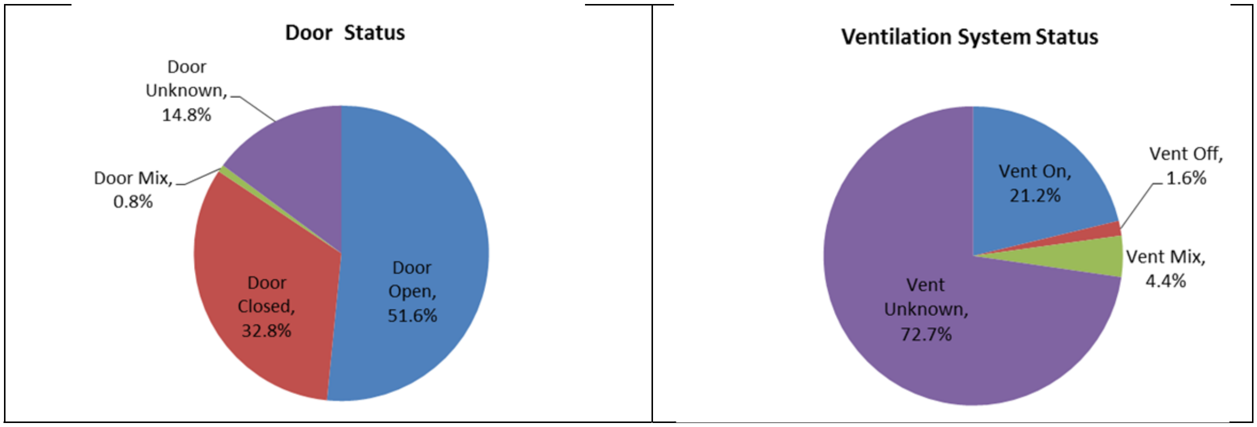
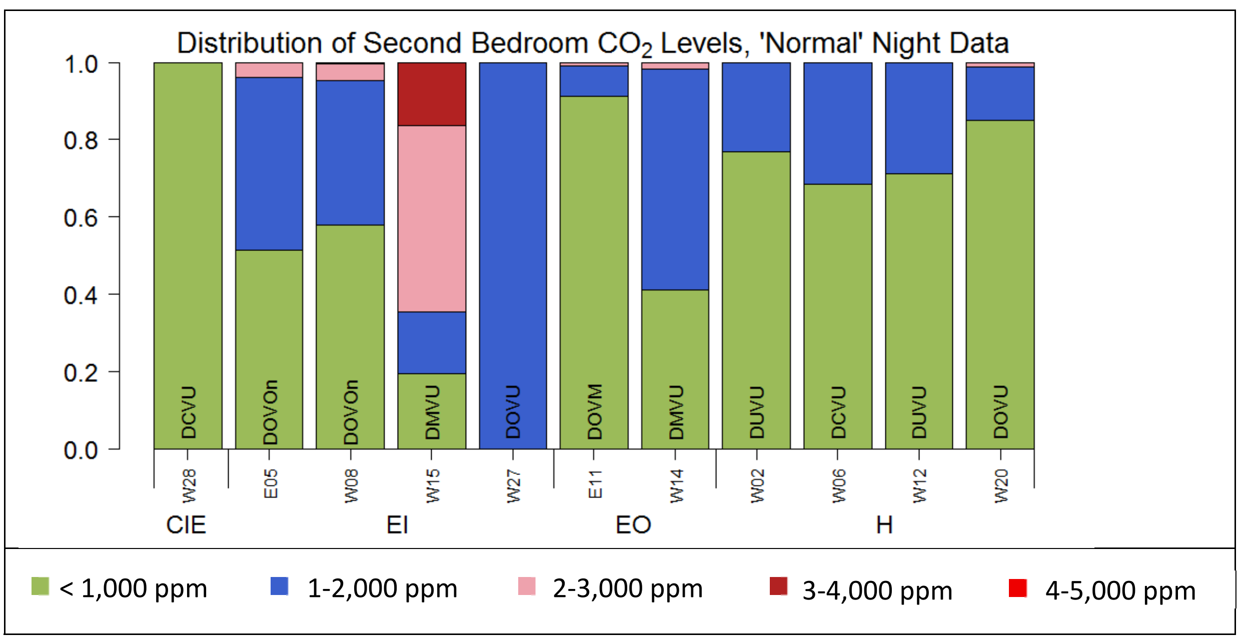


Figure 20 shows distribution of CO_2 levels for occupied second bedrooms at night for each house in the normal period. The labels show the predominant status condition for the second bedroom during this period. Generally, CO_2 levels in the second bedrooms were slightly higher than levels in the master bedroom (consistent with the long-term study test condition results). Three of the 11 houses had CO_2 levels below 1,000 ppm more than 80% of the time. Three of the houses had CO_2 levels over 1,000 ppm at least 50% of the time: one of these, W27, had only two nights of data and one,W15, had CO_2 levels over 2,000 ppm more than 60% of the time.

Figure 20. Distribution of CO_2 levels for the second bedroom in occupied houses – normal period at night



The following observations can be made from the results in **Figure 20** for each ventilation type:

- **CFA Integrated with ERV (CIE)**: House W28 had some of the lowest CO_2 levels in the second bedroom. Even though the bedroom door was closed all the time at night, the high air volumes and ventilation from the CFA system resulted in effective ventilation. The maximum CO_2 reading in the second bedroom at night was 1,017 ppm.

- **Exhaust with Inlet Vents (EI)**: These houses tended to have the highest CO_2 levels. E05 and W08 tended to have a little better performance, which may be due to having the doors open and the ventilation system on. W15 had the worst performance, with an average CO_2 level of 2,100 ppm. The second bedroom door was closed 68% of the time, which likely contributed to this level.
- **Exhaust Only (EO)**: House E11, which has among the lowest CO_2 levels in this set of houses, had its door open and ventilation system on almost all the time. The other EO system (W14), the door was closed over half the time and ventilation operation status was unknown.
- **HRV (H)**: The four HRV systems performed adequately. Even though the houses had some CO_2 measurements over 1,000 ppm, most of these readings were less than 1,200 ppm. The variation in CO_2 levels for the HRV houses was less than for the houses with exhaust ventilation systems.

Table 7 compares the average second bedroom CO_2 levels for the normal and test week periods under the primary door and ventilation status conditions (tests A, B, C, and D). Only eight houses have data for the two periods for one of the test conditions. In five of those houses, the difference between the average CO_2 level in the normal and test week periods was less than 200 ppm. The levels in the other three houses can be explained by limited data, the presence of a CFA heating system (differences in operation of the CFA can influence results), and a relatively small percent difference (for W08).

The researchers assumed that the ventilation system was on for the normal period cases when the ventilation status was unknown. The CO_2 levels were reasonably close for tests A and B for all of the houses except W15 and W28 (no test week data was available for these houses). For W15, the results suggest that, during the normal period, the ventilation system may have been off most of the time when the door was open (normal period results most closely match test C) and was off some of the time when the door was closed (normal period results are between test B and test D). The houses that had the highest CO_2 levels for the long-term study had similar levels during the normal period.

Table 7. Average CO_2 level by ventilation and door status for the normal and test periods – second bedroom

	A: Vent On Door Open		B: Vent On Door Closed		C: Vent Off Door Open		D: Vent Off Door Closed		Vent Unknown Normal Period		Explanation
House	**Normal**	**Test**	**Normal**	**Test**	**Normal**	**Test**	**Normal**	**Test**	**Door Open**	**Door Closed**	
E05	911	932	1,884	1,430	-	1,498	-	2,465	-	-	Limited Data
E11	637	613	898	1,093	996	941	2,184	791	-	-	CFA & Limited Data
W02	-	836	-	1,141	-	1,989	-	2,849	849	-	
W06	-	-	-	1,028	-	-	-	1,376	606	869	
W08	985	957	520	-	2,230	2,703	-	2,977	-	-	17% difference
W12	-	468	-	825	-	-	-	-	631	1,143	
W14	-	902	-	1,556	-	955	-	1,492	862	1,416	
W15	-	1,516	-	1,602	-	2,376	-	2,559	2,499	1,916	
W20	-	945	-	858	-	2,099	-	2,973	958	923	
W27	-	1,033	-	-	-	-	-	-	1,250	-	
W28	-	-	-	-	-	-	-	-	-	722	

Note: Cells are highlighted for cases where the difference between the normal and test period value is greater than 200 ppm or where values are lower than expected.

Key conclusions from this analysis of the normal period data include:

- CO_2 levels are similar for the bedrooms at night during the normal and test week periods.
- Doors being closed or ventilation systems being off contributed to higher CO_2 levels, consistent with the long-term study test week period results.
- During the normal period, the most common bedroom door and ventilation operation status condition (when data was available) was bedroom doors open and ventilation system on (test condition A). This is the condition when the ventilation systems tended to be most effective and measured CO_2 levels were lowest.
- The data for the normal period indicate that the HRV systems perform better than exhaust systems (without CFA).

Impact of Inlet Vents on Ventilation Performance

Inlet vents are mandated for exhaust systems in Washington State, and the added expense is a matter of concern to some builders. The effectiveness of these systems is, therefore, of interest. Throughout the project – from the initial interview through the short-term, long-term, and normal period tests and analysis – the WSU Energy Program team explored the use and performance of these systems for the six houses with inlet vents. In this section the results are compared, contrasted and discussed.

In both the short and long-term studies, the impact of opening or closing fresh air vents was part of the research. It added great time to the research, especially the long-term study, because these tests required doubling the tests for other factors such as ventilation system operation and bedroom door closure. In the short-term study, researchers opened and closed the inlet vents so the status of the vents was clear. In the long-term study, occupants opened and closed the inlet vents according to the test week protocol. The status of the vents was not measured. The large number of test weeks likely resulted in some compliance issues and uncertainty, which are discussed below. During the normal period, occupants were free to operate the vents as they wanted (status was not measured or recorded).

Sample Characterization

To avoid confusion, both the short-term and long-term studies had six houses with inlet vents, but they were slightly different groups. Not all houses in the project were included in the short-term study – two houses with inlet vents (W07 and W08) were not part of the short-term study sample. Two houses with inlet vents included in the short-term study (W14 and W17) operated as exhaust only in the long-term study (inlet vents closed).

The houses with inlet vents have the highest air leakage rates of any group of homes in the project sample. The median leakage rate at 50 Pascals for all 29 houses is 2.0. The median for the houses with inlet vents in the short-term study is 2.8, and 3.0 for those in the long-term study. These houses also are among the smallest in the study. They are a mix of single- and two-story homes.

Each characterization included an interview with the occupants concerning their knowledge and use of their ventilation systems. When the house had inlet vents the questions included their use. Not all of the study houses had complete interviews, but all of them were complete on this point.

The results of the six-house sample for the short-term study is that the occupants in five of them – over 80% – kept them closed at night and mostly all other times before the beginning of the study. For the long-term study the ratio was four of six or two-thirds closed. The reason given by one occupant for closing the vents at night was the incoming air was too cold.

Results for inlet vent impacts are presented for the three approaches: short-term study, long-term study and the normal period study.

Short-term Study

The short-term study analyzed the decay of the CO_2 tracer gas to produce calculated air changes per hour. **Figure 21** shows the results with the inlet vents opened or closed in the three rooms for the six exhaust systems with inlet vents.

- In the bedrooms when the doors are open (test A), there is little difference in the ACH when the vents are open or closed.
- In the main living area when the inlet vents are open and the bedroom doors are open (test A), there is a modest improvement in the mean ACH, but the ACH range is large.
- Conversely, when the inlet vents are open and the doors are closed (test B), the ACH improves slightly on average in the bedrooms (though results are mixed) but is unchanged in the main living area.

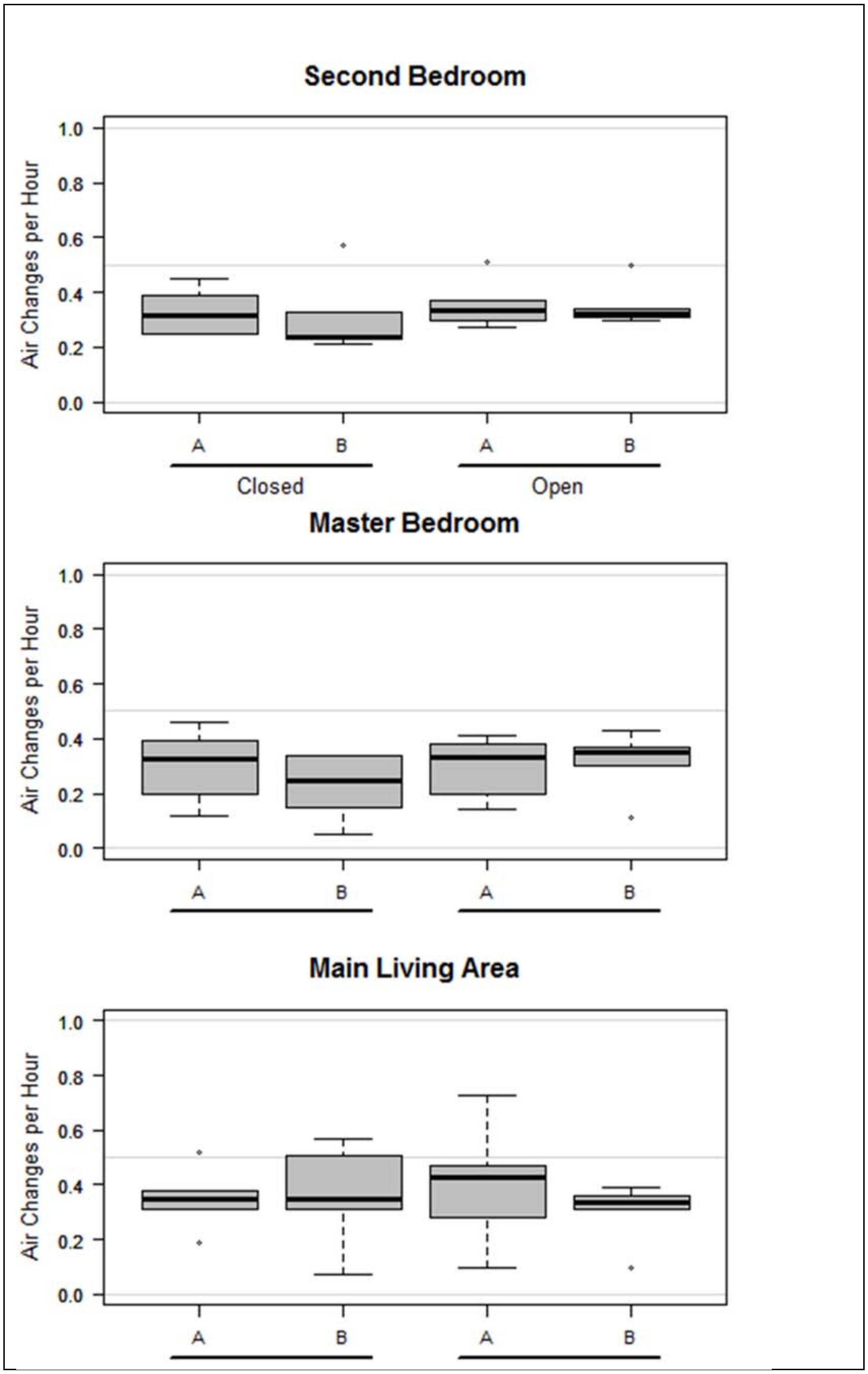
The results suggest that when the bedroom doors are closed, the inlet vents may provide a modest benefit in the bedrooms – the mean improvement in the second bedroom is 0.05 ACH and in the master bedroom is 0.09 ACH. The average ACH with the inlet vents open is 0.35 ACH in the second bedrooms and 0.32 ACH in the master bedrooms. The improvement in ACH for individual houses ranges from -0.07 ACH to 0.11 ACH for the second bedroom (two houses had a negative change) and from 0.03 ACH to 0.21 ACH for the master bedroom. For the master bedroom, the house with the high value did have a path to a continuously operating exhaust fan in the master bath while the house with the low value did not. One of the other four cases also had a continuous exhaust fan in the master bath, though the improvement in ACH was significantly lower. None of the second bedrooms had a return path.

The analysts considered the statistical significance[17] of differences (improvement) in ACH with the vents open or closed when the bedroom doors are closed. For 95% confidence, the improvement is statistically different from 0 for the master bedroom (98% confidence), but not for the second bedroom (81% confidence). The 95% confidence interval for the improvement is -0.032 to 0.125 ACH for the second bedroom and 0.024 to 0.156 for the master bedroom. To determine if the improvement is statistically greater than 0.05 ACH, the confidence level for the second bedroom is just 8% and for the master bedroom is 82%.

For all the other cases (doors open in the bedrooms or doors open or closed in the main living area), the inlet vents do not make an overall difference. Any benefit is usually less than 0.05 ACH, and 9 of the 24 differences in ACH are zero or negative.

[17] A simple paired t-test was used. The sample size was small (6) and for the master bedroom, one high value may skew the results and draw into question the requirement for a normal distribution.

Figure 21. Short-term test ACH with inlet vents open or closed by test condition: ventilation on, doors open (A) and ventilation on, doors closed (B)



Long-Term Study

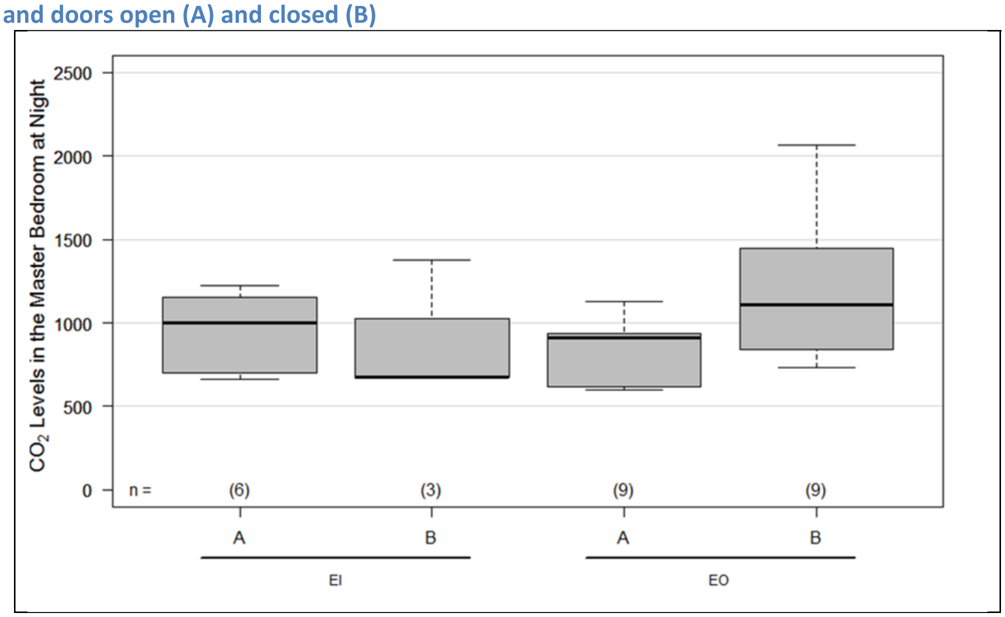
The same long-term tests were performed in the six houses with inlet vents as in all houses in the study, but test weeks were added so the vent status could be changed between open and closed while the other tests were performed.

Unfortunately, the review of data quality showed that the testing sequence protocol was not followed in many of the inlet vent houses. Measured door and ventilation operation data can be used to determine the correct status conditions, but the inlet vent status was not measured and only one of the home occupant journals clearly shows inlet vent status. Because most inlet vent sites did not follow the expected testing sequence and had demonstrated compliance concerns, there was low confidence in the house's inlet vents being open or closed as specified in the test conditions. Thus, simple comparisons between vent open and closed status could not be made.

To gain some insight into the potential benefits of inlet vents, the EO houses (**EO**) were compared directly with the exhaust with inlet vent houses (**EI**), assuming that the vents were open at least some of the time. This comparison is shown in **Figure 22**. If the inlet vents were making a positive difference, the CO_2 levels in the EO houses should be higher. For the doors open case (A), there is little difference. When the doors were closed (B), there was a small improvement in the median CO_2 levels in the inlet vent houses. However, only three inlet vent houses complied with test condition B, reducing the sample size for the comparison, and thereby adding uncertainty to these results. Two of these houses had low CO_2 levels, allowing a small sample to influence the median.

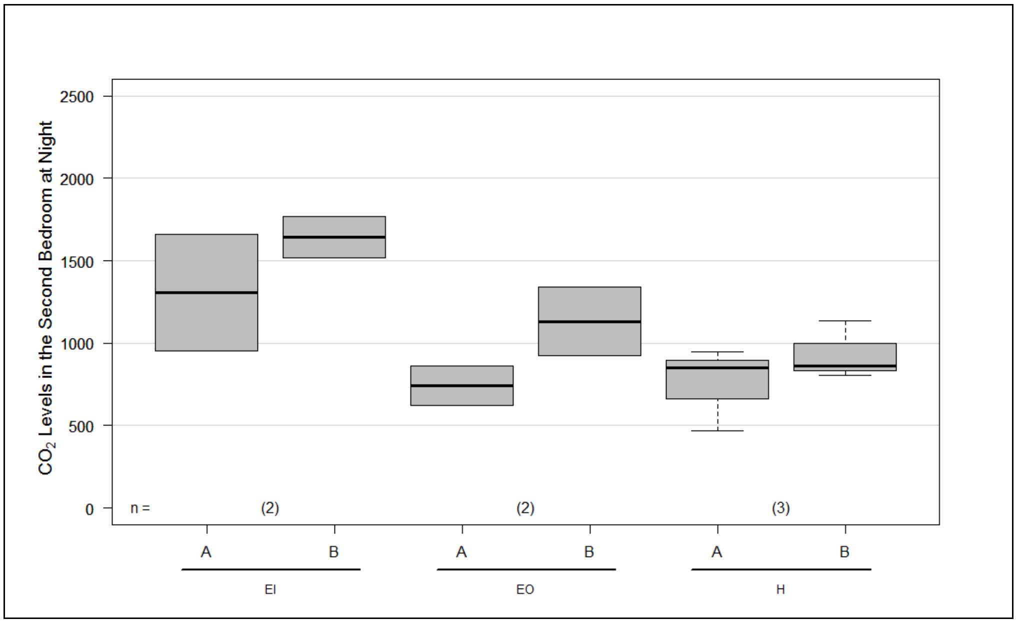
In the case when the ventilation system was off (not pictured), results were the same as when the ventilation was on: there was little difference in CO_2 levels for the open door case (C) in houses with and without inlet vents, but a small improvement when doors were closed (D) for the inlet vent houses.

Figure 22. CO_2 Levels in the master bedroom at night for EO and exhaust with inlet vents (EI) for the ventilation system on and doors open (A) and closed (B)



For occupied second bedrooms, the long-term study results show higher CO_2 levels for the inlet vent (**EI**) houses compared to the exhaust only (**EO**) houses in all cases, suggesting the presence of inlet vents is not a decisive factor in providing adequate ventilation, as shown in **Figure 23**.

Figure 23. Impact of inlet vents on CO_2 levels in second bedroom, test conditions A and B



We can make a number of observations about this figure.

- The number of houses in each sample is small, because the number of occupied second bedrooms with qualified data for these tests is small.
- As in the master bedroom analysis, the status of the inlet vents (**EI**) in the houses in this classification is not known. The analysis includes all test A and B data.
- The other ventilation types perform relative to each other as they did in the short term study and the long term master bedroom study and confirm the general patterns of those analyses.
- If the vents were closed for all the test weeks, the magnitude of the ventilation impact of open inlet vents shown in the short term study is unlikely to bring the mean value of the inlet vent houses into the CO_2 range of the other types of systems in this analysis.

Normal Period Study

Since the status of inlet vents was not monitored during the normal period, direct comparisons of ventilation performance with the vents open or closed cannot be made. In this case, the benefits of houses with inlet vents can only be evaluated by comparing those houses with the other ventilation systems. Whether vents are open or closed depends on occupant behavior.

For the master bedroom, four of the six houses with inlet vents had average CO_2 levels above 1,000 ppm. This is more than the other three ventilation system types, which had one house each with CO_2 levels over 1,000 ppm. For the second bedroom, the four houses with inlet vents tended to have the highest CO_2 levels. The research team did not see any advantages for exhaust systems with inlet vents compared to exhaust systems without inlet vents for the normal period study.

Summary of Inlet Vent Analysis

A clear benefit from inlet vents was not evident.

- The characterization survey documented that inlet vents were normally closed in this sample of homes in proportions ranging from 67% to 80% and that closure was due to perceived discomfort.
- In one case, when the bedroom doors were closed in the short-term test, the inlet vents provided a modest benefit in the bedrooms, but the quantified impact was small.
- For the long-term study, it was difficult to draw conclusions about the benefit of inlet vents due to the small sample sizes and uncertainty about whether the vents were open or closed. In the master bedroom, the mean CO_2 value when the door was closed was slightly lower than in the EO houses. In the second bedroom, the CO_2 was significantly higher in both the door open and door closed cases than for both EO and HRV systems. The long-term tests provided no conclusive pattern and certainly showed no substantial benefit of inlet vents.
- For the normal period analysis, houses with inlet vents had the highest CO_2 levels, suggesting the inlet vents provided no benefit.

Other factors likely contributed to these results more than inlet vents. The next section considers factors influencing ventilation effectiveness.

2. Factors Influencing Ventilation Effectiveness

The analysis of ventilation effectiveness presented above considered the impact of primary variables (such as doors open or closed) in comparing the ability of ventilation system types to remove CO_2 from the master bedroom. This section looks at other factors that affect ventilation performance.

Air flow in buildings is complex. Factors both external and internal impact the air movement between the interior and exterior and between rooms. These factors include house airtightness, house configuration and size, internal air paths, pressure boundaries between zones, occupancy, type of heating distribution system, external air temperature, and wind pressure and direction.

During house characterization, the researchers collected data on house airtightness and size, configuration of the house including floor plan and elevation, ventilation supply, internal air paths between bedrooms and the main living area (return path), occupancy, and heating system.

Beginning temperature and wind conditions were recorded during the short-term study. For the long-term study, external air temperature and wind speed data for Olympia and Spokane (data from three weather stations were averaged during the test period) were mapped to the nighttime analysis data set. The minimum daily temperature was used to represent the temperature for the nighttime period.[18] Analyzing the impact of these factors is complicated. The long-term study and normal period data set contains data on 29 houses under various conditions of occupancy, configuration, and external factors.

[18] The researchers analyzed this data and found that outdoor temperatures during the long-term tests averaged about five degrees colder for houses east of the Cascades compared to west-side houses. Indoor-outdoor temperature differences and wind can increase natural infiltration. However, an initial analysis of the relationship between outdoor temperatures (and wind) and indoor CO_2 levels was inconclusive. Because the resolution of the weather data was at a daily level while the CO_2 data was at 15-minute increments, the research team believes the results of this analysis are not of high enough quality to present.

House-by-House Analysis for the Master Bedroom

The analysis of ventilation effectiveness indicates that the type of ventilation system makes a difference. However, there is a fair amount of variability in the data, which suggests a need to look more closely at individual houses and the factors that may influence this variation. The analysis of results for individual houses begins with consideration of houses on the extremes —those with CO_2 levels that were substantially higher than 1,000 ppm and those with levels that were consistently lower than 1,000 ppm for the master bedroom.

Table 8 shows the houses with mean CO_2 levels over 1,000 ppm for test A (doors open) or test B (doors closed) for the long-term study master bedroom analysis. Of the 13 houses listed, five are EO systems (55% of total cohort), four are exhaust with inlet vents (67% of all inlet vent systems), three are HRV (38% of all HRV systems), and there is one CFA integrated with ERV system (33% of CIE systems).

The data in the table begin to identify factors that contribute to higher CO_2 levels in some houses. These houses are smaller, tighter, have more occupants, do not have a return air path, have low ventilation flows, have occupants with limited knowledge of their ventilation system, and/or do not have a CFA heating system. However, there are cases where some of the factors suggest a house should have lower CO_2 levels than measured in the long-term study. For example, W17 and W29, which have the highest CO_2 levels when the bedroom doors are closed (test B), have ventilation flows from the short-term test that suggest adequate ventilation.

Table 8. Houses with mean CO_2 levels over 1,000 ppm for tests A or B for long-term study

Site #	Mean CO_2 Level (ppm)		Short-Term Calculated ACH		# Occu-pants (Occ.)	House CFM/ Occ.	Area (ft^2)	MBR Area/ Occ.	House ACH_{50}	Return Path	Heating System Type	System Type
	Test A	*Test B*	*Test A*	*Test B*								
W17	1,039	2,042	0.35	0.34	2	25	1,240	150	2.11	no	Radiant Floor	Exhaust Only
W29	902	1,751	-	-	2	19	1,764	160	0.26	no	DHP	Exhaust Only
W20	1,250	1,589	-	-	4	15.5	1,832	130	1.94	yes	DHP	HRV
E22	859	1,385	0.18	0.19	2	40	2,115	180	0.36	yes	DHP	HRV
W15	1,181	1,365	0.20	0.21	2	19.5	1,176	225	2.3	no	Radiant Floor	Exhaust with Inlets
W24	973	1,338	0.25	0.21	2	30	1,900	120	0.71	no	Radiant Floor	Exhaust Only
E18	945	1,312	0.15	0.15	2	31	3,150	250	1.44	no	CFA	Exhaust Only
W08	1,233	-	-	-	5	17.5	1,080	75	3.31	no	DHP	Exhaust with Inlet
W27	1,229	-	0.30	0.15	3	26.5	1,216	100	2.87	yes	Radiant Floor	Exhaust with Inlets
W06	-	1,176	1.04	0.30	3	21	1,881	120	1.42	yes	DHP	HRV
W14	1,136	1,131	0.12	0.05	4	15	3,300	255	2.60	yes	Radiant Floor	Exhaust Only
W28	679	1,080	-	-	4	20	1,970	140	0.29	yes	CFA	CFA Int. - ERV
E05	836	1,037	0.46	0.28	4	15	1,310	120	3.18	no	Radiant Floor	Exhaust with Inlets

Table ranked by test A or B results from largest to smallest CO_2 levels (note that cases without test B results could rank higher); cells highlighted in yellow reflect factors that may contribute to higher CO_2 levels.

At the other end of the spectrum are houses with lowest mean CO_2 levels for test A (doors open) or test B (doors closed) for the long-term study master bedroom analysis. **Table 7** shows the characteristics of these houses, which tend to be larger, leakier, have lower occupancy, have higher ventilation flows, and return paths.

Only two of the houses have short-term test ventilation rates below 0.25 ACH and none have whole house ventilation rates below 20 cfm/occupant. Seven of the 14 houses have CFA heating systems (out of eight houses with CFA heating systems), which could also contribute to lower CO_2 levels due to the mixing they provide. The master bedroom area per occupant also tends to be higher for houses that had lower CO_2 levels.

Table 9. Houses with the lowest mean CO_2 levels for the master bedroom for tests A or B for long-term study

Site #	Mean CO_2 Level (ppm)		Short-Term Calculated ACH		# Occ.	House CFM/ Occ.	Area (ft^2)	MBR Area/ Occ.	House ACH_{50}	Return Path	Heating System Type	System Type
	Test A	*Test B*	*Test A*	*Test B*								
E25	527	633	0.45	0.69	2	33.5	1,496	190	1.08	yes	DHP	HRV
E13	591	796	0.42	0.25	1	55	1,352	360	1.82	no	RF	EO
E16	607	652	0.21	0.24	2	32	2,805	200	2.39	yes	CFA	CFA-Int.
E11	620	836	0.36	0.31	4	22.5	2,364	160	2.76	no	CFA	EO
W04	643	899	0.48	0.85	2	37.5	3,024	190	2.65	yes	DHP	HRV
E19	666	885	-	-	1	22/37.5	1,700	250	3.10	yes	CFA	CFA-Int.-ERV
E09	677	707	0.35	0.33	3	22.5	2,843	160	3.20	yes	CFA	CFA-Int.
W28	679	1,080	-	-	4	20	1,970	140	0.29	yes	CFA	CFA-Int.-ERV
E23	683	692	-	-	2	26	2,843	300	3.10	yes	CFA	CFA-Int.-ERV
E10	693	-	0.50	0.46	2	38	1,896	190	2.00	yes	RF	HRV
E03	729	702	0.21	0.20	2	25.5	1,876	190	0.89	yes	DHP	HRV
E26	714	-	0.39	0.34	2	22.5	1,199	180	3.50	no	DHP	EI
W21	716	960	0.33	0.40	2	30.5	1,971	120	2.26	no	RF	EO
W07	753	736	-	-	2	41	2,080	225	2.93	no	CFA	EI

Table ranked by test A or B results from smallest to largest CO_2 levels; cells highlighted in yellow reflect factors that may contribute to higher CO_2 levels.

To examine the influence of CFA heating systems more closely, **Figure 24** shows the distribution of CO_2 levels for each house for the master bedroom that was presented earlier for the long-term study, but in this case the houses are organized by ventilation system and differentiate houses with CFA heating systems. In addition to the CFA integrated and CFA integrated-ERV ventilation systems, houses with exhaust ventilation systems with CFA heating systems are also differentiated. This figure clearly shows that houses that have ventilation and/or heating systems that do not distribute air throughout the house (exhaust-non CFA) tend to have higher CO_2 levels. The graph also shows the short term study calculated ACH for each master bedroom in the participating houses.

Houses with CFA systems did well as a group because of the air mixing generated by the air handler when it was on. In this sample, the houses with integrated CFA systems (E09 and E16) had the most consistent performance, followed by CFA systems with ERV (E19, E23, and W28). The integrated systems both have CFA with matched supply and returns in the bedrooms. This, coupled with operation of the air handler for ventilation, contributed to their excellent ventilation performance because fresh air was introduced and mixed air was removed from each room by the air handler.

The CFA systems with HRV and ERV performed almost as well as the integrated systems, likely because the ventilation systems provided a constant exhaust in the master bath connected to the master bedroom and a supply of fresh air to the bedroom. The CFA systems in two of these houses have central returns while the third provides supply and exhaust air to each room.

Figure 24. Distribution of CO_2 levels by test condition and ventilation system type including CFA and short-term test ventilation ACH

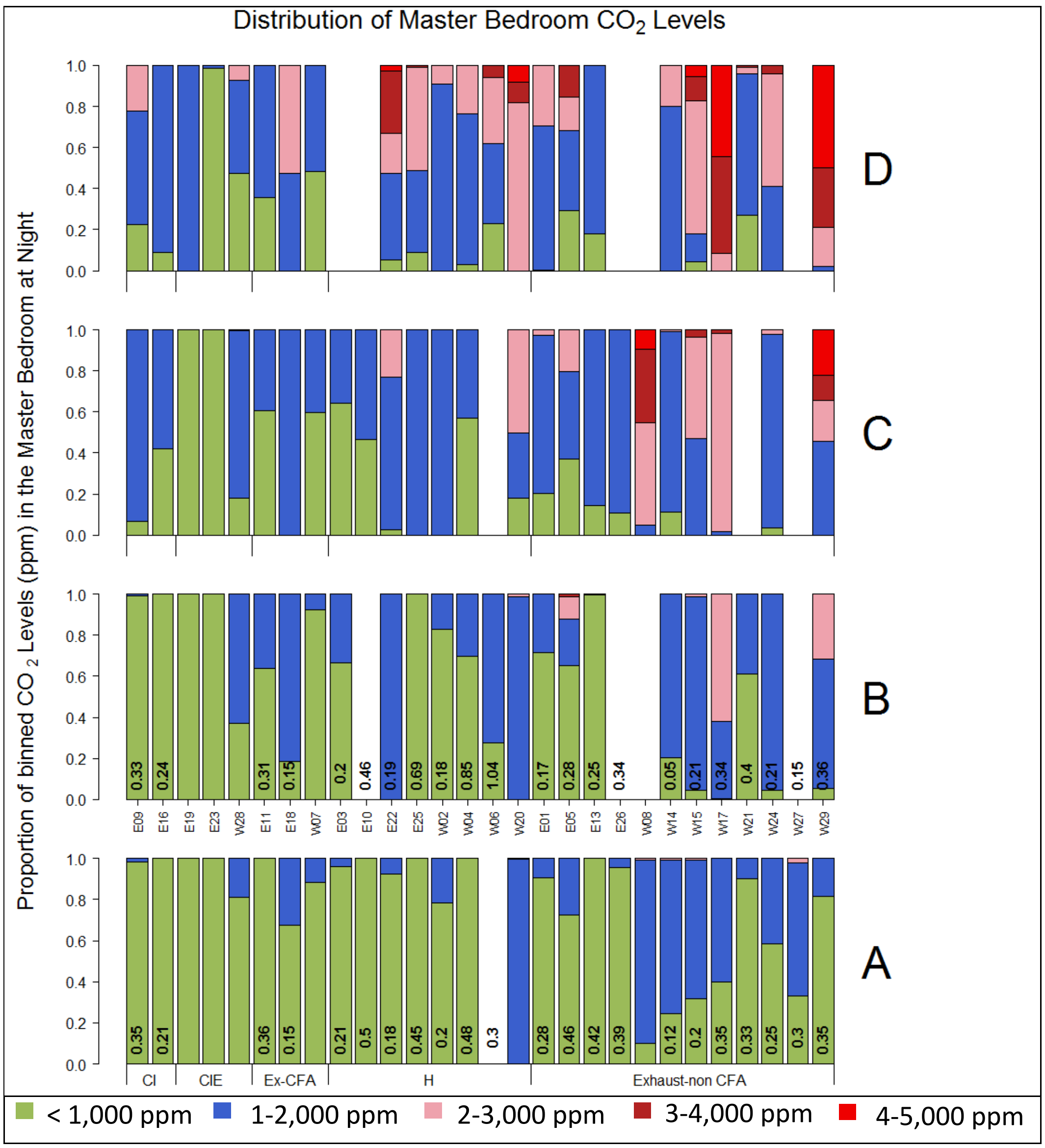


Figure is organized by the following ventilation system types: CFA integrated (CI), CFA integrated with ERV (CIE), Exhaust with CFA (Ex-CFA), HRV (H), Exhaust without CFA (Exhaust-non CFA).

The EO systems in houses with CFA (**Ex-CFA**) all have central returns. The results in test A are similar to the other CFA systems but most show higher CO_2 with the bedroom door closed except W07. The worst of the EO CFA systems is E18.[19] It is puzzling that this house did not perform more like W07. Its overall CFM per occupant is 31, which is higher than most of the houses with inadequate ventilation. E18 is EO with the exhaust fan in the crawlspace and registers in the floor of every room to allow it to draw from the entire house. E18's performance suggests that the EO system may be short-circuiting in the crawlspace.

The HRV systems, which also have supply and exhaust in each space, generally performed well, but had less consistent performance. Higher CO_2 levels in E22 suggest balancing issues that were exacerbated when the bedroom door was closed. W20 had relatively low ventilation levels (CFM/occupant). W06 is one of the systems that did not have measured ventilation system operation data and evidence suggests this system may have only operated 20 minutes each hour.

EO systems in houses without CFA (**Exhaust non-CFA**) had the highest CO_2 levels. Three EO without CFA houses that performed relatively well were E01, E13, and W21, which have high CFM per occupant ratios (E13 has the highest value in the sample at 55). While CFM per occupant seems to be an important factor in the performance of these houses, other factors have influence. For example, E13 has one occupant and the highest master bedroom area per occupant (lowest occupant density).

During the normal period, the results for the master bedroom were similar to the test week period (see

[19] This is the one house with a CFA heating system that appears in

Table 10 with the houses that have the highest CO_2 levels.

Table 10). During this period households were free to operate their ventilation systems and doors as they liked. The researchers made the following observations about factors influencing ventilation effectiveness for each ventilation system type.

- **CFA Integrated (including with ERV)**: These CFA systems tended to have the lowest measured CO_2 levels with one exception – E09. The ventilation system was off 71% of the time for this house during the normal period. Examining the results for E09 more closely, the researchers found that when the ventilation system was on at night (it operated in a ventilation mixed mode), CO_2 levels were below 1,000 ppm almost 100% of the time, and the highest level was 1,088 ppm. Thus, the ventilation system was effective in this house when it operated. There were two other houses in this category where the ventilation system was off a significant amount of time. In these cases, the CFA furnace may have operated enough of the time to provide adequate air mixing to maintain low CO_2 levels. It is also notable that W28, which had mean CO_2 levels over 1,000 ppm for test B during the test weeks, had one of the lowest CO_2 levels during the normal period with a maximum measurement of 993 ppm (the bedroom door was closed most of the time). The higher levels during the test period may have been an anomaly.
- **Exhaust with Inlet Vents**: Four of the six houses with these systems had average CO_2 levels above 1,000 ppm during the normal period. This was more than the other three ventilation system types, which had one house each with CO_2 levels over 1,000 ppm. The house in this category with the best performance (W07) had a CFA heating system and relatively high measured ventilation rate (whole house cubic feet per minute, and CFM per occupant). The houses with the highest CO_2 levels (W08, W15) were the smallest houses in this study, and W08 had five occupants and the lowest master bedroom area per occupant (highest occupant density). The inlet vent houses, in general, were the smallest houses in the study.
- **Exhaust Only**: The five exhaust only houses (out of nine) that had relatively low CO_2 levels had several characteristics that contribute to good ventilation effectiveness: the doors were generally open and ventilation systems were on, two had CFA heating systems, one had only one occupant, and three had relatively high measured ventilation CFM/occupant. Note that E18 is one of the CFA houses in this group and CO_2 levels in the normal period were slightly lower than those measured during the test weeks. The house in this ventilation category with the highest CO_2 levels (W24) had a relatively high CFM per occupant, but the ventilation system was off 74% of the time and the doors closed 38% of the time. The other three houses with higher CO_2 levels had one case with low measured ventilation rate, one case where the doors were closed most of the time, and three cases where the operation status of the ventilation system was unknown.
- **HRV**: Generally, the nine HRV system houses had relatively low and consistent CO_2 levels. Only three houses had CO_2 levels over 1,000 ppm more than 20% of the time and none were over 2,000 ppm. The houses with the lowest CO_2 levels tended to have higher measured ventilation CFM/occupant levels, bedroom doors open, and ventilation systems on. The house with the worst performance (W20) had a low measured ventilation CFM/occupant and the ventilation system operation status was unknown. This house also has four occupants, two dogs, and daytime occupancy. In the other houses with HRV systems that had higher CO_2 levels, ventilation

operation status was unknown, occupants tended to close their doors at night, and measured ventilation CFM per occupant was low; one of these houses had five occupants.

Table 10. CO_2 level distribution by house with status conditions and house characteristics – master bedroom for the normal period

		CO_2 Levels (ppm)					Overall Status	Door Status	Ventilation Operation	Heating System	Occu-pant	Area	Whole House
House	Ventilation Type	Mean	<1k	1-2k	2-3k	3-4k	Door/ Vent[1]	% Closed	% Off	Type	#	ft^2	CFM/ Occupant
E09	CFA Int.	1,182	37%	56%	7%	0%	DCVM	90%	71%	CFA	3	2,843	22.5
E16	CFA Int.	632	99%	1%	0%	0%	DMVM	46%	82%	CFA	2	2,805	32
E19	CFA Int. - ERV	642	100%	0%	0%	0%	DOVOn	0%	0%	CFA	1	1,700	22/37.5
E23	CFA Int. - ERV	730	100%	0%	0%	0%	DMVM	22%	61%	CFA	2	2,843	26
W28	CFA Int. - ERV	634	100%	0%	0%	0%	DCVU	97%	?	CFA	4	1,970	20
E05	Exhaust - Inlet	964	60%	37%	3%	0%	DOVOn	3%	0%	RF	4	1,310	15
E26	Exhaust - Inlet	1,057	42%	58%	0%	0%	DOVM	0%	67%	DHP	2	1,199	22.5
W07	Exhaust - Inlet	674	97%	3%	0%	0%	DCVOn	89%	3%	CFA	2	2,080	41
W08	Exhaust - Inlet	1,252	20%	74%	5%	2%	DOVOn	1%	6%	DHP	5	1,080	17.5
W15	Exhaust - Inlet	1,705	11%	64%	21%	4%	DMVU	58%	?	RF	2	1,176	19.5
W27	Exhaust - Inlet	1,128	50%	50%	0%	0%	DUVU	?	?	RF	3	1,216	26.5
E01	Exhaust Only	732	90%	10%	0%	0%	DOVOn	1%	1%	RF	2	1,656	30
E11	Exhaust Only	683	94%	6%	0%	0%	DOVM	7%	10%	CFA	4	2,364	22.5
E13	Exhaust Only	495	100%	0%	0%	0%	DMVOn	47%	0%	RF	1	1,352	55
E18	Exhaust Only	804	84%	16%	0%	0%	DMVOn	35%	0%	CFA	2	3,150	31
W14	Exhaust Only	888	50%	47%	3%	0%	DOVU	1%	?	RF	4	3,300	15
W17	Exhaust Only	978	46%	53%	1%	0%	DOVU	6%	?	RF	2	1,240	25
W21	Exhaust Only	922	61%	33%	6%	0%	DMVU	64%	?	RF	2	1,971	30.5
W24	Exhaust Only	1,578	23%	52%	22%	3%	DMVM	38%	74%	RF	2	1,900	30
W29	Exhaust Only[20]	775	92%	6%	1%	1%	DOVOn	3%	3%	DHP	2	1,764	19
E03	HRV	802	81%	19%	0%	0%	DOVM	5%	46%	DHP	2	1,876	25.5
E10	HRV	698	99%	1%	0%	0%	DOVOn	0%	1%	RF	2	1,896	38
E22	HRV	612	96%	4%	0%	0%	DUVOn	?	0%	DHP	2	2,115	40
E25	HRV	602	97%	3%	0%	0%	DOVU	0%	?	DHP	2	1,496	33.5
W02	HRV	968	78%	22%	0%	0%	DMVU	53%	?	RF	5	3,675	16
W04	HRV	796	81%	19%	0%	0%	DMVOn	40%	0%	DHP	2	3,024	37.5
W06	HRV	925	54%	46%	0%	0%	DCVU	98%	?	DHP	3	1,881	21
W12	HRV	785	80%	20%	0%	0%	DOVU	0%	?	HRV	4	1,904	19.5
W20	HRV	1,243	7%	93%	0%	0%	DOVU	8%	?	DHP	4	1,832	15.5

Overall status *combines the status conditions from individual nights into a predominant status for a house. DO=door open, DM=door mixed, DC=door closed; VOn=ventilation on; VM=ventilation mixed; VU=ventilation unknown.*

Cells highlighted *in green reflect houses with lower CO_2 levels or conditions or characteristics that favor lower CO_2 levels. Cells highlighted in yellow reflect the opposite.*

[20] W29 has an HRV that was operated in exhaust-only mode during the long-term test period. During the normal period, occupants may have operated the system as an HRV (exhaust and supply mode). This may explain the lower CO_2 level during the normal period that is comparable to the houses with HRV systems.

House-by-House Analysis for the Second Bedroom

As was done in the master bedroom analysis, the researchers considered factors that influence ventilation effectiveness for the occupied second bedrooms in the long-term study. **Table 11** shows the median CO_2 levels for tests A and B for all of the houses in the second bedroom analysis, along with the factors influencing ventilation effectiveness. The houses are listed from the highest to the lowest median CO_2 levels under test A (doors open) and test B (doors closed) conditions.

Five houses have median CO_2 levels over 1,000 ppm when the doors are closed; one of those houses (W15) is also over 1,000 ppm for test A. Like the master bedroom analysis, systems that supply air to the second bedroom tended to have the lowest CO_2 levels. Thus, HRV systems with supply to the second bedroom, the CFA integrated with ERV system, and the EO system with a CFA furnace (E11) had lower CO_2 levels. Note that the two inlet vent houses that did not comply with test B conditions (W08, W27) would likely be listed higher if results for that test were available.

With the exception of house airtightness, the houses with occupied second bedrooms possess a lot of the characteristics that contribute to higher CO_2 levels. The four inlet vent houses are the smallest, which could contribute to their higher CO_2 levels, but they are also among the leakiest. The HRV houses have lower ACH_{50} values, but also are larger. Overall, household occupancy does not appear to be a big factor. Since all these households have children, occupancy tends to be higher. The house with the highest CO_2 levels (W15) has only two occupants (one adult and one teenager who likely spends a lot of time in his/her room). The second bedroom in the third house listed (E05) is occupied by two children, which likely contributes to higher CO_2 levels in this room. It is possible that some of the other second bedrooms are occupied by a small child who spends very little time in the room. The heating system type also seems to play a role – the first five houses listed in the table have radiant floor heating systems and the houses with CFA/HRV heating systems had lower CO_2 levels.

Table 11. Mean CO_2 levels for second bedroom with factors influencing ventilation performance – long-term study

Site #	Mean CO_2 Level (ppm)		Short-Term Test ACH_{50}		Occ.	House CFM/ Occ.	Area (ft^2)	2BR Area/ Occ.	House ACH_{50}	Return Path	Heating System Type	System Type
	Test A	*Test B*	*Test A*	*Test B*								
W15	1,516	1,602	-	-	2	19.5	1,176	150	2.30	no	Radiant Floor	Exhaust- Inlet
W14	902	1,556	-	-	4	15	3,300	204	2.60	no	Radiant Floor	Exhaust Only
E05	931	1,430	-	-	4	15	1,310	105	3.18	no	Radiant Floor	Exhaust- Inlet
W02	836	1,141	0.29	0.49	5+	16	3,675	77	1.02	no	Radiant Floor	HRV
W27	1,033	-	-	-	3	26.5	1,216	130	2.87	no	Radiant Floor	Exhaust- Inlet
W06	-	1,028	0.68	0.54	3	21	1,881	120	1.42	no	DHP	HRV
E11	613	1,093	0.32	0.16	4	22.5	2,364	120	2.76	no	CFA - Gas	Exhaust Only
W08	957	-	-	-	5	17.5	1,080	75	3.31	no	DHP	Exhaust- Inlet
W20	944	858	-	-	4	15.5	1,832	120	1.94	no	DHP	HRV
W28	633	827	-	-	4	20	1,970	140	0.29	yes	CFA	CFA-int-ERV
W12	468	825	0.64	0.82	4	19.5	1,904	140	0.57	no	HRV	HRV

Table ranked by test A or B results from largest to smallest CO_2 levels (note that cases without test B results could rank higher); cells highlighted in yellow reflect factors that may contribute to higher CO_2 levels.

Table 12 presents data from the normal period second bedroom test, along with house characteristics that help explain ventilation system effectiveness. These results are consistent with the long-term study analysis. The following observations can be made for each ventilation type:

- **CFA Integrated with ERV**: House W28 had some of the lowest CO_2 levels in the second bedroom. Even though the bedroom door was closed all the time at night, the high air volumes and ventilation from the CFA system resulted in effective ventilation. The highest CO_2 reading in the second bedroom at night for W28 was 1,017 ppm.
- **Exhaust with Inlet Vents**: These houses tended to have the highest CO_2 levels and were among the smallest houses, which may be a contributing factor. E05 and W08 had slightly better performance, which may be due to having the doors open and the ventilation system on. W15 had the worst performance, with an average CO_2 level of 2,100 ppm. The second bedroom door was closed 68% of the time, which likely contributed to this level.
- **Exhaust Only**: House E11 had among the lowest CO_2 levels in this set of houses. It is the only house with an exhaust ventilation system (including the inlet vent houses) and a CFA heating system; this ventilation system, along with the door being open, helps explain the measured performance. The other EO system (W14), which does not have a CFA furnace and had the door closed more of the time, did not perform as well as E11.
- **HRV**: The four HRV systems performed pretty well. Even though the houses had some CO_2 levels over 1,000 ppm, most of these readings were less than 1,200 ppm. The variation in CO_2 levels for the HRV houses was less than for the houses with EO ventilation systems.

The characteristics of houses that have high and low CO_2 levels suggest that heating system type and the amount of ventilation to each space are key factors influencing ventilation effectiveness. House airtightness, conditioned floor area, occupancy per area, and return path also seem to have influence in combination with other factors. The remainder of this section looks more closely at the influence of these factors.

Table 12. CO_2 level distribution by house with status conditions and house characteristics – second bedroom for the normal period

		CO_2 Levels (ppm)					Overall Status	Door Status	Ventilation Operation	Heating System	Occu-pants	Area	Measured Ventilation
House	Ventilation Type	Mean	<1k	1-2k	2-3k	3-4k	Door/ Vent[1]	% Closed	% Off	Type	#	ft^2	CFM/ Occupancy
W28	CFA Int. - ERV	722	100%	0%	0%	0%	DCVU	100%	?	CFA	4	1,970	20
E05	Exhaust - Inlet	997	51%	45%	4%	0%	DOVOn	9%	0%	RF	4	1,310	15
W08	Exhaust - Inlet	1,057	58%	37%	4%	0%	DOVOn	7%	7%	DHP	5	1,080	17.5
W15	Exhaust - Inlet	2,100	20%	16%	48%	16%	DMVU	68%	?	RF	2	1,176	19.5
W27	Exhaust - Inlet	1,250	0%	100%	0%	0%	DOVU	0%	?	RF	3	1,216	26.5
E11	Exhaust Only	713	91%	8%	1%	0%	DOVM	6%	10%	CFA	4	2,364	22.5
W14	Exhaust Only	1,168	41%	57%	2%	0%	DMVU	52%	?	RF	4	3,300	15
W02	HRV	913	77%	23%	0%	0%	DUVU	?	?	RF	5	3,675	16
W06	HRV	852	68%	32%	0%	0%	DCVU	93%	?	DHP	3	1,881	21
W12	HRV	940	71%	29%	0%	0%	DUVU	20%?	?	HRV	4	1,904	19.5
W20	HRV	963	85%	14%	1%	0%	DOVU	6%	?	DHP	4	1,832	15.5

Overall status *combines the status conditions from individual nights into a predominant status for a house. DO=door open, DM=door mixed, DC=door closed; VOn=ventilation on; VM=ventilation mixed; VU=ventilation unknown.*

Cells highlighted *in green reflect houses with lower CO_2 levels or conditions or characteristics that favor lower CO_2 levels. Cells highlighted in yellow reflect the opposite.*

Analysis of Individual Factors

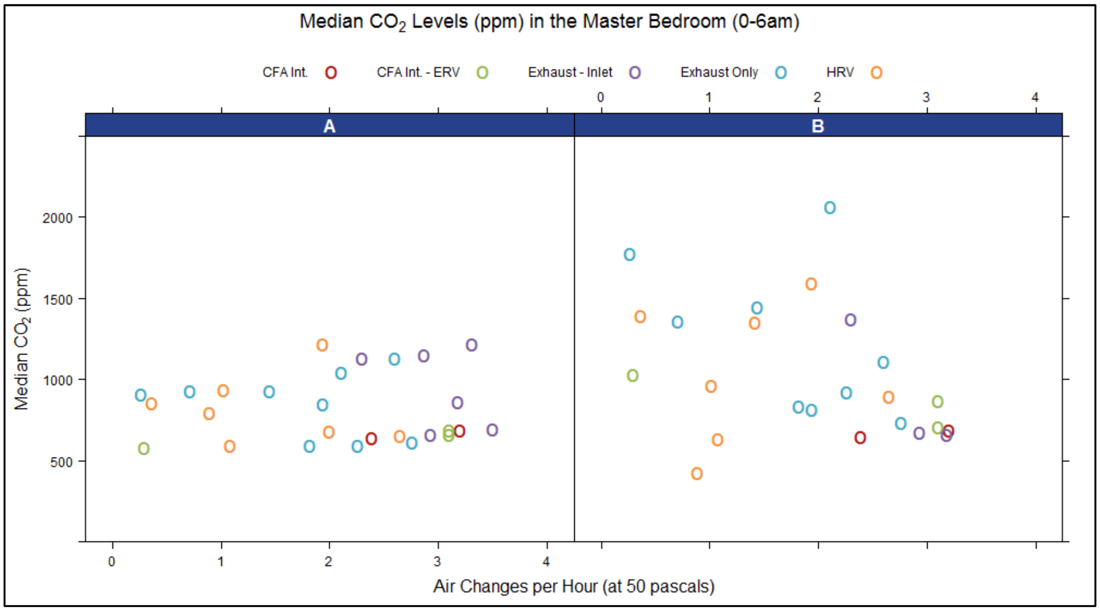
The researchers explored the relationship between individual factors and the CO_2 levels in the houses to better understand factors influencing ventilation effectiveness: airtightness, conditioned area and occupancy, the amount of ventilation, and return air path. More sophisticated statistical techniques would be required to study these factors in greater depth. Given the resources available, the relatively small sample, and the large number of influencing variables, the researchers decided this more detailed statistical analysis was not warranted at this time. The results presented here are intended to inform future research efforts.

Airtightness

Airtightness is plotted against median CO_2 levels for the two test conditions with the ventilation system on **(Figure 25)**. The results show that for test A (ventilation on, doors open), the tightest houses did not have the highest CO_2 levels. The largest portion of low CO_2 levels was for houses with higher ACH, but there are also some leaky houses (high ACH) with high CO_2 levels. There is a modest trend toward higher CO_2 levels in tighter houses for test B (ventilation on, doors closed), but some tight houses with HRV systems had particularly low CO_2 levels and a few other houses had CO_2 levels on the high side.

The relationship between house airtightness and CO_2 levels is clearer for the ventilation off tests (not shown in the graph), but again there are some outliers.

Figure 25. Median CO_2 levels versus house airtightness for test condition A (doors open) and B (doors closed) for each house by system type for the long-term study



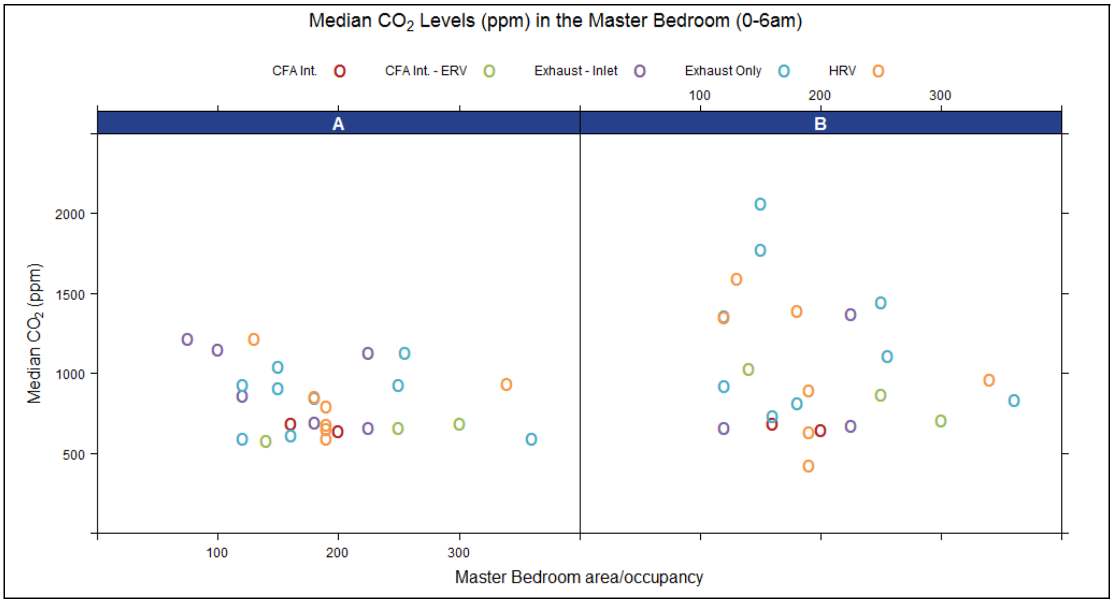
Conditioned Area and Occupancy

To consider the influence of conditioned floor area and occupancy, median CO_2 was plotted against the master bedroom area divided by the number of occupants. The CO_2 levels are expected to rise as the area/person ratio declines.

Median CO_2 levels tended to be higher as master bedroom area per occupant declined (

Figure 26). For all houses the average master bedroom floor area per occupant ranges from 75 ft^2 per person to 360 ft^2 per person (a factor of 4.8). This implies the need to generate 4.8 times as much CO_2 to reach the same concentration in ppm with everything else being equal. While CO_2 levels tended to be higher for the master bedrooms with low area per occupancy ratios, there were differences in the CO_2 levels between houses with similar ratios. There was also wider variation in CO_2 levels for test B (doors closed) than test A (doors open) suggesting other factors, such as ventilation rates per occupant, heating system type, airtightness, and presence or absence of a return path, play a more significant role in CO_2 levels than area/occupancy. Note that some houses included for test A are not included for test B because they did not comply with test B conditions (for example, the two houses with the lowest area/occupancy in test A).

Figure 26. Median CO_2 levels versus master bedroom area per occupant for test condition A (doors open) and B (doors closed) for each house by system type for the long-term study



Ventilation Levels

Measured ventilation levels are compared to the CO_2 levels from the long-term test. Two measures of ventilation levels are used for this analysis. The first uses measured whole house ventilation divided by the number of occupants. Researchers measured ventilation flows for each house during the field visits at the beginning of the study. The second uses the ventilation flows from the short-term test.

Whole house CFM per occupant ranged from a high of 55 to a low of 15, with a mean of 26.5 (**Figure 27**). As whole house ventilation declined, median CO_2 levels increased. The trend line relationship between CO_2 and ventilation levels is clear for test A, but there is variation in CO_2 levels even within similar system types. For example, all but one of the cases with median CO_2 levels over 1,000 ppm is an exhaust system, but there are exhaust systems with relatively low ventilation levels that also have relatively low CO_2. There is more scatter in the test B data, particularly for HRV and exhaust systems. CO2 levels vary by a factor of three or four for systems with similar ventilation flow. This suggests that other factors besides ventilation flow have a significant influence on performance in this situation.

Ventilation flows from the short-term test are compared to median CO_2 levels from the long-term test in **Figure 28**. As was the case for CFM per occupant in the previous figure, there is a relationship between long-term study CO_2 levels and short-term study ventilation flows, particularly for test A. However, there are also significant outliers for test B. Again, the scatter shows the influence of other factors.

Figure 27. Median CO_2 levels in master bedroom versus whole house ventilation per occupant for test A (doors open) and B (doors closed) for each house by system type for the *long-term* study

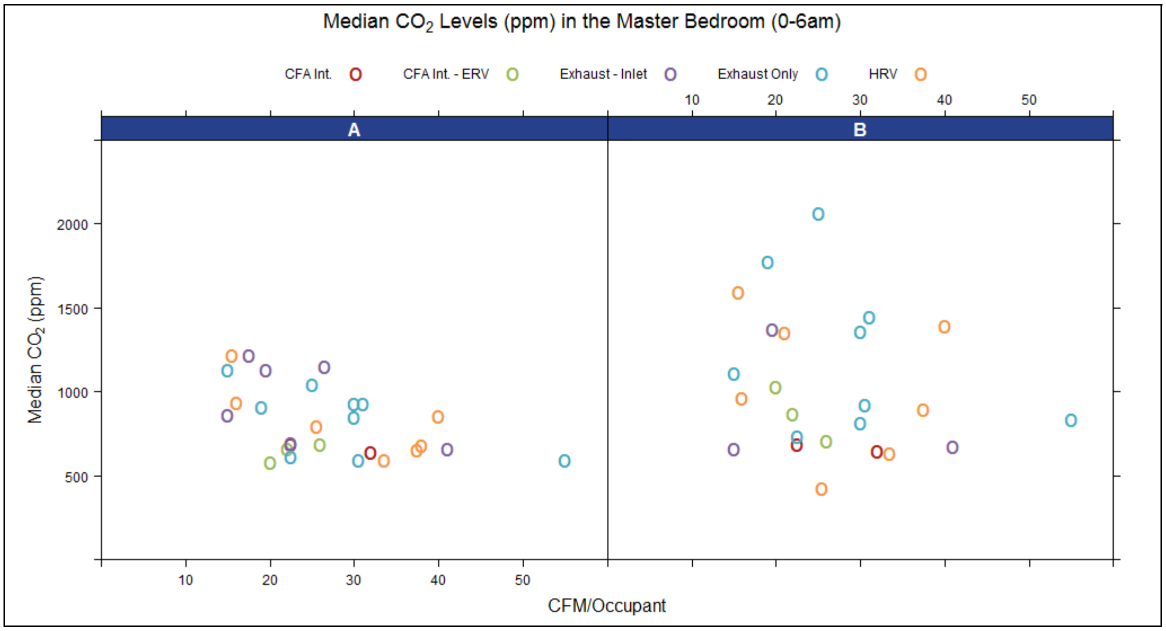
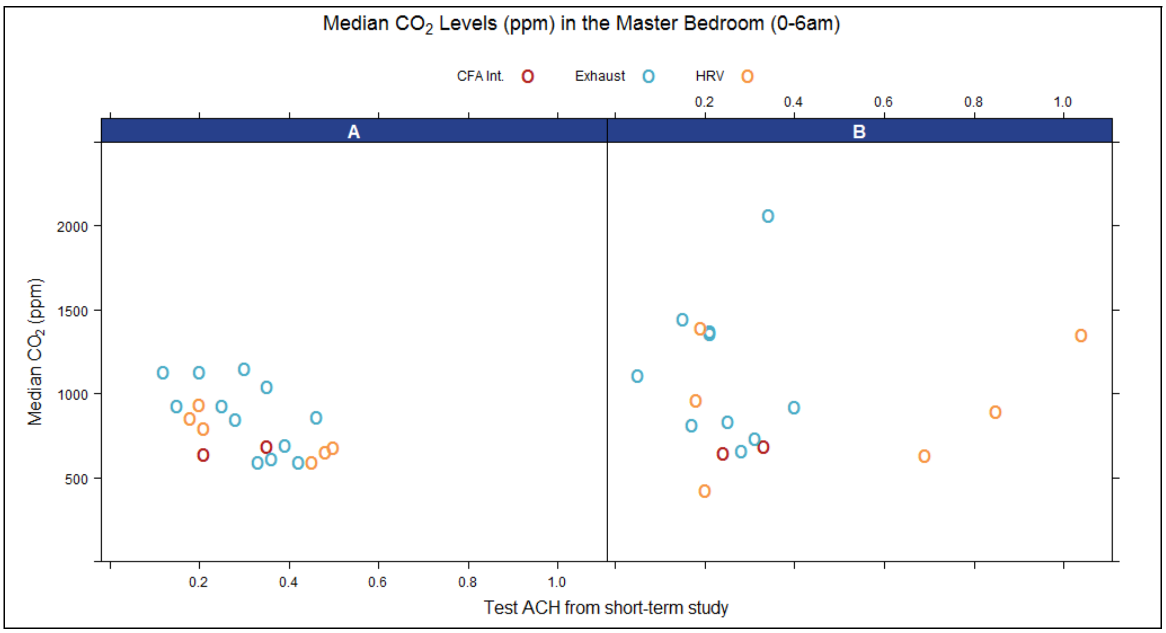


Figure 28. Median CO_2 levels in master bedroom for the long-term study for test A (doors open) and B (doors closed) versus *short-term* test ventilation for each house by system type



Return Air Path

Many of the houses have return paths from the bedrooms or, at a minimum, from the master bedroom to the main living area when doors are closed. The most direct pathways include transfer grills, wall vents, and CFA systems with a return duct in every room. Many more have undercut doors of various heights (but less than two inches), which are not considered to provide an effective pathway in our analysis of return path. These are all passive returns that operate whenever there is a difference in pressure between the rooms connected by the pathway.

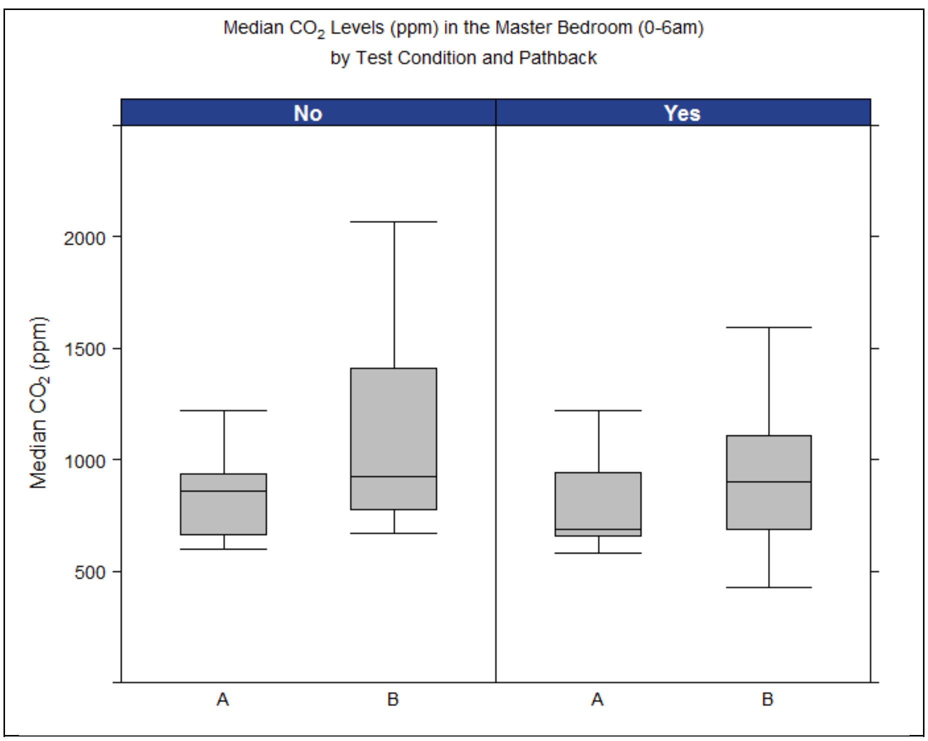
Another effective return path when the ventilation system is operating is an exhaust port for an HRV or ERV system. Most of the houses in the study that were equipped with HRV and ERV had a supply in each bedroom and an exhaust in each bath, including the master bath connected to the master bedroom. The door between the master bedroom and master bath was not monitored, but it was assumed to be open to the bedroom, effectively providing a positive exhaust in the master bedroom. This is classified as a return path for the vent system in the test conditions.

One EO house (W14) and one exhaust with inlet vent house (W27) had vent system fans located in the master bath. They operated as a direct exhaust for the bedrooms when the systems were on, and these houses are classified with those having a return path.

The impact of the return path in the long-term study was analyzed by examining the CO_2 levels in the master bedroom for houses with and without a return path (

Figure 29**)**. The results suggest return paths have a modest impact on ventilation effectiveness (reduced CO_2 levels). For test A, the median CO_2 value went down for houses with a return path, but the range of values was similar. For test B (doors closed), the median values were similar for houses with and without a return path, but the range of CO_2 values was lower for the return path case.

Figure 29. Median master bedroom CO_2 for the long-term study for test A (doors open) and B (doors closed) by absence (No) or presence (Yes) of return air path



Summary of Factor Analysis

This review shows there are relationships between individual factors and the CO_2 levels. Numerous factors influence system effectiveness for every ventilation type:

- Occupancy is a key variable that continually changes. The system must be designed for the house and its potential occupancy.

- Area per occupant is a characteristic of effective ventilation and is a function of house size and occupancy.
- Ventilation level per occupant is a function of occupancy and the ventilation system capacity, design, and proper balancing, particularly in the case of HRV and ERV.
- Return air path characterizes most effective systems. Providing pathways to move air through spaces has a measurable impact.
- Door closure appears to be a function of high occupancy or preference, and doors were closed at night in over 30% of the houses in this study. It must be assumed in ventilation system design that this will be the case and effectiveness must take this into account.
- Heating system type clearly impacts ventilation effectiveness. Heating systems can be grouped according to those that do not enhance ventilation effectiveness (radiant floors and DHP) and those that do (CFA). Heating systems that provide supplies and returns in the bedrooms appear to be the best, but the air mixing assistance provided to exhaust systems by most CFA is clear.
- House airtightness plays a role, but is not determinative.

Effective ventilation systems address as many of these factors as possible. Key factors to success include delivering sufficient ventilation air per occupant to each room, and to providing a means for air to circulate through the house. Without attention to these details, it does not matter how much total air the system moves—it will not necessarily provide effective ventilation.

These research findings show quite clearly the factors that impact ventilation and how they can be used to design effective systems. The analysis shows that these factors are interactive and this research does not quantify those relationships. If the quantitative relationship of these factors is important, a statistical analysis on a larger sample of data will be required to study these interactions in greater depth.

3. Relative Humidity

RH was measured as part of the research study. The researchers examined and analyzed the RH data from the long-term study period to check consistency with the CO_2 trace gas data and to determine if there is value in using RH as an indicator of ventilation effectiveness. The analysis considers overall RH levels, humidity levels in individual houses, and the correlation between RH and CO_2 levels.

Overall RH Levels

The researchers began by considering the humidity levels in the houses as a group to determine where and when humidity levels might be high (or low). ASHRAE Standard 55 indicates people are comfortable at 30% to 70% RH. Issues like condensation, mold, dust mites, and fleas are of less concern at the lower end of this range (30% to 50% RH). For this analysis, the researchers considered the RH in the houses at different ranges.

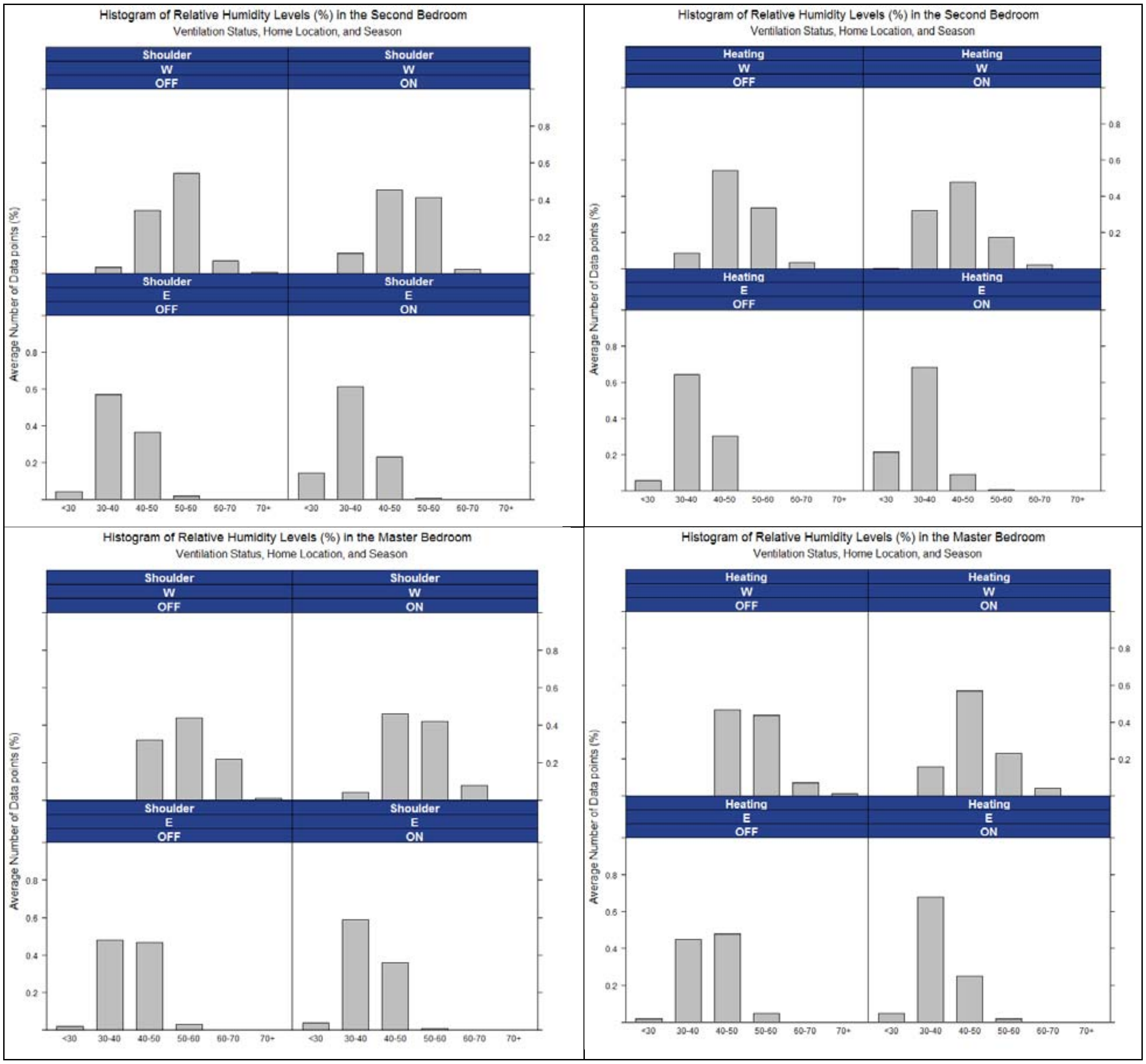
Figure 30 shows histograms for each room with the ventilation on or off, organized into groups of houses that are in the east or west side of the state. Data were collected during the winter (heating) or spring (shoulder) seasons.[21]

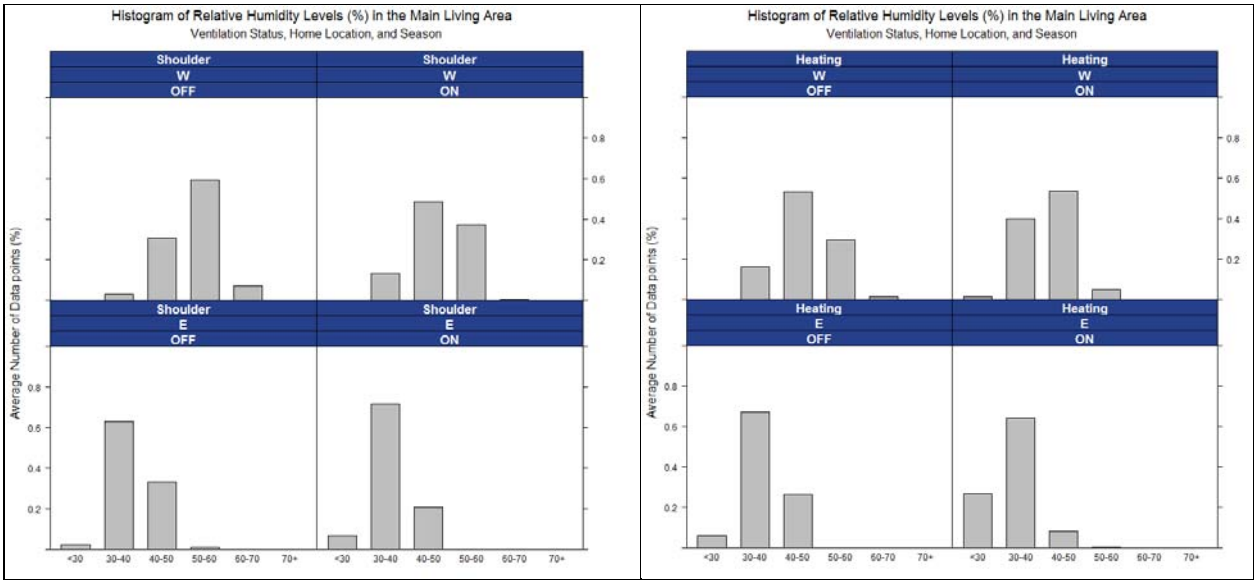
Several observations are evident:

- RH was higher in houses on the west side of the state than on the east side, which was expected because it is colder and dryer on the east side (cold air holds less moisture). The test week measurements in the east-side houses were also done earlier in the season when it was colder.
- For west-side houses, the RH was typically between 40% and 60%, and was occasionally over 60%.
- For the east-side houses, RH never exceeded 60% for any of the rooms and was below 40% a large portion of the time. During the heating season, RH sometimes dropped below 30%, mostly when the ventilation system was on.
- RH tended to be higher in the spring in the west-side houses. There was little difference between the seasons for the east-side houses. This may be partly due to the test week schedule; measurements were taken earlier in the season on the east side, when spring temperatures still may have been cold and the air relatively dry.
- RH was lower when the ventilation system was on. RH was over 60% a little less frequently for the west-side houses, but was also below 40% more often for the east-side houses. RH over 70% for the west-side houses only occurred when the ventilation system was off. The difference in the RH when the ventilation system was on or off was modest and was not as significant as the difference in CO_2 levels when the system was on or off.
- Humidity levels tended to be a little higher in the bedrooms than in the main living area.

[21] To develop the histograms, the distribution for each house is determined and normalized (%) and then the normalized values are averaged across all the houses to ensure houses are weighted equally regardless of the amount of data for each house.

Figure 30. RH by room, east side (E) or west side (W), shoulder (spring) season or heating (winter), and ventilation system operation (on or off)





When the ventilation system was on, the change in RH by ventilation system type (**Figure 31**) did not vary significantly. When the ventilation system was off, RH was slightly higher in the houses with exhaust systems. These houses also tended to have higher humidity levels when the ventilation system was on; the only situation where RH was over 60% is in houses with exhaust systems. The houses with CFA and CFA integrated with ERV systems had the lowest RH, but there are only two houses each with these systems and all four are on the east side of the state, so the low humidity may be due to the location and characteristics of these houses rather than the type of ventilation system. The HRV systems tended to have a greater increase in RH values below 30%.

The hourly distribution of RH is shown in **Figure 32**. The RH variation was less significant than the CO_2 variation. RH levels in the bedrooms were slightly higher at night and in the morning, but the difference was modest. RH levels in the main living area were generally flat. RH levels over 60% were rare, occurring most commonly in the master bedroom in the morning.

In summary, this review of RH levels shows that values over 60% are most likely to occur:

- In west-side houses,
- In the spring season,
- In the master bedroom,
- In the morning, and
- In houses with exhaust ventilation systems.

Values below 30% are most likely to occur:

- In east-side houses,
- In the heating season, and
- In houses without exhaust ventilation systems.

The humidity levels in specific houses were evaluated to confirm these results and determine whether the cases of RH over 60% or below 30% are concentrated in a few houses.

Figure 31. RH levels by room, ventilation system, and ventilation operation

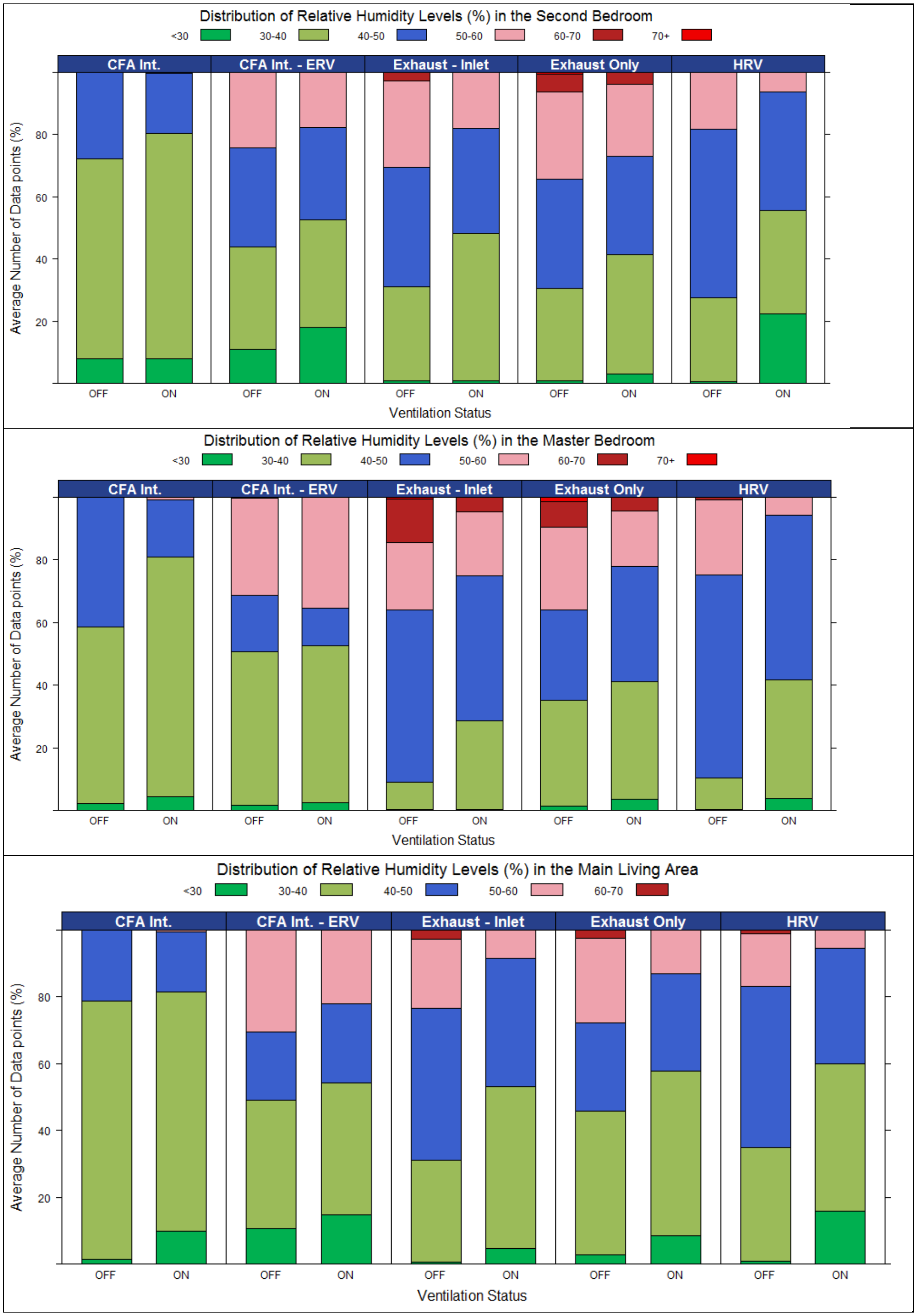
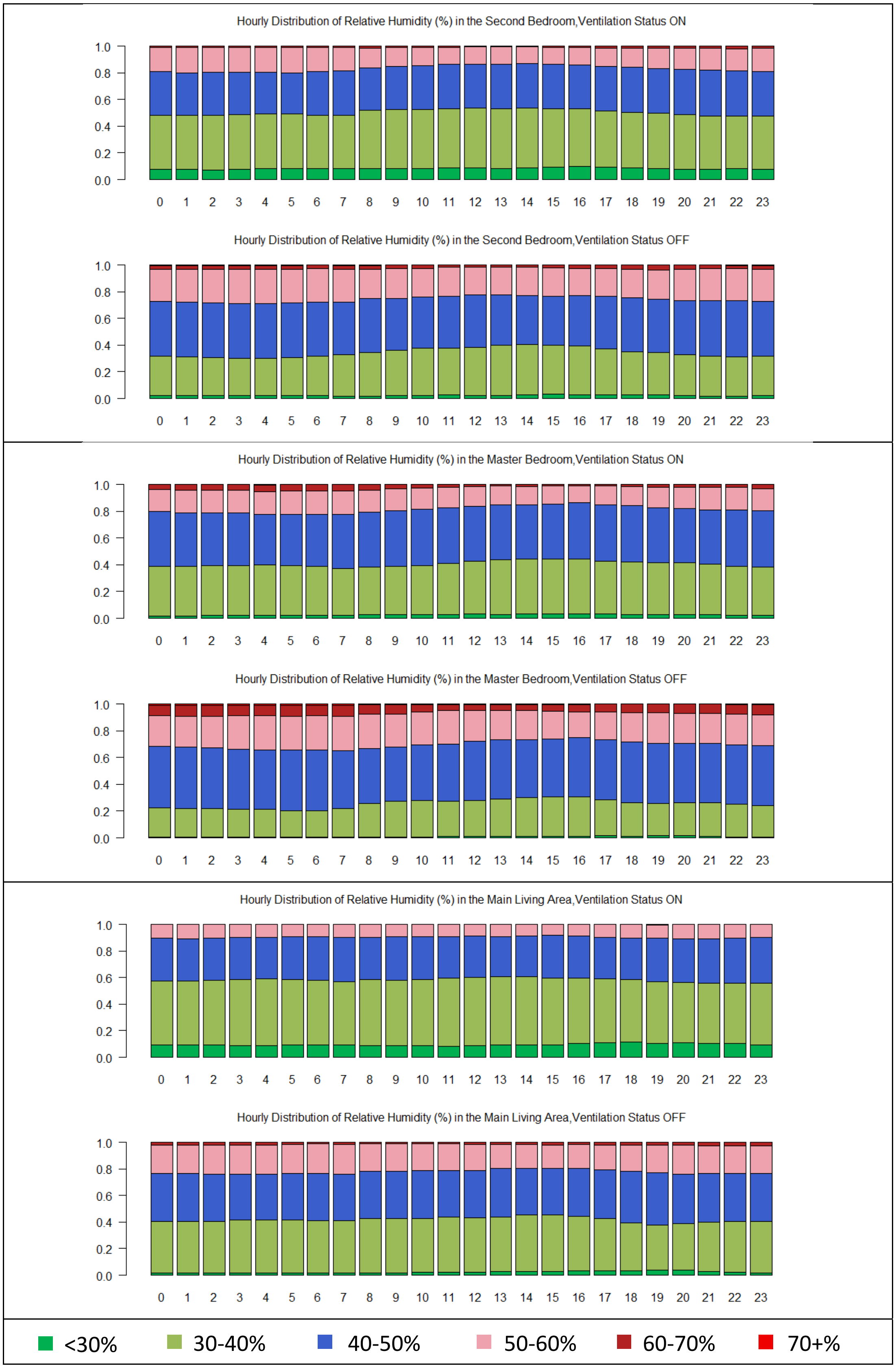


Figure 32. Hourly distribution of RH by room



House RH Levels

Higher RH levels are concentrated in a subset of west-side houses (**Figure 33**). Four houses had humidity levels over 60% when the ventilation system was on: W15, W27, W17, and W24. All of these houses had exhaust ventilation systems and radiant heat and, in most cases, RH levels over 60% occurred in the master bedroom.

Houses with higher RH levels when the ventilation systems were off also tended to have higher levels when the ventilation systems were on. Houses with exhaust-inlet and exhaust-only ventilation systems had the highest humidity levels whether the ventilation system was off or on.

Many east-side houses had RH levels below 40% more than half the time when the ventilation system was on, and some of these had significant portions of time below 30% (E10, E19, E23, and E25). Only four east-side houses (E03, E05, E09, and E18) had RH readings between 50% and 60% when the ventilation system was on. One west-side house (W12) had RH below 40% over half the time. Five west-side houses had RH below 50% all of the time when the ventilation system was on (W02, W04, W07, W08, and W12).

The two houses with the highest RH levels, W17 and W24, did not have occupied second bedrooms at night. Both of these houses have two adult occupants, where one maintains a typical work schedule and the other is home at least part-time during the day. Both houses also have dogs: W17 has two dogs and W24 has one. The west-side houses with an occupied second bedroom are W02, W06, W08, W12, **W14, W15**, **W20, W27,** and **W28**. The last five houses (in bold) have higher RH than many of the other houses.

To consider RH and CO_2 levels, the researchers compared RH and CO_2 levels in the master bedroom for houses with the highest CO_2 levels (

Table 13**)**. The west-side houses with the highest CO_2 levels also had the highest RH levels. The exception to this was W08, one of the smallest and leakiest houses in the study. For the east-side houses with high CO_2 levels, E18 and E22 also tended to have higher RH levels, suggesting that the factors that contribute to higher CO_2 levels also contribute to higher RH levels. Generally, these houses are smaller, tighter, and have more occupants.

Unlike CO_2, RH does not tend to be significantly higher for test B (door closed). This was true not just for the houses listed in **Table 13**; 11 houses had lower or equal median RH for test B compared to test A, confirming that vapor diffusion does not need an air path and moisture generation is not as directly connected to occupancy as CO_2.

Another observation from the nighttime RH values in the master bedroom is the low RH for some houses. Eleven houses (all east side) had median RH at or below 40% for test A (four were below 35%). Eight houses (one is a west-side house) had median RH at or below 40% for test B (four were below 35%). Only three houses had maximum RH over 60% in the master bedroom at night (W15, W17, and W27) for test A or B, and only one of these houses had a 75th percentile RH over 60% for either test A or B (W17). These results for high and low humidity in the master bedroom at night are consistent with the RH levels in **Figure 33**. Houses with the highest humidity levels in the master bedroom at night also have the highest humidity levels in all rooms throughout the day, which suggests that the humidity levels in the master bedroom at night are influenced more by humidity throughout the house than by the occupancy of the master bedroom at night.

Figure 33. RH in individual houses by room and ventilation system operation

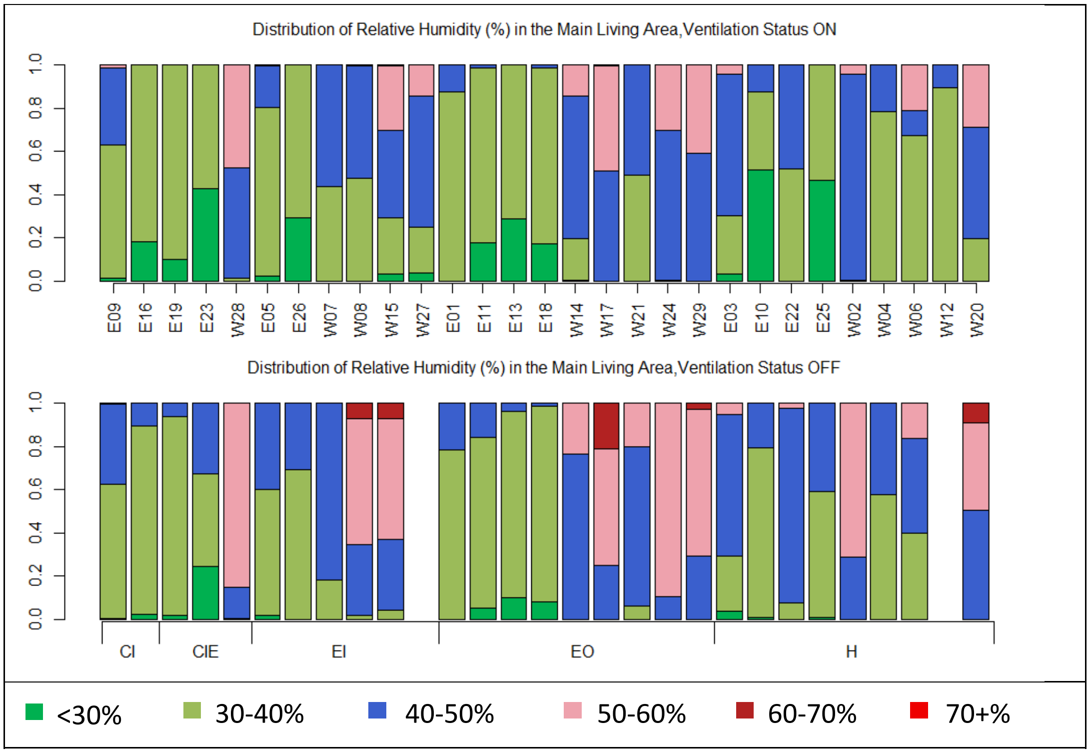


Table 13. RH and CO_2 in master bedroom at night for houses with the highest median CO_2 levels

Site #	Mean CO_2 Level (ppm)		Mean RH Level (%)		Occ.	House CFM/ Occ.	Area (ft^2)	MBR Area/ Occ.	House ACH_{50}	Return Path	Heating System Type	System Type
	Test A	*Test B*	*Test A*	*Test B*								
W17	1,039	2,042	57.8	65.0	2	25	1,240	150	2.11	no	Radiant Floor	Exhaust Only
W29	902	1,751	49.8	49.5	2	19	1,764	160	0.26	no	DHP	Exhaust Only
W20	1,250	1,589	50.1	45.8	4	15.5	1,832	130	1.94	yes	DHP	HRV
E22	859	1,385	42.5	43.6	2	40	2,115	180	0.36	yes	DHP	HRV
W15	1,181	1,365	56.0	54.1	2	19.5	1,176	225	2.3	no	Radiant Floor	Exhaust with Inlets
W24	973	1,338	49.4	51.8	2	30	1,900	120	0.71	no	Radiant Floor	Exhaust Only
E18	945	1,312	44.4	42.6	2	31	3,150	250	1.44	no	CFA	Exhaust Only
W08	1,233	-	43.1	-	5	17.5	1,080	75	3.31	no	DHP	Exhaust with Inlet
W27	1,229	-	55.2	-	3	26.5	1,216	100	2.87	yes	Radiant Floor	Exhaust with Inlets
W06	-	1,176	-	48.3	3	21	1,881	120	1.42	yes	DHP	HRV
W14	1,136	1,131	49.9	48.4	4	15	3,300	255	2.60	yes	Radiant Floor	Exhaust Only
W28	679	1,080	50.6	53.2	4	20	1,970	140	0.29	yes	CFA	CFA Int. - ERV
E05	836	1,037	40.2	43.1	4	15	1,310	120	3.18	no	Radiant Floor	Exhaust with Inlets

Correlation of RH and CO_2

The research team observed that the houses with high CO_2 levels also tended to have higher RH (**Table 11**). To examine this observation more closely, the researchers considered whether there is a correlation between the CO_2 and RH levels. In **Figure 34**, average CO_2 values are plotted versus average RH for each house and for each room. These scatterplots indicate a correlation between CO_2 and RH measurements. Houses with higher average CO_2 levels also tended to have higher RH.

To test the significance of this correlation, the researchers performed a Spearman's rank correlation test[22] on the data. The correlation coefficient is a value between zero and one, with zero being no correlation and one being perfect correlation. The correlation coefficients are 0.79, 0.64, and 0.66 for the master bedroom, second bedroom, and main living area, respectively. These results show strong positive correlation between the average CO_2 and RH levels in these houses, supporting a high level of confidence that the correlation coefficient is greater than zero. The research team hypothesizes that the correlation is strongest in the master bedroom because the occupancy and behavior patterns are most consistent in this room.

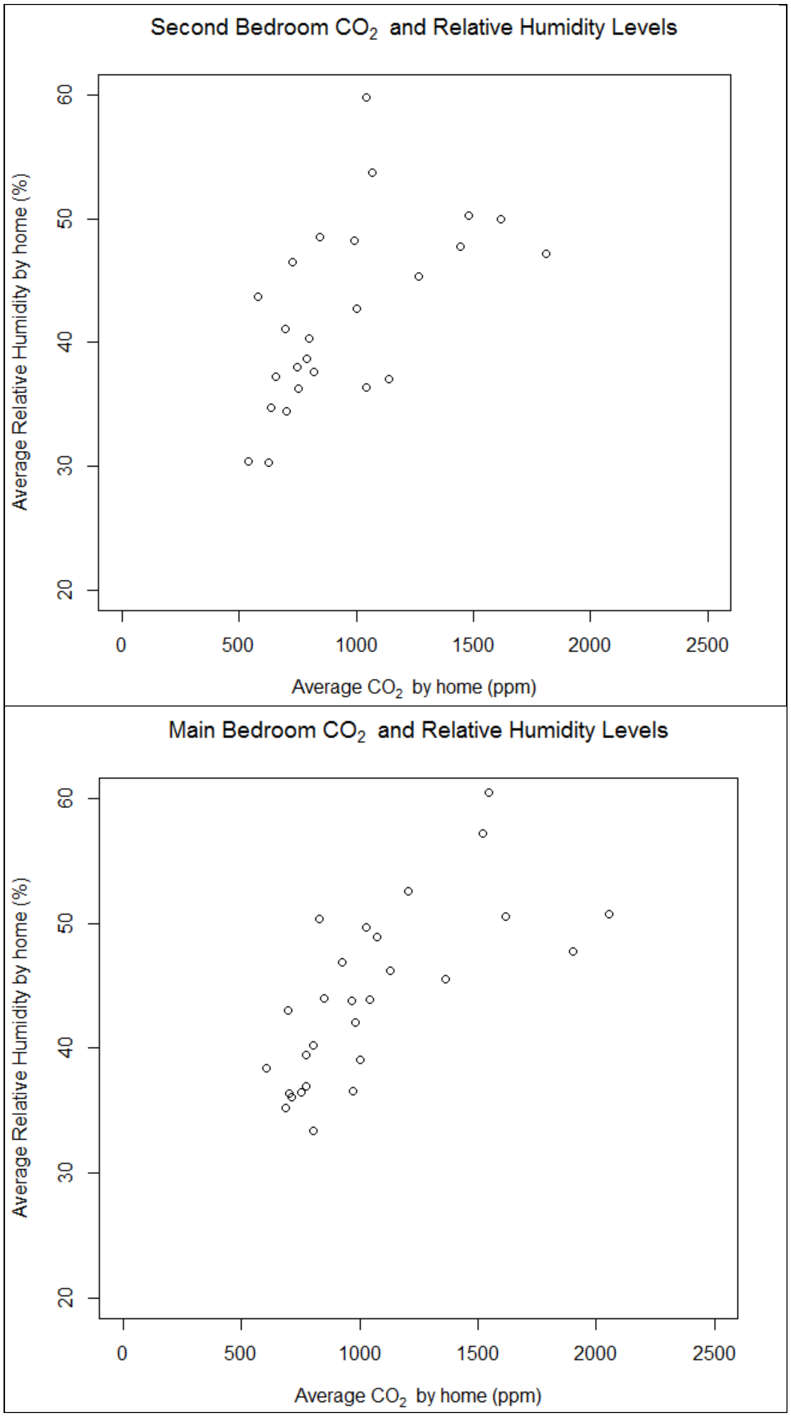
These results suggest that the factors that contribute to higher CO_2 levels in the houses also contribute to higher RH. This includes the type of ventilation system. As noted earlier, houses with exhaust ventilation systems tended to have higher RH and this is consistent with the analysis of CO_2 in the previous sections.

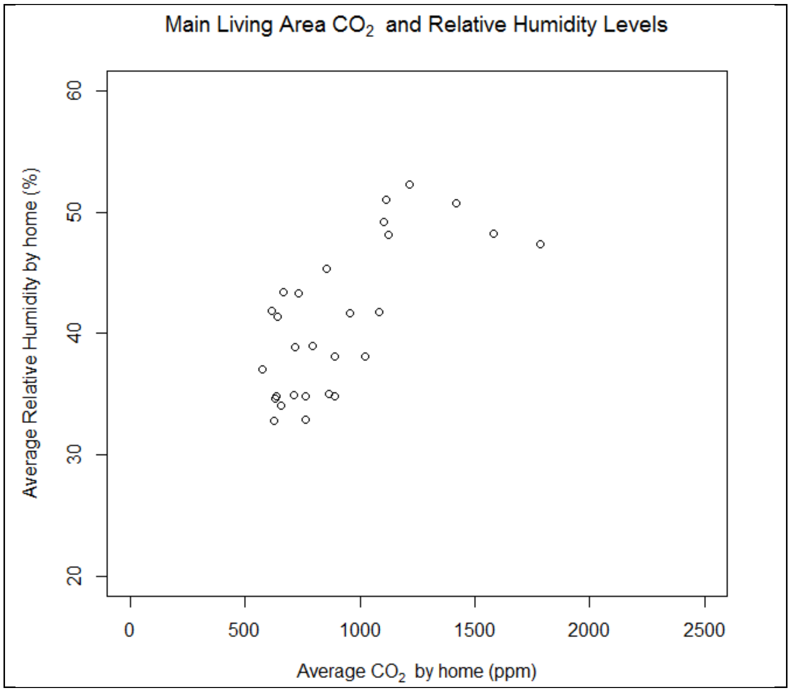
While there is a correlation between average values of CO_2 and RH for the houses, this does not mean that CO_2 and RH track (or parallel) each other over time. Given the different ways that CO_2 and RH are generated in a house and the variation in outdoor humidity levels, we would not expect CO_2 and RH levels in a house to track each other.

Another complicating factor is that RH is influenced by temperature; RH in a house will increase simply by reducing the indoor temperature (e.g., setting back the thermostat at night). Review of CO_2 and RH data over time confirms that CO_2 levels and RH levels do not closely track or parallel each other at hourly or 15-minute intervals. In other words, humidity does not necessarily increase when CO_2 increases, or vice versa.

[22] In comparison to the more standard Pearson's correlation, the Spearman's rank correlation corrects for non-normality in the data.

Figure 34. Average CO_2 values versus RH by room



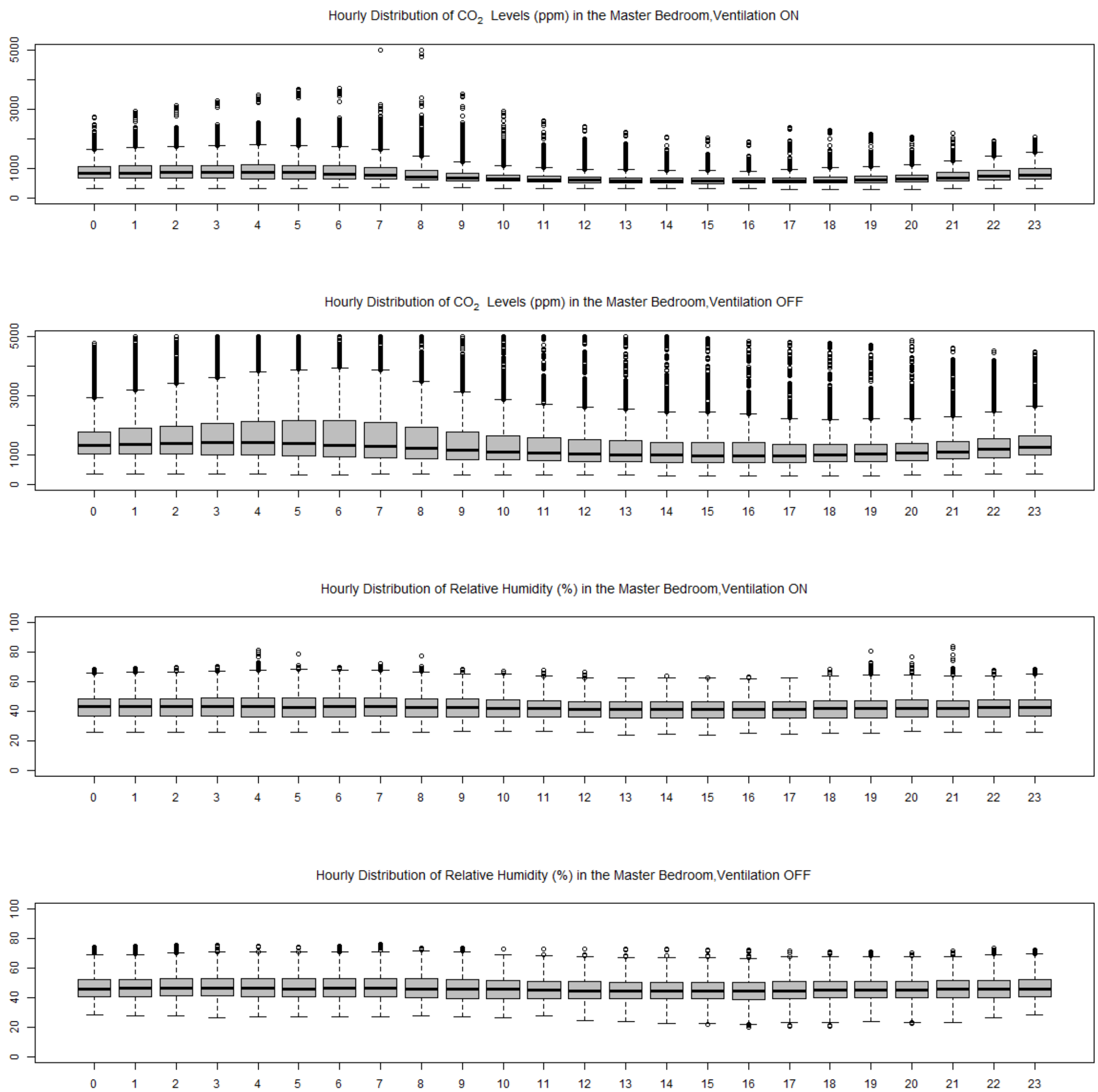


In reaching the conclusion that the houses with high CO_2 levels also tended to have higher RH, the researchers considered the daily hourly profiles for RH and CO_2. **Figure 35** shows boxplots of the hourly data for all of the houses for the master bedroom. The CO_2 levels show much more variation throughout the day than the RH levels. RH levels are consistent throughout the day and tend to vary within a similar range. This indicates that CO_2 more closely reflects occupancy patterns, while RH does not seem to be greatly influenced by occupancy. Plots for the second bedroom and the main living area (not shown) are similar with less notable hourly variation.

The research team also considered plots of CO_2 with RH over time for each of the houses. These plots of 15-minute data are not presented in this report, but visual assessment indicated that CO_2 and RH did not track each other.

These characteristics of RH suggest that it is not as good of an indicator of ventilation effectiveness as CO_2. Even though there is a clear correlation between RH and CO_2 on average, this could be more due to other influencing factors than the type of ventilation system. The difference in RH levels when the ventilation system is on or off is less significant than it was for CO_2.

Figure 35. Hourly profiles for CO_2 and RH in the Master Bedroom with Ventilation On or Off



Summary of RH Analysis

The following points summarize key conclusions from the WSU Energy Program analysis of RH data:

- Ventilation reduces RH in houses, but the impact is less significant than for CO_2.
- The RH for west-side houses is higher than for east-side houses, which reflects the colder and dryer east-side climate.
- Ventilation can contribute to lower RH levels. Low humidity seems to be more of an issue than high humidity in these houses.

- On average, there is a correlation between CO_2 and RH levels (houses with higher CO_2 levels also have higher RH), suggesting that factors that contribute to higher CO_2 also contribute to higher RH.
- RH is not as good of an indicator of ventilation system effectiveness as CO_2, given the very different ways RH and CO_2 are generated and dissipated (e.g., door closure and occupancy do not seem to affect RH). Outdoor ventilation air reduces indoor CO_2 at consistent rates, but does not affect RH consistently because the outdoor moisture level varies significantly with outdoor temperature and other factors. Likewise, indoor RH varies with temperature: reducing the temperature raises RH.

4. Estimated Energy Use

The research question posed for this study focused on the electric energy used by the ventilation systems. It was not the intent of the research to estimate the space conditioning energy use impacts of the various ventilation systems. Instead, the direct energy use of the ventilation system components and the air flows produced were measured; from this data, a more comprehensive estimate of total energy use might be developed later. Only the direct energy use of the ventilation systems is presented in this report.

Ventilation System

The electric energy use of each ventilation system was estimated based on the operation of the ventilation system during the tests and on a one-time amperage measurement under normal (low flow) conditions.

To estimate energy use, the "on" condition was multiplied by the measured power draw of the system. Most of the systems operated continuously, but one of the integrated CFA systems was set up so the furnace fan operated at least 30 minutes each hour (for heating/cooling and/or ventilation) and was left in this mode for the testing. The energy calculations reflect this.

The energy analysis did not account for energy use when the ventilation system operated under high (or boost) flows, assuming ventilation system operation under these conditions would occur only if there was a short-term spot ventilation requirement. Thus, the energy use estimates can be viewed as the additional energy that would be used by these ventilation systems compared to intermittent spot ventilation. Power factor was not measured; a constant 0.8 power factor was used in the energy use calculations based on manufacturers' specifications. If there are significant differences in power factor across the ventilation systems, these estimates of energy use do not account for those differences.

Table 14 shows the estimated fan energy use for the primary system types used in this analysis. Energy use varied widely both within and across categories. The EO systems have the lowest energy use followed by the HRV/ERV systems. The systems that are integrated with CFA have the highest energy use, although there is wide variation within this small group, as shown by the standard deviation and the difference between high and low energy use.

Table 14. Estimated electricity use by ventilation system type

System Type	Count	Average (kWh)	High (kWh)	Low (kWh)	Standard Deviation (kWh)
EO	15	162	547	34	139
HRV/ERV	11	499	765	193	196
Integrated with CFA	3	1,072	1,564	515	431
All	29	384	1,564	34	351

Note: The system type categories shown in this table for the energy analysis vary slightly from the categories used in the performance analysis. This is explained in the discussion for each system type category.

Exhaust Only

EO ventilation systems have the lowest estimated energy use as expected, but there is a very wide range from the lowest to highest use. The eight variable-speed, low-wattage exhaust fan systems had the lowest energy use, averaging 67 kWh/year with a low of 34 kWh/year. The non-variable speed, low-wattage exhaust fans had considerably higher energy use, which primarily reflects differences in fan motor efficiency.

HRV/ERV

There is almost a factor of four between the high and low energy use for the HRV/ERV systems. The difference in efficiency is due to the fan efficiency and the static pressure of the supply and exhaust duct systems. For example the sample contained two sets of houses in which each house had the same model of ERV/HRV as the other house in the set:

- In one set of houses, the energy use of each system was nearly the same, which was not surprising because these two ERVs supplied ventilation air to a CFA distribution system.
- In the other set, the energy use of one HRV was 50% higher (219 kWh) than the other, due to differences in the fan speed for the two systems. One operated at medium (3) speed and the other at low (1) speed. Settings on the ventilation systems can be different due to circumstances or preferences in a home as long as minimum ventilation requirements are met.

Two ERVs with CFA systems are included with the other HRV/ERVs for the energy analysis. The CFA fan energy use for these two systems was not measured because these systems did not rely on the CFA system for their operation; instead, they used the system's ductwork for distribution. As a result, only ERV energy use was calculated.

Integrated with CFA

Only two ventilation systems of this type were included in the study sample. For this energy analysis, a third system was added: an ERV with a CFA system. This system is included in this category (rather than the HRV/ERV category) because the forced air distribution system fans run continuously to distribute the ventilation air.

The integrated with CFA systems provide ventilation air through an outside air damper to the forced air system ducts, with distribution provided by the furnace fan. One of these two systems had a very efficient furnace fan. Even though this furnace fan operated continuously (24/7) during the tests, it still had lower energy use than the other two systems in this category and lower than the average HRV/ERV system. When this system was found, it was operating 12 hours on and 12 hours off each day. It was set to continuous operation at the start of testing to comply with state and ASHRAE Standard 62.2-2010 whole house ventilation standards.

The other integrated with CFA system was designed to operate in ventilation mode 30 minutes during each hour. This control strategy met state and ASHRAE Standard 62.2-2010 whole house ventilation standards, and it was left in this mode during the testing. However, even with this significant reduction in furnace fan operating hours, this system used more than twice as much energy as the other integrated-with-forced air system. The difference is largely due to the efficiency of the furnace fan, but duct system design also could have an impact.

The third system included in this category is an ERV system that dumps ventilation air into a ducted system with three independent distribution fans that run continuously. This is similar to an ERV with CFA, but in this case the forced air fans run continuously. The energy use of this system is the highest of all the systems mostly because of the continuous operation of the distribution fans, but the energy use of the ERV is also included.

Other Issues

Several other issues related to the energy use of the ventilation systems were not considered in this analysis, but should be addressed:

- **Ventilation air energy loads**: The energy loss from the conditioned air exhausted from the house for ventilation and brought in to replace it is significant. The actual energy required to heat this air will vary depending on the location of the house and the efficiency of the heating system. The HRV/ERV systems will usually recover 50% or more of the energy from the exhaust air, significantly reducing the heating energy required, but these are more expensive ventilation systems. The researchers focused only on direct electrical energy used by the ventilation system, and did not attempt to quantify these losses.
- **Contributions of ventilation system energy use to household internal gains**: The heat generated from fan energy use can potentially reduce heating energy use and increase cooling energy use. For exhaust systems, there is no contribution because all of the air is exhausted. However, the integrated with CFA system fans are on the supply side, so any heat energy goes to the household space. Some portion of this energy would be useful heat during the heating season. There would be minimal impacts on cooling from this fan heat energy except for areas where there is cooling load. The internal gains from HRV/ERV systems would be somewhere between these two cases because there is both an exhaust side and a supply side. It was not the purpose of this study to quantify these gains and losses.
- **Duct and distribution system energy losses**: Energy losses from ducts or distribution systems can be due to air leakage, heat loss, and pressure drop in ducts. Energy loss due to air leakage or heat loss is minimal for most of the systems in this study because ducts are either in heated spaces or are very well insulated and sealed. However, at least one system had ducts in the crawl space and some of the HRV/ERV units were located in the crawl space, attic, or other semi-heated spaces. In these cases, duct leakage-induced infiltration and conduction, and duct leakage heating energy impacts are likely. Because the overall effectiveness of the system was under investigation, these factors were not examined in detail in this study.
- **Maintenance issues**: During the initial site visits, the terminus hoods and dampers on many of the exhaust systems were found to be partially blocked or had obstructed operation due to lint buildup or improper installation. This contributes to additional static pressure, higher energy consumption, and reduced flow rate. Before beginning the study, the researchers replaced dirty filters and cleaned fans so the measurements of energy use reflected clean systems. One measurement taken with a dirty fan before cleaning showed almost 30% higher energy use. Some

of the variable speed exhaust fans increase speed to maintain flow if the static pressure increases due to dust build up, dirty filters or blocked flow. If filters are not replaced and fans and their housing are not kept clean, the energy use of some ventilation systems will increase or the air flow rate will be reduced. Maintenance, an important component of ventilation effectiveness, is examined in the next section.

- **Run time and system control**: How systems are controlled impacts energy use. The amount of time the ventilation fan operates impacts energy use, as do other control features, such as fan speed settings and how often and how long the system goes into high-speed mode. Not all users understood how to manage the control features of the systems. For testing, all but one of the systems ran continuously during the ventilation system "on" tests in order to meet the requirements of ASHRAE Standard 62.2-2010.

In summary, the ventilation system energy use varied significantly across the three different ventilation system types. The CFA integrated systems used the most energy; EO systems used the least. There was also significant variation within each ventilation system category due primarily to the fan efficiency. The complete analysis for each system is included as **Appendix B**: Table of Short-Term Study Calculated ACH Rates by Test.

5. Home Occupant Knowledge and Satisfaction with Ventilation Systems

The home occupants were interviewed at the beginning of their participation in the long-term study to assess their satisfaction with their system and its performance, including comfort and indoor air quality, and knowledge of their ventilation system, its condition, and its operation and maintenance requirements.

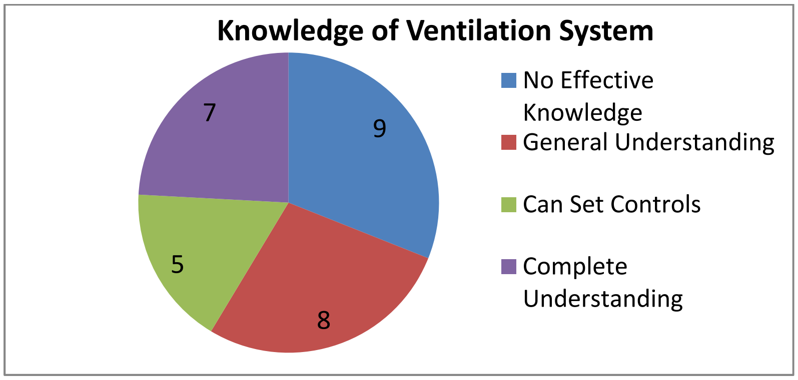
Satisfaction

The occupants of 27 of the 29 houses (93%) reported general satisfaction with the performance of their ventilation systems – most without qualification.

Knowledge

The home occupants' knowledge of their ventilation systems ranged from very limited to very knowledgeable. **Figure 36** shows the occupants' spread among the four knowledge groups: no effective knowledge, general understanding, able to set controls, and complete understanding.

Figure 36. Spread of the four knowledge groups



The home occupants who had no effective knowledge of their systems did not understand the system function, controls, or maintenance. Those who had a general understanding knew how the system operated, but may not have known how to control or maintain the system. Occupants who understood how to control the system were quite knowledgeable about settings and maintenance. Those who had a complete understanding were likely to be involved in the design or construction of the house.

The fact that over 90% of the occupants were satisfied with their system performance and indoor air quality even though over half of them did not have enough knowledge to operate or maintain the system is troubling, especially where the lack of knowledge correlates with unresolved operation and maintenance issues found by the researchers. It means that occupant satisfaction is not a good indicator of ventilation system performance. Further, if something was seriously wrong with the system, the home occupant would probably be unable to recognize it or take appropriate action.

Home occupants may be confused about the function of inlet vents. Of the six houses where the normal position of the vents prior to the study was known, they were closed in four houses and open in two houses. In two of the houses with inlet vents (E05 and E26), the researchers reported that the home occupants did not understand the function of the inlet vents. Even during the long-term study, when home occupants were briefed about the proper operation of inlet vents by the research team, inlet vents were often left closed in heating season and forgotten about in non-heating season. Homeowners were confused about what position they should be in and what they are supposed to do.

The study did not include detailed interviews to ascertain where occupants obtained their ventilation system knowledge. This would still be possible, and probably would be helpful in designing ways to increase home occupant knowledge. The groups that had complete understanding, understood the controls, and were able to maintain and operate their systems may have insights about how to effectively convey this knowledge to home occupants.

System Condition

Once a house qualified for the study – meaning that it had the needed ventilation system type and tested within the required range of airtightness – the next step was to determine the condition of the ventilation system. This included a thorough inspection. In some cases, the system needed repair. In many cases, filters and other components needed to be cleaned in order to operate properly.

The system was also tested and, if necessary, brought into legal compliance with Washington state law. Washington's ventilation requirement is found in Washington State Ventilation and Indoor Air Quality Code 2006 Edition (Chapter 51-13 of the Washington Administrative Code). This code has been interpreted by the State Building Code Council to be met by complying with the ASHRAE Standard 62.2-2010 (SBCC Interpretation 10-05). If the system was not in compliance after necessary repair and cleaning, the controls were adjusted to provide qualifying operation time. These adjustments are included in the control issues category, which also includes inaccessible controls and other issues that did not result in noncompliance with Standard 62.2-2010.

Noncompliance with Standard 62.2-2010 on initial characterization was found in ten of the houses – about one-third of the total sample. Most of the systems in this category were EO or exhaust with inlet vent systems. The HRV and ERV systems tended to exceed the minimum requirement – some by large margins. The main issue was lack of sufficient operation time in the control setting. Some of the systems were unable to meet the required minimum flow rate because of improper installation or clogged filters. After repair, cleaning, and resetting controls, all of the systems met the ventilation requirements of Standard 62.2-2010, and all of the testing was done with the systems in this condition.

Although home occupants were generally satisfied with their systems, the systems exhibited a number of issues, such as design and installation problems, including controls that needed to be reset and fans and ducts that needed to be cleaned in order to operate properly. Controls were often placed in inaccessible locations, and they all lacked labels, meaning that technically none of the systems complied with code requirements.

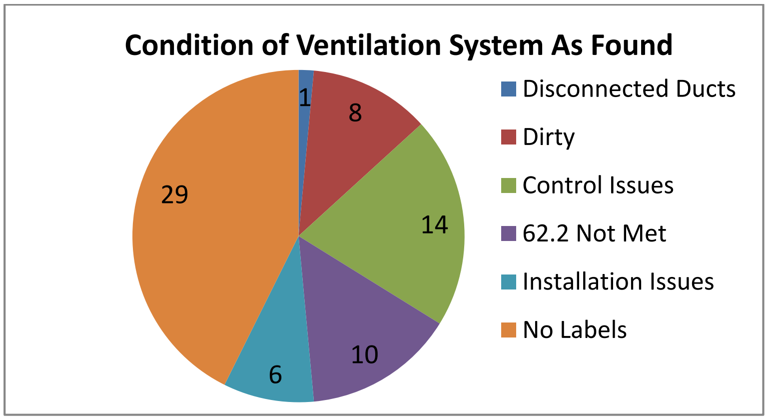
The researchers also found that some of the ¼-inch mesh pest screens at terminations and intakes on the exterior of houses were plugged with insects and lint. Without proper maintenance, most systems can eventually fail to deliver expected airflow. These screens will not likely receive routine maintenance when they are located in inaccessible areas, such as on roofs.

Several houses with exhaust systems were found to have damper movement impeded or completely blocked by duct fasteners, paint, or a sharply bent exhaust duct. Without flow-rate testing, it is likely these problems would not be discovered and the systems would never have provided proper flow rate.

With HRV/ERV systems, commissioning with flow-rate testing would help to assure effective distribution and solve other problems as well. For example, one HRV system was found to be installed backward, with the bedrooms connected to the exhaust side and bathrooms and kitchen connected to the supply side. The researchers fixed this issue prior to characterizing the system.

Figure 37 depicts the issues discovered by the researchers when auditing the ventilation systems. Many houses had more than one issue. All houses lacked labels on the ventilation systems as required by state law. Labels are important because, without them, it is highly likely the system will be deactivated.

Figure 37. Ventilation system issues observed



As indicated in **Table 15**, it is highly likely that these systems will not be operated or maintained as intended without effective home occupant education. The researchers found all home occupants to be interested in learning about their ventilation systems and capable of operating and maintaining them when shown how to do it, so targeted education efforts look promising.

Table 13 summarizes the number of issues belonging to each knowledge class as determined by the field researchers. It appears that an inverse relationship exists between the level of knowledge and the number of issues exhibited by the ventilation system. The less knowledge demonstrated by the homeowners, the greater number of issues noted. The ratio of issues simply divides the total issues per knowledge class by group size and expresses it as a percentage. The higher the percentage, the greater the per capita system issues for that group. Because the ratio of issues increases as knowledge decreases, a strong correlation is indicated.

Table 15. Occupant knowledge of ventilation system maintenance and compliance needs

Knowledge Class	Group Size	Dirty	Malfunction	Control	Duct	62.2 Not Met	Total Issues	Ratio of Issues per Group Member
Complete understanding	7	1	1				2	.29
Able to set controls	5	2					2	.40
General understanding	8	2	2	6	1	4	15	1.88
No effective knowledge	9	3	3	8		6	20	2.22

Correlation of Knowledge, System Condition, and Satisfaction

There was a substantial relationship between knowledge and ventilation system issues, except for labeling, which was universally ignored by the installers of the systems. The percentage of issues per group (aside from labeling, which is not included in the analysis) increased as knowledge decreased.

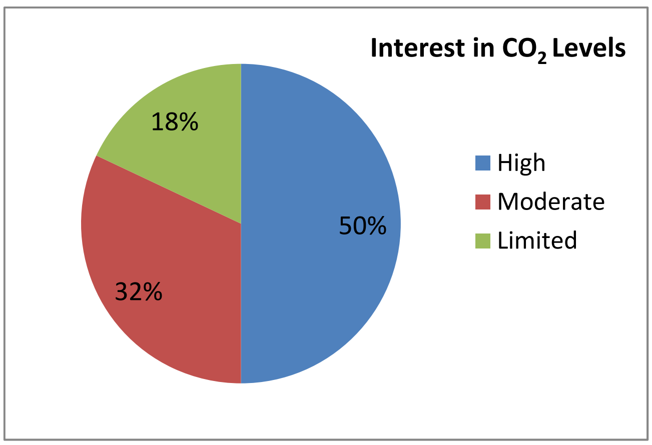
No correlation was found between homeowner satisfaction and system knowledge. Of the two dissatisfied home occupants, one was very knowledgeable and had modified ERV supply and exhaust ports for comfort but still had indoor air quality and moisture issues that were resolved by the field researchers. The second dissatisfied home occupant was not knowledgeable, but was dissatisfied with the ability of the system to remove moisture. The problem was diagnosed by the researchers as low air flow caused by improperly installed ductwork, which was solved when the builder replaced the duct.

Interest in CO_2 Levels

The WSU Energy Program team also ascertained the interest of most of the home occupants (22) in the CO_2 levels shown by the monitors placed in their houses. Most of the occupants (50%) were very interested while the second largest group (32%) was moderately interested. **Figure 38** shows the occupants' level of interest in CO_2 readings.

Over 80% indicated moderate to high interest in the CO_2 readings, with the great majority of these having high interest. This indicates that CO_2 monitors in bedrooms may be a way to interest people in the operation of their ventilation systems.

Figure 38. Occupant interest in CO_2 readings



Summary Conclusions

This study presents the findings and conclusions of a ventilation effectiveness study in houses with low air leakage. A total of 29 houses with five different types of ventilation systems were included in the study. The ventilation system types that were studied were exhaust ventilation (EO and exhaust with inlet vents), HRV (including ERV), CFA integrated, and CFA integrated with ERV.

The summary conclusions presented here are drawn from the research findings in this report.

Relative Performance and Ventilation System Effectiveness

- When the ventilation system was off, measured natural infiltration and CO_2 levels clearly demonstrated the need for ventilation in houses with low air leakage.
- The ventilation systems significantly reduced CO_2 levels in the bedrooms at night compared to no ventilation.
- In general, ventilation systems that provided ventilation air to each space (CFA integrated and HRV) provided more effective ventilation than the exhaust-type systems. This is particularly true for the bedrooms when the doors were closed. However, there were differences in the relative performance of the different systems across the analysis methods used.
- There was a great deal of variation in ventilation performance among the houses, both within and across ventilation system types. For example, some exhaust systems performed better than some HRV systems.
- The most relevant factors impacting HRV performance are balancing issues causing low flow to rooms and ventilation operation.
- A comparison of exhaust ventilation systems with and without inlet vents provided inconclusive results; a clear benefit from inlet vents is not evident. In the short-term test, the inlet vents provided a modest benefit in one case, when the bedroom doors were closed. For the long-term and normal period studies, no benefit from inlet vents was evident.

Factors Influencing Ventilation Effectiveness

- Heating system type was important. Houses with CFA heating systems tended to have lower CO_2 levels.
- Important factors include house size, bedroom area per occupant, house airtightness, ventilation return air path, ventilation per occupant, ventilation operation, door status and occupancy.
- Ventilation systems that were less effective in maintaining CO_2 levels tended to have lower ventilation flows in the rooms being ventilated. This explains some of the variation in performance across the same type of ventilation system in different houses.
- Other factors not considered in this analysis could influence CO_2 levels: opening windows, operating spot ventilation, and operating a clothes dryer.

Relative Humidity

- Ventilation reduces RH in houses, but the impact is less significant than the impact of ventilation on CO_2.

- Ventilation can contribute to low RH levels. Low humidity seems to be more of an issue than high humidity in these houses.
- On average, there is a correlation between CO_2 and RH levels (houses with higher CO_2 levels also have higher RH), indicating that factors that contribute to higher CO_2 also contribute to higher RH.

Energy Use

- There is a fairly wide variation in fan energy use both within and across ventilation system types.
- The exhaust systems have the lowest fan energy use (34 to 547 kWh/year), followed by the HRV/ERV systems (193 to 765 kWh/year), and the integrated with CFA systems (515 to 1,564 kWh/year).
- This analysis considered only the direct energy use of the ventilation systems. Other energy use factors, such as ventilation air energy loads (HRV/ERV systems have heat recovery), are appropriate topics for further analysis.

Home Occupant Knowledge and Satisfaction

- The home occupants' knowledge of their ventilation systems ranged from very limited to very knowledgeable. Fewer than half had a good understanding of how to maintain and control their systems.
- WSU Energy Program researchers identified a number of ventilation system issues during site visits to the participating homes, including lack of ventilation systems labels as required by Washington state code, control issues, and fans and ducts that were in need of cleaning or repair.
- This study demonstrated a substantial relationship between lack of knowledge and higher numbers of ventilation system issues (except labeling, which was universally ignored).
- Without effective home occupant education, it is highly unlikely that these systems will be operated or maintained as intended. Over time, this could result in significant deterioration in system performance.

Recommendations

This Pacific Northwest Ventilation Effectiveness Study provided valuable experience and insights about ventilation system effectiveness in new houses that are in the top tier of house airtightness. These findings have implications for policy and building codes as well as future research.

Codes and Standards

Public policy should focus on ventilation effectiveness. The results of this study apply to any gaseous or particulate pollutant, including carbon monoxide, radon, nitrogen oxide, formaldehyde and cigarette smoke, as well as CO_2 and water vapor. This is particularly important as houses become tighter like those in this study, a trend likely to continue into the future.

The study findings revealed key areas that clearly require policy and code changes:

- No houses had labels on ventilation controls as required by code. The existing legal requirement that ventilation controls be labeled needs to be enforced.
- Field research identified a number of system issues and a correlation between the number of issues and occupant knowledge of their ventilation system. Builders should be required to brief home buyers on ventilation system operation and maintenance, and system instructions and a schematic should be left at the house for reference and future occupants.
- Field research identified control system and access issues. Systems should be designed for easy operation and maintenance. Controls should be in a convenient location and filters should be accessible. Screens that can clog with lint and require cleaning should not be located at roof level or be otherwise difficult to access; they should be located where the home occupant can easily access and clean them.
- Field research identified systems that did not meet minimum ventilation requirements, and the study results identified a great deal of variation in ventilation system performance, suggesting flow and balancing issues. All ventilation systems should be commissioned for proper flow and control settings.
- Study results did not support the conclusion that inlet vents are beneficial. Interviews with home occupants showed 67 to 80% kept them closed. While not definitive, the results raise questions about whether inlet vents provide any benefit. The requirement for inlet vents should be reviewed.
- Power usage and effectiveness indicate that CFA Integrated Systems should continue to be a ventilation option, but only with ECM motor variable speed air handlers.
- Study results show that ventilation systems that provided adequate ventilation to each space were most effective. This was particularly true for bedrooms when doors were closed. Ventilation systems need to provide adequate ventilation for all occupied spaces. Each space needs to have a supply and/or return path to the ventilation system.

Potential Areas for Future Field Research

This study did not address several topics, which should be considered for future research:

- Only direct ventilation (fan) energy use was analyzed. Research the exhaust air penalty of each system and the actual heat recovery of HRV and ERV systems. Consider other factors such as the impact of air leakage, conductive heat loss, and duct static pressure on ventilation system energy use and performance.
- Household occupant behavior was not address and could be an important influence on ventilation effectiveness. Account for the impact on ventilation effectiveness of exhaust appliances other than the ventilation system, window opening, and other related behavior.
- The study collected daily outdoor temperature and wind speed data, which was not adequate for drawing conclusions. Explore the impact of outdoor temperature and wind speed on ventilation effectiveness using hourly measurements.
- The field research suggests that ventilation performance could decline over time. Consider whether ventilation effectiveness declines over time due to operation and maintenance issues.
- This study used CO_2 as a trace gas to evaluate ventilation effectiveness. Other gaseous pollutants may have different characteristics. Consider if gaseous pollutants such as radon are mitigated by effective ventilation.
- The study was conducted with systems operating at or above the minimum ventilation rates required by ASHRAE 62.2-2010. It would be valuable to learn the *lowest* ventilation rates at which effective ventilation can be provided by each system type.

Insights about Conducting Future Research

The experience gained from evaluating the performance of ventilation systems is valuable for future research. This learning experience provided the following lessons and insights:

- **Establish consistent field data collection protocols**: House characteristics and measurements were collected at each house during instrumentation set up. Consistent measurement protocols, forms for recording the data, data entry, and data quality control procedures need to be established at the beginning of the project to ensure that consistent, high-quality data is collected and reduce the need to repeat measurements or deal with missing data. On a larger scale, this is also important for ensuring consistency among different research studies.

- **Provide consistent system set-up protocols**: Each ventilation system was set up to meet ASHRAE Standard 62.2-2010. However, this is a minimum standard and systems can exceed this performance level. In this study, some systems had much higher flows than others. To ensure valid comparisons, the controls on different systems should be set using a standard process. This is particularly true for ventilation systems that have many control options. The implications of occupants changing the settings also need to be considered.

- **Encourage real-time, remote data management and quality control procedures**: This field study involved a relatively small number of houses but still produced a large amount of data. The ability to collect data in real time rather than waiting for the next physical visit to the house to collect the data would help reduce issues caused by missing data. If real-time, remote data collection is not possible, cost-effective procedures need to be set up to validate that data is being recorded properly so problems can be corrected. Quality control and data documentation need to occur in real time.

- **Simplify the experimental design**: The experimental design for this study was complicated. There were six test weeks in both the heating and shoulder season for standard houses and ten test weeks in each season for houses with inlet vents. This is challenging for occupants and may have contributed to the lack of compliance for some houses, particularly the houses with inlet vents. It also significantly complicates the analysis because the measured data needs to be tested for compliance. Significant portions of data were excluded because test conditions were not met, and this loss of data made it much more difficult to make valid comparisons. A simple experimental design with longer data collection periods would provide more data for analysis and make it easier to draw conclusions.
- **Determine analysis procedures at the beginning of the study**: The analysis approach should be developed as part of the experimental design before field data collection begins. Preliminary analysis of data should occur during the data collection period to validate the process and ensure that valid results can be obtained. This allows experimental design problems to be addressed.

Appendix E: Data Quality Issues and Data Compliance Approach describes in more detail the data quality issues and data compliance challenges.

Appendices

A. House Characteristics
B. Ventilation System Characteristics and Energy Use
C. Short-Term Test ACH Rates
D. House-By-House Figures of Long-Term Study CO_2 Levels
E. Data Quality Issues and Data Compliance Approach

Appendix A: Table of Ventilation System Characteristics and Energy Use by Test Site

				Energy Use (Power Factor 0.8)					Ventilation Flows			
House	Category	Ventilation System	Operation Schedule	Amp Draw – Normal Operation	Amp Draw – Boost	Voltage (V)	Ventilation Fan Wattage (W)	Energy Use Normal Operation (kWh/year)	Measured Ventilation CFM[1]	ASHRAE 62.2 Ventilation CFM[1]	% of 62.2 Ventilation	Measured CFM/Occupant
E01	Exhaust	WH Exhaust	Continuous 24/7	0.07	0.12	120	6.7	59	60	47	129	30
E03	HRV	HRV	Continuous 24/7	0.57	2.72	120	54.7	479	51	49	104	25.5
E05	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.65	N/A	120	62.4	547	59	40	147	15
E09	Integrated	Integrated w/ CFA	50% run time hourly	3.60	N/A	120	345.6	1135	135/50%	45	150	22.5
E10	HRV	HRV	Always on low	0.80	2	120	76.8	673	76[2]	34	224	38
E11	Exhaust	WH exhaust, upstairs bathroom	As-found set for 14 hours daily run time: 4-8 am, 10-2, 4-10 pm. Continuous for study	0.38	No boost	120	36.5	320	90	58	155	22.5
E13	Exhaust	WH Exhaust	On 100% – Fan was hard-wired into house circuit, breaker also controlled kitchen lights, etc.	0.23	Boost disabled by WSU upon request	120	22.1	193	55	36	153	55
E16	Integrated	Ducted forced air with Integrated w/CFA	As-found 12 hours ON, 12 hours OFF	0.70	N/A	120	67.2	515	64	53	121	32
E18	Exhaust	WH Exhaust	Continuous 24/7	20.0	No boost	120	20.0	175	62	51	120	31
E19	HRV	Integrated ERV	Operated on "Intermittent" as-found, operated on "Minimum" during testing cycles.	0.34	0.78	120	32.6	286	44/75[2]	39	113/192	22/37.5[2]
E22	HRV	ERV	100% ON	0.12	0.68	230	23.022.1	202193	80	44	182	40
E23	HRV	Integrated ERV	Continuous 24/7	0.33	0.83	120	31.7	278	52	47	111	26
E25	HRV	HRV	As-found 40-min	0.76	0.90 (speed 5	120	73.0	639	67	45	149	33.5

				Energy Use (Power Factor 0.8)					Ventilation Flows			
House	Category	Ventilation System	Operation Schedule	Amp Draw – Normal Operation	Amp Draw – Boost	Voltage (V)	Ventilation Fan Wattage (W)	Energy Use Normal Operation (kWh/year)	Measured Ventilation CFM[1]	ASHRAE 62.2 Ventilation CFM[1]	% of 62.2 Ventilation	Measured CFM/Occupant
			recirculation and 20-min OSA. Operated speed 3 continuous ON/OFF for study. System boosts to speed 5 with bath switches									
E26	Exhaust	WH Exhaust	As-found, max 30-min. runtime, manually operated. Continuous for study	0.17	N/A	120	16.3	143	45	42	107	22.5
W02	HRV	HRV	Low speed 24/7	0.9	1.25	120	86.4	757	80	81	99	16
W04	HRV	HRV	As found, continuous operation with 1 hour of occupant operated boost per day	0.22	2.40	230	42.240.5	370355	75	60	125	37.5
W06	HRV	HRV	As found, 20 min. on at low speed every hour. Intended continuous for study, but may have operated only 20 minutes/hour	0.5	1.20	120	48.0	420	63	49	129	21
W07	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.3	N/A	120	28.8	252	82	46	178	41
W08	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.2	N/A	120	19.2	168	88	56	157	17.5
W12	HRV	HRV	24/7 with bath exhaust and heating boost to speed 3	0.4	0.82	230	76.873.6	673645	78	49	159	19.5
W14	Exhaust	WH Exhaust	Continuous 24/7	0.07	0.10	120	6.7	59	60	56	107	15

				Energy Use (Power Factor 0.8)					Ventilation Flows			
House	Category	Ventilation System	Operation Schedule	Amp Draw – Normal Operation	Amp Draw – Boost	Voltage (V)	Ventilation Fan Wattage (W)	Energy Use Normal Operation (kWh/year)	Measured Ventilation CFM[1]	ASHRAE 62.2 Ventilation CFM[1]	% of 62.2 Ventilation	Measured CFM/Occupant
W15	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.08	Deactivated	120	7.7	67	39	42	93	19.5
W17	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.04	0.07	120	3.8	34	50	42	119	25
W20	HRV	HRV	Continuous low-speed with bath boost	0.91	1.05	120	87.4	765	62	48	129	15.5
W21	Exhaust	WH Exhaust	Continuous 24/7, both fans	0.04	0.07	120	3.8	34	61	49	124	30.5
W24	Exhaust	WH Exhaust with ducted passive vents	Continuous 24/7	0.04	Deactivated	120	3.8	34	60	49	122	30
W27	Exhaust	WH Exhaust with inlet vents	Continuous 24/7	0.07	0.10	120	6.7	59	80	36	222	26.5
W28	Integrated	ERV with independent ducted fan assist distribution	Continuous 24/7 low-flow balanced flow with bath boost	1.86	3.67	120	178.6	1564	80	57	140	20
W29	HRV/ Exhaust	HRV (set to exhaust only for long-term study)	Continuous 24/7 level I (exhaust only)	0.18	0.40	230	34.633.1	303290	38	48	79	19

1. Continuous unless otherwise noted
2. Reported flows inconsistent

Appendix B: Table of Short-Term Study Calculated ACH Rates by Test

					Average measured test ACH of specific locations in the home			Average R^2		
Site ID	Test Protocol	Ventilation System Status	Door Status	Inlet Vent Status	Second Bedroom	Master Bedroom	Main Living Area	Second Bedroom	Master Bedroom	Main Living Area
E01	A	On	Open	NA	0.27	0.28	0.26	0.94	0.99	0.99
E01	B	On	Closed	NA	0.20	0.17	0.27	0.95	0.87	0.99
E01	C	Off	Open	NA	0.05	0.05	0.07	0.98	0.89	0.91
E03	A	On	Open	NA	0.28	0.21	0.2	0.99	1.00	1.00
E03	B	On	Closed	NA	0.69	0.2	0.25	0.99	1.00	0.99
E03	C	Off	Open	NA	0.06	0.04	0.07	0.89	0.99	0.95
E05	A	On	Open	Closed	0.45	0.46	0.37	0.99	0.99	1.00
E05	A	On	Open	Open	0.51	0.35	0.47	0.99	0.99	0.99
E05	B	On	Closed	Closed	0.57	0.28	0.51	1.00	1.00	0.98
E05	B	On	Closed	Open	0.50	0.34	0.39	1.00	1.00	0.99
E05	C	Off	Open	Closed	0.13	0.1	0.1	0.98	0.99	0.91
E09	A	On	Open	NA	0.36	0.35	0.38	1.00	1.00	1.00
E09	B	On	Closed	NA	0.33	0.33	0.35	1.00	1.00	1.00
E09	C	Off	Open	NA	0.05	0.07	0.09	0.96	0.99	0.99
E10	A	On	Open	NA	0.62	0.5	0.52	0.99	0.99	0.99
E10	B	On	Closed	NA	0.94	0.46	0.47	1.00	1.00	0.99
E10	C	Off	Open	NA	0.23	0.25	0.22	1.00	1.00	0.99
E11	A	On	Open	NA	0.32	0.36	0.39	1.00	1.00	0.98
E11	B	On	Closed	NA	0.16	0.31	0.45	0.99	0.99	0.97
E11	C	Off	Open	NA	0.08	0.03	0.14	0.99	0.97	0.98
E13	A	On	Open	NA	0.24	0.42	0.44	0.99	1.00	1.00
E13	B	On	Closed	NA	0.16	0.25	0.44	0.99	0.99	0.99
E13	C	Off	Open	NA	0.03	0.04	0.04	1.00	0.99	0.98
E16	A	On	Open	NA	0.20	0.21	0.21	1.00	1.00	1.00

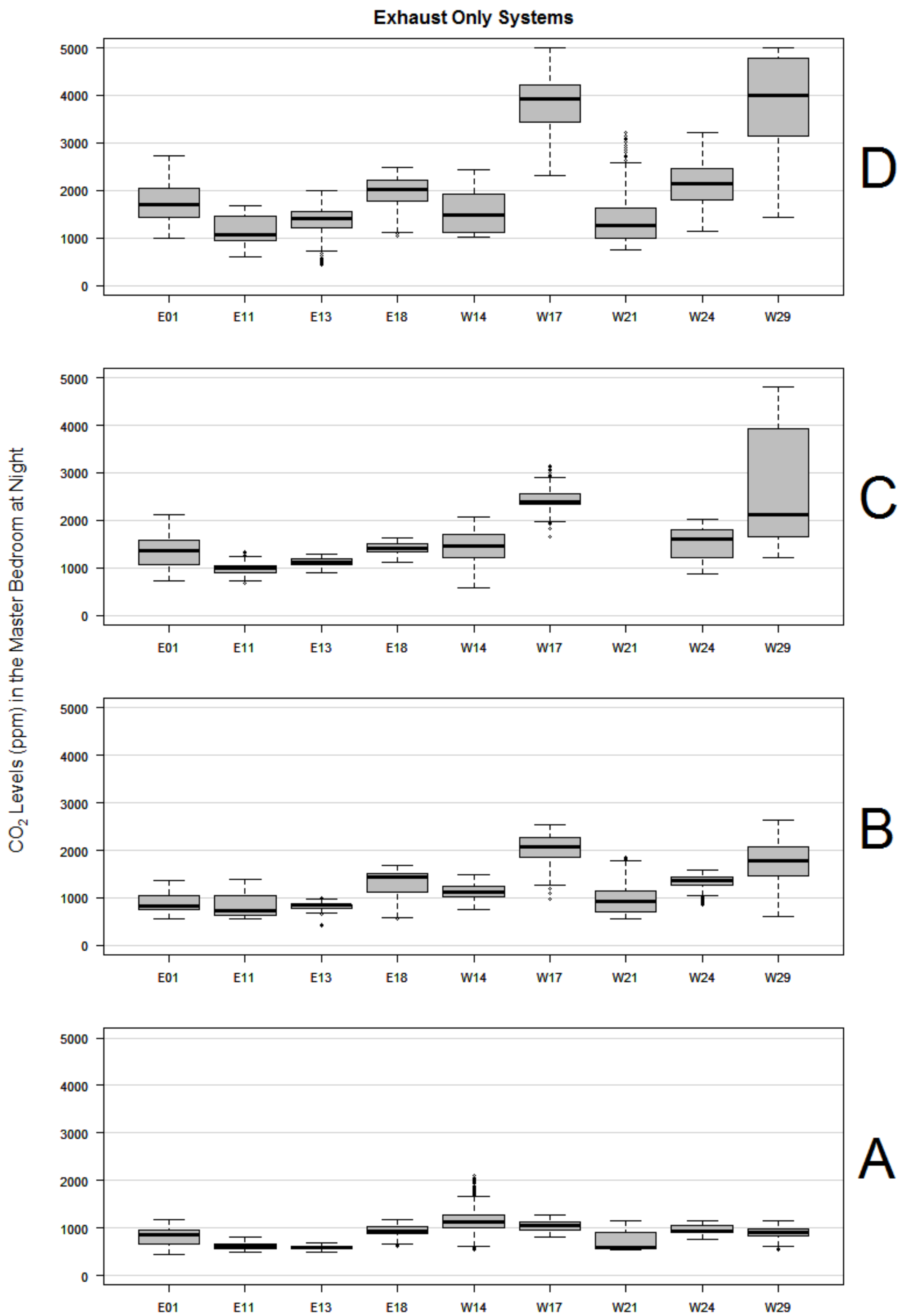
					Average measured test ACH of specific locations in the home			Average R^2		
Site ID	Test Protocol	Ventilation System Status	Door Status	Inlet Vent Status	Second Bedroom	Master Bedroom	Main Living Area	Second Bedroom	Master Bedroom	Main Living Area
E16	B	On	Closed	NA	0.21	0.24	0.21	1.00	0.98	1.00
E16	C	Off	Open	NA	0.04	0.05	0.06	0.96	0.99	0.90
E18	A	On	Open	NA	0.21	0.15	0.09	0.99	0.99	0.99
E18	B	On	Closed	NA	---	0.15	0.09	---	0.91	1.00
E18	C	Off	Open	NA	0.10	0.02	0.04	0.99	1.00	1.00
E22	A	On	Open	NA	0.56	0.18	0.21	1.00	0.99	0.99
E22	B	On	Closed	NA	0.57	0.19	0.18	0.96	0.94	0.99
E22	C	Off	Open	NA	0.03	0.03	0.04	0.99	0.99	0.97
E25	A	On	Open	NA	0.67	0.45	0.37	0.96	0.98	1.00
E25	B	On	Closed	NA	0.99	0.69	0.30	0.97	0.97	0.99
E25	C	Off	Open	NA	0.03	0.04	0.04	1.00	0.99	0.97
E26	A	On	Open	Closed	0.37	0.39	0.38	0.99	1.00	0.99
E26	A	On	Open	Open	0.37	0.38	0.43	1.00	1.00	0.99
E26	B	On	Closed	Closed	0.33	0.34	0.33	0.99	0.99	0.96
E26	B	On	Closed	Open	0.31	0.43	0.34	1.00	1.00	1.00
E26	C	Off	Open	Closed	0.09	0.09	0.07	0.98	0.98	0.96
W02	A	On	Open	NA	0.29	0.2	0.20	0.96	1.00	1.00
W02	B	On	Closed	NA	0.49	0.18	0.20	1.00	1.00	1.00
W02	C	Off	Open	NA	0.07	0.05	0.11	0.99	0.97	0.98
W04	A	On	Open	NA	0.53	0.48	0.49	0.99	1.00	0.99
W04	B	On	Closed	NA	1.39	0.85	0.43	0.99	1.00	0.99
W04	C	Off	Open	NA	0.08	0.05	0.10	0.97	0.98	0.85
W06	A	On	Open	NA	0.68	0.30	0.25	0.94	1.00	0.98
W06	B	On	Closed	NA	0.54	1.04	0.25	0.97	0.93	0.93
W06	C	Off	Open	NA	0.08	0.14	0.06	0.90	0.97	0.51
W12	A	On	Open	NA	0.64	0.42	0.32	1.00	1.00	1.00

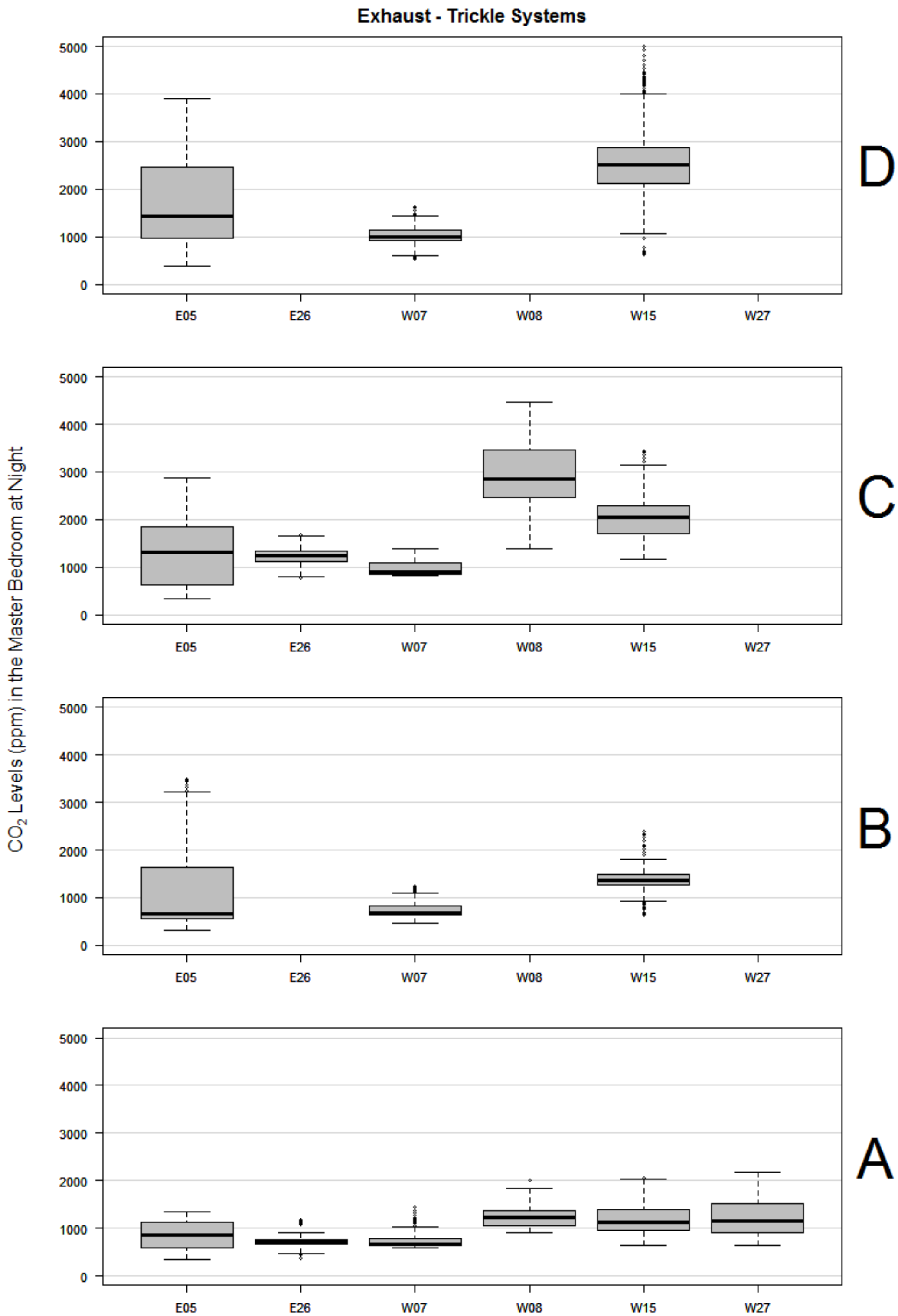
					Average measured test ACH of specific locations in the home			Average R^2		
Site ID	Test Protocol	Ventilation System Status	Door Status	Inlet Vent Status	Second Bedroom	Master Bedroom	Main Living Area	Second Bedroom	Master Bedroom	Main Living Area
W12	B	On	Closed	NA	0.82	0.60	0.25	1.00	1.00	1.00
W12	C	Off	Open	NA	0.03	0.04	0.03	1.00	1.00	0.97
W14	A	On	Open	Closed	0.26	0.12	0.19	0.99	1.00	0.91
W14	A	On	Open	Open	0.31	0.14	0.10	0.98	1.00	0.99
W14	B	On	Closed	Closed	0.24	0.05	0.07	0.99	1.00	0.92
W14	B	On	Closed	Open	0.3	0.11	0.10	0.97	1.00	0.98
W14	C	Off	Open	Closed	0.16	0.02	0.15	1.00	0.30	0.88
W15	A	On	Open	Closed	0.25	0.20	0.33	1.00	0.99	0.93
W15	A	On	Open	Open	0.30	0.31	0.28	1.00	1.00	0.97
W15	B	On	Closed	Closed	0.23	0.21	0.31	0.98	0.99	0.98
W15	B	On	Closed	Open	0.32	0.30	0.33	0.99	1.00	1.00
W15	C	Off	Open	Closed	0.09	0.13	0.08	0.99	0.93	0.96
W17	A	On	Open	Closed	0.39	0.35	0.52	1.00	1.00	0.94
W17	A	On	Open	Open	0.36	0.41	0.73	1.00	0.99	0.70
W17	B	On	Closed	Closed	0.21	0.34	0.57	1.00	0.99	0.95
W17	B	On	Closed	Open	0.32	0.37	0.31	1.00	0.99	0.81
W17	C	Off	Open	Closed	0.09	0.05	0.10	1.00	1.00	0.95
W21	A	On	Open	NA	0.22	0.33	0.23	0.99	1.00	0.99
W21	B	On	Closed	NA	0.17	0.40	0.17	1.00	0.96	0.94
W21	C	Off	Open	NA	0.08	0.05	0.07	0.99	0.95	0.97
W24	A	On	Open	Closed	0.22	0.25	0.20	1.00	0.98	0.99
W24	A	On	Open	Open	0.20	0.36	0.26	0.93	0.99	0.96
W24	B	On	Closed	Closed	0.21	0.21	0.22	0.99	1.00	1.00
W24	B	On	Closed	Open	0.22	0.26	0.25	1.00	0.99	0.99
W24	C	Off	Open	Closed	0.03	0.04	0.03	1.00	0.98	0.99
W27	A	On	Open	Closed	0.25	0.30	0.31	1.00	0.99	1.00

					Average measured test ACH of specific locations in the home			Average R^2		
Site ID	Test Protocol	Ventilation System Status	Door Status	Inlet Vent Status	Second Bedroom	Master Bedroom	Main Living Area	Second Bedroom	Master Bedroom	Main Living Area
W27	A	On	Open	Open	0.27	0.2	0.42	0.91	1.00	1.00
W27	B	On	Closed	Closed	0.23	0.15	0.36	1.00	1.00	1.00
W27	B	On	Closed	Open	0.34	0.36	0.36	0.99	1.00	1.00
W27	C	Off	Open	Closed	0.20	0.16	0.14	0.97	0.98	1.00
W29	A	On	Open	NA	0.33	0.35	0.22	0.95	0.95	1.00
W29	B	On	Closed	NA	0.36	0.36	0.19	0.98	1.00	0.97
W29	C	Off	Open	NA	0.02	0.02	0.03	0.99	0.99	1.00

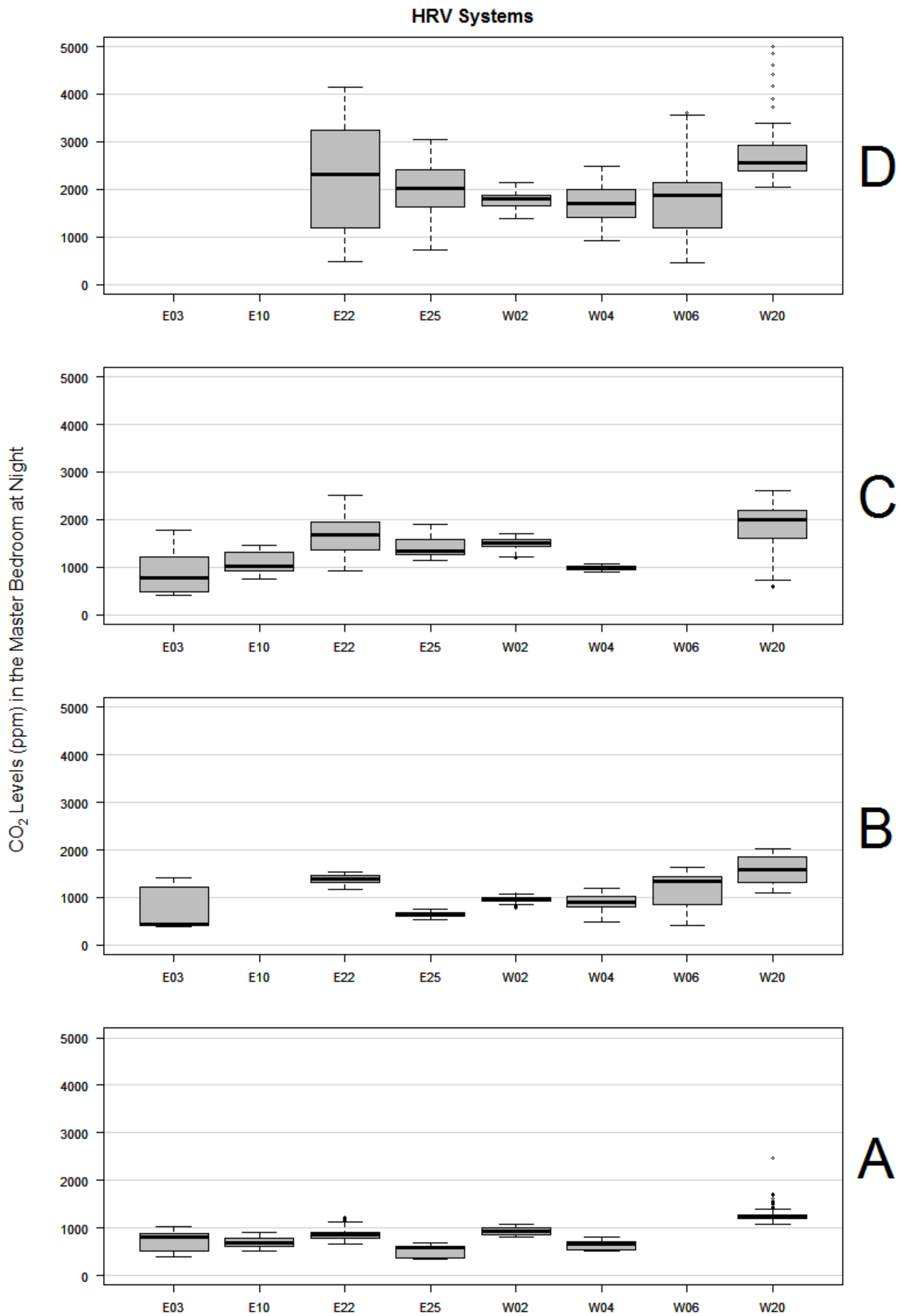
Appendix C: Figures of Long-Term Study CO_2 Values by Ventilation System Type

These figures show CO_2 levels in the master bedroom at night by system type and test condition for each house. If a house is omitted from a panel, it did not have any data compliant with the given test condition.

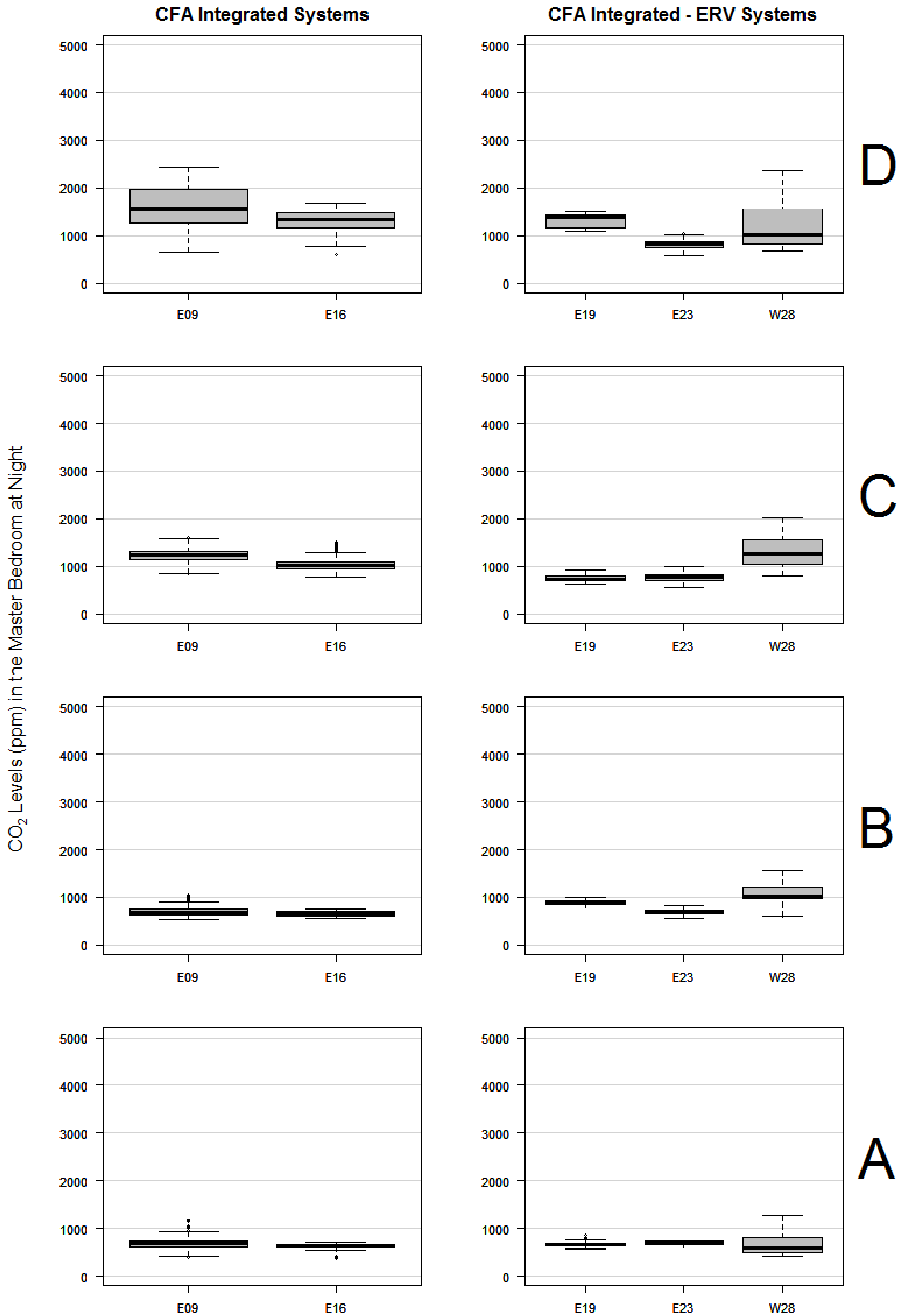




Exhaust - Trickle Systems
CO_2 Levels (ppm) in the Master Bedroom at Night
D
C
B
A
E05
E26
W07
W08
W15
W27
0
1000
2000
3000
4000
5000

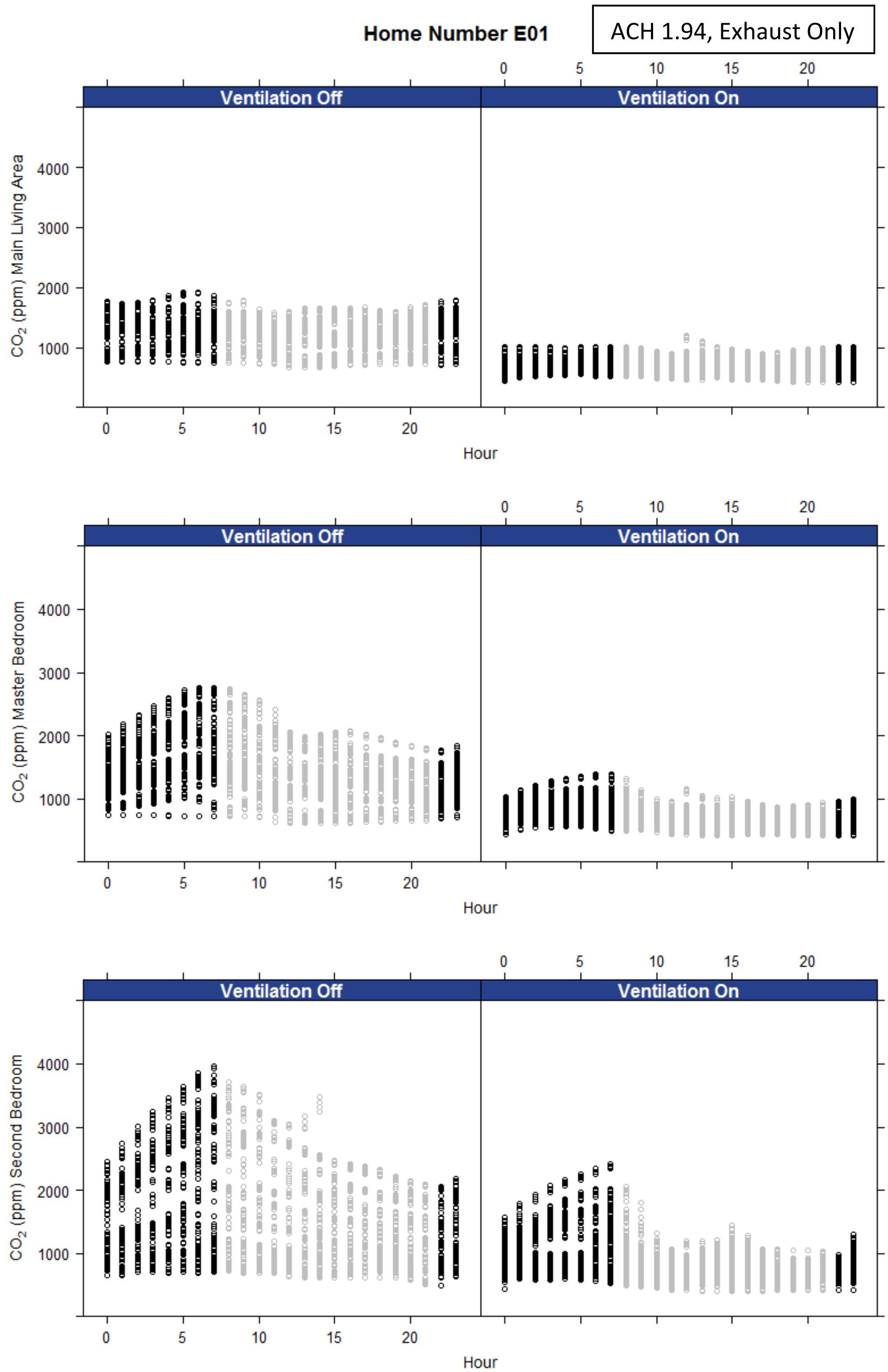


HRV Systems
CO2 Levels (ppm) in the Master Bedroom at Night
D
C
B
A
5000
4000
3000
2000
1000
0
E03
E10
E22
E25
W02
W04
W06
W20

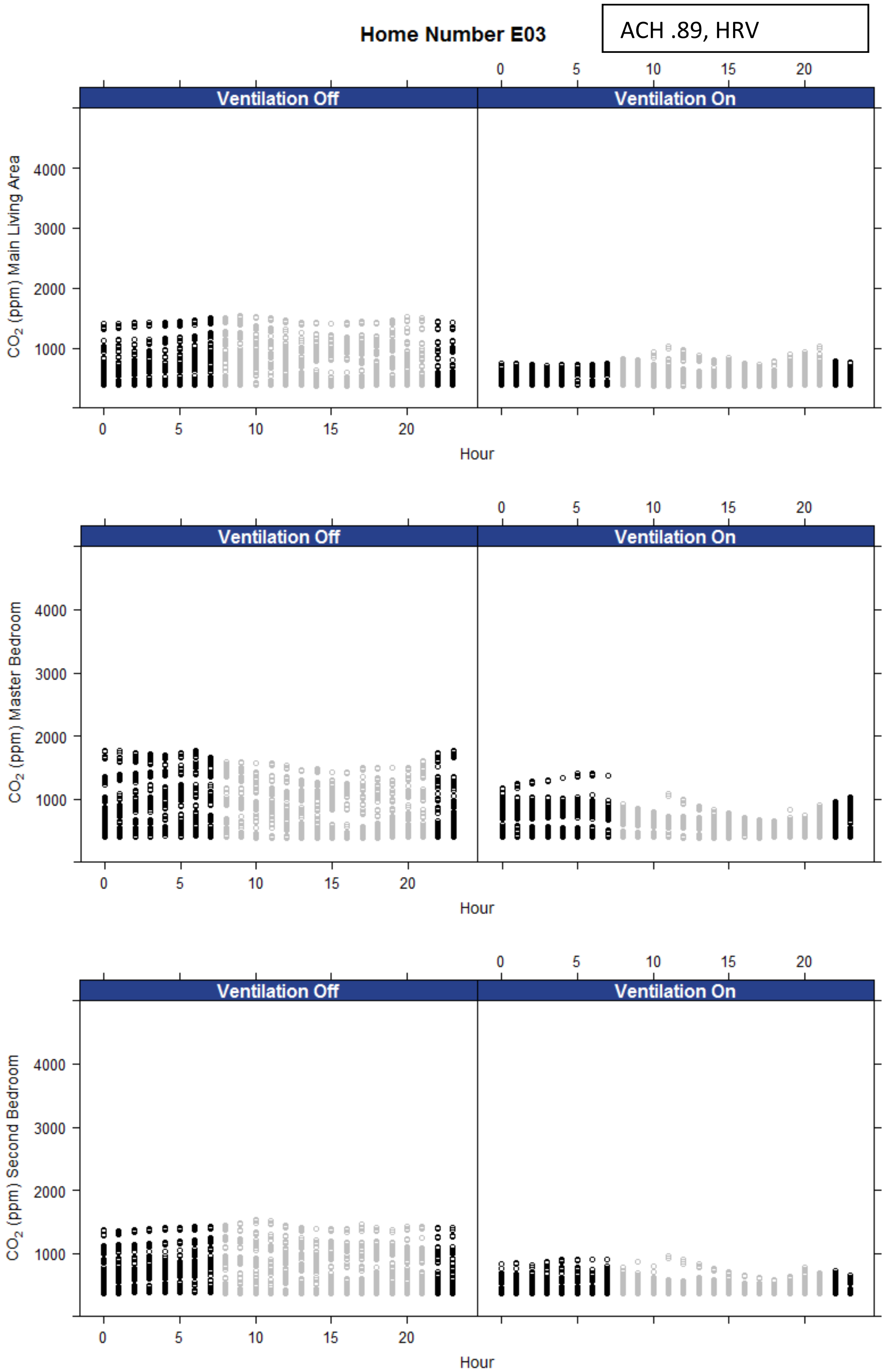

CFA Integrated Systems
CFA Integrated - ERV Systems
CO2 Levels (ppm) in the Master Bedroom at Night
D
C
B
A
E09
E16
E19
E23
W28
0
1000
2000
3000
4000
5000

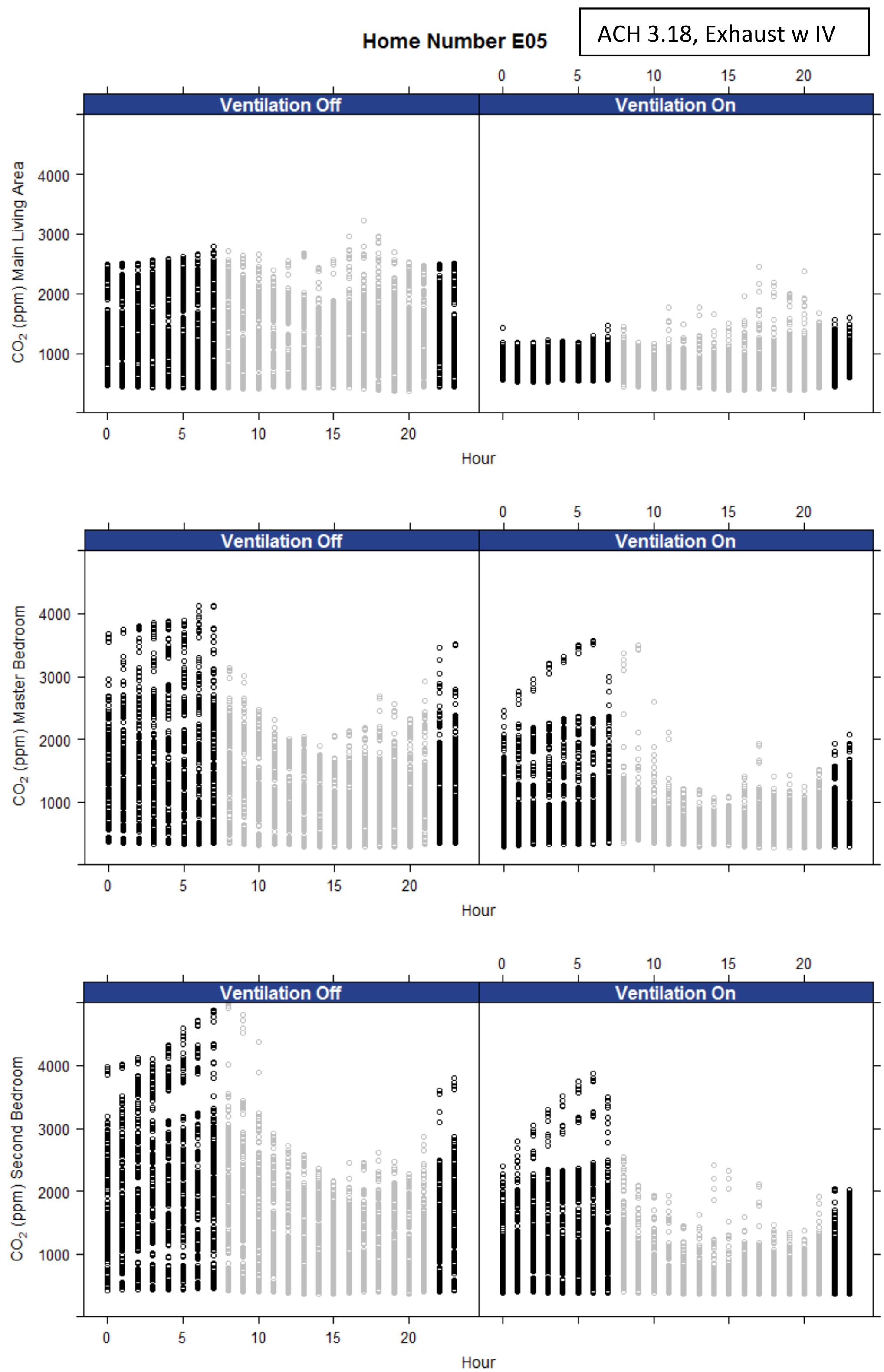
Appendix D: Figures of Long-Term Study Hourly CO_2 Values by House

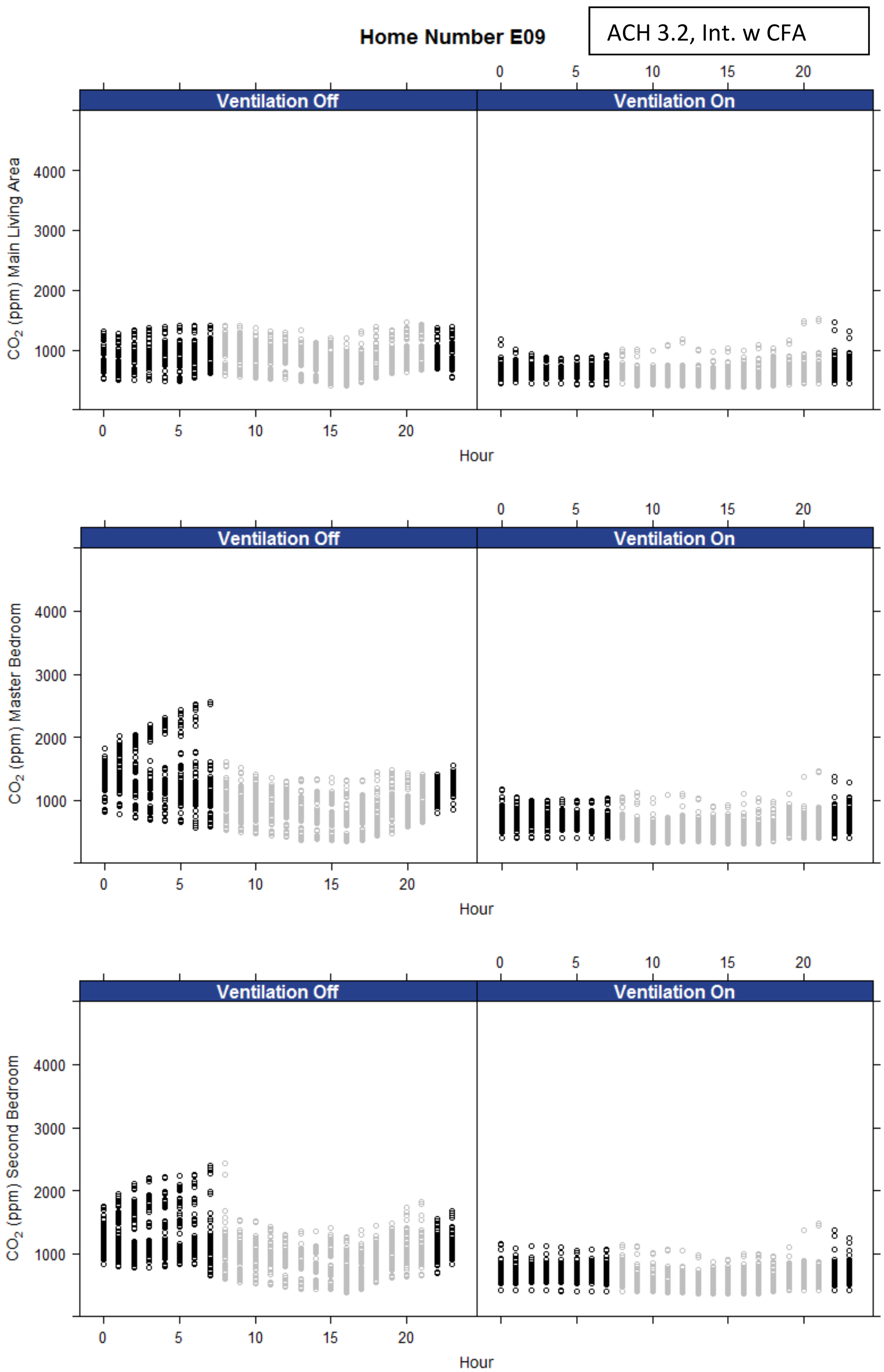
Hourly CO_2 levels measured in the main living area, master bedroom, and second bedroom during ventilation on and ventilation off conditions for each house. Not all houses have all bedrooms or all ventilation statuses represented.

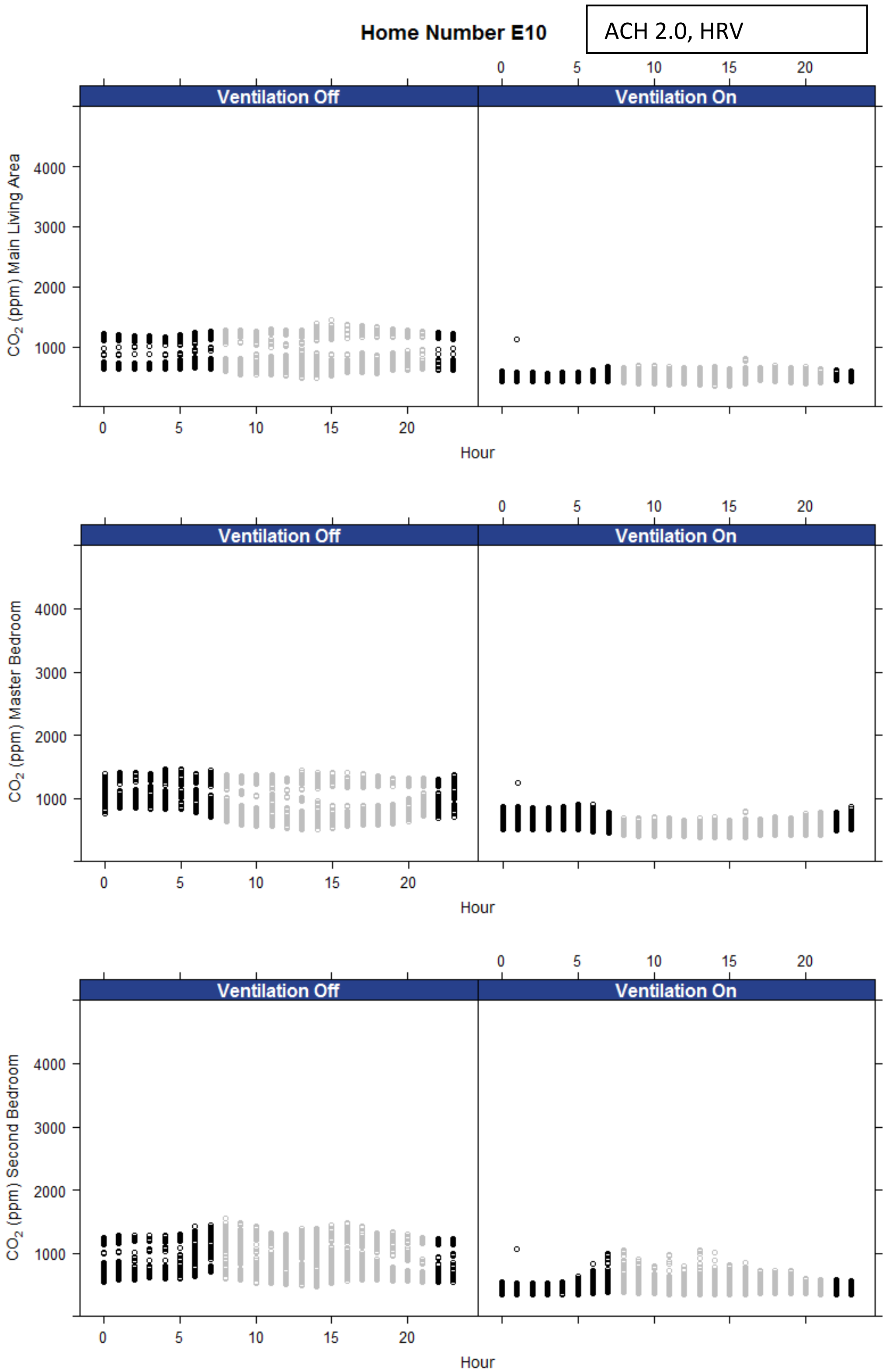


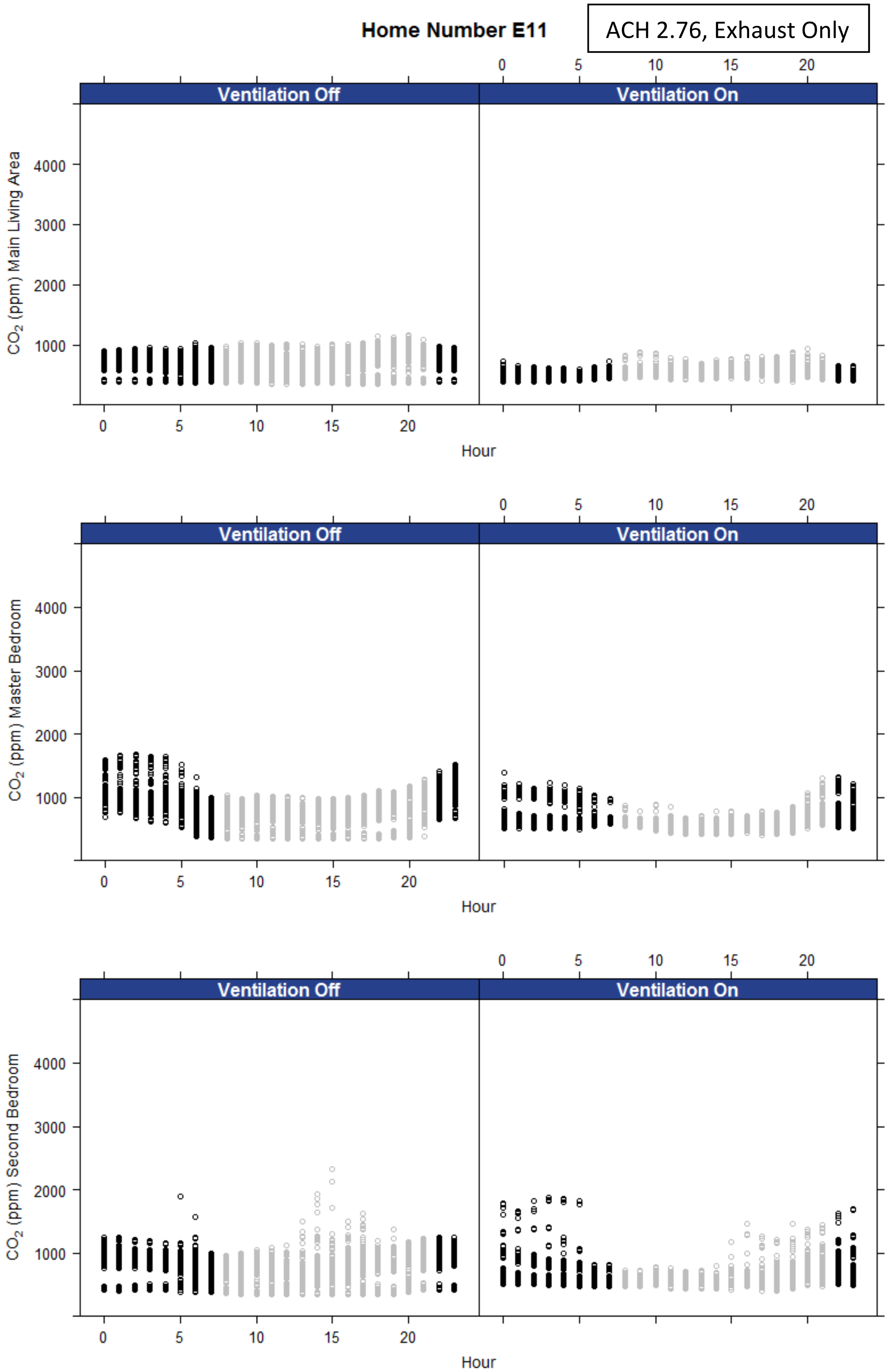
Home Number E01
ACH 1.94, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Master Bedroom
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Second Bedroom
Hour


Home Number E03
ACH .89, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour


Home Number E05
ACH 3.18, Exhaust w IV
Ventilation Off
Ventilation On
CO_2 (ppm) Main Living Area
Hour
Ventilation Off
Ventilation On
CO_2 (ppm) Master Bedroom
Hour
Ventilation Off
Ventilation On
CO_2 (ppm) Second Bedroom
Hour


Home Number E09
ACH 3.2, Int. w CFA
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
4000
3000
2000
1000
0
5
10
15
20
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Master Bedroom
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Second Bedroom
Hour

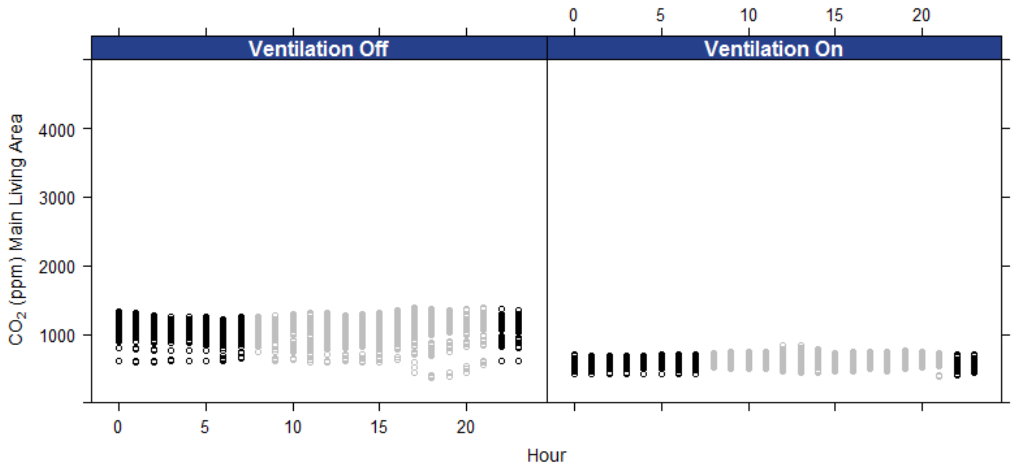

Home Number E10
ACH 2.0, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
4000
3000
2000
1000
0
5
10
15
20
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Master Bedroom
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Second Bedroom
Hour

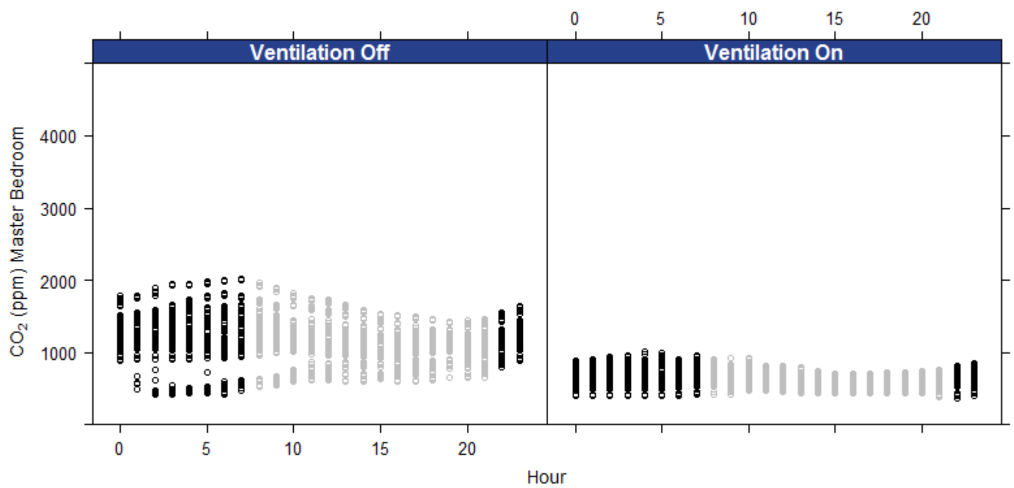


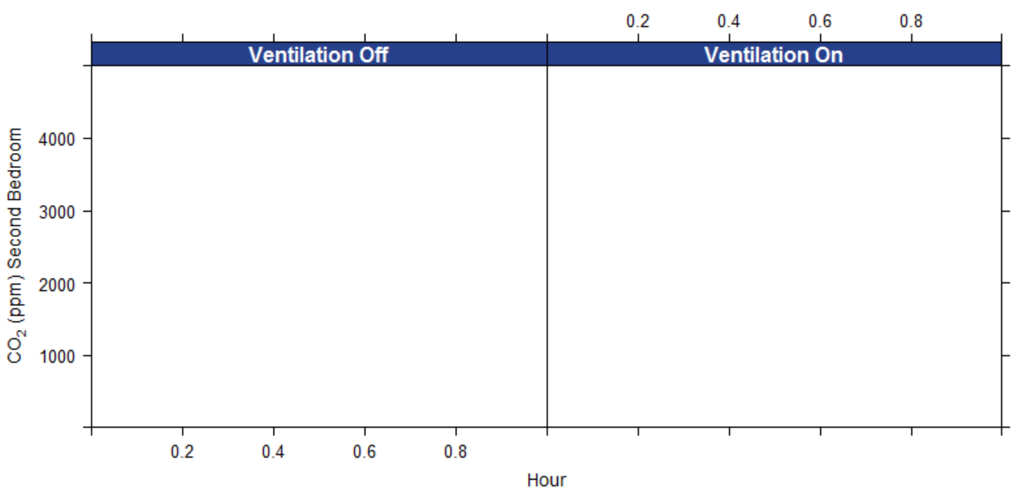
Home Number E11
ACH 2.76, Exhaust Only
Ventilation Off
Ventilation On
CO_2 (ppm) Main Living Area
CO_2 (ppm) Master Bedroom
CO_2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour

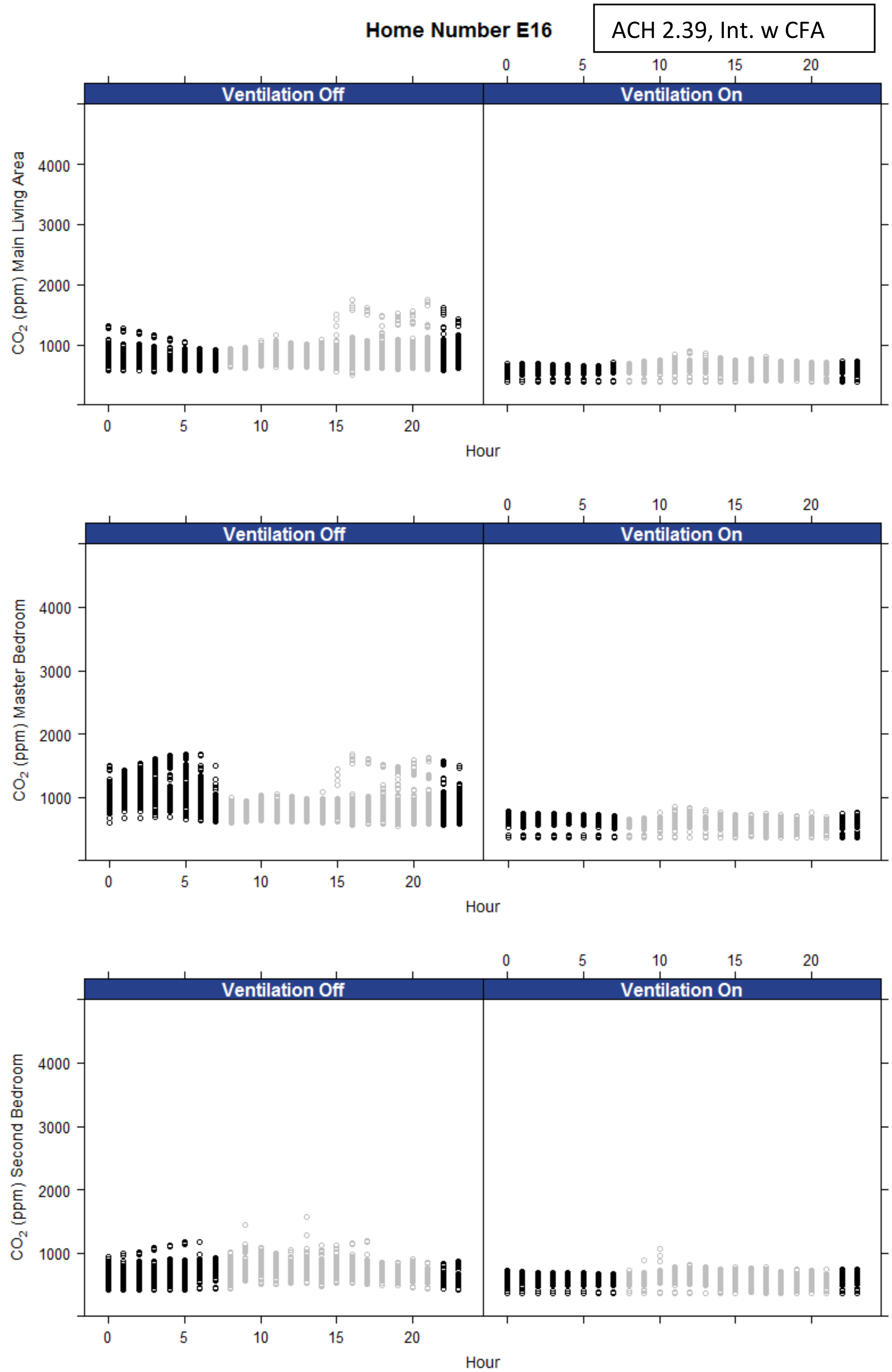
Home Number E13

ACH 1.82, Exhaust Only

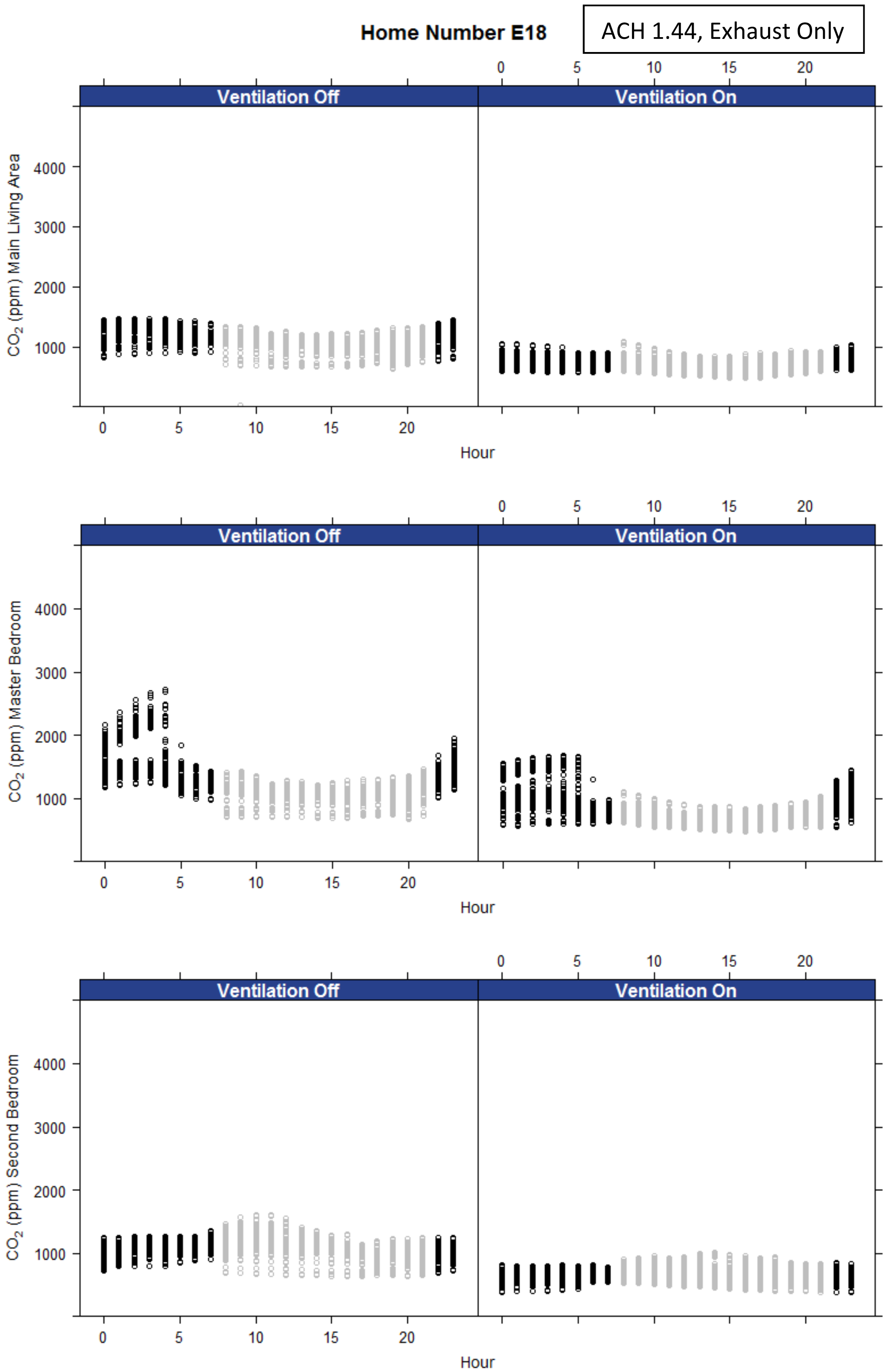


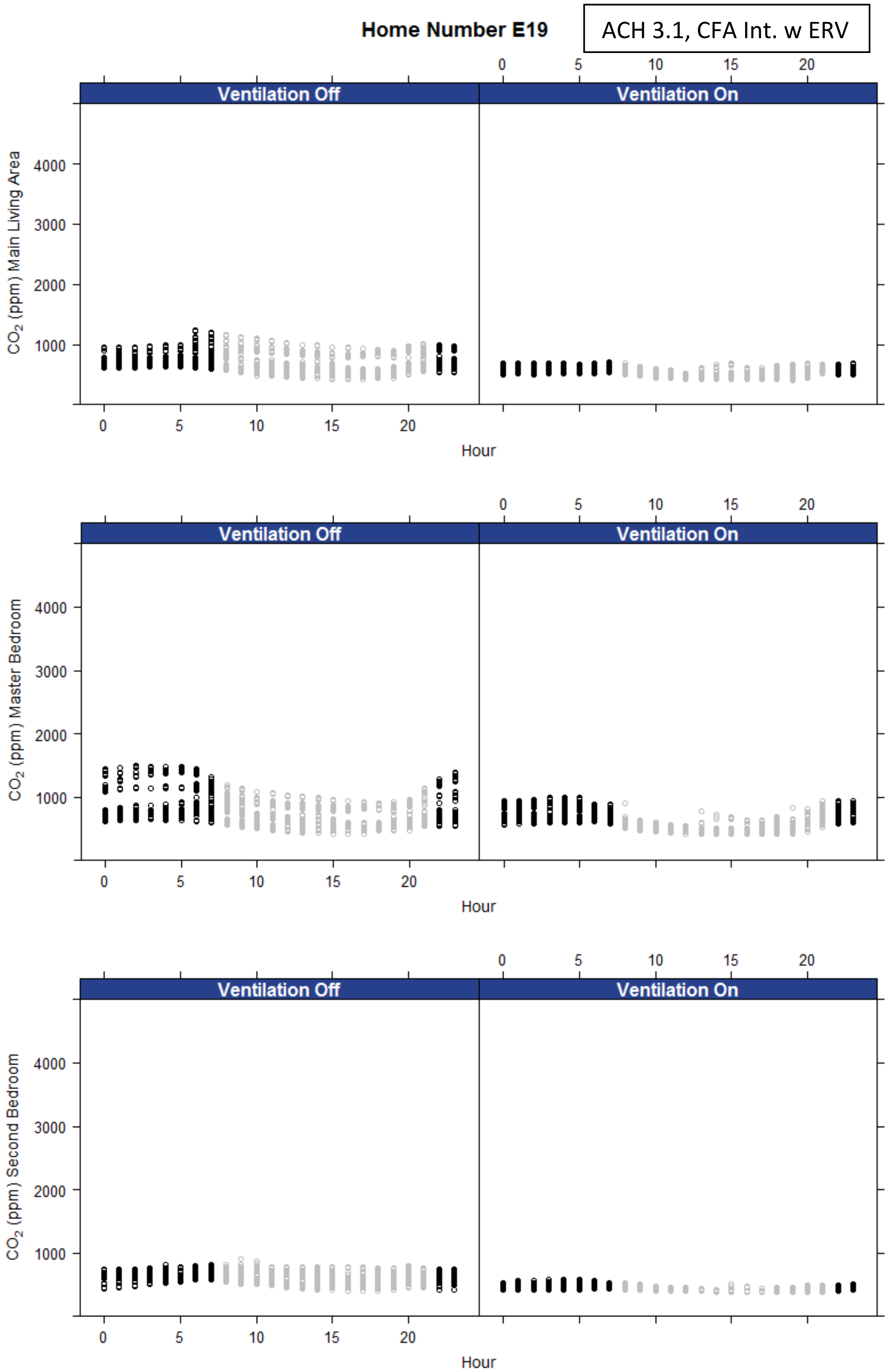


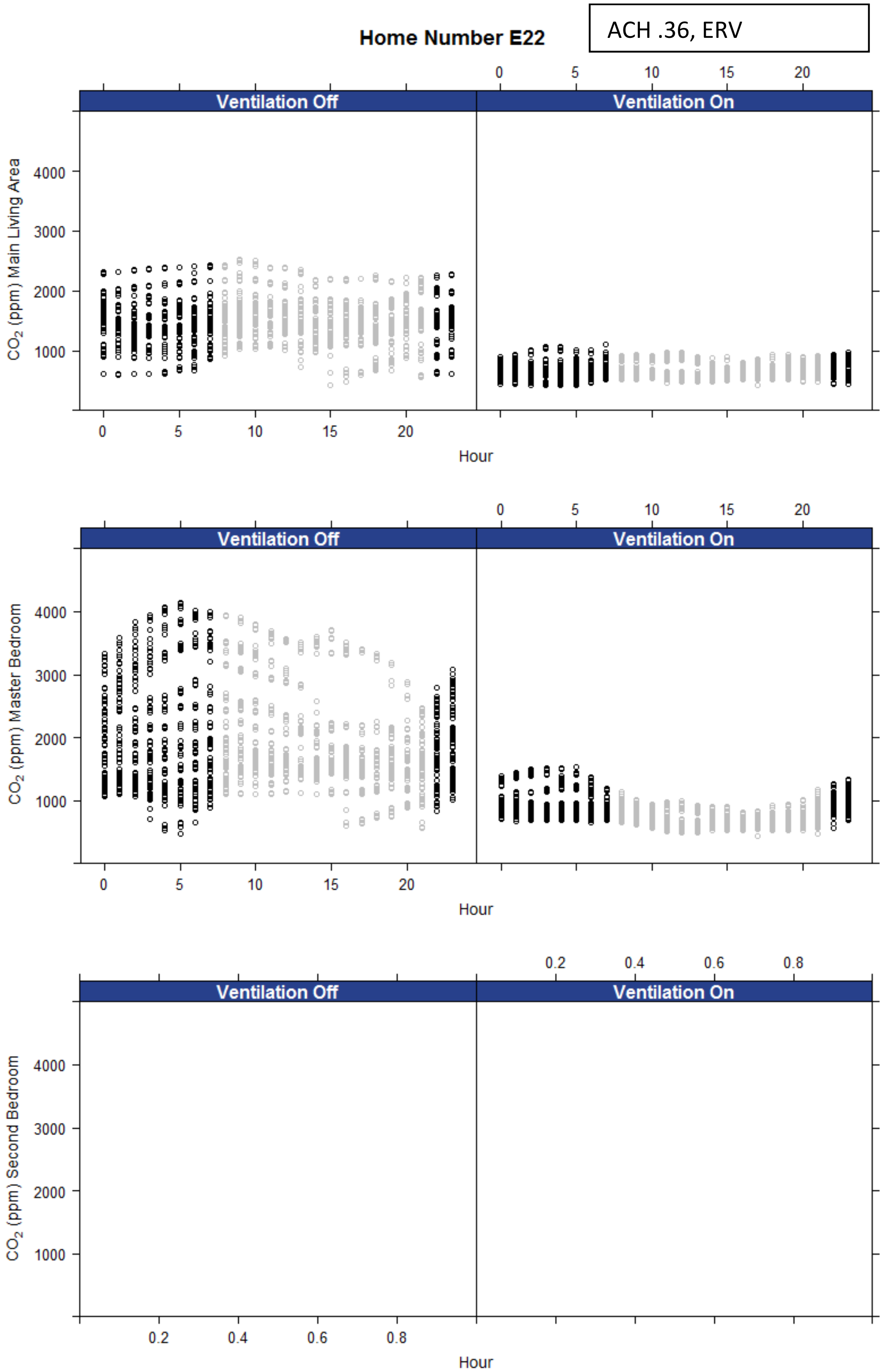


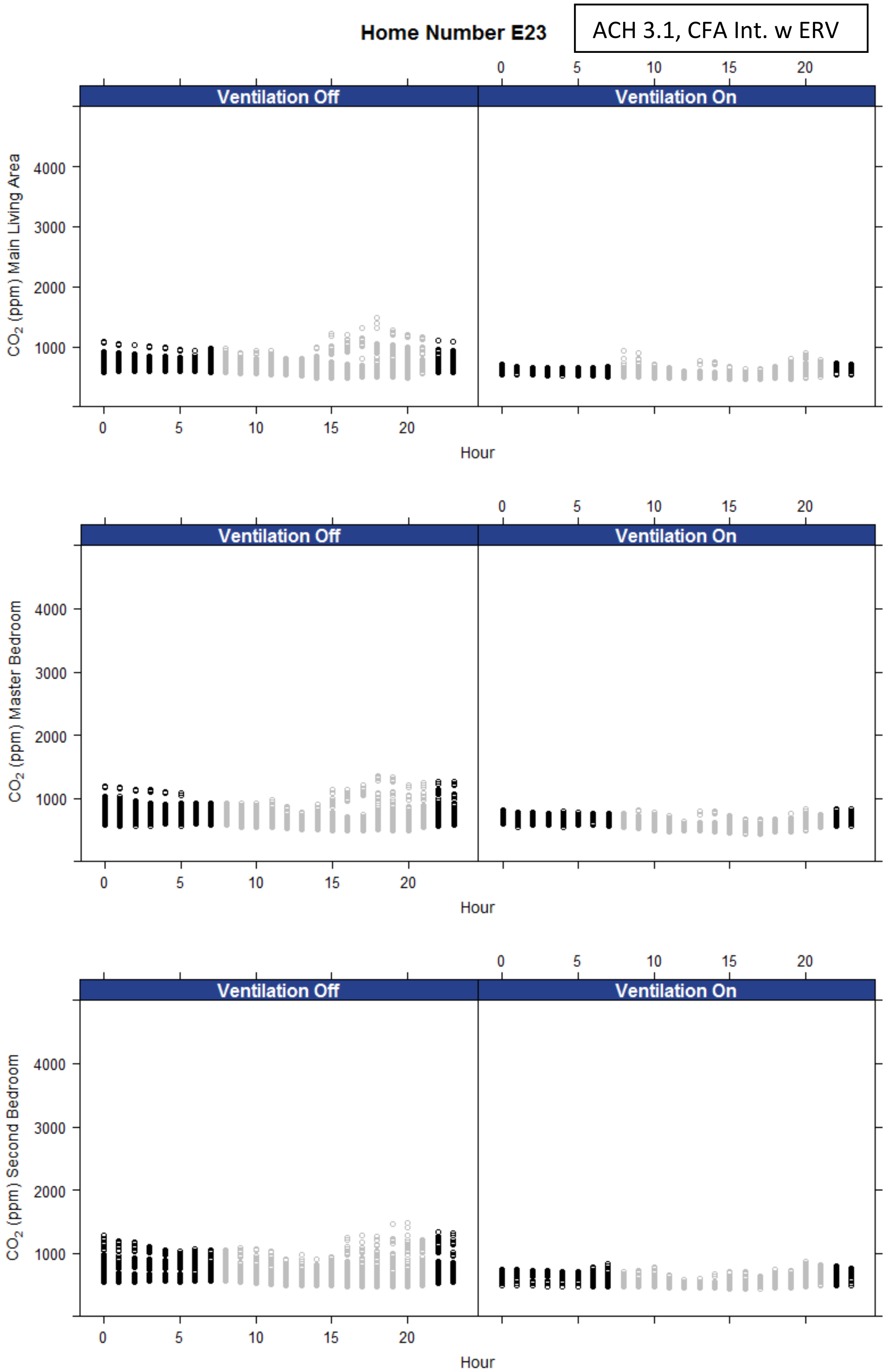


Home Number E16
ACH 2.39, Int. w CFA
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
4000
3000
2000
1000
0
5
10
15
20
Hour

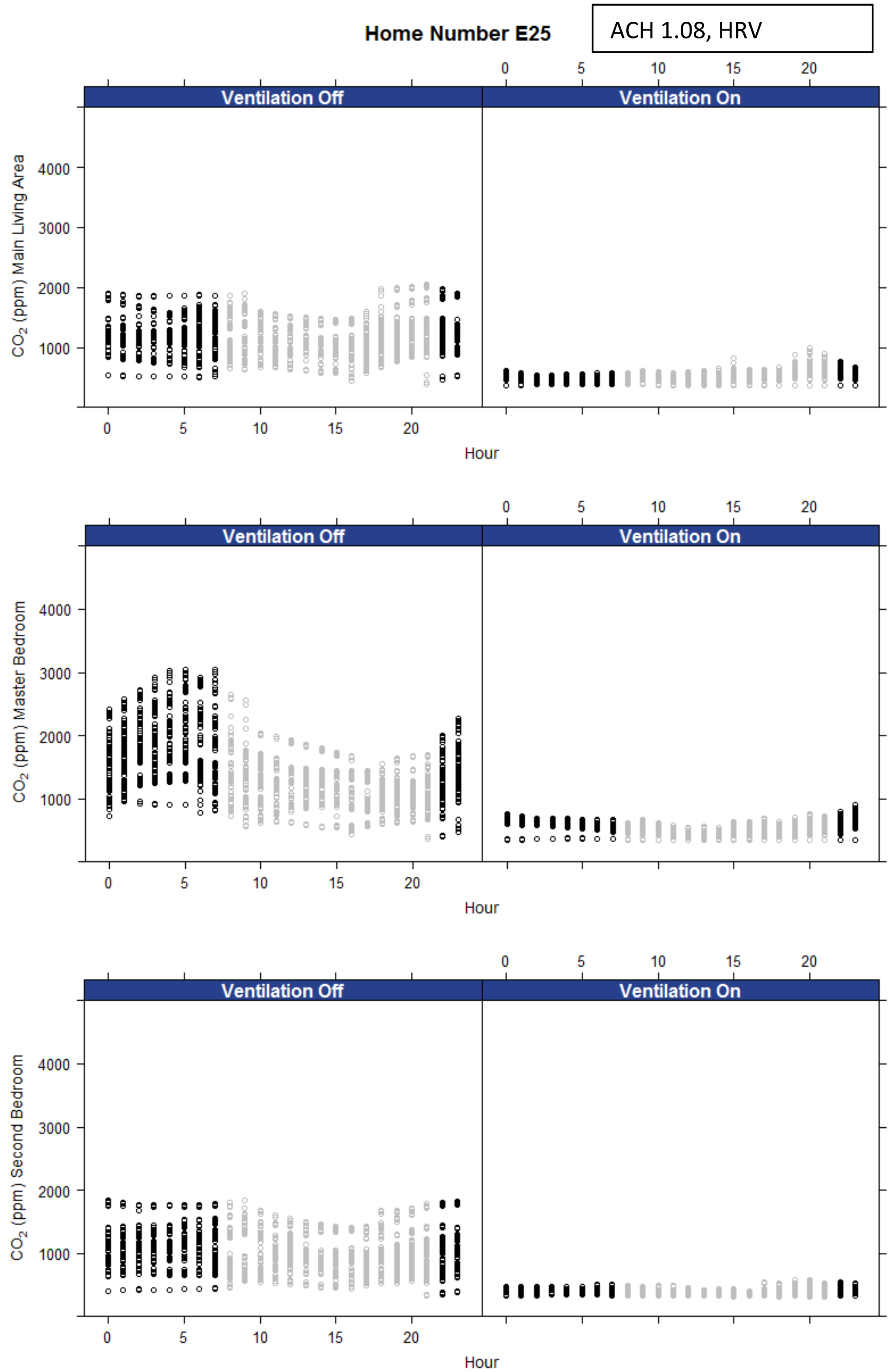

Home Number E18
ACH 1.44, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
4000
3000
2000
1000
0
5
10
15
20
Hour

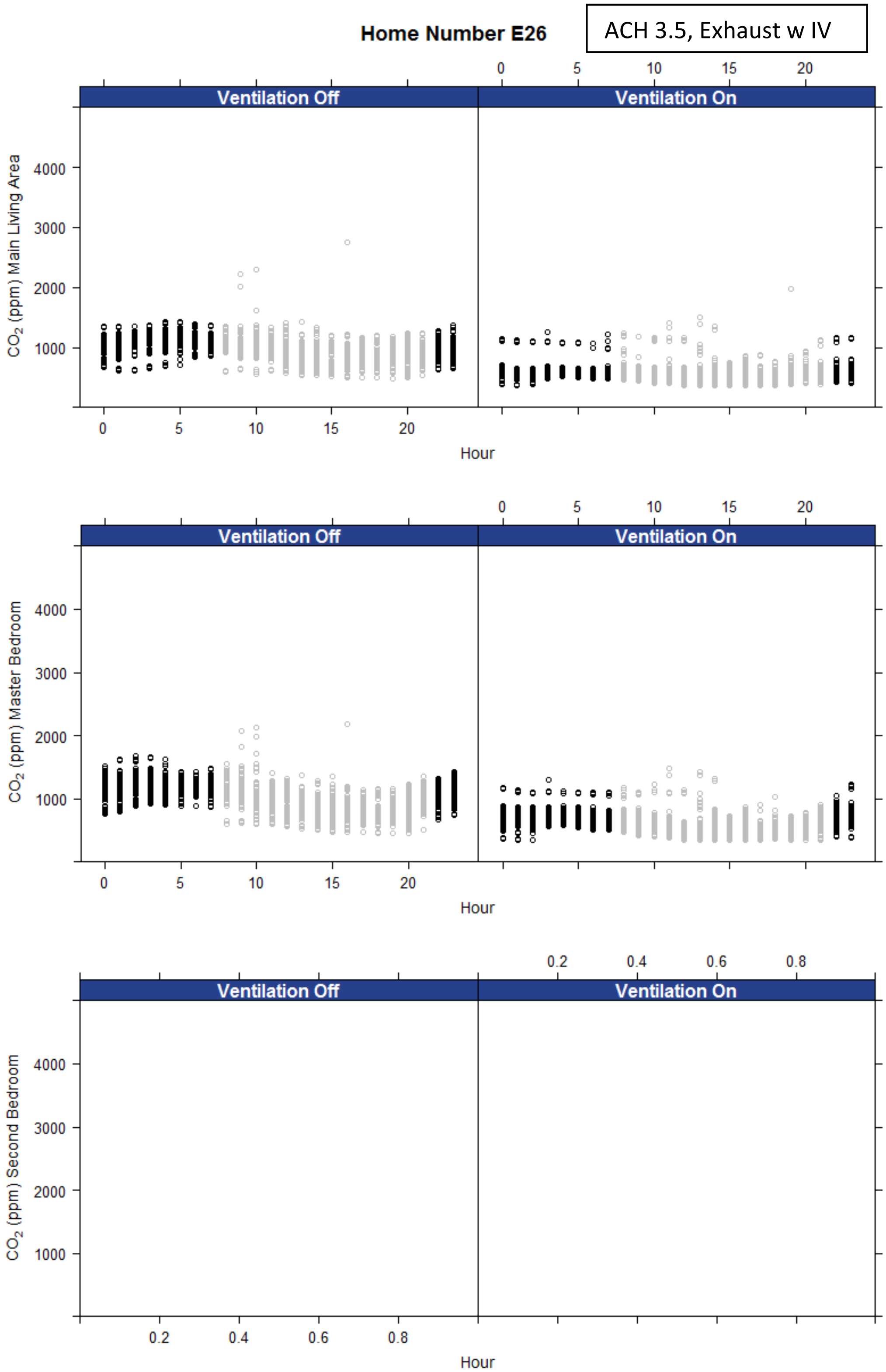

Home Number E19
ACH 3.1, CFA Int. w ERV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour

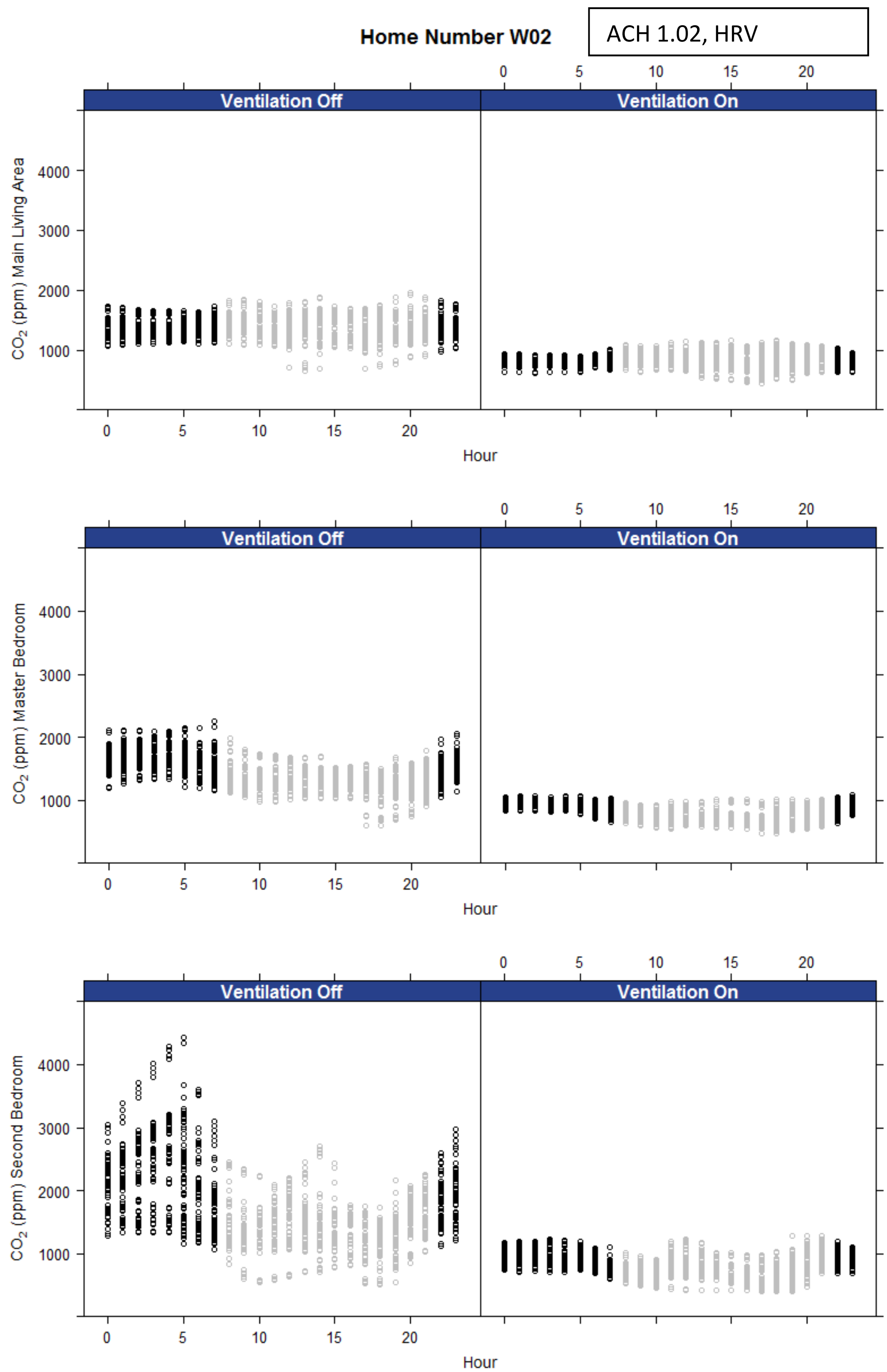

Home Number E22
ACH .36, ERV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
0.2
0.4
0.6
0.8
Hour

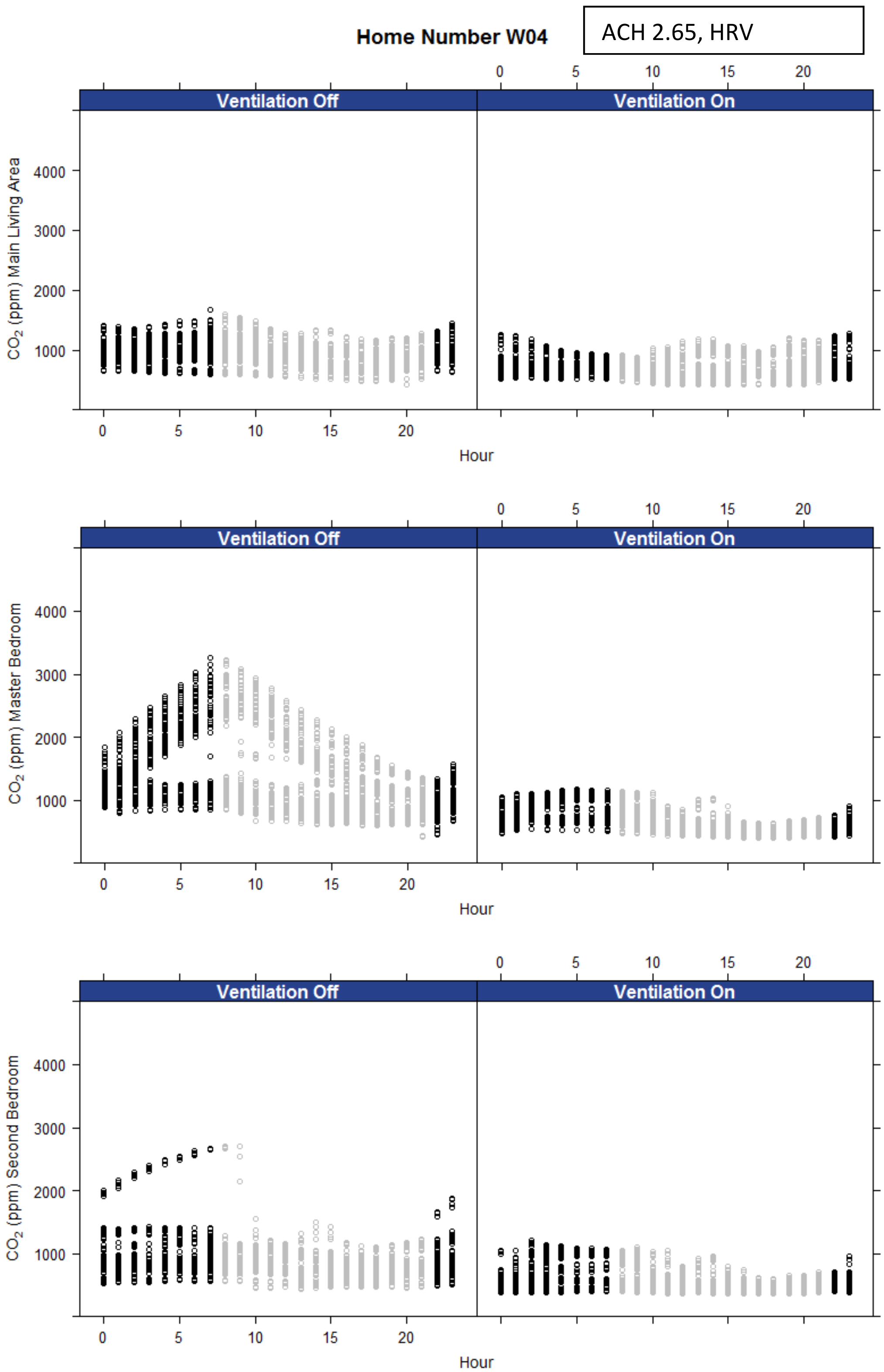


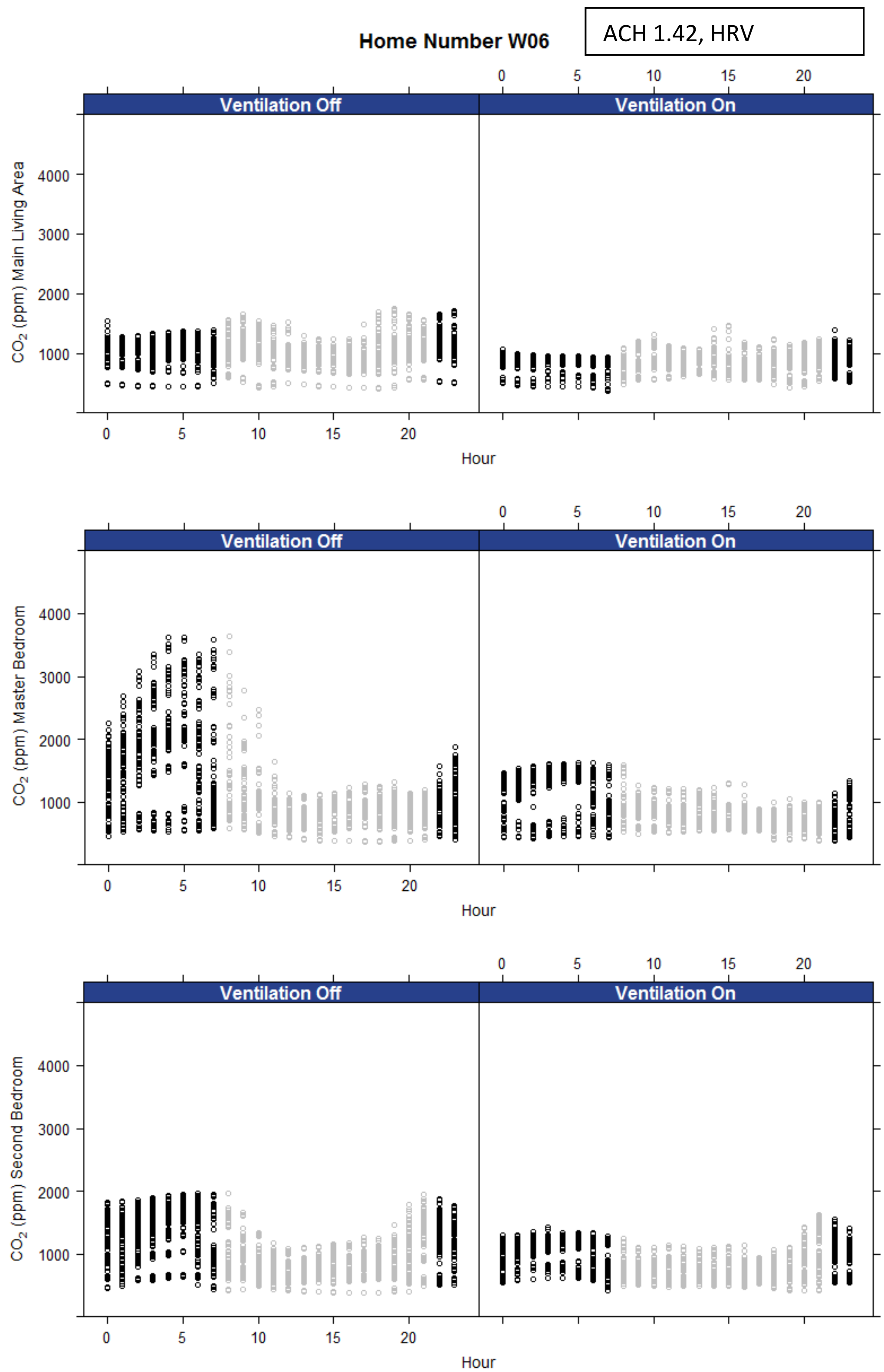
Home Number E23
ACH 3.1, CFA Int. w ERV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
4000
3000
2000
1000
0
5
10
15
20
Hour
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom

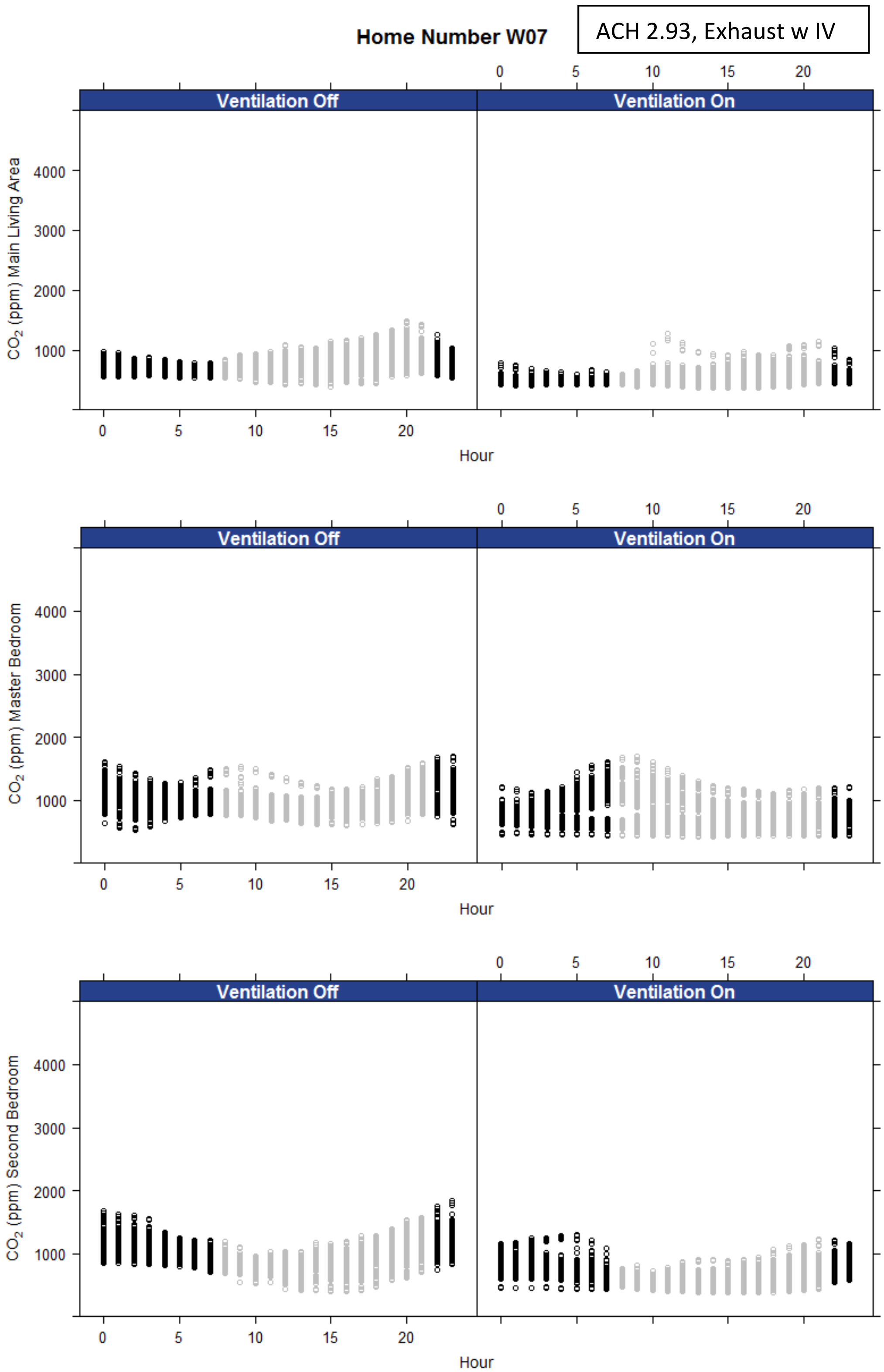

Home Number E25
ACH 1.08, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour

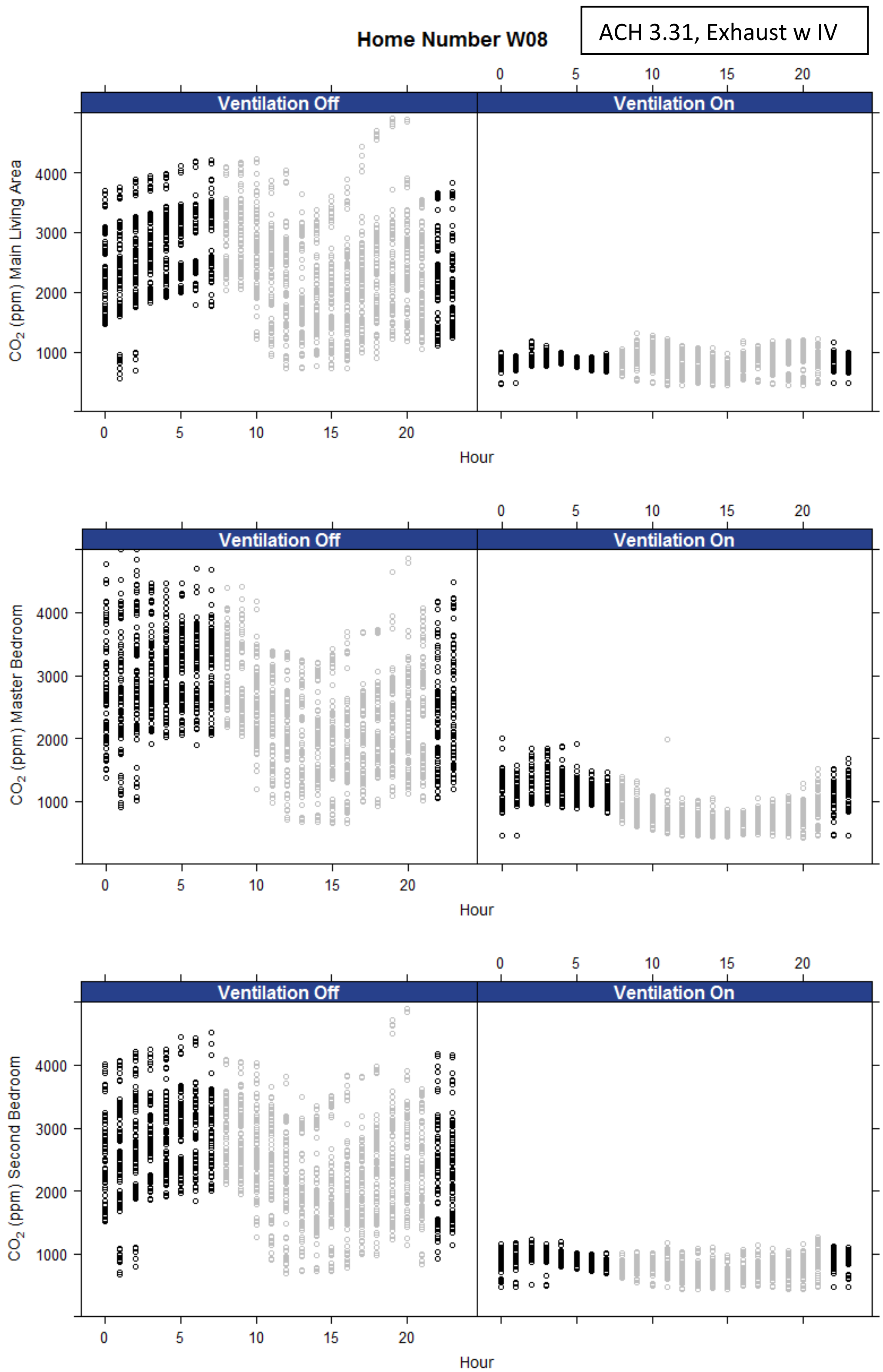

Home Number E26
ACH 3.5, Exhaust w IV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0 5 10 15 20
1000 2000 3000 4000
0.2 0.4 0.6 0.8


Home Number W02
ACH 1.02, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour


Home Number W04
ACH 2.65, HRV
Ventilation Off
Ventilation On
CO_2 (ppm) Main Living Area
CO_2 (ppm) Master Bedroom
CO_2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour


Home Number W06
ACH 1.42, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour

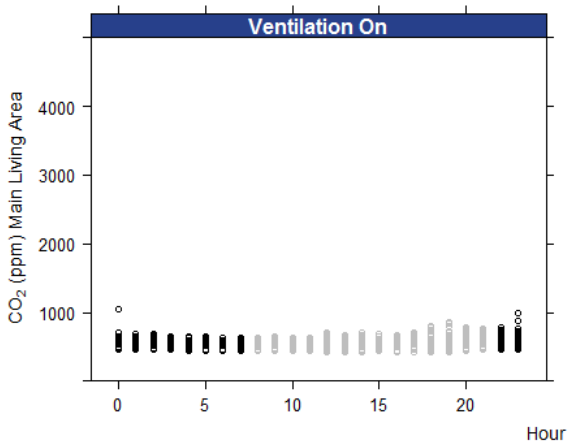

Home Number W07
ACH 2.93, Exhaust w IV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000

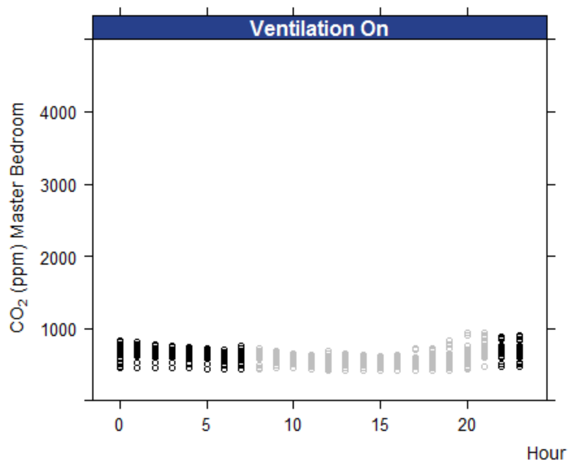


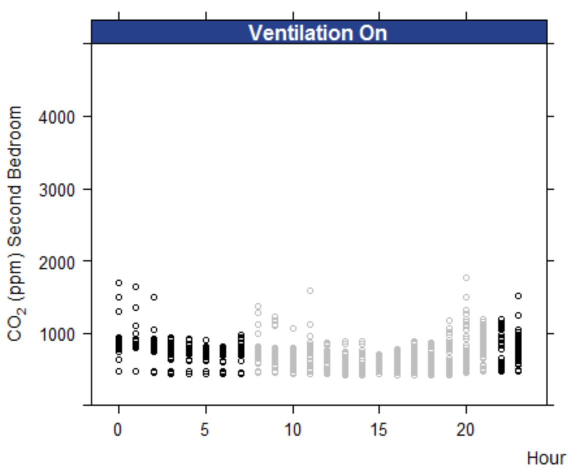
Home Number W08
ACH 3.31, Exhaust w IV
Ventilation Off
Ventilation On
CO_2 (ppm) Main Living Area
1000
2000
3000
4000
0
5
10
15
20
Hour
Ventilation Off
Ventilation On
CO_2 (ppm) Master Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour
Ventilation Off
Ventilation On
CO_2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour

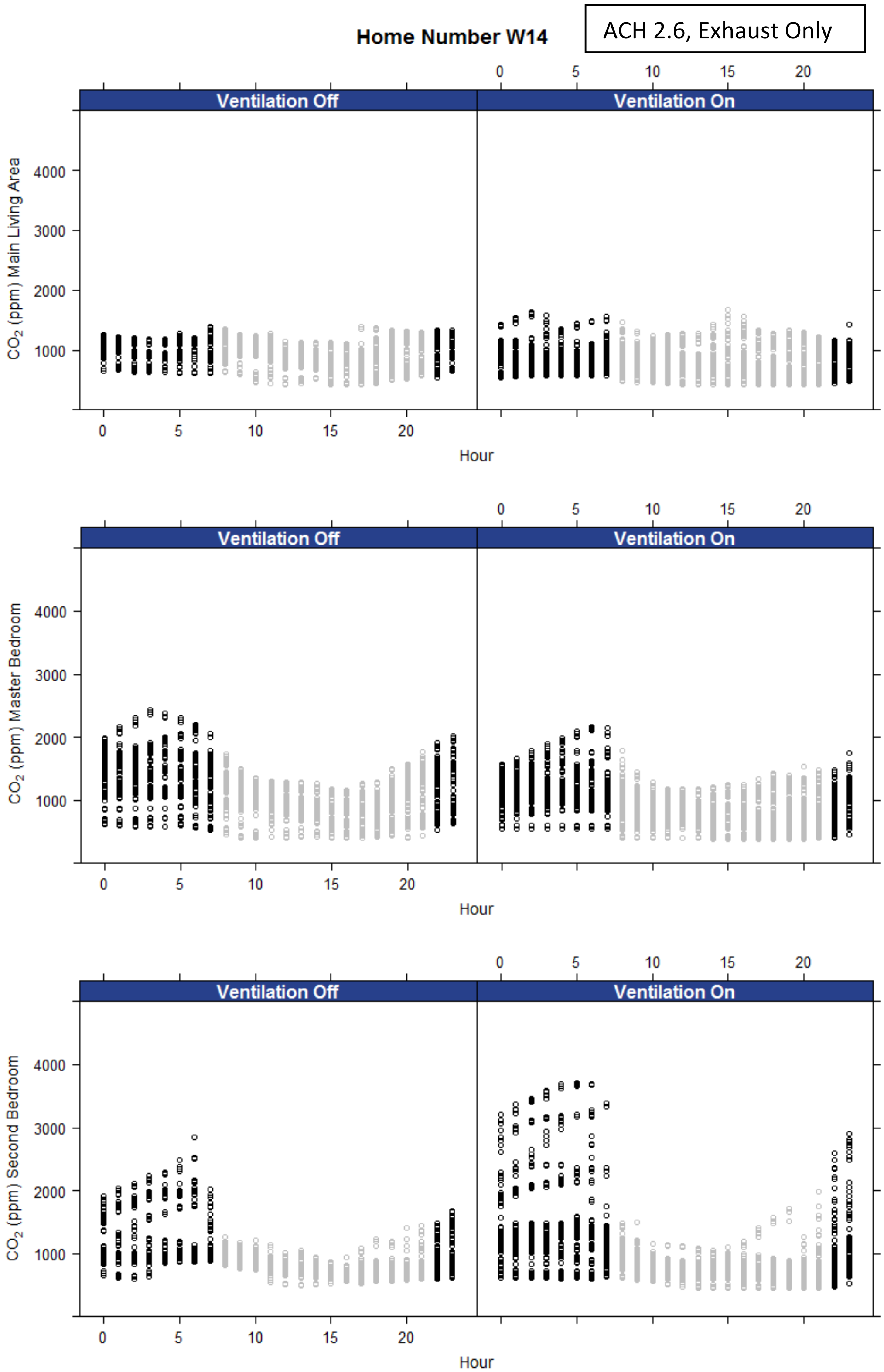
Home Number W12

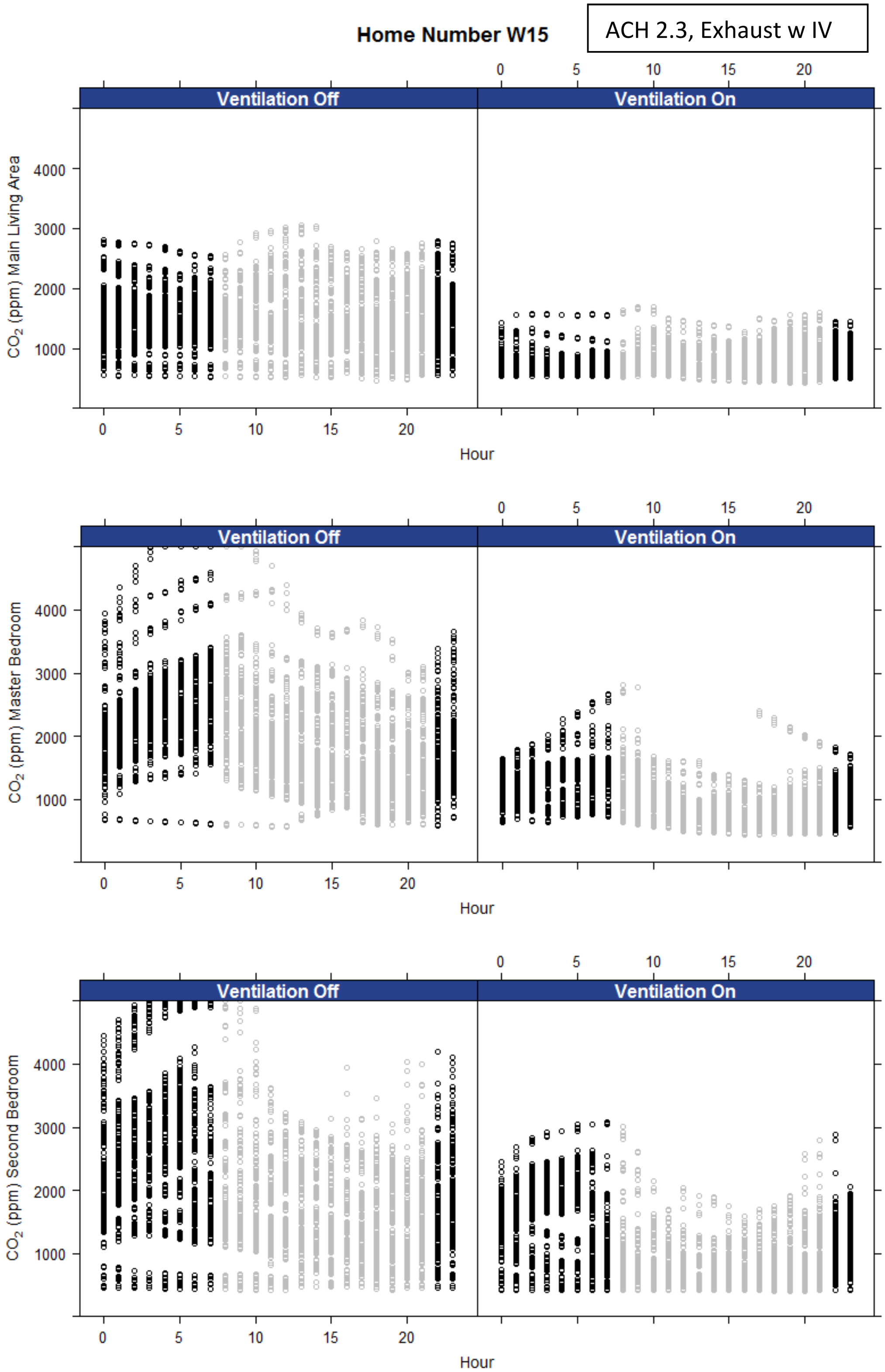
ACH .57, HRV

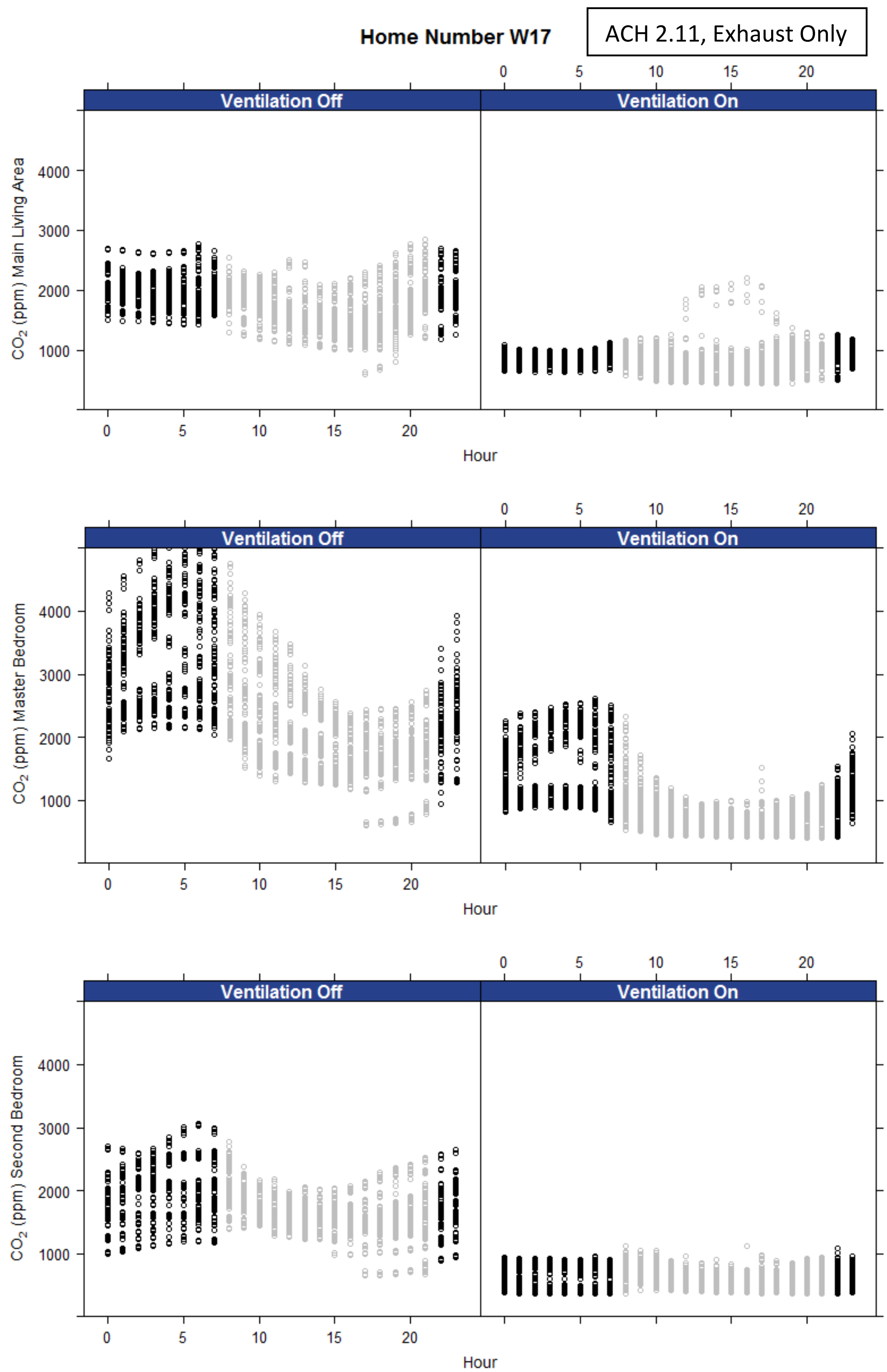


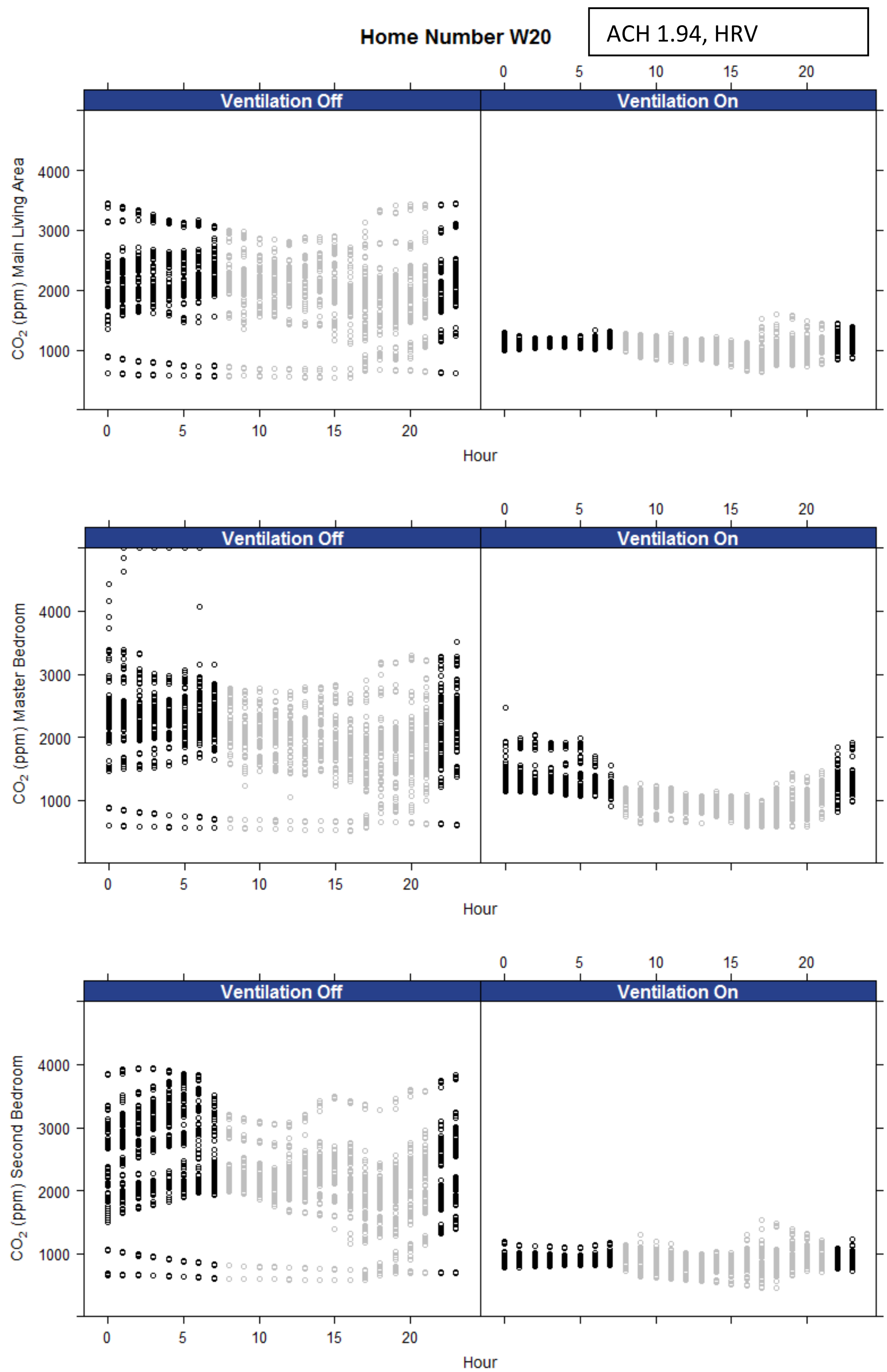


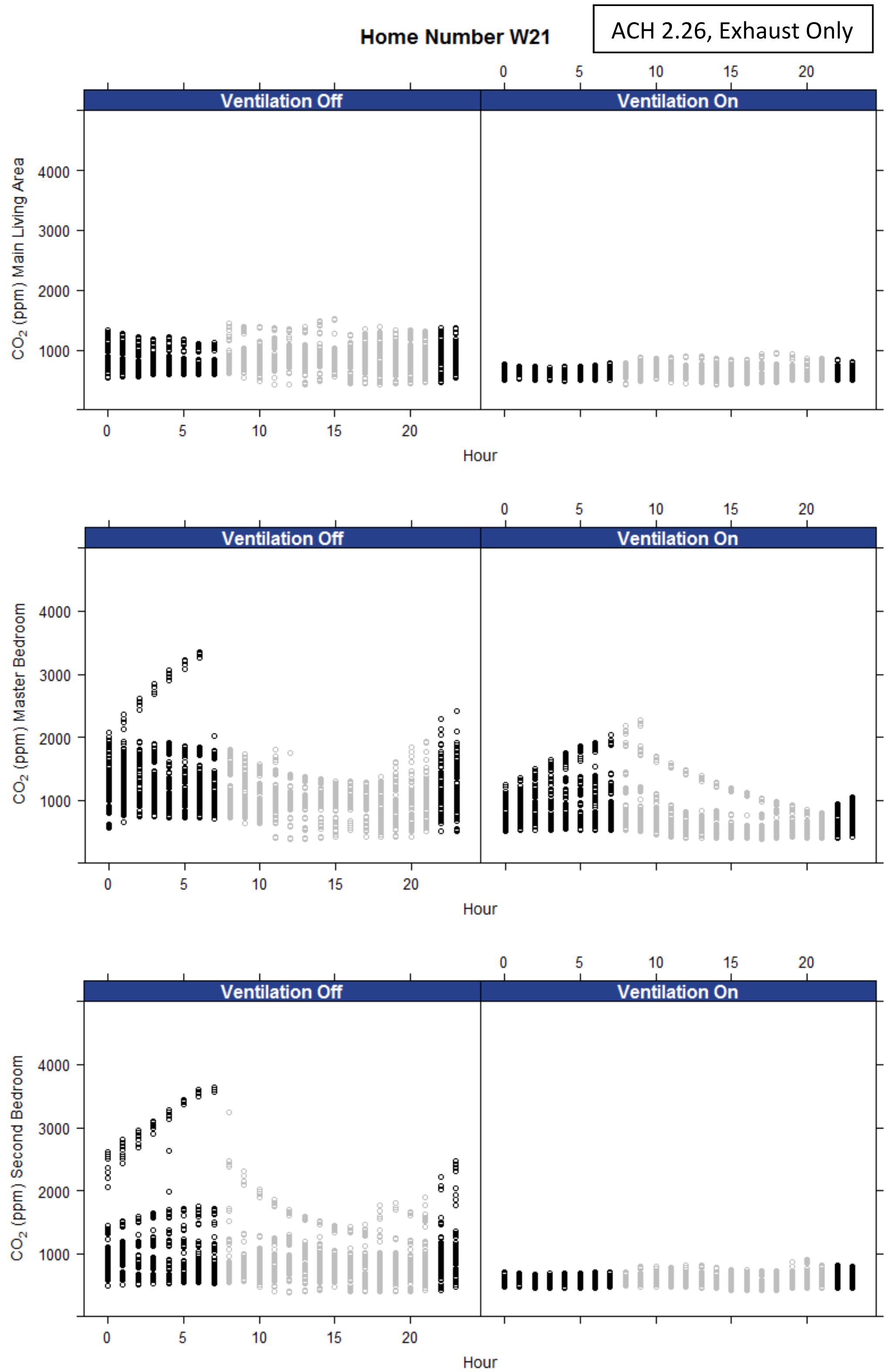


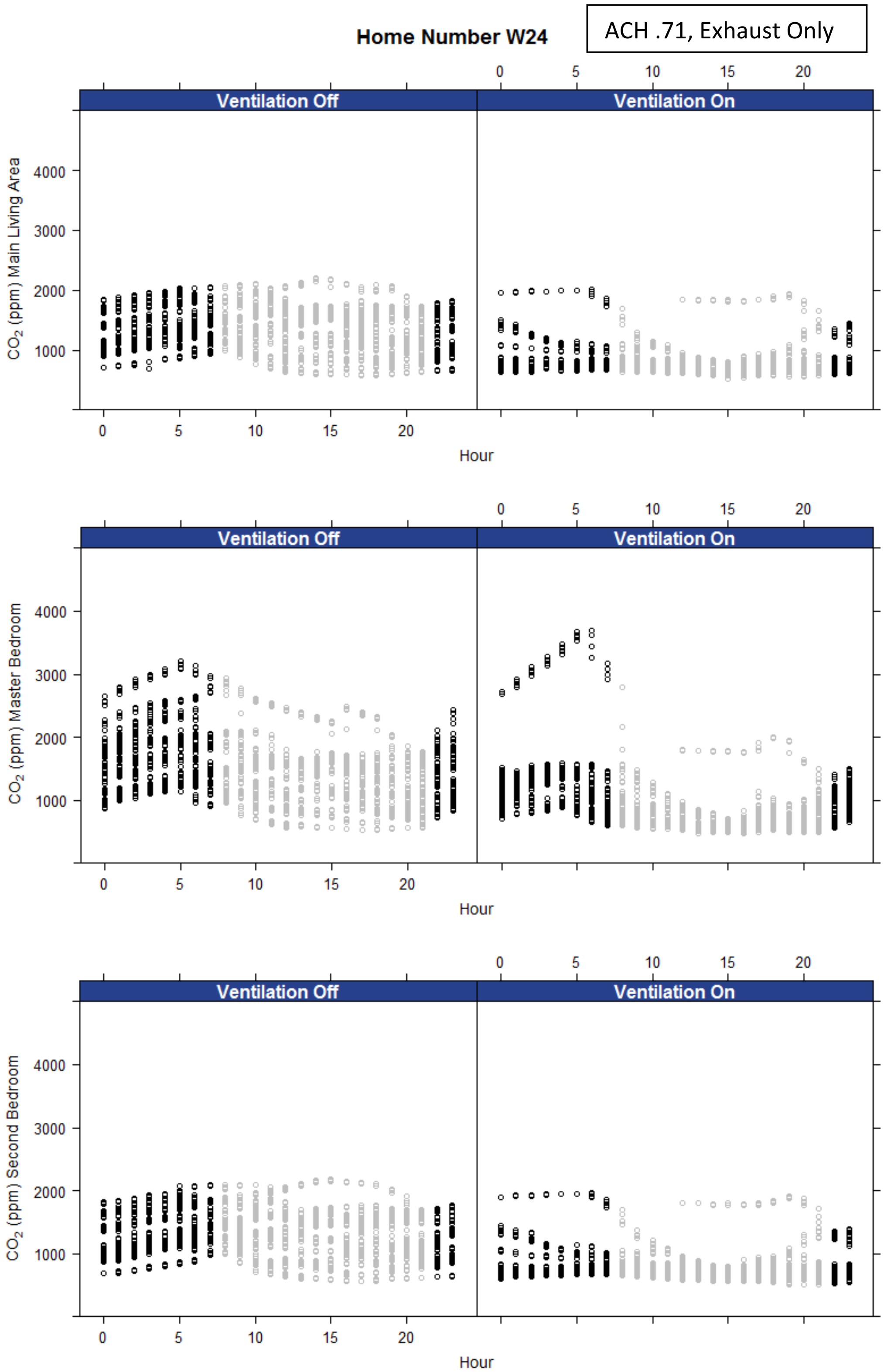

Home Number W14
ACH 2.6, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000


Home Number W15
ACH 2.3, Exhaust w IV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000


Home Number W17
ACH 2.11, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000

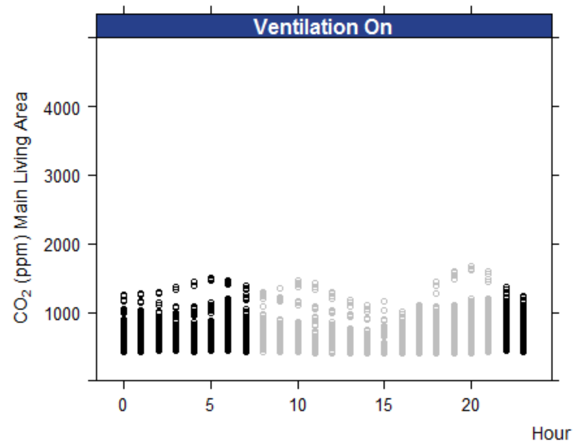

Home Number W20
ACH 1.94, HRV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
4000
3000
2000
1000
0
5
10
15
20
Hour

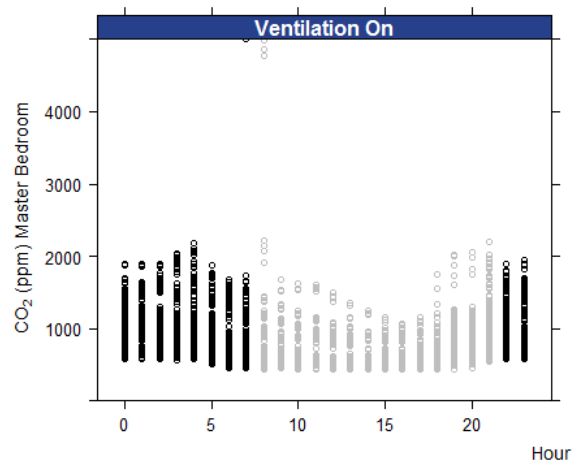

Home Number W21
ACH 2.26, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Master Bedroom
Hour
Ventilation Off
Ventilation On
CO2 (ppm) Second Bedroom
Hour

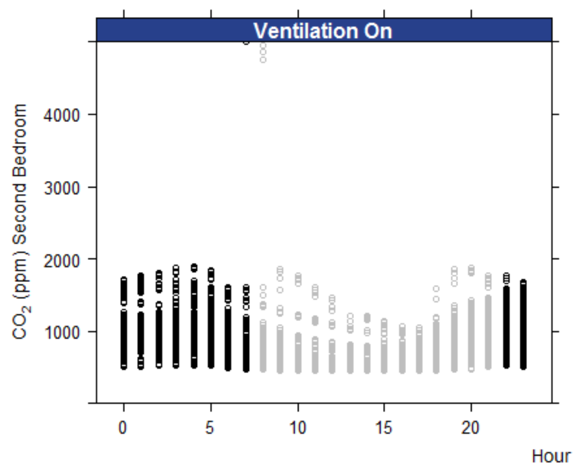

Home Number W24
ACH .71, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000

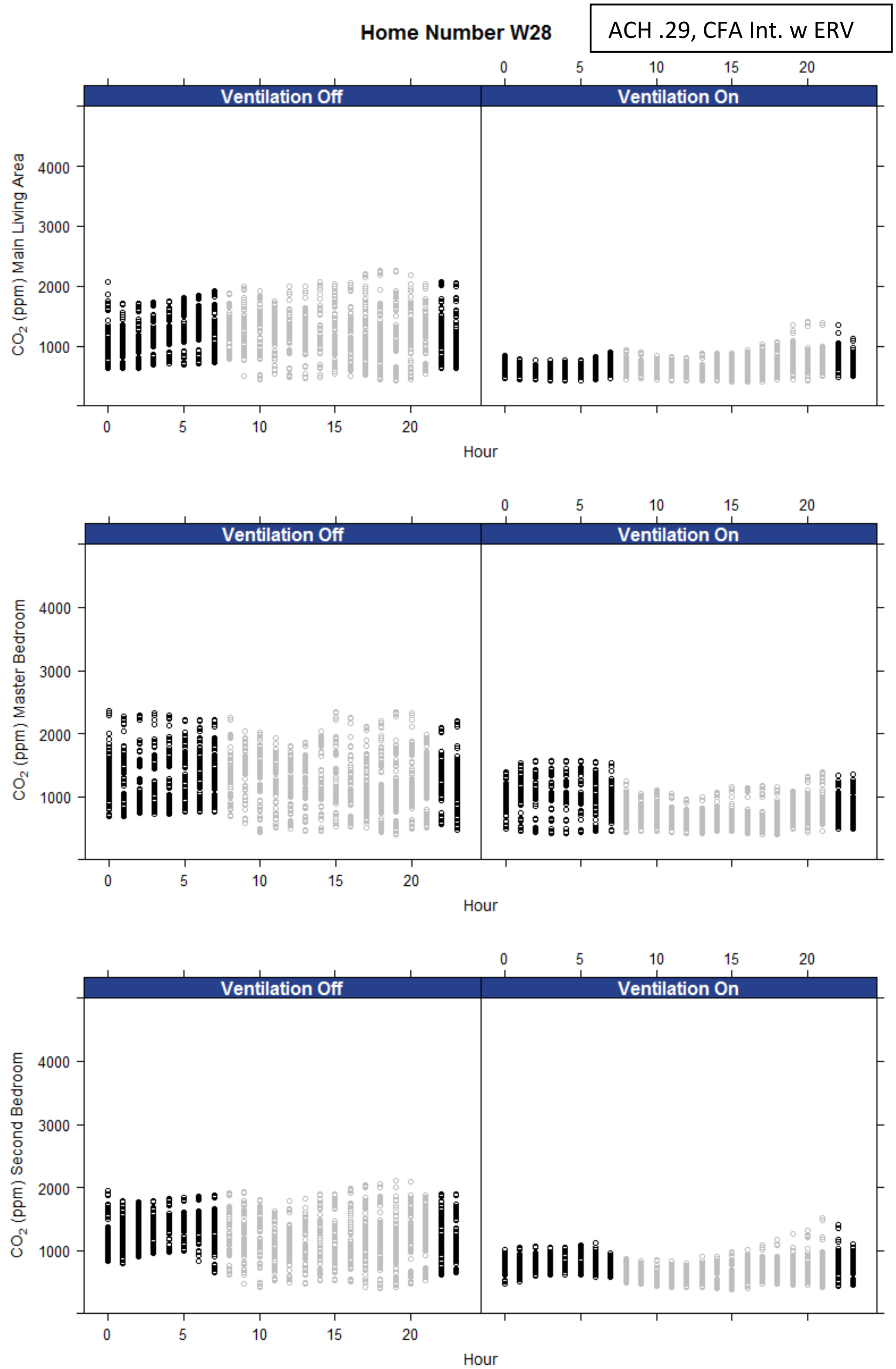
Home Number W27

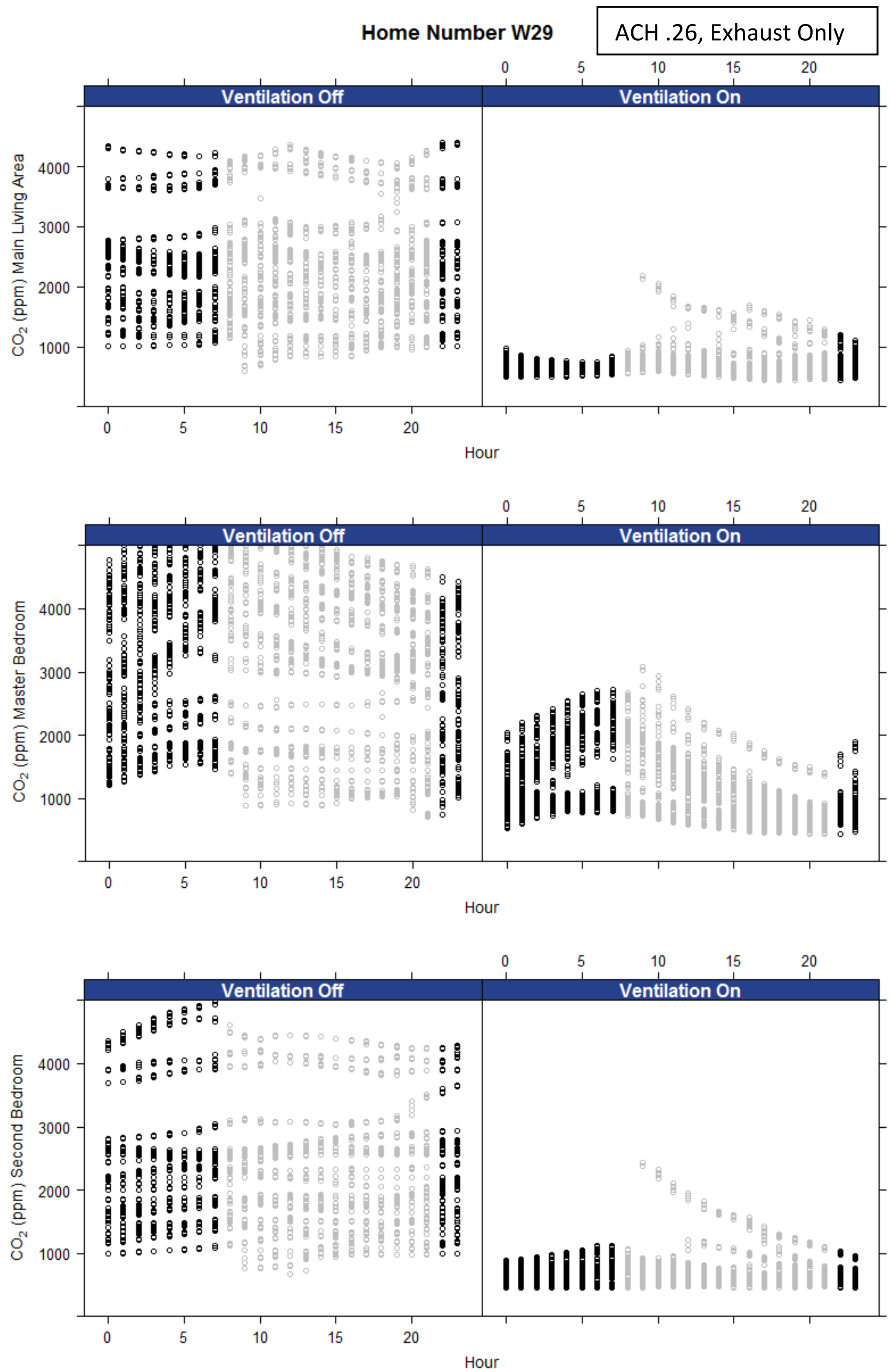
ACH 2.87, Exhaust w IV








Home Number W28
ACH .29, CFA Int. w ERV
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
1000
2000
3000
4000
0
5
10
15
20
Hour


Home Number W29
ACH .26, Exhaust Only
Ventilation Off
Ventilation On
CO2 (ppm) Main Living Area
CO2 (ppm) Master Bedroom
CO2 (ppm) Second Bedroom
Hour
0
5
10
15
20
1000
2000
3000
4000

Appendix E: Data Quality Issues and Data Compliance Approach

Data quality issues were documented in the master data templates for each house and summarized in data quality notes to support the creation of the final data set and categorize the data for analysis. This list summarizes the key data quality issues that were identified and reviewed.

- **CO_2 Data**: Only one house (E19) had faulty CO_2 data for a test period (heating season). Additionally, in a small number of cases the CO_2 reading was zero. Faulty and zero-reading data points were removed from the analysis. There were also a very small number of spikes in CO_2 measurements. Some of these readings were due to the tracer gas tests occurring during a test week, which were removed from the data set. Others were unexplained. Because it is difficult to differentiate a legitimate spike from an error (for example, someone breathing on a sensor), unusual spikes were left in the data set.

- **Door Closure Data**: In some cases, door closure data was missing. There are a couple of cases where there was no bedroom door, or data for the bedroom was not recorded. Nine other houses had at least some missing door data due to a battery problem, faulty sensor, or data download problem.

- **Ventilation Operation Data**: This was the most significant data quality issue for the study. Four houses had faulty measured fan operation data. The measured data showed either that the ventilation system was on all the time (sensor was too sensitive) or only on when the system was in boost mode (sensor was not sensitive enough). In these cases, there was other data to support that the ventilation system was turned on and off. In seven other cases, no ventilation fan operation data was measured. Most of these involved exhaust systems that were hard wired in such a way that it was difficult to set up a measurement for fan operation. In all of these cases, the lack of fan operation data makes it more difficult to determine when the ventilation systems were on or off and when they switched from one mode to the other. Occupant journal data was used to determine when the systems were on or off in cases with no fan data, but as a result, there was less confidence for these houses. A ventilation data flag was added to the data set in order to identify whether ventilation operation was measured, faulty, or not measured (i.e., no fan data).

- **Journal Data**: Data from the occupant journals was entered into a spreadsheet template and copied into the master data template for each house. Data entry was reviewed for a select group of houses (about half the cases) where journal entry issues were identified. Data entry issues that were corrected usually involved the wrong date or test status being entered. Journal data was also examined in cases when the journal data and the measured data did not match (for example, when the journal said the fan was off and the data showed it was on). When there was accurate measured data, it was always used to determine the test status. Still, this does raise data confidence concerns for test sites that did not follow the standard test week sequence. The three sites where journal and measured data did not match were all houses that had exhaust with inlet vent systems. Because the status of the inlet vents was not measured, this significantly reduced confidence in the journal data for inlet vent status. A confidence flag was added to the data set to identify the houses with high, medium-high, or medium data confidence.

- **Occupants Out of Town**: Some occupant journals had data indicating when occupants were out of town. This data was used to identify and exclude the data during these periods from the analysis. However, there is some potential for bias if some occupants did not record out of town information in their journals. Known out-of-town periods are annotated in the "QCFlag" data field.

- **15-minute Interval Data**: All data in the data set was recorded in 15-minute intervals starting on the hour. However, two houses recorded data in 30-minute intervals during the heating season period. There are also several situations where a sensor was set up and did not record data beginning on the hour. Thus, the data were out of sequence with the other sensors. When this was the case, the data periods were shifted by creating weighted averages of adjacent data.

Data Compliance Approach

Preliminary data exploration demonstrated varying levels of participant compliance with expected test conditions. Door status, particularly in some houses, did not always follow experimental test conditions as residents went about their daily routines. To refine the dataset to address the experimental variables of interest, several compliance screening routines were applied. The process for determining compliance with experimental test conditions was complicated and hierarchical. Because the CO_2 level at any particular moment depends on prior levels and changing conditions in the house, it was not simply a matter of determining compliance for each individual record; a compliance threshold for more extended periods was also required.

The midnight to 6 a.m. period was selected for analysis, because:

- Inspection of the dataset suggested that, although there were some changing conditions in the evening, conditions were likely to be fairly stable after participants retired for the night, and
- It was likely that occupants would be in the room for several consecutive hours during this period, creating one of the situations where the need for ventilation would be the greatest. Because the analyses presented in this report focus on nighttime CO_2 levels in the master bedroom, that is the compliance process outlined in this appendix.

Using Measured Values with Specific Adjustments

Where possible, sensor-measured ventilation and door status values were organized into one of five bins, as shown in **Table E-1**.

Table E-1. Data bins

Bin	Sensor Value	Door Status	Ventilation System Status
1	0-20	Open	Off
2	21-40	Non-Compliant	Non-Compliant
3	41-60	Non-Compliant	Non-Compliant
4	61-80	Non-Compliant	Non-Compliant
5	81-100	Closed	On

In this way, each 15-minute record was categorized. Following categorization, several test sites with measured data required adjustments to the binned ventilation status. For example:

- **E09** – This site had measured data, but due to the configuration of this particular CFA integrated system, the fan cycled off 50% of the time each hour when the ventilation system was in use. For ventilation on test weeks, the binned ventilation system status value was adjusted to "5."
- **E16** – For test weeks one and three during the heating season, this site was missing ventilation operation data. Journal and/or furnace data was used to verify ventilation status and adjust the corresponding binned value.

Because the majority of houses with measured fan data complied with expected ventilation protocols, houses with no measured fan data (or faulty fan data) were assigned a binned ventilation status corresponding to the expected ventilation status for an assigned test week. This assumed that houses without measured fan data were 100% compliant with expected ventilation status, which may or may not have been the case. Additionally, where houses were known to be missing bedroom doors, binned door values were adjusted accordingly (to Bin 1). This approach allowed the maximum number of houses and records to be included in the initial pool of data.

A calculated test condition was derived for each individual record from binned ventilation and door values. For the purposes of the analysis dataset, the calculated test condition was figured separately for each of the bedrooms. The master bedroom was calculated as shown in **Table E-2**.

Table E-2. Calculated test condition for master bedroom

Ventilation Fan Bin	Master Bedroom Door Bin	Calculated Test Condition	Description
5	1	A	Ventilation on, doors open
5	5	B	Ventilation on, doors closed
1	1	C	Ventilation off, doors open
1	5	D	Ventilation off, doors closed

If binned values fell outside the thresholds listed above, the record was assigned a value of "YYY," indicating non-compliance with any test condition. "ZZZ" was used to indicate instances where missing values precluded test condition calculation.

80% Compliance by Period

Once calculated test conditions were assigned for every observation, a second set of compliance screens were applied. For the nighttime master bedroom dataset, CO_2 levels between the hours of midnight and 6 a.m. were of interest. Observations that fell within that window were extracted from the larger database for further examination. In order for records to be compliant with the calculated test condition, a particular calculated test condition (A-D) had to be assigned to at least 80% of a given six-hour period. If "YYY" or "ZZZ" values comprised more than 20% of the records for a six-hour period, that period was considered noncompliant. If none of the calculated test conditions A through D encompassed 80% or more of a given six-hour window, that period was similarly considered noncompliant. The experimental test condition that comprised 80% or more of the given period was assigned to the entire period as the "resolved" test condition and used in analyses. The purpose of compliance screening was to ensure that the measured CO_2 levels used in analyses reflected the expected experimental parameters.

Removing Data and Requiring Full Six-Hour Periods

Data points were removed according to specific criteria because:

- The ventilation status for houses without ventilation fan meters could be approximated with some level of confidence only during test weeks, included data was restricted to experimental test weeks.
- Information about periods when participants were out of town for extended periods was provided in many of the journals and was used to remove periods when the house was likely to be empty and, therefore, near atmospheric CO_2 levels.
- When tracer gas test days occurred during experimental test weeks, these specific days were removed because the seeding of CO_2 in the house resulted in elevated CO_2 levels that were experimentally induced.
- Noncompliant periods could not reliably be assigned to a specific test condition; any noncompliant period identified in the compliance screens described above was removed.
- Only complete six-hour periods were included in the analyses. This requirement was imposed to ensure a more even sampling of the hours between midnight and 6 a.m.
- The data was inspected for any "zero" CO_2 levels, which were assumed to be caused by intermittent faulty readings. Zero or missing CO_2 values were dropped from the final analysis dataset.

Although these screens removed a substantial amount of data from the analysis dataset, the intent was to retain data points where the response variable (CO_2 in the master bedroom) was measured during experimental conditions.

Table E-3 lists the number of records that remained in the final nighttime master bedroom dataset used for analysis for each house and resolved test condition. Blank cells appear where compliance screening indicated test conditions were not met for a specific house.

Table E-3. Number of records that remained in the final nighttime master bedroom dataset

	Resolved Test Condition			
Site #	Ventilation on, Doors open (A)	Ventilation on, Doors closed (B)	Ventilation off, Doors open (C)	Ventilation off, Doors closed (D)
E01	744	384	336	360
E03	600	72	648	
E05	648	864	720	480
E09	252	372	228	204
E10	1,007		432	
E11	360	288	480	288
E13	672	528	336	312
E16	336	216	336	144
E18	480	312	336	144
E19	168	120	240	96
E22	336	72	216	240
E23	48	264	288	312
E25	144	264	192	288
E26	576		528	
W02	84	264	120	264
W04	144	168	144	168
W06		360		480
W07	120	960	72	744
W08	120		432	
W14	480	168	432	120
W15	504	624	480	624
W17	576	288	288	288
W20	288	144	264	264
W21	120	384		552
W24	72	264	240	168
W27	384			
W28	96	480	216	336
W29	360	336	336	312