U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Energy Savings With Acceptable Indoor Air Quality Through Improved Airflow Control in Residential Retrofits

June 2023

Building
America

Available electronically at Office of Scientific and Technical Information website (www.osti.gov)

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

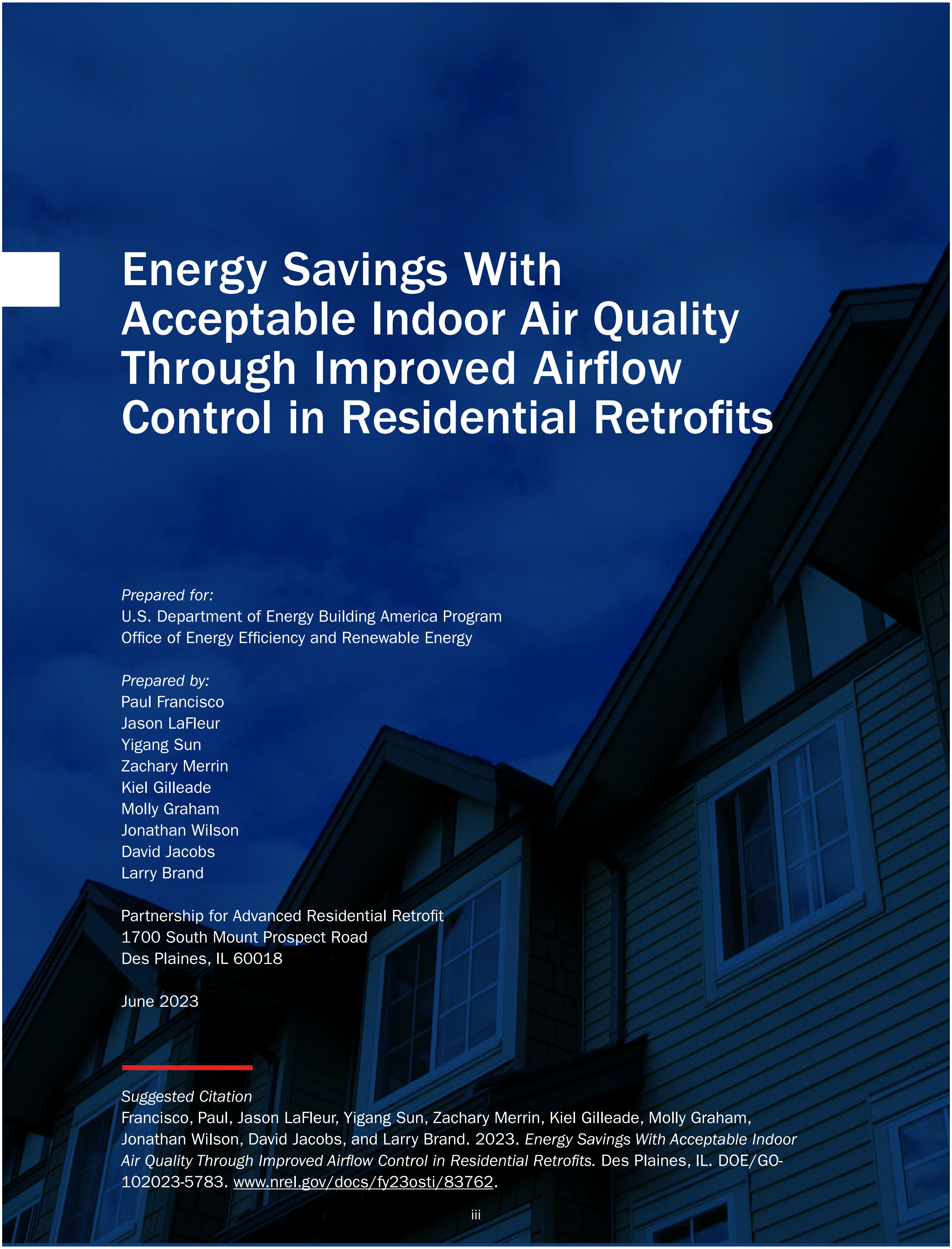
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

OSTI www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

NTIS www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov



Energy Savings With Acceptable Indoor Air Quality Through Improved Airflow Control in Residential Retrofits

Prepared for:
U.S. Department of Energy Building America Program
Office of Energy Efficiency and Renewable Energy

Prepared by:
Paul Francisco
Jason LaFleur
Yigang Sun
Zachary Merrin
Kiel Gilleade
Molly Graham
Jonathan Wilson
David Jacobs
Larry Brand

Partnership for Advanced Residential Retrofit
1700 South Mount Prospect Road
Des Plaines, IL 60018

June 2023

Suggested Citation
Francisco, Paul, Jason LaFleur, Yigang Sun, Zachary Merrin, Kiel Gilleade, Molly Graham, Jonathan Wilson, David Jacobs, and Larry Brand. 2023. *Energy Savings With Acceptable Indoor Air Quality Through Improved Airflow Control in Residential Retrofits.* Des Plaines, IL. DOE/GO-102023-5783. www.nrel.gov/docs/fy23osti/83762.

This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number EE0007057.

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

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

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

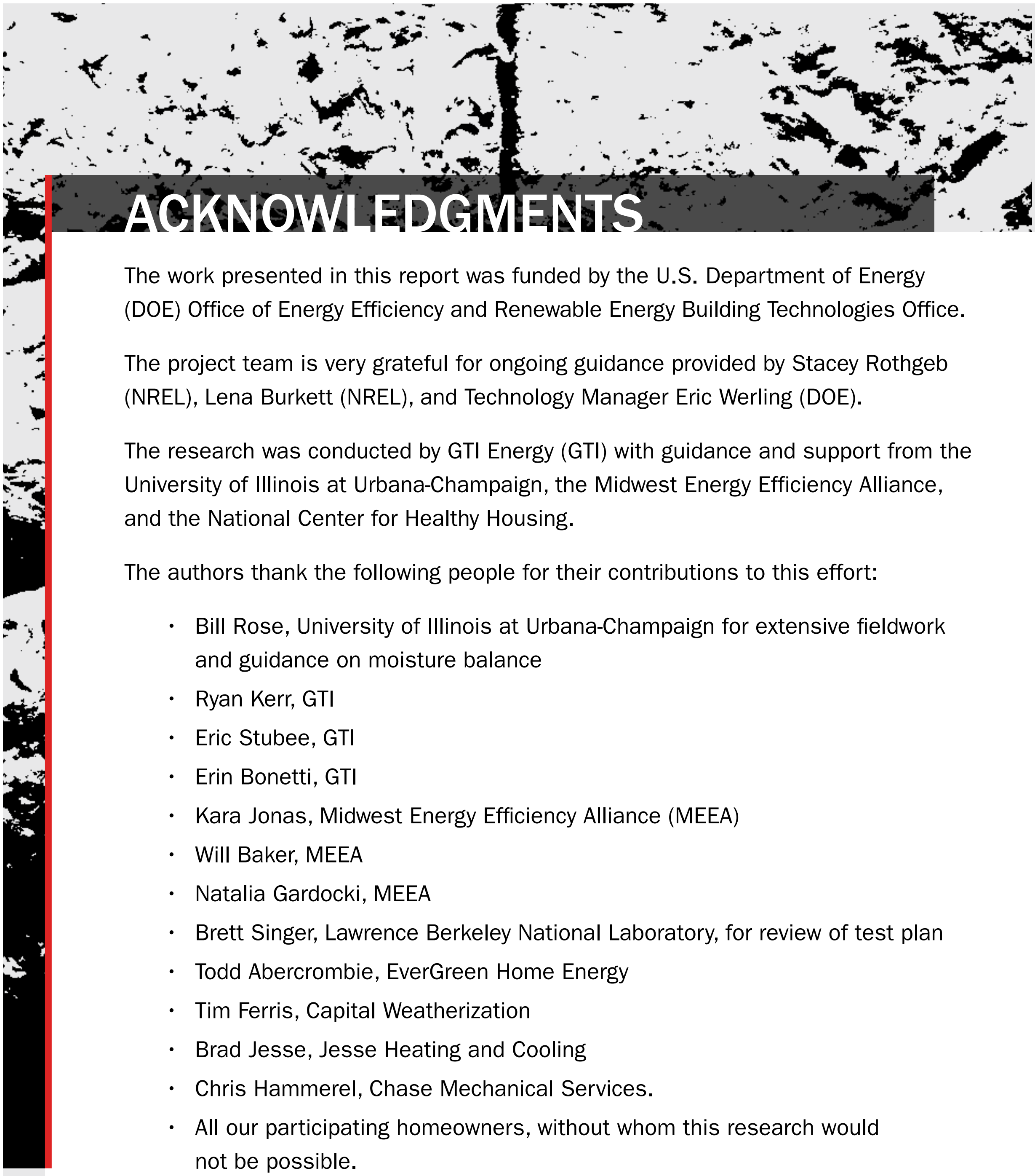
FOREWORD

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

In cooperation with the Building America Program, the Partnership for Advanced Residential Retrofit is one of many Building America teams working to drive innovations that address the challenges identified in the Program's Research-to-Market Plan.

This report, *Energy Savings With Acceptable Indoor Air Quality Through Improved Airflow Control in Residential Retrofits,* explores the impact on indoor air quality in residential retrofits focused on energy efficiency, and also explores the difference of supply ventilation and exhaust ventilation approaches on various contaminants of concern.

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



ACKNOWLEDGMENTS

The work presented in this report was funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy Building Technologies Office.

The project team is very grateful for ongoing guidance provided by Stacey Rothgeb (NREL), Lena Burkett (NREL), and Technology Manager Eric Werling (DOE).

The research was conducted by GTI Energy (GTI) with guidance and support from the University of Illinois at Urbana-Champaign, the Midwest Energy Efficiency Alliance, and the National Center for Healthy Housing.

The authors thank the following people for their contributions to this effort:

- Bill Rose, University of Illinois at Urbana-Champaign for extensive fieldwork and guidance on moisture balance
- Ryan Kerr, GTI
- Eric Stubee, GTI
- Erin Bonetti, GTI
- Kara Jonas, Midwest Energy Efficiency Alliance (MEEA)
- Will Baker, MEEA
- Natalia Gardocki, MEEA
- Brett Singer, Lawrence Berkeley National Laboratory, for review of test plan
- Todd Abercrombie, EverGreen Home Energy
- Tim Ferris, Capital Weatherization
- Brad Jesse, Jesse Heating and Cooling
- Chris Hammerel, Chase Mechanical Services.
- All our participating homeowners, without whom this research would not be possible.

Photo Credits

Cover, from top to bottom: Photos from iStock 182149008, 178447161, 184944590, 467972591;

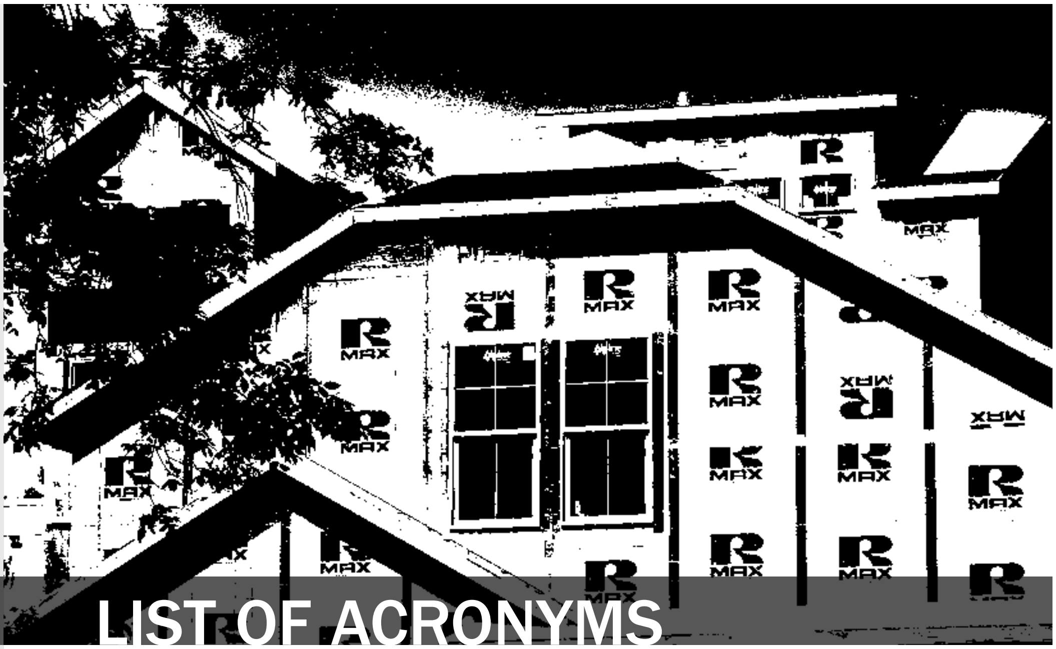
Page ii and iii: Photo from iStock 182149008;

Page v: Photo by Dennis Schroeder, NREL 28764;

Page vi: Photo from iStock 183245764;

Page vii: Photo from iStock 496703961;

Page viii: Photo from iStock 148484827.



LIST OF ACRONYMS

ACH	air changes per hour
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
ATSDR	Agency for Toxic Substances and Disease Registry
CFM	cubic feet per minute
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GTI	GTI Energy
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
ISO	International Organization for Standardization
ISTC	Illinois Sustainable Technology Center
MEEA	Midwest Energy Efficiency Alliance
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NTP	National Toxicology Program
OEHHA	Office of Environmental Health Hazard Assessment
PARR	Partnership for Advanced Residential Retrofit
$PM_{2.5}$	particulate matter (diameter less than 2.5 micrometers)
REL	reference exposure level
RH	relative humidity
VOC	volatile organic compound
WHO	World Health Organization

EXECUTIVE SUMMARY

The Partnership for Advanced Residential Retrofit (PARR) has been a U.S. Department of Energy (DOE) Building America team since 2009, with a primary focus on upgrading the performance of existing buildings to reduce energy loads. In this project, PARR's work explored the integration of airflow-focused measures in residential retrofit homes with the goal to maximize energy savings while ensuring acceptable indoor air quality (IAQ) using a systems approach to controlling four contributing air streams:

- Building air leakage (natural, uncontrolled infiltration)
- Forced-air distribution system static pressure and airflow rate
- Distribution system duct leakage
- Mechanical ventilation.

This project addressed airflows in houses, their combined impact on energy use and IAQ, and the comparative effects of typical insulation and air sealing practices versus integrated system-level retrofits. Additionally, practical considerations for contractors taking either approach were addressed. Finally, the effects of supply ventilation and exhaust ventilation on IAQ were compared in occupied homes.

Background

Concerns about IAQ and health impact energy efficiency programs. IAQ concerns have been cited by some programs as reasons to not air seal homes. Other programs, such as DOE's Weatherization Assistance Program, address the issue by allowing for expenditures on health and safety and requiring certain health and safety measures such as ventilation.

This project evaluated the relative IAQ impacts of different airflow-related measures such that IAQ can be considered when prioritizing air sealing efforts. The relationship between contaminant levels and infiltration is complex. Infiltration-driven air exchange can provide pathways for contaminants to enter the living space from outdoors and attached areas (e.g., basements, garages, crawl spaces, soil), or it can dilute contaminants that are already indoors. With uncontrolled air exchange, the amount of dilution or transport can be highly variable. Mechanical ventilation carries an energy penalty but introduces outside air into a home and is a core element of standards designed to mitigate IAQ hazards.

This study shows that the common belief that IAQ will deteriorate if energy measures are introduced can be overcome. Comprehensive energy retrofits in buildings may then be implemented with greater confidence that detrimental IAQ impacts will not occur. The project provides guidance for delivering residential retrofits that achieve both good IAQ and energy savings.

The objectives of the project were to:

- Provide both good energy savings and good IAQ using an integrated systems approach to controlling the four contributing air streams: ventilation, infiltration, forced-air system airflow, and duct distribution.
- Assess the potential for integrating a systems approach into contractors' standard business practices.
- Determine the impact of different ventilation approaches on IAQ contaminants of concern.

Following an initial literature review and workshop soliciting input from practitioners and experts in residential building performance, a set of enhanced retrofit measures to systematically manage airflows was developed. The research team's hypothesis was that the enhanced retrofits will show either improved IAQ with the same energy savings, or improved energy savings with the same IAQ. An integrated assessment was developed to measure the impact of these measures on IAQ and energy savings both before and after energy improvement measures during the study.

Phase 1

The project was divided into two phases of research. Phase 1 focused on homes undergoing a home performance retrofit. The sample set included homes with crawl spaces and unfinished basements, and some with attached garages. The team identified 27 single-family homes in Illinois (cold climate), split into 16 control and 11 treatment homes. All homes in the project received ventilation that complied with American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62.2-2016. Control homes received standard home performance retrofits such as attic air sealing and improved insulation, and treatment homes received those same standard measures plus system-focused airflow management, which included:

- Air sealing at the foundation level, including slab penetrations, cracks, sump pumps, and slab/wall interfaces, in addition to more standard measures of air sealing rim band joist locations
- Air sealing at the garage interface with the living space, including living space located above
- Duct sealing for leakage reduction in the unfinished basement/crawl space level
- Air handler system flow via improving total external static pressure in ducts.

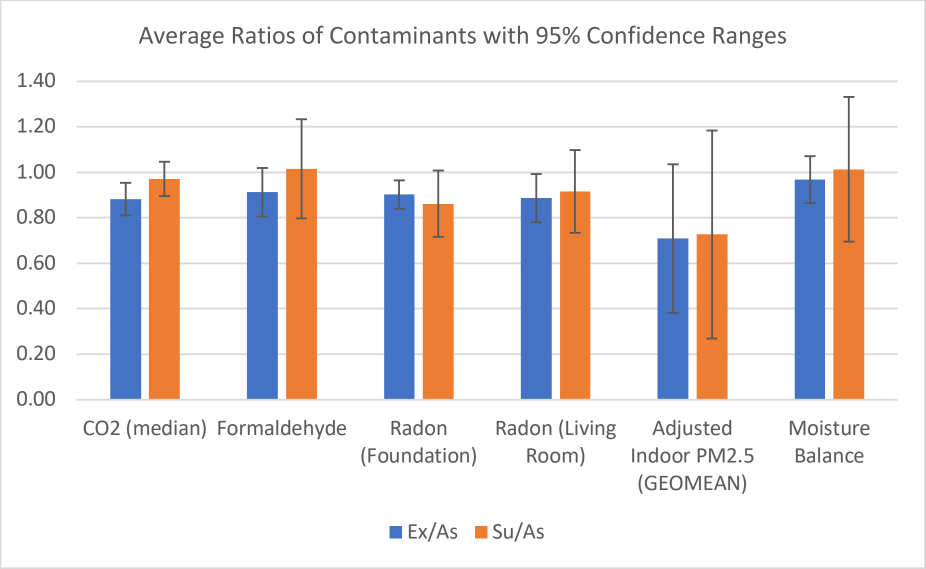
Energy use and IAQ contaminants during Phase 1 were measured pre- and post-intervention for 3 weeks. The IAQ components measured were formaldehyde (continuous indoor emission, 1 week), radon (soil/exterior emission, long-term averaged over 1 week), CO_2 (human generation), and humidity (human, soil, and outdoor generation). Energy for heating and cooling and ventilation were also monitored. Field tests were conducted in heating months and in cooling months to avoid window opening that is common during swing seasons.

Phase 1 of the project relied on close cooperation between the research team and home performance contractors who delivered either standard or enhanced measures to clients. Contractors who chose to participate were already implementing some of the advanced measures as part of their own standard business practices, and so were not representative of a more basic level of service. The study relied heavily on the ability of the contractors to identify potential homes, explain and sell the study to homeowners, and install the retrofit measures. Site recruitment proved to be challenging for the participating contractors for several reasons, including finding qualifying homes, the additional scope of work and associated expenses for treatment homes, the need to delay work to allow for pre-retrofit testing, and availability of utility incentives, which in some cases covered a significant amount of the home performance retrofit costs.

The results of Phase 1 found few statistically significant impacts on IAQ of energy retrofits in either group. This lack of statistical significance can be viewed positively, as evidence that it is possible to conduct comprehensive energy efficiency retrofits without negatively impacting IAQ, and that the measures that the contractors were already implementing supported maintaining IAQ. To the extent that there were statistically significant impacts on IAQ, they showed that IAQ improved following retrofit compared to pre-retrofit IAQ testing. However, incorporation of additional diagnostics and enhanced measures to meet the “treatment” home requirements was not easily integrated into the contractors’ business practices, and it is likely that these additional measures would require programs to both mandate and compensate for this additional work for it to become common.

Phase 2

In Phase 2 of the project, no energy retrofits were performed; rather, the focus was a comparison between the impacts of no ventilation, exhaust ventilation, and supply ventilation on IAQ conducted in three 2-week stages. The first stage was with no whole-dwelling ventilation running (the as-is condition), the second stage had exhaust ventilation running such as existing bath exhaust fan(s) that complied with the required ASHRAE Standard 62.2-2016 ventilation rate, and the third stage had supply ventilation running that complied with ASHRAE Standard 62.2-2016.



Exhaust to as-is and supply to as-is ventilation comparisons

IAQ contaminants were measured in Phase 2 for one week with each ventilation strategy. The IAQ components measured in Phase 2 were formaldehyde (continuous indoor emission), radon (soil/exterior emission), CO_2 (human generation), humidity (human, soil, and outdoor generation), and fine particles ($PM_{2.5}$, variable indoor and outdoor generation). Fifteen homes fully completed the Phase 2 study.

Phase 2 results found no statistically significant differences in contaminant impacts between supply and exhaust ventilation. Compared to no ventilation, both approaches showed reductions in contaminant levels for most contaminants, though most of these reductions were not statistically significant. The only two statistically significant reductions compared to no ventilation were with exhaust ventilation for CO_2 and radon.

Conclusions

While many of the results in Phase 1 were inconclusive, the findings further support the expectation that energy efficiency retrofits installed with proper ventilation systems will have no adverse effects on IAQ in homes. CO_2 and building moisture decreased slightly post-retrofit. With respect to the latter, moisture balance and improved envelope air sealing indicates that reducing infiltration helps reduce dampness in homes.

A limitation in the study is that the participating contractors were a self-selecting sample of contractors who already implemented some measures that considered IAQ, and so we cannot draw conclusions from the data on how the approach may have improved IAQ relative to a more basic level of measures. The small sample size was also a limitation of this study, and future studies with larger samples could have more statistically significant results. In any case, the study confirms that consideration of measures impacting both energy and IAQ positively can lead to good outcomes.

The second phase explored differential impacts of supply versus exhaust ventilation strategies on IAQ. There has been substantial controversy regarding whether one approach is superior. The results showed that both strategies resulted in improved IAQ across measured contaminants, and that some contaminants were reduced more by exhaust ventilation, and some were reduced more by supply ventilation. However, most results were not statistically significant given the limited sample size. IAQ improvements that were statistically significant were primarily for exhaust ventilation. The results reinforce that ventilation does benefit IAQ and suggests that the choice of ventilation strategy may depend on the local climate, soil conditions, outdoor air quality, and primary contaminant(s) of interest, though more study is needed to conclusively determine the extent to which exhaust or supply ventilation impacts specific contaminants

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background and Motivation

A significant amount of research has been conducted by Building America on residential ventilation, infiltration control, and reduced duct leakage. Research has explored increasing ventilation levels to better control indoor air quality (IAQ), reducing infiltration to less than 0.5 ACH50 in single-family buildings, and controlling duct leakage to below the 5% level recommended by Air Conditioning Contractors of America manual D. No research has been done, however, on the interaction between ventilation, infiltration, and ducting to answer the question of how acceptable IAQ can be achieved with lower energy costs by controlling these air streams.

This report seeks to answer that question and also addresses the relative benefits of different spot or whole-home ventilation strategies for homes receiving residential energy efficiency retrofits. The current state-of-the-art approach to managing infiltration, ducting, and ventilation in residential retrofits is by minimizing air infiltration from all sources, installing a space-conditioning system sized to the load, and using ventilation systems to meet the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) 62.2 requirements. This approach does not consider the system interaction between the infiltration, ducting, and ventilation airflows. Additionally, ASHRAE Standard 62.2 is currently silent on the relative benefits of different ventilation strategies. It is reasonable to expect that different ventilation strategies (e.g., supply versus exhaust) will result in different IAQ outcomes. However, the majority of research on this issue to date has centered on new, tight construction, without occupants, and with assumed (or manufactured) contaminant sources and emission rates. This project evaluated a first-of-its-kind systems approach to residential retrofits managing air sealing, ventilation, and air distribution during actual weatherization and home performance improvement projects, with the goal of optimizing energy efficiency, IAQ, comfort, and ventilation energy savings in the cold climate zone 5.

This project addressed airflows in houses, their combined impact on energy use and IAQ, and the comparative effects of standard versus system-level retrofits. Additionally, it developed practical considerations for contractors taking either approach, and compared supply and exhaust ventilation effectiveness in existing homes. The airflows considered in this study include:

- Building air leakage (natural, uncontrolled infiltration)
- Conditioned air distribution (duct leakage and forced-air system flow rate)
- Mechanical ventilation.

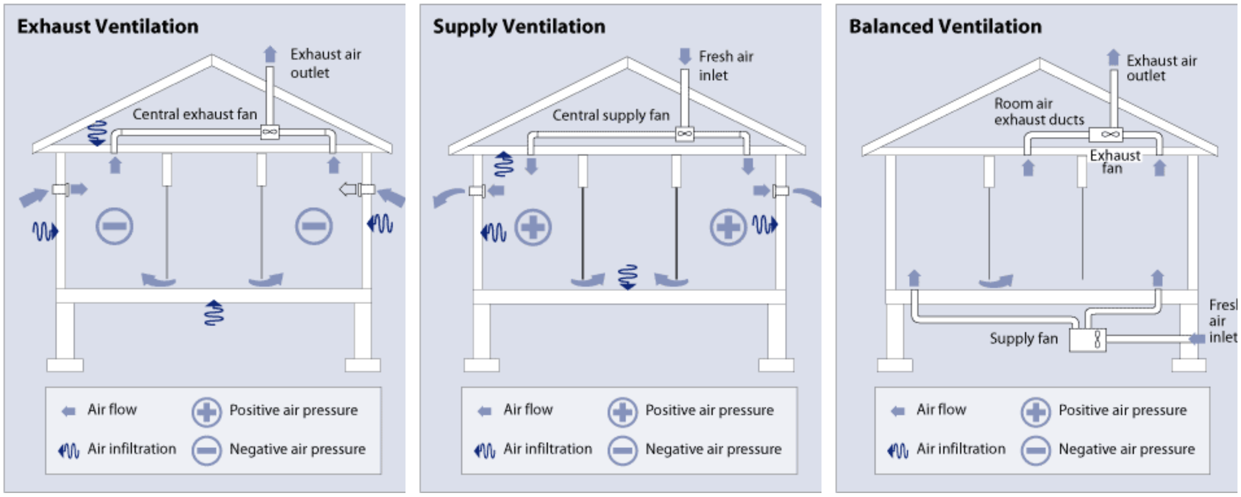
Air infiltration typically represents 25%–40% of a home's heating and cooling costs, according to DOE (2000). Air sealing is therefore one of the most common and effective retrofit measures. The relationship between contaminant levels and infiltration is complex. Infiltration-driven air exchange can provide pathways for contaminants to enter the living space from outdoors and attached areas, or it can dilute contaminants that are already indoors, thereby improving IAQ. Since this air exchange is uncontrolled, the amount of dilution or transport can be highly variable.

Although attic sealing generally attracts the most focus for energy savings, air bypasses such as those located near a garage or crawl space are more likely to allow pathways for contaminants to enter the home. Pollutants that originate below ground will be less able to enter the home if air sealing is done at the floor. It is also possible that air sealing at the ceiling may reduce ground-source contaminants due to the shifting of the neutral level in the building's pressure plane and the resulting reduced driving pressure at the floor. This project evaluated the relative IAQ impacts of different air sealing measures such that IAQ can be considered when prioritizing air sealing efforts.

Ducted forced-air systems for space conditioning have the potential to directly or indirectly interface with infiltration control and ventilation approaches to produce an overall system that provides energy efficiency and good IAQ. Duct leakage can carry a big energy penalty and can also serve as a direct pathway for unintended contaminant transport. Further, depending on whether leaks are located on the supply or return, they have the potential to adversely impact the pressures in the home and can therefore indirectly be a mechanism for contaminant transport. The impact of duct leakage will depend on the location of the ducts within the home. Ducts in basements and crawl spaces—which were the dominant location in this study—will be an entry point for soil and foundation-space contaminants. Ducts in garages—present in a minority of homes—serve as an entry point for garage contaminants. While these effects are well-established, IAQ-based duct system adjustment is often not included in retrofit programs. Forced-air system flow rate has impacts on energy, comfort, and IAQ. This is especially true for cooling, where the building infiltration and flow rate have a substantial impact on humidity control. Improving filtration and dehumidification may alter the type of or need for ventilation for good IAQ.

Mechanical ventilation carries an energy penalty but introduces fresh outside air into a home and is a core element of ventilation standards designed to mitigate IAQ hazards. Residential mechanical ventilation retrofit practices can be categorized into one of three types, with common installation practices listed below and shown in Figure 1:

- **Exhaust ventilation** – Replacing an existing bathroom exhaust fan with a ventilating model designed to provide some degree of continuous ventilation.
- **Supply ventilation** – Integrating an outside air duct and motorized damper to let in fresh air into a central fan such as a furnace blower; also known as central fan integrated supply ventilation.
- **Balanced ventilation** – Ensuring a system of air exchange with equivalent flows into and out of the home; typically achieved by linked supply and exhaust, or an energy recovery ventilator.



Exhaust Ventilation **Supply Ventilation** **Balanced Ventilation**

Figure 1. Typical mechanical ventilation systems in residential retrofits

Figure from DOE

It is common for residential practitioners to prefer their favorite ventilation options as being "clearly" the best. However, as with air sealing, the reality is more complex. Supply ventilation may reduce the entry of ground-source contaminants such as radon (Collignan and Powaga 2019), and exhaust ventilation may be preferred for occupant-generated contaminants. For material-source contaminants, there is evidence that supply ventilation is better at reducing pollutants such as formaldehyde (Hun et al. 2013). Since material-source contaminants such as formaldehyde depend on the vapor pressure, they will also be emitted faster when they are removed faster. As such, until such time as the formaldehyde within the materials is substantially removed, the impact effectiveness of ventilation to reduce formaldehyde concentration may be muted. Overall, the "best" ventilation option may actually depend on the nature of the contaminants and the specific geography of the home. Optimizing mechanical ventilation to provide the best combination of contaminant control and energy use is a goal of this project.

Based on the discussion above, a primary motivation of this work was an investigation into inefficiencies associated with controlling air movement in buildings. The project developed a "systems approach" for managing air sealing, ventilation, and air distribution system retrofit to achieve energy savings while maintaining acceptable IAQ. Key topics investigated include:

1. The relationship between air sealing for infiltration control and contaminant levels
2. Best practices for combining ducted HVAC systems and ventilation systems for IAQ control, minimum energy consumption, and occupant comfort
3. The impact of different ventilation strategies on contaminant levels.

The Partnership for Advanced Residential Retrofit (PARR) has been a Department of Energy (DOE) Building America team since 2009, with a primary focus on upgrading the performance of existing buildings to reduce energy loads. A significant part of that research has been the study of forced-air systems, ducted distribution systems, ventilation, and combustion air-related research. The principal research partners of PARR, GTI Energy (GTI), the Illinois Sustainable Technology Center (ISTC), and the Midwest Energy Efficiency Alliance (MEEA) have a combined 100 years of experience working in residential building energy efficiency. PARR's work for this project involved a systematic integration of residential retrofit measures in residential retrofit homes with the goal to maximize energy savings while ensuring acceptable IAQ in residential retrofit homes using a systems approach to controlling the four contributing air streams: ventilation, infiltration, forced-air system airflows, and duct distribution.

1.2 Purpose and Objectives

The objectives of the project were:

1. Provide both energy savings and good IAQ using a systems approach to control the four contributing air streams: ventilation, infiltration, forced-air system airflow, and duct distribution.
2. Assess the potential for this systems approach to be integrated into home performance contractors' standard business practices.
3. Determine the impact of different ventilation approaches on IAQ contaminants of concern.

To meet the project goals, the PARR team developed a four-pronged research program focused on (1) reducing infiltration air streams that introduce the most contaminants, rather than the common air sealing approach focusing on the attic, (2) proper sizing and airflow, including low static pressures in the ducts for forced-air space conditioning systems, (3) airtightness of duct systems, and (4) closely coupling ventilation with the IAQ needs of the space. In Phase 1 of this study, an integrated assessment was developed to measure the impact of these measures on IAQ and energy savings both before and after energy improvement measures. Phase 2 assessed the impacts of different ventilation strategies on IAQ contaminants.

The primary aim of this study was to evaluate whether a systematic approach to airflow management will result in energy benefits at no IAQ penalty, or IAQ benefits at no energy penalty, or benefits in both energy and IAQ. Implementation of energy retrofits in buildings could then be made with greater confidence that new IAQ issues would not be introduced, and existing IAQ risks may be mitigated.

1.2.1 Potential Impacts

This project supports Building America's goal to demonstrate market-relevant strategies to enable 40% energy savings in existing homes (pre-post retrofit) by 2030. PARR recognizes savings can come from improved technologies, but also that realizing maximum savings requires an integrated implementation of technologies and techniques. This integration is often missing in the retrofit sector where budgets are lower than in new construction and where there are limitations resulting from the characteristics of the existing structure.

There are ~140 million housing units in the United States, 63% single-family detached homes and 26% multifamily units. Over a quarter were built before 1959, and the average life cycle of a single-family home is 130 years (U.S. Census Bureau 2019). Although many buildings remain untouched, energy upgrades are beginning to gain a foothold in this market with the availability of guidelines from the Building America Solutions Center, contractor training, and utility rebates. The DOE Weatherization Assistance Program estimates its impact to include energy savings for about 7 million families since 1976, and PARR currently estimates 100,000 homes per year are weatherized. This vast market represents the opportunity for energy savings in this project.

PARR's previous research indicates that energy savings associated with energy efficiency retrofit measures vary significantly from 6% for a furnace tune-up to 30% for a whole-house upgrade with the right combination of air sealing, insulation, and equipment upgrades. Post-upgrade, ventilation systems are often added to these homes as a requirement. Based on earlier work, using the systems approach provides significant benefits to the consumer, with improved IAQ and a lower overall cost (Brand 2015).

Historically, home performance contractors and weatherization professionals have been reluctant to perform advanced air sealing strategies over concerns of negatively impacting IAQ, because reduced (even uncontrolled) airflow means fewer pathways for contaminant removal (Manual 2011). The current study shows that the common belief that IAQ will deteriorate if energy measures are introduced can be overcome. The project provides guidance for delivering residential retrofits that achieve both good IAQ and energy savings.

2 Background

The PARR team established a foundation of existing knowledge to synthesize the whole-home approach to residential retrofit through extensive literature review and input from ventilation and IAQ experts and practitioners. Investigations were focused on information to help meet the project's competing priorities of maximum energy savings, optimal IAQ, minimum cost, and maximum transferability to the retrofit marketplace. Some of these initial findings are summarized in the following sections.

Although there is ample research observing the energy impacts of various home performance or weatherization measures and a solid foundation of research investigating relationships between these measures and IAQ in single family homes, more work is needed that focuses on actual, existing homes. This project built upon established understanding of the physics, engineering, and chemistry of airflows, heat transfer, contaminant transport, and construction practices by adding real-time observations of occupant behavior, the actual working conditions of older homes, and the knowledge and abilities of tradespeople making a living in the home performance industry.

2.1 Literature Review

2.1.1 Benefits

Earlier projects provide limited guidance regarding the expected extent of impacts from airflow management. Not all of the following impacts were expected to be realized at each house in the current project; however, past studies provided ample evidence that the effects being explored in this project had high impact potential.

- Nitschke et al. (1988) found a potential 50%+ reduction in soil gases (e.g., radon) due to sealing foundation connections to ground.
- Previous research from PARR members indicates the potential for an average of about 41% reduction in contaminants due to air sealing to reduce garage transport (Merrin et al. 2018).
- Regarding literature quantifying the impacts of duct leakage on IAQ, there are studies (Hubbard et al. 1988; Rose 2015) that suggest forced-air systems help to equalize basement and first floor radon concentrations. There is substantial anecdotal evidence that duct leaks in basements resulting in depressurized space are a major source of combustion safety issues.
- Addressing issues with air handler flow can have an impact on latent removal capacity, with an 8% increase, going from 400 to 300 cfm/ton (Parker et al. 1997).
- A recent study by the U.S. Department of Housing and Urban Development showed a 25%–30% reduction in certain contaminants due to adding 62.2-compliant ventilation in the context of weatherization (Francisco et al. 2016).

- Sherman and Walker (2012) reported that many weatherization practitioners used a building tightness limit, stopping air sealing just below the point where a mechanical ventilation system was necessary, to avoid the expense of installing a mechanical ventilation system in a retrofit situation.

2.1.2 IAQ Control

A literature review targeted to IAQ, residential retrofits, and measurements performed in actual homes in cold climate regions was completed. Specifically, PARR reviewed work on the effects of different ventilation systems on IAQ and energy use in homes.

Several studies identified the importance of the goals of the current project for future research. For example, Martin (2014) specifically referenced finding methods for controlling indoor air contaminants “in ways other than outdoor air exchange” as a needed alternative to some popular ventilation strategies. In addition, several studies expressed a need for more observation of ventilation systems in occupied homes, or a need to combine more rigorous up-to-date health surveys with IAQ analyses, or a need to more closely study the energy impacts of common duct and air sealing practices in different parts of the country.

One of the most comprehensive evaluations of residential retrofit practices to date is the *National Retrospective Evaluation of the Weatherization Assistance Program* led by the Oak Ridge National Laboratory in collaboration with many others. The evaluation consists of 21 reports on multiple facets, including the measured impacts of retrofit practices on IAQ. That report investigated 514 single-family homes in 35 states and observed 5 indoor environmental quality parameters, including carbon monoxide, radon, formaldehyde, temperature/humidity, and moisture (Pigg et al., 2014).

There is abundant literature on the energy and IAQ benefits of air sealing; however, it is not as simple as more is better. By interfering with natural infiltration in specific areas, air sealing can interact with the existing complex dynamic between airflows and natural infiltration of a home, which can benefit or not benefit occupants from an IAQ perspective. Air sealing, as well as duct sealing, are a home performance or heating, ventilating, and air conditioning (HVAC) contractor’s best tools for source control and can tip the balance of pressure across one or more interior spaces. In particular, air sealing and duct sealing are important means of limiting IAQ contaminants from undesirable places, such as garages and foundation areas.

Rudd (2014) describes the dangers to occupant health, which can occur when make-up air entering a depressurized living space originates in the garage. According to Rudd’s review of prior research, this situation is relatively common and introduces harmful pollutants into the home such as carbon monoxide, respirable particulate matter, benzene, and a variety of other compounds depending on what chemicals and materials are stored in the garage. Although air sealing impacts are typically complex in the way they control source pollutants and change airflows in a home, it is reasonable to assume similar IAQ benefits could result from air sealing along other borders between living spaces and poor-IAQ areas, such as crawl spaces, unfinished basements, attics, or other foundation areas. Likewise, duct sealing should be a primary concern from an IAQ standpoint for two reasons: 1) ducts are often located in areas with poor IAQ such as unfinished basements, crawl spaces, or attics, and 2) excessive duct leakage can lead to uneven pressure throughout a home. Such imbalances could result in issues with backdrafting and combustion products being pulled into a home. The same pressure scenario presents an issue with moisture as well, where humid air outside could be drawn inside (Aldrich et al. 2011). When it comes to protecting against interior pollution sources, such as furniture or occupant behaviors, air sealing alone may have limited or even detrimental effects, but duct sealing provides contractors with opportunities to improve IAQ in concert with envelope air sealing.

Ventilation is another critical retrofit component impacting pressure balancing and IAQ. There is a limited amount of literature comparing the IAQ impacts of different types of ventilation, and the literature that exists demonstrates that different ventilation strategies may impact specific contaminants in different ways (Widder et al. 2017; Rudd and Bergey 2014).

Radon is a particularly challenging IAQ parameter to control given that its entry into homes is an extremely complicated process. The Weatherization Assistance Program study found that while it is possible that increased ventilation through mechanical means potentially reduces radon concentrations by forcing the exchange of indoor air with fresh air, mechanical ventilation could also depressurize the indoor environment, particularly near foundation spaces, which tends to increase the migration of soil gasses into living spaces. A concurrent follow-up study measuring the impact of exhaust-only ventilation on radon and humidity in 18 homes in Colorado, Iowa, Minnesota, and Ohio (Pigg 2014) found evidence that any increase in incoming radon from the ventilation-caused depressurization of basement or foundation areas was overcome by the dilution effect of the ventilation system, finding no instances of increasing radon levels. In contrast, a study sponsored by the U.S. Department of Housing and Urban Development examining the differences in several IAQ metrics and occupant health outcomes between low-income homes with and without ventilation saw radon levels increase in the basement but decrease on the first floor, consistent with the view that exhaust ventilation produces slight negative pressures (drawing soil gas through the foundation), but with significant dilution from outdoors leading to living space improvements (Francisco et al. 2015).

2.1.3 Energy Impacts of Common IAQ Measures

Residential buildings are estimated to consume up to 23% of the country’s annual source energy, and a large amount of research has been conducted on the energy reduction impacts of common retrofit measures such as air sealing, duct sealing, and insulation (Logue et al. 2013). Measured home performance research has shown that measuring air infiltration levels to inform retrofits can save 100 to 450 CFM50 per crew hour through better training and feedback (Chitwood 2012, 109). The authors reviewed several major studies for consistency and their ability to inform the current project.

From the perspective of energy savings, air sealing and insulation are viewed as the most important components of any retrofit or low-energy construction strategy, demonstrated in both modeling (Logue et al. 2013) and field studies (Tonn et al. 2014; Blasnik et al. 2014). Often representing up to half of a retrofit measure package's attributable energy savings in many climates, air sealing must also be performed with a critical eye toward IAQ and airflow impacts through the home. Even very simple and small air sealing actions can have dramatic IAQ consequences.

Similarly, duct sealing represents a significant energy savings opportunity but also a potentially more complicated one from a contractor standpoint because much of the distribution system can be concealed in building cavities, and duct sealing is not a typical measure performed by home performance contractors. Past research has shown the potential of household reductions in energy consumption of 16%–20% (Davis 1993, Palmiter and Francisco 1994, Cummings et al. 1994). Knowledge of the particulars of static pressure, system efficiency, and airflow requirements may not be widespread, and more training among practitioners is needed (Edwards et al. 2015).

Ventilation energy impacts are also situation specific. As different ventilation strategies affect airflows in different ways, energy penalties vary widely. In general, ventilation represents a trade-off with energy-saving measures, but from the perspective of balancing energy costs with ensuring IAQ, it is likely necessary. Most research has shown minimal energy penalties from correctly designed and operated ventilation systems; however, as with duct sealing, gaps exist in product, installation, and operational knowledge (Less et al. 2015).

2.1.4 Recommendations

These findings informed the whole-home approach to residential retrofits performed in this project that balances and optimizes four air streams—ventilation, infiltration, forced-air system total airflow (at the air handler), and duct distribution—with the competing priorities of maximum energy savings, maximum IAQ, minimum cost, and maximum transferability to the retrofit marketplace.

The project team incorporated the major findings of this review in the following ways:

- There are a number of different indoor air contaminants to be concerned about, including small particulates, formaldehyde, radon, moisture, and several point-source generated pollutants such as acrolein, as described in Lawrence Berkeley National Laboratory's 2011 summary report, *Why We Ventilate* (Logue et al. 2011). The introduction of contaminants to living spaces also varies depending on the contaminant, with some coming in from outdoors, some via human activities, some from materials within the home, and some from the soil. The test plan was designed to include a suite of contaminants representing as many of these entry routes as possible, taking into consideration their particular measurement requirements and other study parameters.
- Because of these different entry routes, air sealing and ventilation can also have different impacts on different contaminants. Each contaminant was considered individually, as demonstrated in subsequent portions of this report, and we attempted to optimize conditions across a range of possibilities.

- System flows and duct leakage can have considerable impacts on dehumidification performance, pressure differentials, and the connections between the house and other spaces that may be contaminant sources.
- The literature suggests differing impacts between exhaust and supply ventilation depending on the contaminant. However, much of the existing fieldwork has been performed in unoccupied homes, and usually in new, tight homes. Thus, the need for research under everyday circumstances in occupied, older homes with workmanship that is reflective of market conditions is imperative and implemented in this project.

2.2 Expert Meeting

An expert meeting was held in Chicago on January 19, 2016, with Building America teams, national laboratories, and other industry experts in the field of IAQ related to airflows in buildings[1] to solicit expert advice for the program, specifically the measurement parameters and methods for measurement. A distinct challenge of this project was how to control the variables to be able to recognize specific energy and IAQ benefits. A set of IAQ parameters was established with expert input, along with the measurement devices and frequency of measurement.

2.2.1 Outcomes

Based on the expert meeting, the following decisions were made regarding the field study methodology:

- Both control and treatment homes will be included in the study.
- Ventilation rates compliant with ASHRAE 62.2-2016 will be provided for both control and treatment houses.
- Filtration will match the utility energy efficiency program standard as a baseline. A new filter will be provided as part of baseline treatment.
- Health questionnaires will not be included in the study.
- Particles will be measured when opportunities permit. Particulate measurements will not be a central part of the control/treatment study. Opportunities depend on occupant agreement and instrument availability. Both gravimetric and particulate count instruments will be considered.
- Work will be scheduled for closed-window seasons. Occupants will be asked to keep a log of any time that windows are opened.
- Crawl spaces will be included in the study. The baseline treatment for crawl spaces will be a sealed crawl space (unvented, ground cover, insulation, and air sealing of rim joist).

---

[1] Attendee list included in Appendix A

2.2.2 Experimental Design Discussion

Much of the current and recent IAQ research discussed in this meeting is covered in the literature review portion of the report, so details are only reported for discussions around other project decisions.

IAQ and Ventilation Strategy

There was significant discussion around prioritization of indoor contaminants. The contaminants identified for monitoring in the project are included in Table 1. Although research shows that IAQ has significant health impacts, such as allergies and respiratory distress—especially in children—health surveys may not be able to reflect health status due to IAQ versus other health factors. Defining acceptable numbers for most contaminants is challenging because there are no legally enforceable standards for residential indoor air. Using formaldehyde as an example, the World Health Organization (WHO) recommends 80 ppb, the National Institute for Occupational Safety and Health (NIOSH) and the Federal Emergency Management (FEMA) recommend 16 ppb, the Agency for Toxic Substances and Disease (ATSDR) has established a minimum risk level of 8 ppb, and the State of California recommends 7 ppb for non-cancer health effects. Formaldehyde, along with multiple other contaminants, has seasonal fluctuations, with warm weather leading to more formaldehyde than cooler weather. In addition to elimination of contaminant-emitting sources in a home, ventilation may be an effective method to help reduce contaminants given that ventilation purges the air. Toxicity of formaldehyde and the other air contaminants measured in this study are discussed later.

The attendees developed a matrix showing how different ventilation strategies might impact dilution of IAQ contaminants. In Table 1, a “+” indicates a positive effect on dilution of the contaminant (i.e., higher dilution), “0” represents no anticipated impact, and “+”, “++”, and “+++” represent anticipated beneficial impact by strength. This discussion was less focused on the most appropriate ventilation rate (because there is not a single number that always works) than qualitatively on the best ventilation strategy. The first set of distinctions to be made are those among exhaust, supply, and balanced whole-house ventilation, as well as filtration and kitchen ventilation. This discussion identified the importance of installing multiple types of ventilation in the study and switching back and forth. Exhaust-only represents almost the entire market, while supply ventilation represents perhaps a few percent of residential buildings and balanced ventilation represents less than 1% of existing buildings. The consensus was to install both exhaust-only and supply-only, and to flip-flop in the course of the monitoring period in a subset of the houses, if funds permit. This became the focus of Phase 2, discussed in detail later.

Table 1. Relationship Between Ventilation and Contaminant Dilution

Contaminant ⇨ **Type of Vent. ⇩**	**Radon**	**Formaldehyde**	**CO_2**	**$PM_{2.5}$**	**Humidity**	**Operational Considerations**	**Energy**
Exhaust	Basement -/0 Living +	+	+	Outside + Inside +	+		$$
Supply	++ depends on ducts	++	+	Outside -/0 Inside +	+	Filter Maint./Repair	$$$$
Balanced	+	++	+	Outside -/0 Inside +	+	Filter Maint./Repair	Clean $ Clogged $$$
Filtration	0	0	0	Outside ++ Inside ++	0	Runtime? Maint./Repair	
Kitchen	~0	~0	~0	Outside ~0 Inside ++	+		

The various releases of ASHRAE 62.2 were discussed and the consensus was to use 62.2-2016 (the most current version at that time) in the research test plan. The importance of having a control group in the study rather than simply relying on pre- and post-treatment to make conclusions was recognized and led to the consensus that homes should be paired as control and treatment. Control homes would receive only typical energy retrofits focusing on attic air sealing and insulation, along with ASHRAE 62.2-2016 ventilation exhaust, while homes receiving advanced treatment would receive additional upgrades as follows:

- Air sealing at the foundation and garage interface with the living space
- Duct leakage reductions for IAQ
- Increases to heating/cooling system flow via improvements in reducing external static pressure in ducts.

Research Conditions

Defining the research conditions for the testing period to enable a clear relationship between the measures implemented and IAQ and energy benefits was a critical part of the project. An appropriate monitoring period was selected as 3–4 weeks. Attendees agreed that to the extent possible, testing should occur during closed-house conditions in the winter and summer, avoiding swing seasons.

To limit IAQ impacts as much as possible to ventilation, homes with smokers were excluded from the study. Homes with high ACH50 were also excluded from participation in the study. It was decided that selection of an appropriate cutoff for airtightness would be taken up at a practitioner meeting to ensure that high infiltration would not confuse the impact of the mechanical ventilation.

Homes with crawl spaces are very common in the Midwest, the site of the study, so they were included. Discussions during the practitioner meeting and in a subsequent series of email exchanges led to the conclusion that both control and enhanced treatment houses with crawl spaces should have treatment as part of the baseline program. In summary, all baseline measures implemented were at least as rigorous as the business-as-usual treatment.

2.3 Practitioner Workshop

A practitioner workshop was held in Chicago on February 17, 2016, to identify the most common upgrades currently applied in the field and how those practices may be modified with little training for the project. Aside from receiving valuable input that would help make the project more applicable to real-world retrofit market conditions, the practitioner workshop also served a role in soliciting participation interest from business owners, energy auditors, and other retrofit professionals. The PARR team used the workshop to recruit contractors to assist in site selection, data collection, treatment home measure implementation, and other test plan needs throughout the project period. Besides the PARR team, several private contracting companies, utility program implementation companies, residential retrofits advocacy organizations, state-level weatherization agencies, and representatives of the Building America program attended.[2]

2.3.1 Outcomes

Several important observations resulted from this meeting. Installers are skilled in duct sealing, but may perform only limited system balancing, indicating a need for further training in this area. In the realm of crawl space treatments, practices can vary significantly, and the research team had to weigh the best approach for the project. Feedback revealed that installation of ventilation systems is not common with most contractors, though weatherization teams have significant experience with this.

The PARR team concluded the meeting with a call for recommendations from the practitioners, considering the standard practices discussed. Several key recommendations influencing the project test plan arose, including:

- The proposed ventilation standard for both control and treatment houses, ASHRAE 62.2-2016, is feasible with a small amount of technical assistance for contractors.
- Substantial equipment donation from major manufacturers should be feasible.
- Installing both supply and exhaust ventilation should be feasible from a contractor installation/skill level standpoint.

---

[2] Attendee list in Appendix A

- Educational components should focus on communicating IAQ concerns and solutions to homeowners. A messaging guide will be developed as part of the test plan and used for homeowner reports.
- Data collection could be a concern without substantial buy-in from contractors and homeowners. The project team should develop a robust communications plan that includes messaging guidelines for contractors, a public-facing website, and informational materials for homeowners.
- Crawl spaces must be addressed in a consistent fashion, and the project team should draw up clear specifications for actions to be taken that meet utility program requirements.
- Static pressure measurements should be made during pre- and post-test assessments.
- Focusing air sealing attention away from easy attic air leakage opportunities and onto less common areas posing potential IAQ concerns will only be accomplished with a small, trusted base of contractors who have received substantial guidance from the project team.
- Homes with smoking occupants should be omitted from the sample.
- The project team must create clear screening criteria to enable the selection of homes within proper air tightness, HVAC system sizing, construction type, and occupant behavior ranges.
- This project could suffer from the problem of homes being too different from one another to gain true counterfactuals. The screening criteria must be narrow to avoid this.
- The project team should consider matching one control home to one test home based on screening criteria to control for as many differences as possible.
- The project team and contractors should emphasize to homeowners and in measure selection the importance of both supply and return duct sealing.
- Window opening poses a potential problem, and the project team should consider the use of window loggers, at least during summer months.
- The project team should consider the measurement of volatile organic compound (VOCs); the practitioners were very interested in learning more about how their work affects VOCs and how they can communicate this to their customers.
- The project team should consider recruiting participant homeowners through an HVAC contracting company whose customers are already receiving a new HVAC system. This could present challenges, however, with establishing a data baseline.
- Contractors expressed the view that recruitment of sufficient homes should be feasible, that they would be able to conduct additional measurements and make treatment/control decisions with training by project staff, and that the practices described could be integrated into their normal business practices.

2.3.2 Standard Practices for Residential Retrofits

A significant benefit of the practitioner workshop was the opportunity to understand current standard practice for Illinois residential retrofits, the most common upgrade measures, and recent trends in regional contractor preferences, skills, and weaknesses.

Air Sealing

While air sealing measures are commonly performed and contractor knowledge and abilities are high due to a regional programmatic emphasis on Building Performance Institute (BPI) training and certification, there are several areas for potential improvement. Most contractors begin air sealing work at the attic hatch and then move outward along the attic floor while running a blower door. Top plates were identified as a commonly missed opportunity. Once a desired target is hit, generally a 25%–35% reduction over baseline air leakage as measured by pre- and post-retrofit blower door tests in CFM50, air sealing efforts often stop. This “productivity versus profitability” maximization represents a clear gap in performance. According to national best practices and BPI guidelines, all meaningful air sealing should be completed in the attic as well as other locations in the home. Although in the region most air sealing throughout the house occurs in the attic, some utilities rebate rim joist insulation and thus it is common practice for contractors in those areas to use spray foam insulation to seal the cavity. Contractors view this work as easy to do and a simple sell to customers (homeowners).

Ventilation

Current practice for ventilation is difficult to pin down and dependent on the contractor and area. The Illinois state weatherization program reported that while nearly every home in the program receives mechanical ventilation of some type, program managers struggle to enforce ventilation standards with many contractors. There was general agreement among meeting participants that there has not been enough education on ventilation best practices among the contractor base in Illinois or Iowa, particularly with the ASHRAE 62.2 standard. Additional contractor education would provide the ability to explain the benefits of ventilation well enough to justify the cost and alleviate fears of losing a customer to a competitor promising only air sealing and insulation.

Duct Sealing

Regional duct sealing standard practices can vary greatly. For example, in new construction, some builders insist on mastic during assembly and some simply call an aerosol sealant provider before inspection. Duct leakage testing is relatively new as a common practice in Illinois, and many contractors have only just begun to work with specialized testing equipment such as duct blasters. The Iowa market is somewhat different, as the HVAC SAVE program has been popular there for several years, and many contractors are knowledgeable about duct system efficiency. However, Chicagoland utility rebates have promoted duct sealing in the region and caused standard practice in northern Illinois to shift in recent years. To qualify, a system must be 60% inside a building’s thermal envelope; mastic, tape, or aerosol sealant must be used; and BPI duct efficiency tables must be adhered to. However, one practitioner pointed out that some contractors working on leaky houses are able to seal a register or a few boots and hit the rebate target, missing out on substantial efficiency and IAQ upgrade potential.

There is a noticeable division in the industry—building envelope measures such as air sealing and insulation are commonly confined to one set of field practitioners, and HVAC and duct-related measures are confined to another set with different training backgrounds and skill sets. Among those contractors who do focus on HVAC systems, duct system leakage and static pressure are not always addressed; too often they go uncalculated and even unconsidered due to lack of knowledge or lack of incentive.

Addressing Crawl Spaces

The most common regional practice for addressing crawl space concerns involves un-venting the space, adding ground cover, and then insulating walls. Insulation is common in recent years as many contracting companies have added spray foam capabilities to their standard offerings. There was general agreement that much of the success in addressing crawl spaces stems from a company's particular approach to quality management, and companies with strong protocols and accountability will perform this measure well.

Local utility programs require standard practice to involve 6-mm poly barriers, 8-inch overlaps between sheets, and quality sealing on all sides. It was recommended that heavier poly sheeting be used in this project, as durability increases dramatically with thickness, but price remains manageable. The addition of radon mitigation systems is ideal but not standard practice; however, these are more common in state weatherization retrofits. Also, ejector pits in basements are common and may contribute to IAQ issues. As a result, 8-mm ground covers were to be installed over bare dirt in foundation spaces for any homes in the project.

2.3.2.1 HVAC

Concerns over HVAC system sizing were raised multiple times. Specifically, meeting participants were worried about the impact of envelope and duct sealing measures on already-oversized HVAC systems. Air conditioning oversizing was a particular concern, as participants view this type of oversizing as a critical driver of excess energy consumption. It was suggested that Manual J calculations be performed on each study home to enable some sort of normalization of other data after the treatment phase. Also, homes with very oversized systems could be screened out of the sample during site selection.

2.3.3 Homeowner Perceptions

Meeting participants discussed how homeowners generally do not understand IAQ issues and solutions, but it is becoming a more important topic of concern as younger homeowners enter the market. Many may believe IAQ contaminants are limited to carbon monoxide and that solutions to other IAQ contaminants are limited to plasma generators, UV systems, or filters, with little awareness of source control opportunities. There was agreement that among homeowners, duct sealing is not typically associated with IAQ concerns. Many homeowners do not know where their ducts are or if contaminants are being introduced into living spaces through leaky duct systems. Some homeowners may fail to understand the connection between air sealing and ventilation, but many see how air sealing and IAQ are linked. This project incorporated homeowner education to facilitate the correct air sealing measures for maximum IAQ control, but along with this, contractor training for communicating IAQ benefits to customers is needed. Many contractors may feel uncomfortable talking about IAQ with customers unless the customer specifically raises the topic.

3 Phase 1: Treatment vs. Control

3.1 Phase 1 Approach

Following the literature review and input from practitioners and experts in residential building performance, a set of measures was developed to test the hypothesis that through improved, systematic management of airflows either IAQ will be improved without sacrificing energy savings, or energy savings will be improved with the same IAQ.

Improved, systematic management of airflows was considered as a package as well as a suite of up to four airflow management measures. The first major area was infiltration, addressed by air sealing to minimize heating and cooling losses. In the second package, ventilation was improved by provision of interlocked exhaust fan with a supply side ventilation system to provide controlled air exchange and minimize energy use for ventilation make-up. Third, duct leakage was reduced both to address the energy penalty due to leakage to outside and to minimize infiltration and potential IAQ problems caused by unbalanced duct leakage. The final major area addressed was optimization of air handler flow for improvement of comfort and humidity control. The design of the protocol sought to determine the impact of both the suite of measures as a whole and the impact of the individual measures on IAQ and energy to answer the following research questions:

1. Can the energy performance of a home be improved without an IAQ penalty, and/or can IAQ performance be improved without an energy penalty?
2. Are some contaminants particularly responsive to systematic improvements in airflows?
3. Are improvements to some airflows particularly capable of making improvements in IAQ?

The test period started in June 2016 and, due to recruitment challenges and delays, ran through the end of the project in February 2021. The team identified 27 single-family homes in Illinois (cold/very cold climates), split into 16 control and 11 treatment homes, with matching housing type if possible; each pair consisted of a control home with standard retrofits and a treatment home with “enhanced measures.” Each participating house underwent a 3-week period of baseline monitoring followed by retrofits and a subsequent monitoring period. The control homes received standard utility efficiency program measures while the treatment homes received those same standard measures plus system-focused airflow management. Detailed information on the measures included is provided below:

Standard Measures (implemented in control homes):

- Conventional weatherization measures, which included a home performance approach of pre-testing infiltration and post-testing of infiltration, following best practices as well as utility program requirements.

- Standard home performance treatment which included attic air sealing, improving existing insulation levels, and insulating rim joists in unfinished basement / crawl space locations. Weatherstripping and/or gasketing around doors was added when this was missing. Air handler filters were also replaced.
- Duct sealing was not performed unless the weatherization program included a replacement furnace / air conditioner, at which point direct connections between the distribution system and the replacement equipment were sealed, typically with UL-181 listed foil faced tape.
- To comply with ASHRAE 62.2 ventilation requirements, a continuous ventilating exhaust fan with adjustable flow was installed in one of the bathrooms and set to required ventilation rates.

Enhanced measures (installed in treatment homes) consisted of standard measures with some additions intended to better control airflows in the buildings:

- A systematic airflow management approach was emphasized, where the home performance contractor went beyond air sealing the “lid” of the home and also targeted air sealing based on zonal pressure diagnostics to identify areas of the home needing more attention.
- Basement enhancements included sealing of the slab or foundation wall, sealing of sump pumps, and sealing of all accessible ductwork.
- The addition of a central fan integrated supply ventilation system, consisting of a fresh air duct to outdoors with a motorized damper and controller that would open the damper and activate the furnace air handler fan in compliance with required ASHRAE 62.2 ventilation rates. This was installed in addition to an exhaust ventilation fan installed as a standard measure.

Table 2 summarizes these differences in retrofits for control and treatment homes.

Table 2. Summary of Control vs. Treatment Protocols

Control Home Standard Measures	Treatment Home Enhanced Measures
• Conventional weatherization • Standard home performance measures in attic/rim joist • Little or no duct sealing • Exhaust-only ventilation	• Systematic airflow management • Enhanced home performance in basement • Exhaust and/or supply ventilation

3.2 Phase 1 Contractor and Study Home Selection and Recruitment

MEEA maintains a pool of qualified contractors as part of managing the Illinois Home Performance with ENERGY STAR® program. These contractors have had long-standing relationships with MEEA, and either participated in or instructed classes for the Building Science Training Series. This pool was the basis of contractor recruitment efforts for this study, and the most engaged contractors were invited to participate in our initial practitioner meeting to help inform the structure and strategy of Phase 1. The study relied heavily on the ability of contractors to identify potential homes, explain and sell the study to homeowners, and install the retrofit measures.

The initial recruitment effort focused on houses that were scheduled to be upgraded as part of the Illinois Home Performance with ENERGY STAR® program. However, the partnering contractors in this program found recruitment to be much more difficult than anticipated and lost interest. This resulted in a pivot to working primarily with two contractors in Central Illinois who were partners in Ameren Illinois' energy efficiency programs. These contractors partnered in part because they were already championing some of the approaches targeted in the study and wanted to see data emerge to support those approaches.

This project relied on close cooperation between the research team and the contractors who delivered either standard treatment or control treatment to clients. However, it quickly became clear that additional non-standard diagnostics and determination of treatment/control potential would have to be performed directly by the project team.

The general approach of the protocol followed these steps:

1. Contractor enrolls the home.
2. Visit for instrumentation installation scheduled and conducted as soon as possible following recruitment.
3. Baseline measurements recorded for three to four weeks.
4. Interventions completed as soon as possible following baseline.
5. Based on contractor scope of work and initial diagnostics, PARR team identified home as a "treatment" or "control" home candidate.
6. Post-intervention measurements recorded for three to four weeks as soon as possible following intervention. Homes receiving both supply and exhaust ventilation were then measured for an additional three to four weeks, alternating between the two ventilation systems for three weeks each.

Field tests were conducted in heating months and in cooling months to avoid window opening that is common during swing seasons.

3.2.1 Site Eligibility

To be eligible, treatment homes were expected to have post-retrofit airtightness of no more than 6.5 ACH50. Since homes were enrolled prior to retrofits being installed this was based on projections using pre-retrofit airtightness levels and common reductions based on experience. If 6.5 ACH50 did not seem attainable based on the initial diagnostic visit, the homes were disqualified.

The focus of the project was on homes with crawl spaces and unfinished basements. Initially, the project just included unfinished basements, but recruitment was difficult based on the eligibility criteria so having a crawl space was added as an additional eligibility criterion to expand the pool of potential homes. Presence or absence of an attached garage was a primary condition for matching treatment and control homes. Matching whether there was living space above the garage was desired but not considered essential.

Candidates with single forced-air heating systems were targeted. Homes with hydronic heating systems, or with multiple furnaces serving multiple zones were excluded. Use of minor heating appliances, other than unvented gas space heaters, did not lead to exclusion.

For analysis, control and treatment homes were matched according to the factors listed below. Once a treatment home was identified the research team worked with partner contractors to identify a suitable control home to be tested in a similar season (winter or summer) during the study. Key matching factors were:

Essential

- Air leakage. Pre-retrofit air leakage should be within 2 ACH50 of the treatment home (e.g., a control should be in the 6–10 range for a treatment home with a starting value of 8 ACH50).
- Presence/absence of attached garage.
- Presence/absence of ducts in the basement.

Preferred

- Number of stories.
- Presence/absence of crawl space section attached to basement.
- Presence/absence of ducts in the garage.
- Foundation wall type.
- Type of furnace/water heater (electric/gas, Type I/Type IV).
- Dryer in basement.
- Vented range hood.
- Presence/absence of central air (essential for homes tested in the summer).
- Further details on performance targets for control and treatment homes are provided in Table 4.

3.2.2 Site Recruitment

Despite working with contractors at the outset of the study design, site recruitment proved to be more challenging than expected. Contractors provided the following pain points, which impacted the number of homes they were able to recruit:

- *Eligibility* – It proved to be difficult to find compatible homes that met the eligibility criteria and whose owners were willing to participate in the study. Attempting to pair treatment and control homes further increased the recruiting complexity.
- *Upgrade cost* – The treatment home measures could be costly to the homeowners, and depending on the home, complicated for the contractor. The initial incentive for treatment homes was $150 to the homeowner and $150 to the contractor, which was not enough to motivate participation. Incentive levels were adjusted several times during the course of the study in attempts to improve recruitment. This included dramatic increases for treatment homes to help incentivize for the additional measures and required covering close to 80% of the costs when combined with the utility incentives.
- *Delaying home performance jobs for pre-retrofit testing* – The testing required to obtain baseline metrics before the retrofit measures were installed required additional time to complete the overall project, and not all residents were willing to wait. This became a hurdle to recruiting participants in the study.
- *Seasonality* – Because pre- and post-retrofit data collection could not happen during shoulder seasons, it was challenging to complete site recruitment, data collections, and retrofits within a single heating or cooling season.
- *Utility incentives availability* – Programs exhausted their funds before the program year was complete, such that many fewer homes were in the pipeline for energy efficiency upgrades at those times.
- The final set of 27 homes included in the study are described by Table 3; 20 of the homes had basements (7 of which were either fully or partly finished), and 7 had crawl spaces. One result was that contractor estimates of achieving post retrofit below 6.5 ACH50 were not achieved in as many homes as anticipated.

Table 3. Phase 1 Site Building Characteristics

Characteristic	Minimum	Median	Maximum	Mean
Square Footage	900	1,567	3,000	1,711
Stories	1	1.5	2.5	1.54
Bedrooms	2	3	4	3.04
ACH50 Pre	3.42	10.74	22.89	12.14
ACH50 Post	2.35	8.34	15.11	8.27

3.2.3 Contractor Recruitment

Initially during the expert meeting, several contractors expressed a strong interest in participating in the study. Four attended the practitioner meeting. They found value in the study methodology and wanted to be involved not just to potentially increase their business, but also understand the IAQ impacts from their work. Many had a genuine interest in understanding how they could affect and ultimately improve IAQ for their customers. Unfortunately, when it was time to start the study, contractors were not as eager to participate. Many of the barriers boiled down to contractors struggling to incorporate the study into their work and business models. Some of the pain points included:

- *Finding time to "sell" the study* – Participating in the study required homeowners to go above and beyond the "typical" energy efficiency retrofit and also required behavioral changes of the residents to ensure the data could be collected, such as keeping windows closed and leaving data collection instrumentation undisturbed. This homeowner education was an additional step for the contractor and required the homeowner to opt in to the study.
- *Performing pre- and post-diagnostic analysis on the home* – Again, the time component of coordinating and conducting the pre- and post-retrofit diagnostic testing on the homes, typically 2 or more hours, was a barrier for contractors.
- *Submitting the research related paperwork* – The study required additional paperwork from the contractors, above and beyond what they already must do for their own business operations and for any utility incentive programs the home was participating in. For these small businesses, time is money, and the additional time required did not equate to additional business or adequate revenue.

The results of this aspect of the project were that contractors were interested in the study but struggled to integrate the additional advanced airflow diagnostics and research practices into their business operations without substantial support from the project team. Partnering contractors also were already performing many advanced IAQ retrofit practices, diluting the difference between treatment and control homes. A conclusion is that, independent of the scientific merits of the systematic approach, it will not be easily adopted unless it becomes standard practice. Given the additional diagnostics required, compensation to contractors would also need to increase for advanced IAQ diagnostics to become standard practice.

3.3 Phase 1 Methodology

3.3.1 Research Design

3.3.1.1 Control and Treatment

The Phase 1 study was conducted on 27 homes in Illinois within Climate Zone 5, of which 16 were control and 11 met the requirements to be treatment homes. Not all homes received the same energy conservation measures, so the research team planned to pair treatment with control homes of similar characteristics and measures. While it was possible to pair them based on primary characteristics such as foundation type, home size, and season, with the limited sample size recruited during the project, it was difficult to draw conclusions through the pairing technique when considering the above factors and others such as occupancy, stack effect, and kitchen ventilation systems. Therefore, the primary control versus treatment analyses were based on the sample-wide measurements. The attempt to do pairing of homes of similar characteristics and measures did produce an overall sample that was similar across control and treatment homes. Control homes received standard retrofits according to normal program processes, with measures including:

- The additional installation of ventilation compliant with ASHRAE 62.2-2016.
- Typical “low-hanging fruit” such as air sealing at the attic and increasing ceiling insulation.
- Duct improvements were not typically considered for control homes.

Because the partnering contractors already took more of a whole-home approach than is common, they also considered other air leakage pathways, such as from the basement to outdoors.

Treatment homes received “enhanced measures” of the airflow management package, the details of which depended on characteristics of the particular home. There was a greater focus on air sealing at non-attic locations, and duct improvements were included. Duct improvements could include both air sealing of leaks and measures to reduce static pressures, as appropriate. In many homes, some pre-retrofit conditions already met project requirements and so measures relevant to those characteristics were not required for a home to qualify as a treatment home.

Over the course of the study, similar control and treatment homes were sampled within the same season (winter or summer) to ensure that environmental conditions were comparable. Shoulder seasons were avoided to reduce window opening.

Treatment homes received additional measures focused on airflow management, with an eye toward both IAQ and energy. These measures included:

- Increased focus on air sealing between the basement and outside, and between crawl space areas and the home. Success was determined using series leakage zonal pressure diagnostics.
- Increased focus on air sealing between the house and attached garages when there is not ductwork in the garage. Success was determined using series leakage zonal pressure diagnostics.
- Duct sealing in foundation spaces. Success was determined using Duct Blaster tests, or Delta-Q tests when Duct Blaster tests could not be done and Delta-Q was practical.
- Forced-air system airflow commissioning. This included both proper fan speed (especially important for summer dehumidification) and duct system pressures. Success

was determined by airflow measurements using a Duct Blaster or TrueFlow air handler flow measurement device, and by measuring plenum pressures.

- Optimal air handler flow and ductwork system pressures, with total external static pressure < 0.50 in w.c.

Examples of some of treatment measures implemented in participating homes are shown in Figure 2.

Figure 2. Treatment measures included duct sealing (left), air sealing and insulating rim band joists (middle), and air sealing crawl space and basement slabs (right).

3.3.1.2 Measures and Improvement Targets

Table 4 shows the minimum requirements for these study metrics as well as preferred targets. The aim was to achieve the preferred targets, but in no case was a measure considered successful if it did not meet the minimum. In this table, “All” (under “IAQ samples”) includes all contaminants being measured, including CO_2, radon, moisture, particulates, and formaldehyde.

Table 4. Criteria for Airflow Management Measures

Issue	Diagnostic	IAQ Concerns	Standard intervention	Enhanced intervention	Soft Target	Hard Target
Envelope air leakage	Blower door	All	Contractor choice	Depends on initial airtightness and opportunities	< 6.5 ACH50	Within 10% of soft target (7.15 ACH50)
Soil gas entry	Visual	Rn, moisture	None	Sealed sump pumps, ground covers over bare dirt, large cracks sealed	--	--
Basement to outside leakage	Zonal Pressure Diagnostics	Moisture balance, temperature, relative humidity	Contractor choice	Air sealing between foundation and outside	Leakage area of foundation to outside should be less than leakage area of attic to outside	--
House to crawl space leakage	Zonal Pressure Diagnostics	$PM_{2.5}$ (provisional), radon, moisture	Contractor choice	Air sealing between foundation and outside	Leakage area of house to crawl space should be less than leakage area of attic to outside	
Duct leakage in foundation or garage spaces	Duct pressurization, Delta-Q if duct pressurization not possible	Moisture, radon, $PM_{2.5}$ (provisional)	None	Seal supply leaks to outside, return leaks in basement or garage	20% total duct	10% total duct leakage or 6% leakage to outside
Air handler flow	Pressure matching	Moisture	None	Adjust speed tap, reduce duct restriction, add ducted return, as appropriate	--	1) 300–350 cfm/ton for cooling 2) Provides suitable temperature rise for heating
Plenum pressures at highest operating speed	Pressure w.r.t. duct ambient	--	None	Modify ducts as appropriate – focus on return or supply based on pressures measured	50 Pa maximum in each plenum, return measured upstream of filters/coils	125 Pa external static, return measured upstream of filters/coils
Ventilation	Flow meters	All	Exhaust unless contractor chooses otherwise	Exhaust unless contractor chooses otherwise, also supply in some homes	--	62.2-2016 compliant

In some homes, we expected to install both supply and exhaust ventilation. Equipment and controls were donated by industry partners. However, evaluation of both ventilation strategies would have required an additional three-week monitoring period and the challenges and flow of the study precluded this as a viable approach. This led to the development of Phase 2, which is detailed later in this report.

3.3.2 Data Collection

During the first visit at each site, data were collected on home characteristics, airflow diagnostics were conducted, and instrumentation was deployed for IAQ and energy use metrics. Airflow diagnostics and instrumentation deployment were repeated during the site visit following retrofit. Sampling periods for IAQ and energy use monitoring were three weeks before and after retrofit, except for formaldehyde and radon, as noted below.

Home characteristic data were collected, including: physical dimensions of the building, number of bedrooms, number of residents, foundation type, and make/model/type of space and water heating equipment. Moisture problems were also noted. As standard practice, combustion safety testing, including time to last spillage under worst-case conditions and carbon monoxide measurements, was performed. Furnace gas consumption rate was monitored by clocking the gas meter, and usage was recorded using state sensors on the furnace gas valve(s).

Airflow diagnostic data included blower door tests to measure whole-building envelope leakage, zone pressure diagnostics to identify critical leakage paths, duct leakage diagnostics for total duct leakage and duct leakage to outside using the fan pressurization technique, air handler flow measurement, and ventilation flow measurements. Blower door and zone pressure tests were performed using an Energy Conservatory Minneapolis Blower Door System (Model 3) with a DG-700 manometer, and measured leakage in cubic feet per minute at 50 Pa depressurization (CFM50) in accordance with RESNET Standard 310. Duct pressurization tests used an Energy Conservatory Minneapolis Duct Blaster System with a DG-700 manometer, and measured leakage in CFM at 25 Pa. Air handler flow measurements were performed with either the Duct Blaster or an Energy Conservatory TrueFlow air handler flow meter. Ventilation flow measurements were conducted with an Energy Conservatory Exhaust Fan Flow Meter.

Relevant home characteristics, blower door test results, and ventilation flow data were combined to determine whole-dwelling ventilation requirements according to ASHRAE 62.2-2016. This calculation used Appendix A of ASHRAE Standard 62.2 to account for local exhaust deficits as appropriate.

Indoor Air Quality Monitoring Equipment

Indoor air contaminants and air thermal conditions monitored during the test periods included air temperature and RH (relative humidity), carbon dioxide, radon, and formaldehyde. Samplers, as shown in Figure 2 were placed in open locations away from windows and doors, out of the direct flow of supply and exhaust registers, and not in bathrooms or kitchens.

Figure 3. Phase 1 IAQ monitoring equipment

Air temperature and relative humidity: HOBO U12-013 data loggers (±0.38°F accuracy) were used to record the air temperature and RH on the first floor (usually in the living room) and in the basement (if there was a basement) during the whole test period. The sampling interval was set at 5 minutes. The data loggers were usually placed on a table, a countertop, or a shelf 2.5 to 5 feet above the floor.

Carbon dioxide: A Telaire 7001 CO_2 sensor (±50 ppm accuracy) was used to monitor the carbon dioxide concentration on the first floor (usually in the living room) during the whole test period. It was connected to an external channel of the HOBO U12-013 data logger, which would record the first floor's air temperature, RH, and CO_2 concentration in the same file at a one-hour sampling interval.

Radon: Radelec E-Perm electrets with S Chambers (±1.4 pCi/L accuracy) were used to measure the radon levels on the first floor (usually in the living room) and in the basement (if present) during one week of the test period before the retrofit and another week after the retrofit. While longer duration sampling would have been desirable, the passive samplers provide the average radon level over the one-week sampling period. To increase the reliability of the readings, duplicate electrets were placed side by side at every sampling location. When the percent difference of the two electret's readings relative to their average was less than 15%, the average was used as the measurement result. When the two samplers had substantially different readings, i.e., their relative percent difference was greater than 15%, the lower reading was used because accidental discharge is the primary failure mechanism for electrets, which leads to an overestimation of radon levels.

Formaldehyde: A single UME^X 100 Passive Sampler by SKC (± 25% accuracy) was used to sample the formaldehyde concentration of the first floor (usually in the living room) during one week of the test period before the retrofit and another week after the retrofit. After one week's sampling, the sampler badge was shipped overnight to the SGS lab in New York for analysis. These samplers have a lower detection limit of 0.2 ppb for a 7-day test.

Particulates: Particulates were not part of the original research design but were added during the course of the project because they are important and should be measured whenever possible. To the extent that equipment was available, particulates were measured with TSI DustTrak 8530 (± 5% accuracy) loggers. Particulates were not able to be measured in all control/treatment home pairs on a long-term basis.

HVAC Operational Data

The running states of the furnace, the air conditioner (in cooling season), and exhaust fans were monitored to measure the space conditioning and ventilation during the entire measurement period.

Furnace blower fan, gas valve, and exhaust fan(s): A Hawkeye 300 Micro Split-Core On/Off current sensor was clamped on a wire of the furnace blower fan, furnace gas valve (in heating season), and each exhaust fan (usually in bathrooms), to monitor the furnace and exhaust fan's operation. An Onset HOBO State Data Logger (UX90-001) was connected to each of the Hawkeye 300 sensors to record their state data during the entire test period.

A Hawkeye 922 Split Core Current Sensor was clamped on a wire of the air conditioner (in cooling season) to measure the current to drive the air conditioning. A HOBO UX120-006M Analog Data Logger was connected to the current sensor for data logging.

Some homes replaced non-condensing furnaces with condensing equipment as part of their energy efficiency retrofits. Despite notifications warning HVAC contractors to preserve data collection sensors installed inside the existing furnaces, in some cases they were not recovered, resulting in data loss.

The typical sequence for data collection procedures for a test home is included in Appendix C. Following the completion of pre- and post-retrofit testing, the raw data were processed, and the team generated a report for the homeowner detailing the results for their home. A representative homeowner report for Phase 1 can be found in Appendix E.

All data collection was done via a standardized report template (see Appendix C for an example). Ideally the data collection periods before and after the retrofit were in the same season (heating or cooling) in the same year. However, some home retrofits were completed too late in the season and made the post-retrofit test impossible to conduct in the same season of the year. In those cases, a post-retrofit test was conducted in the same season of the following year.

3.3.3 Analysis Methods

Analyses were conducted to compare pre- and post-retrofit IAQ and energy metrics, compare metrics between treatment and control homes, and to explore whether there were statistically significant relationships between retrofit measures and IAQ outcomes. Analyses of pre- to post-retrofit changes between treatment and control homes were based on comparisons of ratios of post-/pre- values. Comparisons between pre- and post-retrofit metrics and comparisons between treatment and control were made using a two-tailed paired t-test performed as part of data processing. Assessments of relationships between parameters were done using linear regressions.

In the discussions of results below, the uncertainties from this analysis reflect the 95% confidence interval. Results that are statistically significant at either the 90% level ($p<0.1$) or 95% level ($p<0.05$) are highlighted.

Energy and temperature/humidity analyses were done separately for summer and winter groups to assess any seasonal impact. There were very few homes in the summer group and more homes in the winter group, and no statistically significant difference was noted. Specifically, for each contaminant, the team assessed how much change there was in the treatment homes compared to any change in the control homes. To maximize the comparability of treatment and control homes, similar homes were tested in similar seasons (winter, summer), with weather conditions normalized based on current knowledge of weather dependence of the various contaminants and infiltration on environmental conditions. There are multiple approaches to assess moisture in homes, with RH being most recognized but with the downside of being very temperature dependent. Additionally, there is currently no accepted standardized method for determining building wetness as a single property calculable from measured data. This is complicated by the fact that outdoor conditions play a large role in indoor humidity. To account for this, the PARR team evaluated the following metrics:

(Change in) moisture balance: This method evaluates the elevation in indoor vapor pressure over outdoor conditions. The method’s pros include accounting for outdoor conditions, and it has an established International Organization for Standardization (ISO) standard to reference. However, the method was not developed for cooling, dehumidification impacts. This technique was used to evaluate the house structure only, not cooling and dehumidification systems.

(Change in) Relative Humidity: Pros – matters for mold growth as function of temperature, and is a highly recognized metric for comfort in standards such as Air Conditioning Contractors of America Manual RS and ASHRAE 55; Cons –RH is very temperature dependent and does not directly account for outdoor humidity levels.

In addition to using diagnostic measurements to evaluate the success of the installation of the enhanced measures, the PARR team also used the diagnostic measurements to explore what factors are correlated with changes in IAQ in our sample.

3.4 Phase 1 Results

3.4.1 Technical Results

The sections below provide detailed results for each of the IAQ components investigated in Phase 1 in detail.

3.4.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is an occupancy-driven IAQ contaminant where discrete events such as large indoor gatherings or extended gas-oven usage can cause high short-term concentrations, as well as poor ventilation in bedrooms. If these events were more present in one measurement period than another, this could unduly skew typical values if mean averages were used. Therefore, medians were used as the evaluation metric after first assessing differences in concentration for each home first. The median CO_2 concentration for the control sites was 699 (range ± 213) ppm before retrofit and 608 (± 222) ppm following retrofit. While it indicates a moderate reduction of roughly 15%, the difference between these values is not statistically significant (p=0.63). The median CO_2 concentration for the treatment sites was 654 (± 217) ppm before retrofit and 652 (± 163) ppm following retrofit; the difference between these values is also not statistically significant (p=0.92).

When using CO_2 as a proxy for IAQ, typical action levels are suggested when levels exceed 1,000 ppm. Only two sites had median CO_2 concentrations above 1,000 ppm during the pre-retrofit measurement period, and only three exceeded that level during the post-retrofit measurement period. The highest pre-retrofit median CO_2 concentration was measured at 1,338 ppm, and the highest post-retrofit concentration was measured at 1,191 ppm. Figure 4 shows the aggregate distribution of indoor CO_2 measurements. The energy efficiency retrofits do not appear to have increased CO_2 levels significantly.

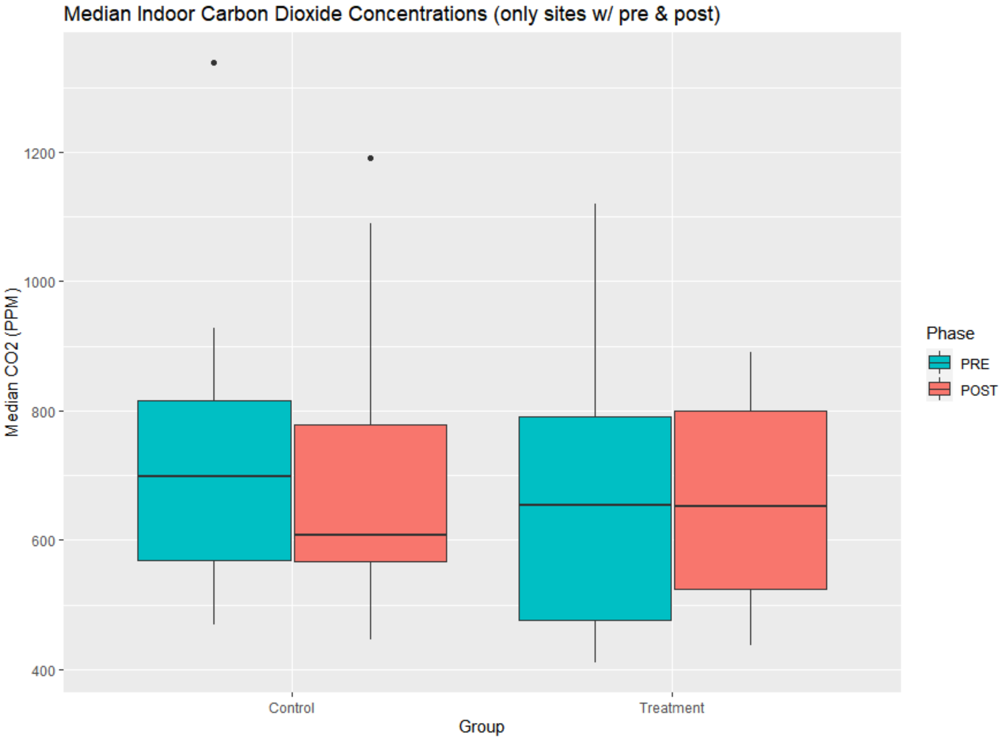


Figure 4. Phase 1 median carbon dioxide concentrations for control and treatment groups

3.4.1.2 Radon

Radon levels are strongly impacted by external factors. Significant weather, such as large precipitation events can cause short-term spikes in radon concentrations. Ideally, radon is tested with a similar nearby control site during the same period, and individual sites can be corrected against their individual control. Unfortunately, due to the study design, eligible participants, and other logistics, time matched control sites were not included in this study.

Because of the inherent variability in radon concentrations, long-term tests are preferred for measuring representative levels in a building; monthlong tests yield results with 40% coefficient of variation from the annual average, and 90-day tests improve that to 25% (Steck 2005). Because long-term tests are often not feasible, shorter tests can give an approximation of radon levels. A weeklong test (the nominal length of the radon tests in this study) should have a coefficient of variation about the annual average radon concentration of ~63% based on interpolation from Steck's findings. Uncertainty bars with a magnitude of 63% have been added to the radon data visualizations. An overlap of these uncertainty bars within a site indicates that there is not a change in radon level beyond what is likely to result from natural variability.

Figure 5 shows the distribution of radon levels in the primary living space, while Figure 6 shows that in the basement foundation level of the home. For the living space, the control group had similar mean levels of 3.7 (± 2.3) pCi/L pre-retrofit, and 3.6 (± 2.9) pCi/L post-retrofit, the difference between these results is not statistically significant (p=0.94). The treatment group had a much larger difference between the pre and post living level measurements, with a mean of 2.9 (± 1.5) pCi/L before and 4.1 (± 2.5) pCi/L after retrofit. Although this difference is larger than that of the control sites, and the pre- results are below the 4 pCi/L U.S. Environmental Protection Agency (EPA) action level (dotted line in Figure 5) while the post- results are above it, the difference between these values is not statistically significant (p=0.19). There was also not a statistically significant difference in the living level post-retrofit readings between the treatment and control sites (p=.63).

Only two sites (T04 and C13) did not have overlap between the uncertainty range for the pre and post data. Site T04, a treatment site, exhibited very low radon levels (0.6 ±0.4) pCi/L pre-retrofit and moderate ones (11.5 ±7.3) pCi/L post-retrofit. Site C13, a control site, had moderate levels (4.1 ±2.6) pCi/L pre-retrofit, and low levels (0.3 ±0.2) pCi/L post-retrofit.

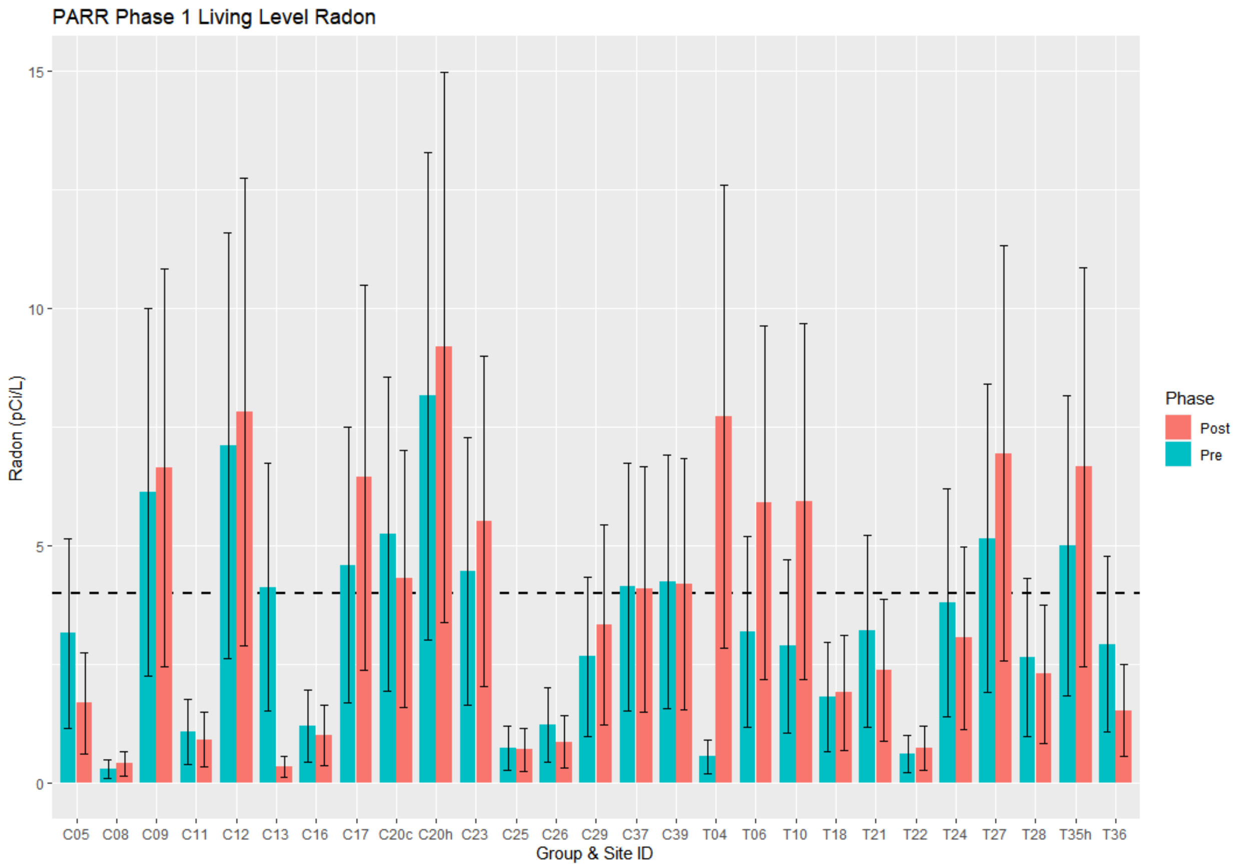


Figure 5. Phase 1 living level radon levels in control & treatment homes pre- and post-retrofit

For the basement radon levels, the control sites had mean concentrations of 6.2 (± 4.3) pCi/L pre-retrofit, and 7.1 (± 5.2) pCi/L post-retrofit; the difference between these results is not statically significant (p=0.64). The treatment sites had mean concentrations of 4.8 (± 2.4) pCi/L pre-retrofit, and 6.1 (± 3.3) pCi/L post-retrofit; the difference between these results is not statically significant (p=0.41). There is also not a statistically significant difference in the basement post-retrofit readings between the treatment and control sites (p=.59), suggesting the energy retrofit with addition of exhaust ventilation did not significantly increase radon levels.

For the basement data, only site T04 had pre and post uncertainty ranges that did not overlap. The similarity between the trend for both the basement and living level radon sensors at this site increases the likelihood that the data are correct, but the source of the change is unclear. The higher radon levels post-retrofit could be a result of the retrofit activities, it could be an issue with the testing procedure and quality control (such as the occupants opening their windows during the pre-testing), or it could be the result of natural variation in the radon concentration (where the pre-testing happened at an especially low radon period and/or the post testing occurred during a period of high radon).

Out of the 26 total sites (including both C20c and C20h, which are the same building but considered different sites because they were tested in different seasons), 12 pre-retrofit measurements and 13 post-retrofit measurements were above the EPA action level of 4 pCi/L in their lowest living level when considering finished or partly finished basements as living spaces, suggesting again that there was not a significant increase after retrofit.

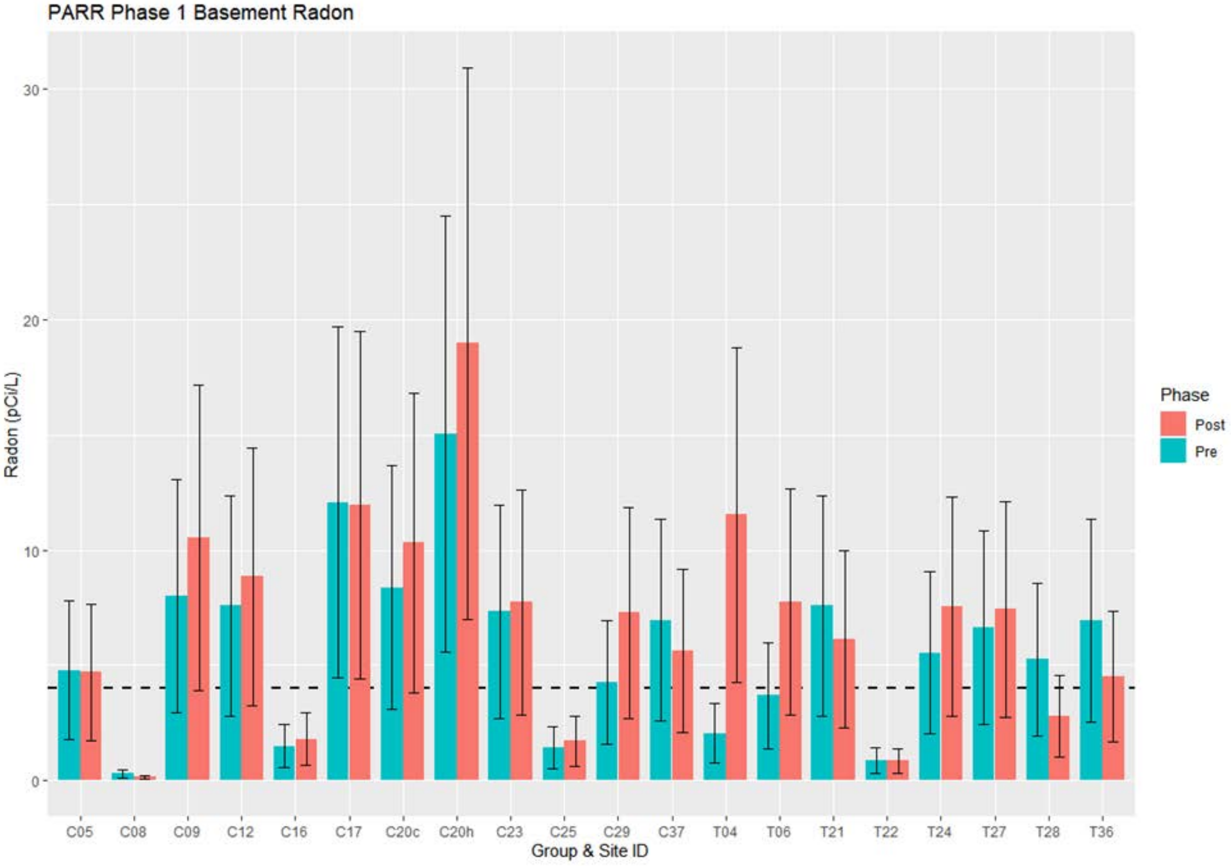


Figure 6. Phase 1 basement radon levels in control and treatment homes pre- and post-retrofit

3.4.1.3 Formaldehyde

As seen in Figure 7, formaldehyde concentrations measured at individual sites were relatively low, with even the highest recorded measurement of 0.043 mg/m^3 below the sensor's validation range of 0.06–3.0 ppm (0.074–3.7 mg/m^3). The lower detection limit of the sensors is 0.2 ppb for a 7-day test. There is no single agreed upon standard for indoor residential formaldehyde levels, and the suggestions from agencies vary widely. For example, the World Health Organization has an IAQ guideline for formaldehyde exposure of 0.1mg/m^3 (80 ppb), and California's Office of Environmental Health Hazard Assessment (OEHHA) has a reference exposure level (REL) of 0.009 mg/m^3 (7 ppb). Out of the 54 total formaldehyde measurements, only 14 were outside of that range, all of which were slightly below the OEHHA REL. A few values were slightly below the OEHHA REL, and the rest were between the OEHHA REL and the WHO IAQ guideline. The control group had mean concentrations of 0.01 (± .005) mg/m^3 and 0.01 (± .007) mg/m^3 for the pre and post phase respectively, and the treatment group had mean concentrations of 0.02 (± .01) mg/m^3 for both pre and post measurements. There is not a statistically significant difference in the pre/post results for either group (control p value = 0.33, treatment = 0.8). There was also not a statistically significant difference between the post-retrofit measurements at the treatment and control sites (p=0.12). This suggests that retrofit did not significantly increase formaldehyde levels.

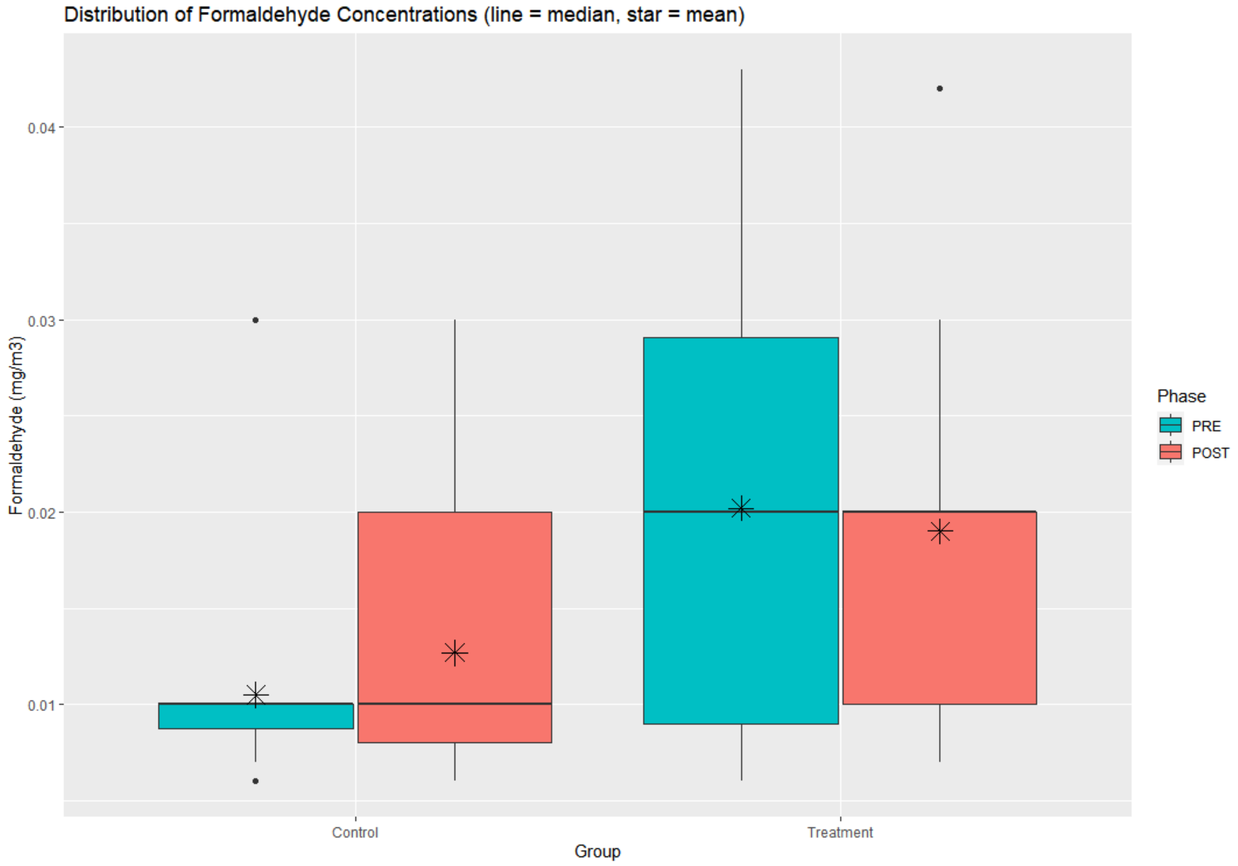


Figure 7. Phase 1 distribution of formaldehyde concentrations in control and treatment groups pre- and post-retrofit

3.4.1.4 Temperature

For the heating season sites, the control sites averaged 68.9°F (± 4.0) pre-retrofit and 68.8°F (± 3.3) post-retrofit, and the treatment sites averaged 68.7°F (± 6.6) pre-retrofit and 67.5°F (± 4.3) post-retrofit. Neither of these pre/post differences are statistically significant (p=0.69 and 0.93, respectively). There was more differentiation between the foundation temperatures. The control group had mean foundation temperatures of 67.5°F (± 4.3) pre-retrofit, and 64.0°F (± 3.8) post-retrofit. The treatment group had average foundation temperatures of 66.2°F (± 4.8) pre-retrofit, and 63.8°F (± 3.0) post-retrofit. Neither of these pre/post differences are statistically significant (p=0.77 and 0.32, respectively).

For the cooling season sites, the control sites had average living level temperatures of 72.6°F (± 4.1) pre-retrofit, and 74.7°F (± 0.8) post-retrofit, and the treatment sites had 74.7°F (± 0.8) pre-retrofit and 73.5°F (± 1.6) post-retrofit. In the foundation spaces, the control sites averaged 67.9°F (± 4.3) pre-retrofit, and 70.6°F (± 2.2) post-retrofit, and the treatment sites averaged 72.4°F (± 2.1) pre-retrofit, and 72.5°F (± 1.0) post-retrofit. Because of the small sample size, t-tests results are not included for this data, but plots of the mean results for indoor air temperature are shown in Figure 8. Outdoor temperatures were used to normalize between pre- and post-retrofit analyses for both cooling season sites and heating season sites.

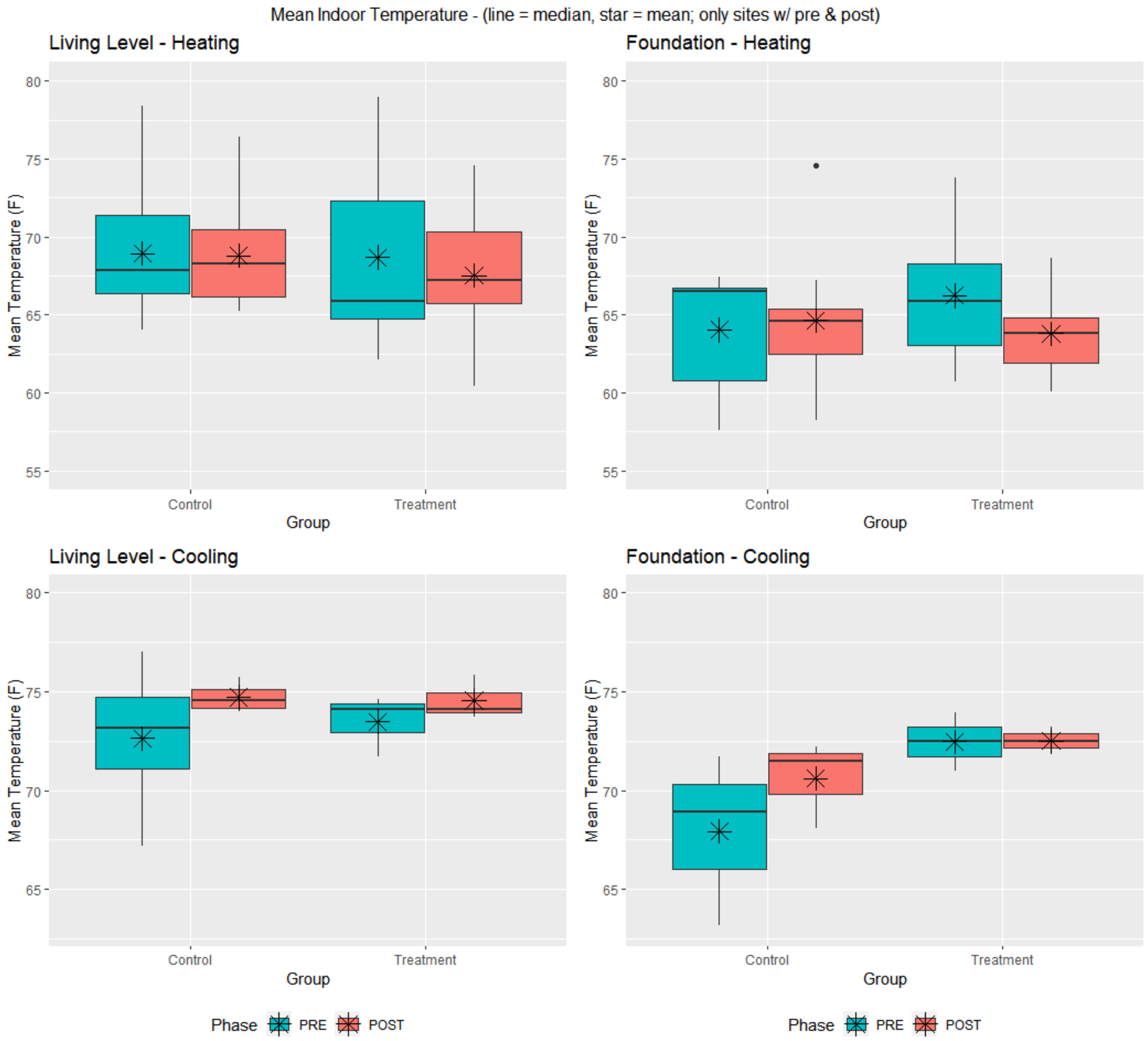


Figure 8. Phase 1 mean indoor temperature at living level and foundation during heating and cooling periods

3.4.1.5 Moisture

Moisture was evaluated using the RH and by calculating the "moisture balance" per ISO Standard 13788. RH is a metric that is more recognized by the general public, but it is temperature dependent. The moisture balance approach uses vapor pressure, which is temperature independent, to characterize the wetness of buildings. The moisture balance method is based on an analysis of the elevation of indoor vapor pressure (in Pascals [Pa]) over outdoor vapor pressure, as a function of outdoor temperature. While vapor pressure itself is temperature independent, the elevation of indoor vapor pressure over outdoor vapor pressure has been shown to be a function of temperature, with the elevation being smaller at warmer outdoor temperatures and increasing as outdoor temperature gets colder (see ISO 13788). Higher moisture balance values indicate damp homes. ISO 13788 defines several moisture "indoor climate classes" at 270 Pa increments. Levels above 810 Pa, which is the lower point of Class IV, indicate a damp indoor space.

Figure 9 shows the mean indoor RH for control and treatment groups. The control sites had a mean living level RH of 42.3% (± 9.3) pre-retrofit, and 42.7% (± 10.6) post-retrofit. The treatment sites had 46.4% (± 11.7) pre-retrofit, and 45.6% (± 10.5) post-retrofit. There is not a statistically significant difference between either of these two sets of measurements (p=0.92 and 0.86, respectively).

The foundation RH was 47.7% (± 12.2) pre-retrofit, and 49.6% (± 10) post-retrofit at the control sites. At the treatment sites, the foundation RH was 45.9% (± 10.8) pre-retrofit, and 49.7% (± 8.9) post-retrofit. There is not a statistically significant difference between either of these two sets of measurements (p=0.68 and 0.45, respectively).

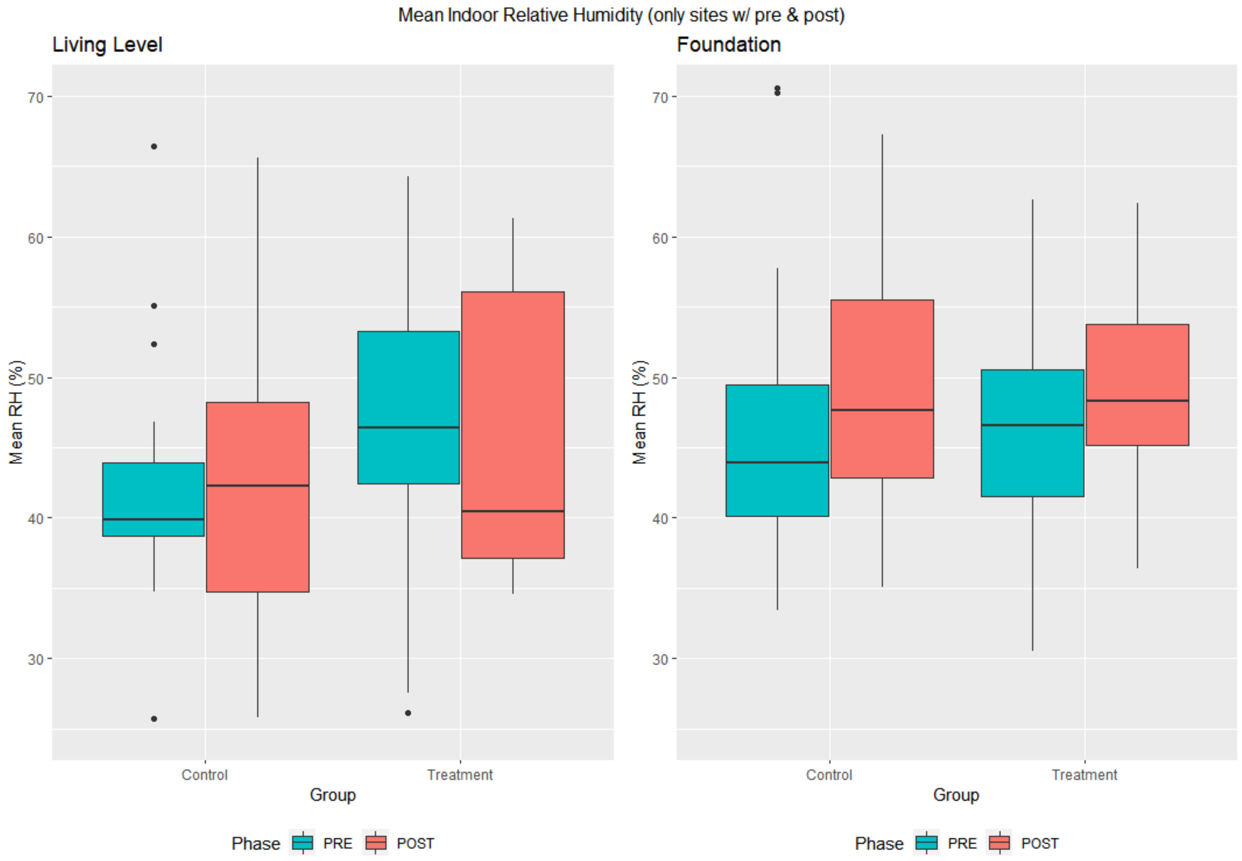


Figure 9. Phase 1 mean indoor relative humidity at the living level and foundation

Several sites lacked sufficient data during the pre, post, or both phases to calculate a meaningful moisture balance, which requires a minimum of four days' worth of data during which time the outdoor temperature is between 0°–15°C (32°–59°F). Figure 10 shows the moisture balance from all sites and has missing bars for tests with insufficient or missing data; however, all statistics presented below only consider sites with both pre and post data. The three dashed horizontal lines on the graph represent the upper bounds of the "indoor climate classes" from ISO Standard 13788, including Class C1 – "Buildings with a low humidity production," C2 – "Well ventilated buildings with a limited humidity production," C3 – "Moderately ventilated bldgs. with a higher hum. Production," and C4 – Buildings with a high humidity Production." Two homes had moisture balance results indicating that they fell into Class C4 in one testing period, meaning that at those times they met the definition of a damp home.

The average moisture balance at the control sites was 504.6 Pa (± 200.4) pre-retrofit, and 403.8 Pa (± 173.4) post-retrofit. A paired t-test showed that reductions were statistically significant at the 90% level (p=0.062) as well as for the full sample (p=0.074).

The average moisture balance at the treatment sites was 421.7 Pa (± 158.1) pre-retrofit, and 390.3 Pa (± 139.8) post-retrofit. A paired t-test did not demonstrate statistical significance for these homes (p=0.67).

These results suggest that the retrofits did not increase moisture and may have decreased moisture levels in these homes.

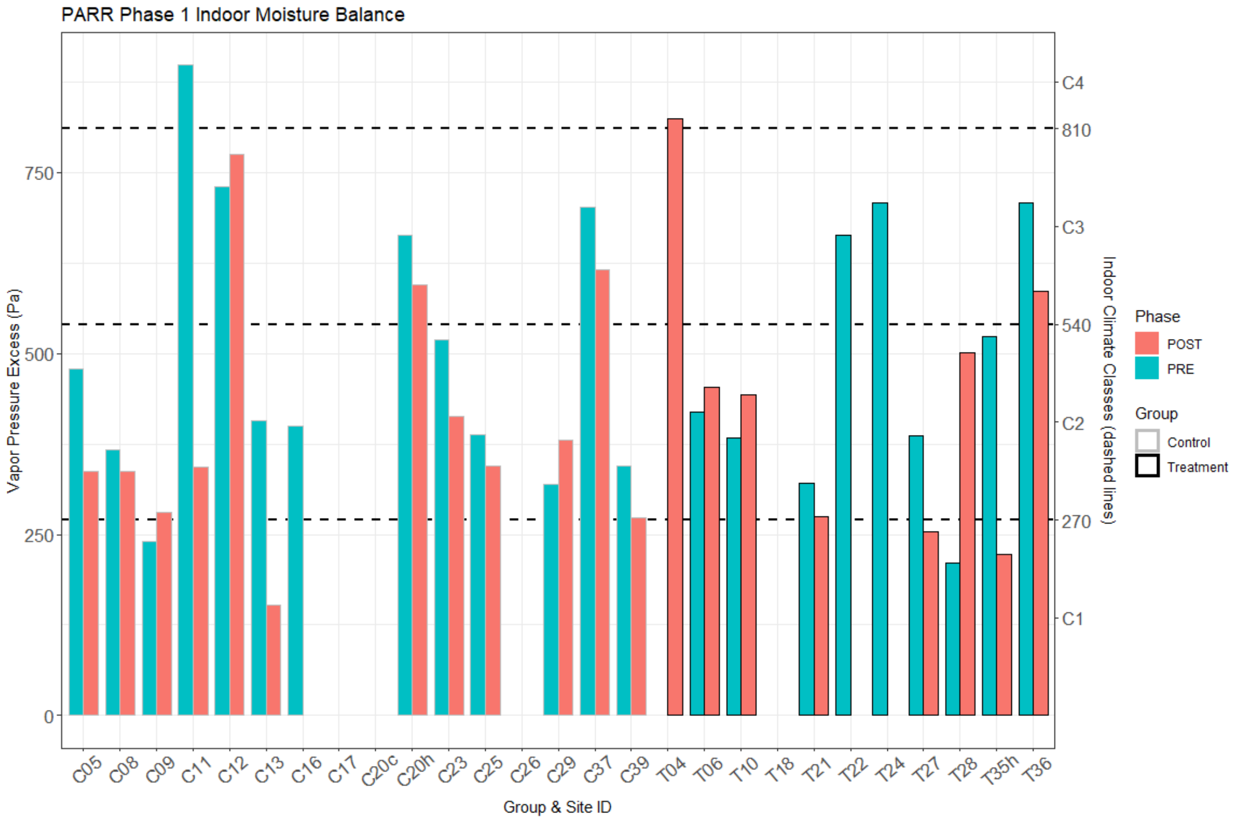


Figure 10. Phase 1 indoor moisture balance for control and treatment homes

3.4.1.6 Duct Leakage

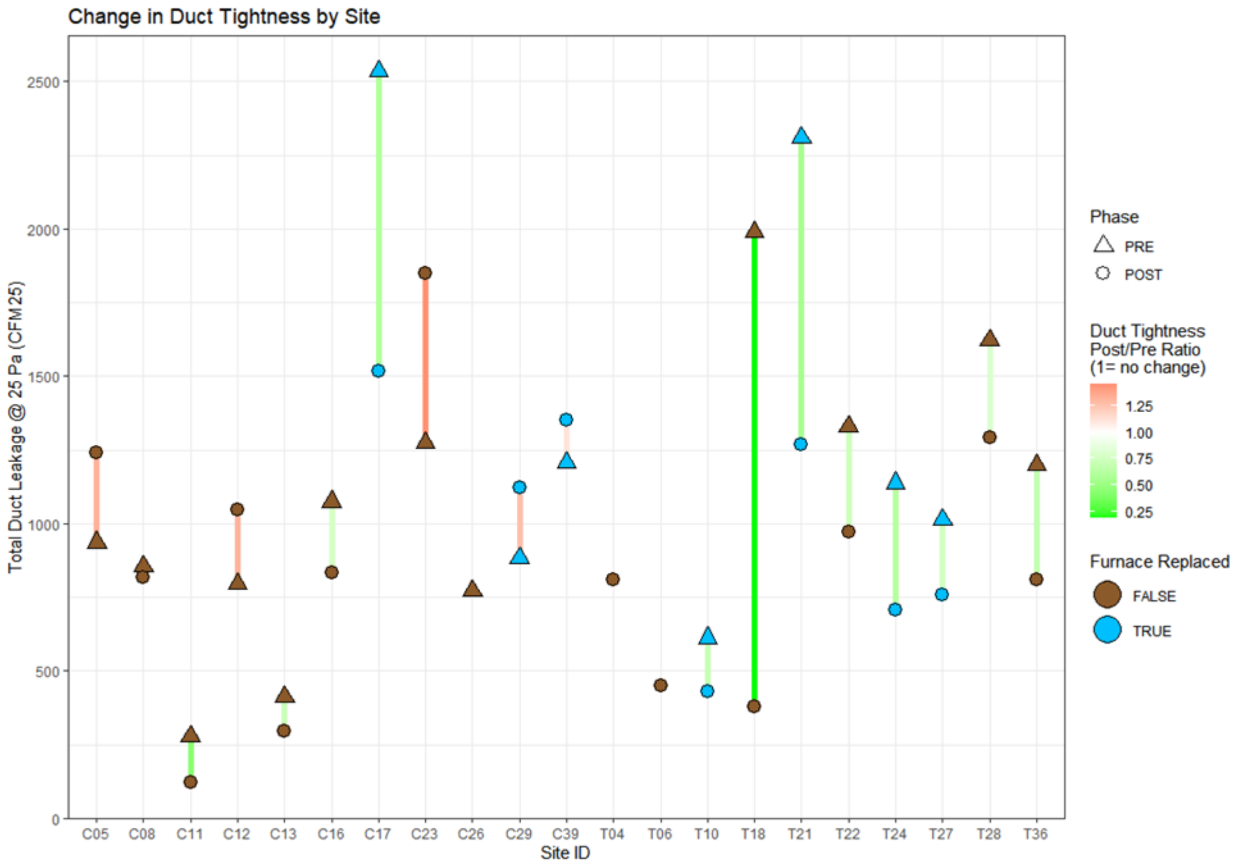


Figure 11. Phase 1 change in duct leakage between pre- and post-retrofit conditions for control and treatment homes

Figure 11 shows the measured duct leakage both pre and post at each of the sites with at least one viable duct leakage measurement result. The vertical lines show the change in magnitude of the duct leakage, and the color of the line indicates an increase (red) or decrease (green) in duct leakage. The color of the points indicates if the furnace air handler was replaced (blue) or not (brown). All treatment homes showed a reduction of duct leakage. Five of the eleven control homes with valid data for both pre and post conditions showed an apparent increase. Duct leakage reductions were not statistically associated with either house size or heating system capacity. This is not a surprise given that large duct leakage is often due to discrete large leaks or characteristics such as panned joist returns that are independent of size of a home or its heating system capacity.

3.4.1.7 Energy Use

Energy use was evaluated in terms of therms per degree day (base 65) based on the fuel energy (natural gas or propane consumption for the heating season sites, and electricity consumption of the evaporator unit for cooling season consumption) consumption of the main space-conditioning device. Electrical consumption from air-conditioning units was converted from units of kilowatt-hours to therms. Other building energy consumption (including electricity to run air handler blowers, ventilation fans, and other household gas or electrical use) is not considered in this analysis. Figure 12 shows the pre and post energy use per degree day for each individual site. The triangles indicate the amount of space conditioning energy used during the pre-retrofit measurement period, and the circles indicate that used during the post measurement period. The colored line connecting the two points indicates if the energy consumption went up (red) or down (green), and the intensity of the color corresponds to the magnitude of the change. The color of the points indicates if the site was tested during the heating season (magenta) or cooling season (cyan).

For the combined treatment and control groups, the average energy consumption was 0.12 therms/degree day for the cooling season, and 0.16 therms/degree day for the heating season. There was no statistically significant difference between heating season energy consumption at the treatment and control sites (p= 0.82); there were insufficient control sites with energy data tested during the cooling season (n_{pre} =1, n_{post}=2) to compare the two groups. Additionally, there was not a statistically significant difference between the sample-wide pre-retrofit and post-retrofit energy consumption data (cooling season p=0.91, heating season p=0.92).

Of the 17 sites that had energy per degree data for both the pre and post periods, 9 had lower energy use during the post-retrofit period, and 8 had higher energy use. Most of these differences at each site were small, and longer-term data collection may have yielded more insights. The average change for the entire sample was a reduction of 1.4%. The control sites averaged 0.03 fewer therms of consumption per degree day, and the treatment sites consumed on average 0.0008 more therms per degree day.

There is not a statistically significant difference in the change in energy use between the two groups (p=0.26). After normalizing for weather and thermostat setpoint, some homes experienced a slight increase in energy use following retrofit.

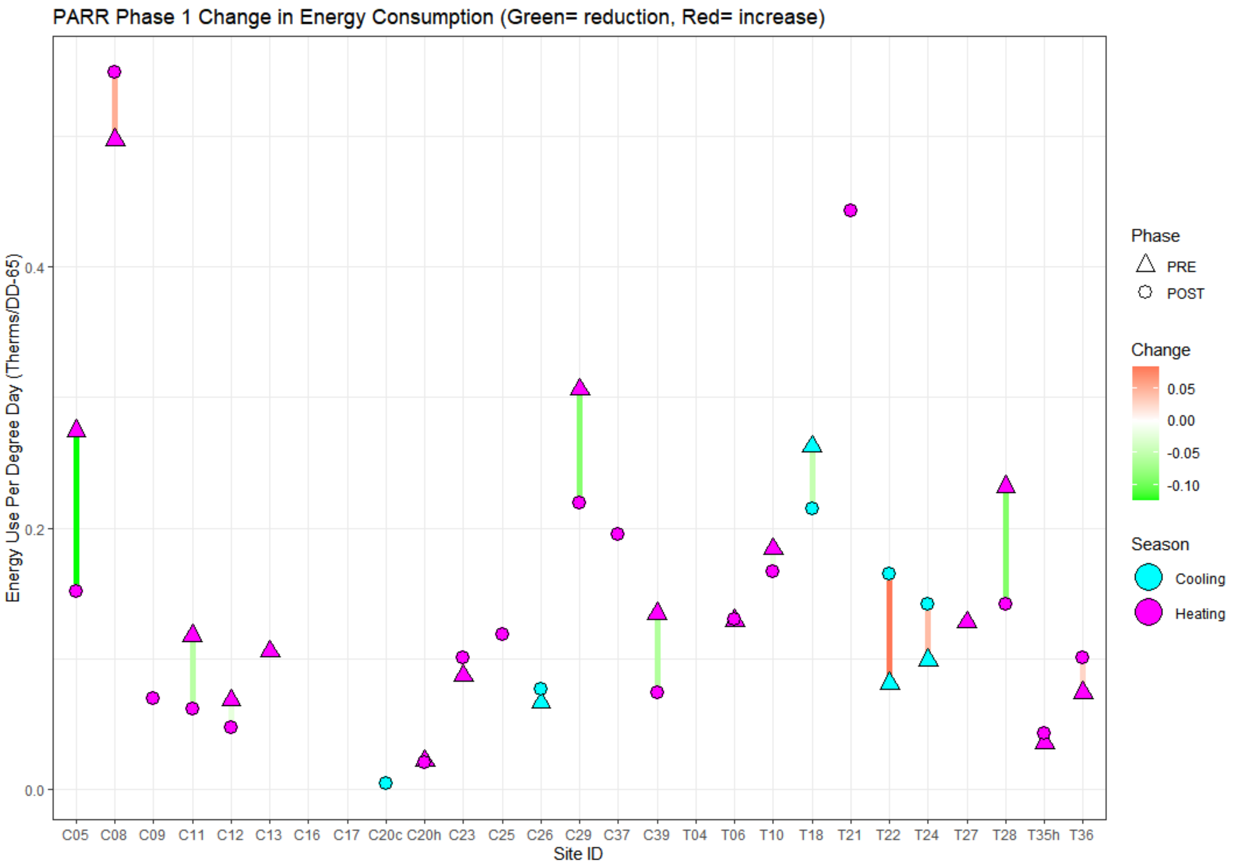


Figure 12. Phase 1 change in energy consumption between pre- and post-retrofit conditions for control and treatment homes

Energy use was also specifically evaluated in the context of changes to the building envelope and HVAC systems. Figure 13 shows the distribution of energy consumption versus the amount of continuous ventilation added during retrofit. The y-axis is the energy consumed per degree day as a ratio of post-retrofit over pre-retrofit. The horizontal line at y=1 indicates no change in energy consumption, points above that line had higher energy consumption per degree day during the post-retrofit measurement period relative to the pre-retrofit period, and points below indicate a reduction.

There is a weak positive relationship between the amount of ventilation added and energy consumption for both the treatment and control groups (treatment r^2 =0.35, control r^2= 0.55).

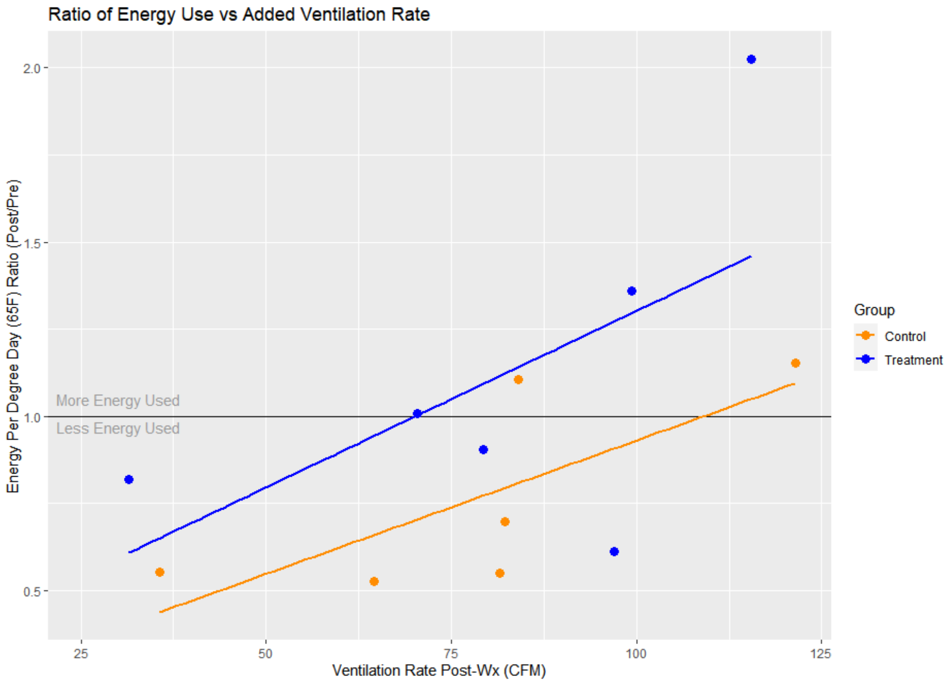


Figure 13. Phase 1 ratio of energy use versus added ventilation rate

Pre and post blower door testing was performed on all control and treatment homes. Figure 14 shows the relationship between space conditioning system energy use (excluding air handler blower electrical consumption) and building envelope tightness. The y-axis is the same as the previous graph, and the x-axis shows the building envelope tightness as a ratio of the post-CFM50 over the pre-CFM50. Points to the left of the vertical line at x=1 indicate that the building envelope got tighter, and to the right indicate that the envelope got leakier. There is no statistical significance (p=0.15) between the treatment and control groups for the ratio of ratios of the energy consumption per degree day (post/pre) versus the envelope tightness (post/pre).

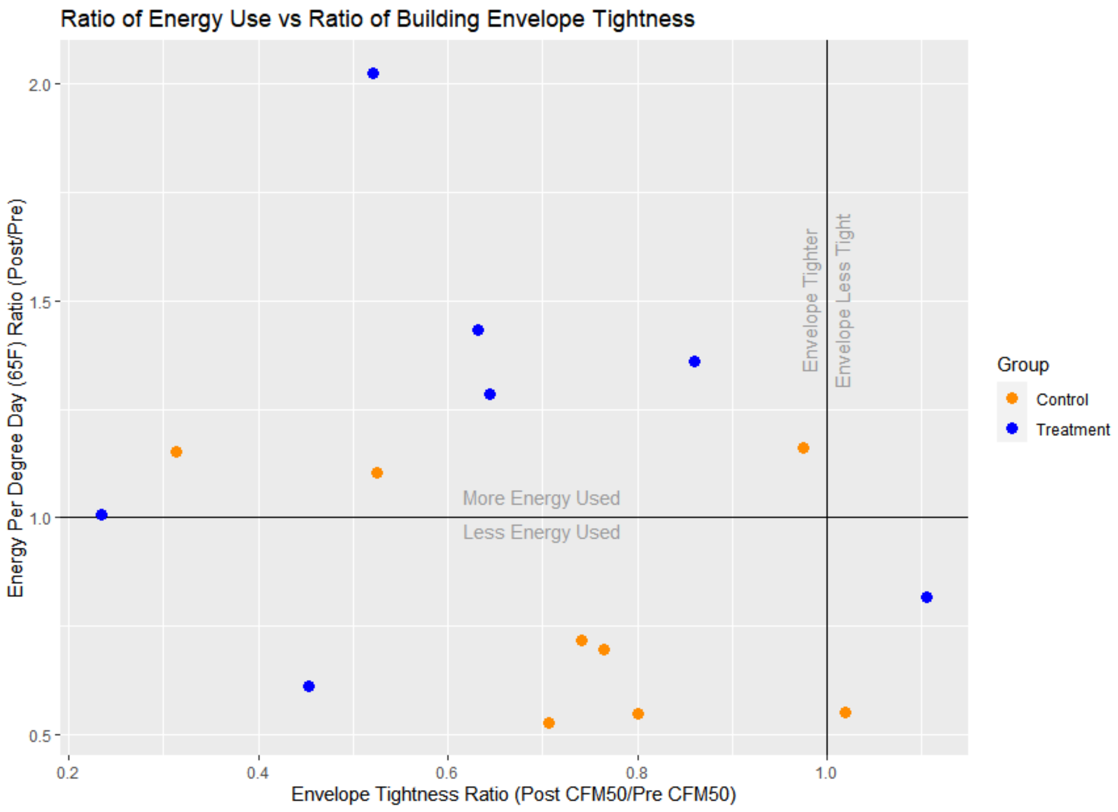


Figure 14. Phase 1 ratio of energy use versus ratio of building envelope tightness

For analyzing the impact on IAQ, Table 5 describes the sample-wide (not differentiated between treatment and control sites) relationships between the building energy metrics, and the measured contaminants. A ratio for each contaminant was calculated as the average contaminant concentration post-retrofit divided by the average concentration pre-retrofit. A ratio of 1 indicates post-retrofit contaminant concentrations were equal to pre-retrofit concentrations, a ratio less than 1 indicates that post-retrofit concentrations were lower than pre-retrofit concentrations. For all but one of the energy metrics, a similar ratio was calculated as the measured value post-retrofit divided by the measured value pre-retrofit. The exception is the "Added Ventilation" for which a ratio cannot be calculated because none of the sites had continuous ventilation prior to the retrofit. For the "Added Ventilation" metric, a non-ratio value of the total amount of ventilation airflow (in CFM) was used.

Linear regressions were performed between the metrics and contaminants, and the p-values of those linear models are presented in Table 5. Envelope tightness versus moisture balance and duct tightness versus formaldehyde were significant at the 90% level. Radon is not included because of its inherent variability and difficulty to assess changes as anything other than that normal variability. The relationship between moisture balance and envelope tightness indicates that reducing infiltration can help control moisture balance, and the relationship between duct tightness and formaldehyde suggests that tightening ducts can result in lower formaldehyde levels.

Table 5. P-Values From Sample-Wide Analysis of Building Efficiency Metrics vs. Contaminant Concentrations

Metric	Carbon Dioxide	Moisture Balance
Envelope Tightness	0.706	0.081*
Duct Tightness	0.300	0.738
Added Ventilation[1]	0.773	0.224
Air Handler Flow	0.335	0.548
Energy per DD	0.442	0.473

*Statistically significant at the 90% level

[1] This value is not a pre/post ratio, because none of the sites had pre-retrofit continuous ventilation.

4 Phase 2: Supply vs. Exhaust

4.1 Phase 2 Approach

As discussed previously, the results of Phase 1 showed minimal differences in IAQ between the control and treatment homes, and recruitment for whole-house retrofits was challenging. A more targeted protocol was adopted for a second phase of the project to assess the specific impacts of different ventilation strategies. For this protocol, no energy retrofits were performed; rather the focus was a comparison between the impacts of no ventilation, exhaust ventilation, and supply ventilation on 15 homes. Some of these homes were participants in Phase 1 as treatment homes, but most were new candidates. The response of contaminants to each ventilation type was monitored for one week in each mode.

This protocol addresses in more detail the research question of whether some contaminants are particularly responsive to systematic improvements in airflows, specifically whether supply or exhaust ventilation have a stronger impact on energy and/or IAQ.

4.2 Phase 2 Site Eligibility and Recruitment

Eligible homes were single-family homes with single system forced-air heat with capability of a minimum 30 cfm of required ventilation using an existing exhaust fan and occupied by nonsmokers. Because home performance improvement was not required, these homes were primarily recruited outside of the normal contractor-based path, although there were a couple of homes that qualified under both Phase 1 and Phase 2. Although most homes in Phase 2 did not have other retrofit measures conducted, they were required to need at least 30 cfm of mechanical ventilation to be eligible for participation. Homes were primarily recruited through the University of Illinois email weekly newsletter. All tests in Phase 2 occurred during the heating season.

The final set of 18 homes included in the study is described by Table 6. Twelve of the homes had basements, and six had crawl spaces.

Table 6. Phase 2 Site Building Characteristics

Characteristic	Minimum	Median	Maximum	Mean
Square Footage	750	2,400	4,506	2,544
Stories	1	2.00	2	1.64
Bedrooms	1	3.50	6	3.44
ACH50	3	5.6	13	6.3

4.3 Phase 2 Methodology

4.3.1 Research Design

The methodology looks at three weeks of IAQ measurements: one week of baseline (no ventilation), one week with exhaust ventilation rates compliant with ASHRAE 62.2 including infiltration credit, and one week of supply ventilation also set to the same ventilation rate as the exhaust rate. The IAQ components measured were formaldehyde (continuous indoor generation), radon (soil/exterior generation), CO_2 (human generation), humidity (human and outdoor generation), and $PM_{2.5}$ (variable indoor and outdoor generation).

4.3.2 Data Collection

During the first visit at each site, data were collected on home characteristics, airflow diagnostics were conducted, and instrumentation was deployed for IAQ metrics. Instrumentation deployment was repeated for each of the three stages of monitoring, each of which lasted one week. The first stage was with no whole-dwelling ventilation running (the as-is condition), the second stage had exhaust ventilation running, such as existing bath exhaust fan(s), that complied with the required ASHRAE Standard 62.2-2016 ventilation rate, and the third stage had supply ventilation running that complied with ASHRAE Standard 62.2-2016. Supply ventilation used the Aircycler g2 system, which combines an intake duct that connects to the return plenum, a motorized damper, and controls to deliver the required flow using the furnace air handler. This system typically had to be installed by an HVAC contractor. All ventilation flows were measured to ensure compliance.

Because of the SARS-CoV-2 pandemic in spring 2020, some sites had sampling suspended before completion. In these sites, the last phase was repeated upon restarting fieldwork later in 2020.

Home characteristic data were collected on the physical dimensions of the building, number of bedrooms, number of residents, and foundation type.

4.3.2.1 CFM50 and Ventilation Data

CFM50 was determined via a blower door test with the Energy Conservatory Blower Door System (Model 3) with a DG-700 manometer. During the blower door test, all exterior doors and windows of the test house were closed, all interior doors were open, the door to the basement was open (if there was a basement), the door to the garage was closed (if there was an attached garage), the water heater was turned to low, and the fireplace was sealed with tape or its damper was closed.

The ventilation data collected included the flow rates of the exhaust fans in each full bathroom, and the flow rates of the range hood and exhaust fan in the kitchen (if there was a range hood or an exhaust fan in the kitchen). These airflows were measured with an Energy Conservatory Exhaust Fan Flow Meter with a DG-700 manometer. It was also checked whether there was an operable window in each full bathroom and in the kitchen. Based on the collected ventilation data and usage loggers, general home information including the number of occupants and the home's target required ventilation was calculated according to ASHRAE Standard 62.2-2016, and data could be analyzed in context of various fan operation.

4.3.2.2 Indoor Air Quality Data

Indoor air contaminants and air thermal conditions monitored during the test periods include air temperature and RH, carbon dioxide, radon, formaldehyde, and $PM_{2.5}$.

Air temperature and relative humidity: HOBO U12-013 data loggers were used to record the air temperature and RH on the first floor (usually in the living room) and in the basement (if there was a basement) during the whole test periods. The sampling interval was set at 5 minutes. The data loggers were usually placed on a table, countertop, or shelf 2.5 to 5 feet above the floor.

Carbon dioxide: A Telaire 7001 CO_2 sensor was used to monitor the carbon dioxide concentration on the first floor (usually in the living room) during the whole test periods. It was connected to an external channel of the HOBO U12-013 data logger, which recorded the first floor's air temperature, RH, and CO_2 concentration in the same file at the same sampling interval.

Radon: RadStar RS300 radon monitors were used to measure the hourly radon levels on the first floor (usually in the living room) and in the basement (if there was a basement) during the test periods. To increase the reliability of the radon's readings, two radon monitors were placed side by side at every sampling location. The averages of the readings from the two monitors were used as the measurement results.

Formaldehyde: UME^X 100 passive samplers by SKC were used to sample the formaldehyde concentrations on the first floor (usually in the living room, not on or near newer furniture) for the test periods. A new sampler was deployed for each sampling week. The first two weeks' formaldehyde samplers were stored in a freezer right after their week's sampling. After the third week sampler was collected, all the three samplers were shipped overnight to the SGS lab in New York for analysis.

$PM_{2.5}$: Two PurpleAir PA-II sensors were used to sample the $PM_{2.5}$ levels in the living room and outdoor. The sensor in the living room was placed on a table or a shelf, which was about 2.5 to 4 feet above the floor. The sensor for outdoor $PM_{2.5}$ sampling was hung outside about 3 to 4 feet above the ground.

The normal data collection procedures for a test home are provided in Appendix D. Following the completion of testing, the raw data were processed, and the team generated a report for the homeowner detailing the results for their home. A representative homeowner report for Phase 2 can be found in Appendix F.

Ideally, the three ventilation scheme tests were performed in three consecutive weeks. However, the AirCycler's installation could not be scheduled in time for some homes, which resulted in a time gap of one or more days between two ventilation scheme tests. The three ventilation scheme tests in two homes were also not performed in the normal order as Week 1 for as-is, Week 2 for exhaust-only, and Week 3 for supply-only.

4.4 Phase 2 Results

4.4.1 Technical Results

Eighteen homes took part in the Phase 2 study; indoor air contaminants were sampled over three test conditions: (1) as-is, (2) exhaust-only, and (3) supply-only ventilation. As a result of the COVID pandemic, sampling was paused mid-study for homes #12, #14, #15, and #21. The as-is and exhaust test conditions were collected pre-pandemic (February–March 2020); the supply test condition was collected later in the year once it was safe to do so (September–October 2020). To avoid repeating the study in full, the supply-only ventilation was sampled following a repeated exhaust sampling period that would be used to relate the supply collected during the pandemic with the pre-pandemic as-is. Three homes (#11, #14, #15) did not complete the supply test condition because of installation challenges. These homes are excluded from some analyses below.

In summary, of the 18 homes sampled, 13 completed the study as normal, 2 completed the study over two seasons (#12, #21), and 3 sampled only the as-is and exhaust (#11, #14, #15 – the latter two homes have two exhaust samples). In the next section, we note when a statistical test is adjusted for homes #12 and #21. Uncertainties in the reported analyses reflect 95% confidence intervals.

4.4.1.1 Impact of Ventilation Strategy on Contaminants

To avoid seasonality effects, comparisons of contaminant concentrations were limited to homes in which all three sampling periods were conducted in the same season (n=13).

4.4.1.2 Carbon Dioxide (CO_2)

As with Phase 1, CO_2 medians were used as our evaluation metric to minimize data skew due to short-term discrete events. The average median CO_2 reading in the living room across the normally sampled homes [n=13] was 636 (±147) ppm for as-is, 577 (±154) ppm for exhaust, and 609 (±156) ppm for supply. No statistical significance was found between as-is and exhaust ($p=0.55$) and as-is and supply ($p=0.69$) based on paired t-tests. Only 2 homes out of the full 18 homes sampled had a median CO_2 reading over 1,000 ppm: #14 (1,173 ppm for as-is) and #35 (1,335 ppm for as-is and 1,029 ppm for supply). Figure 15 shows the spread of median CO_2 readings for the normally sampled homes.

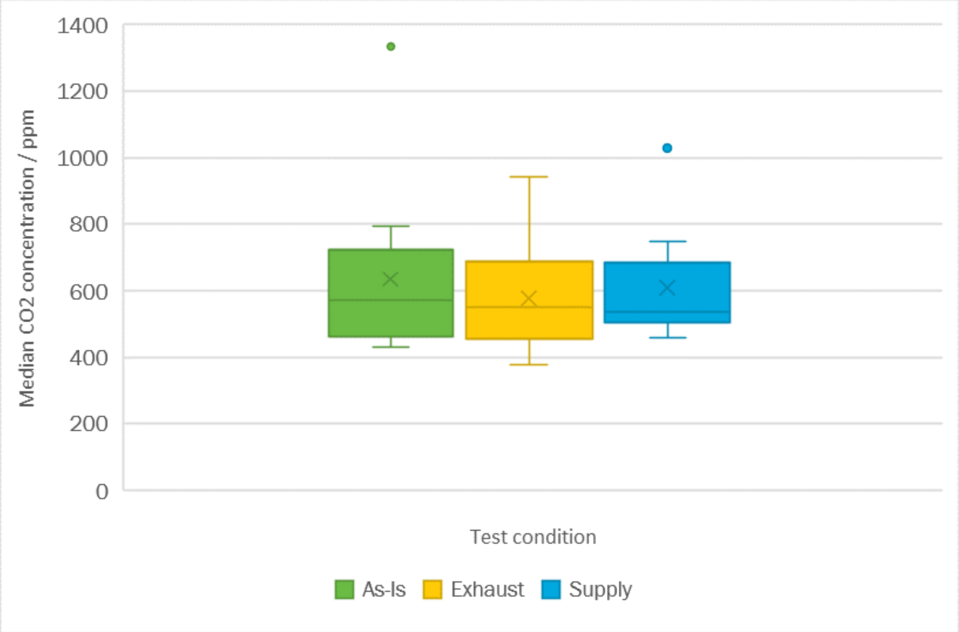


Figure 15. Phase 2 median CO_2 readings in the living room [N=13]

The ratio of median CO_2 for exhaust to as-is [n=18] and supply to as-is [n=15] was calculated for all homes and is illustrated in Figure 16. Both the exhaust and supply ventilation strategies demonstrated an ability to lower[3] median CO_2 with the ratios of the average exhaust/as-is being 0.88 (± 0.072) and the average supply/as-is ratio being 0.97 (± 0.076). While no statistical significance was found between the exhaust/as-is and supply/as-is metrics (p=0.19) [n=15], the 95% confidence interval for the average of exhaust/as-is was under a ratio of 1, which means that the exhaust ventilation reduction was statistically significant (p=0.003, from regression analysis). The supply/as-is ratios did not show statistical significance (p=0.427).

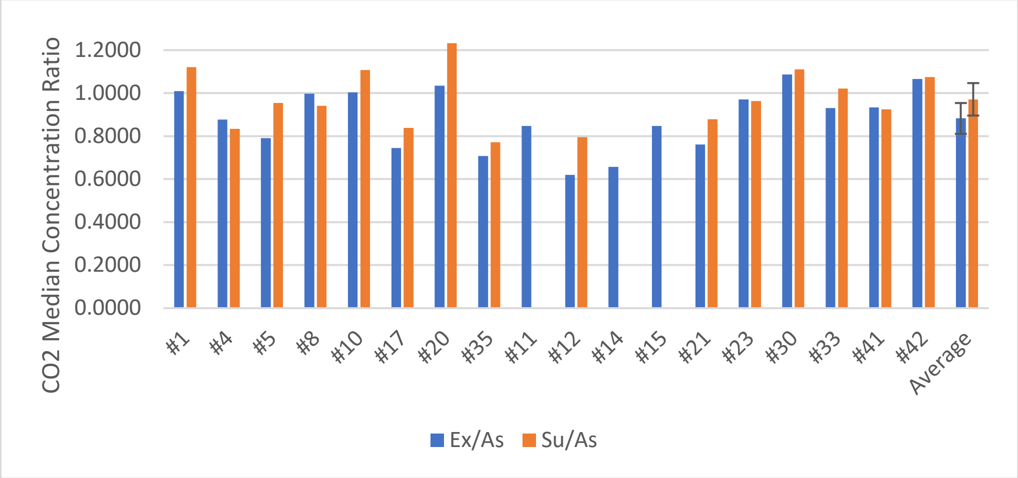


Figure 16. Phase 2 ratio of median CO_2 in the living room for exhaust/as-is and supply/as-is [n=18]

---

[3] Ratios below 1 show an improvement of the ventilation strategy over as-is.

4.4.1.3 Formaldehyde

Measured formaldehyde concentrations were low, with the highest recorded measurement being 0.30 ppb (#33 for as-is). The average formaldehyde reading for the living room across all normally sampled homes [n=13] was 11 (±4) ppb for as-is, 9 (±2) ppb for exhaust, and 9 (±2) ppb for supply. These are standard deviations of the measured values, which are still above the sensor's lower detection limit. No statistical significance was found between as-is and exhaust (p=0.40) or as-is and supply (p=0.35) based on paired t-tests. Figure 17 shows the spread of formaldehyde readings for the normally sampled homes.

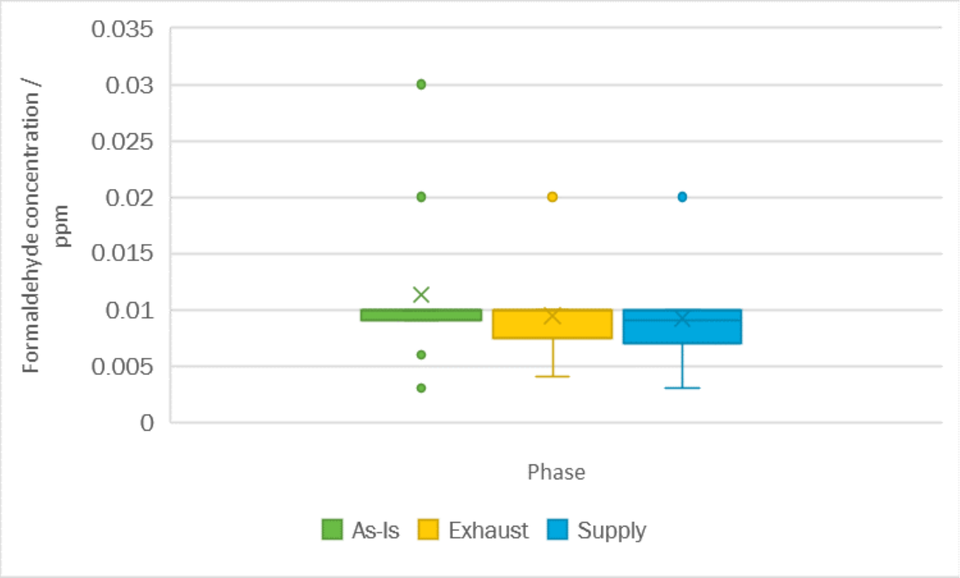


Figure 17. Phase 2 formaldehyde readings in the living room [n=13]

The exhaust/as-is [n=18] and supply/as-is [n=15] ratios for formaldehyde were calculated for all homes and are illustrated in Figure 18. The average exhaust/as-is ratio was 0.91 (± 0.107), and the average supply/as-is ratio was 1.02 (± 0.22). No statistical significance was found between the ratio metrics (p=0.45) [n=15]. As the sampler's validation range is 0.06 to 3.0 ppm,[4] and the largest detected reading was below this range, it is difficult to draw conclusions as to the impact of either ventilation strategy over as-is. However, the results suggest that adding either supply or exhaust ventilation did not measurably increase formaldehyde off-gassing.

---

[4] Specifications for the UME^{x}100 Passive Sampler can be found here: https://www.skcinc.com/media/documents/Flysheets/umex-100-fly-1529.pdf

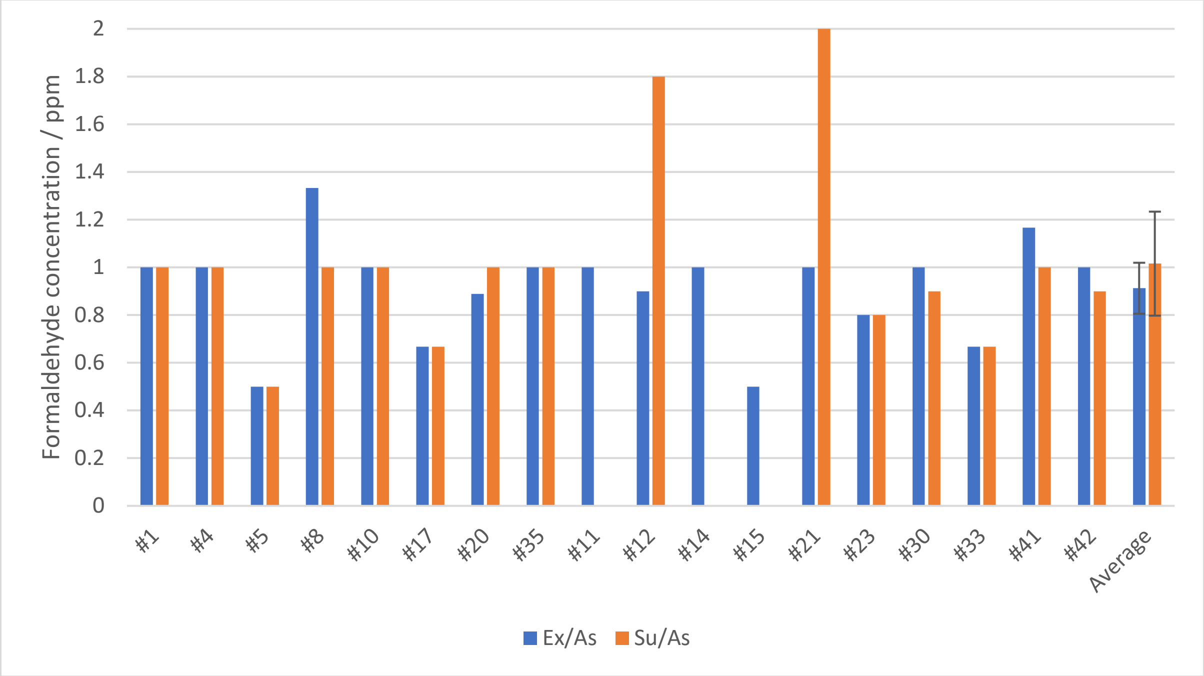


Figure 18. Phase 2 ratio of formaldehyde in the living room for exhaust/as-is and supply/as-is [n=18]

4.4.1.4 Radon

Radon was measured in both the basement (when present) and living room. Six homes did not have a basement and were fully over a crawl space. The average radon reading across the normally sampled homes for the basement [n=8] was 2.39 (±1.44) pi/CL for as-is, 2.13 (±1.28) pi/CL for exhaust, and 1.87 (±1.04) pi/CL for supply. For the living room [n=13], the average radon reading was 2.13 (±1.27) pi/CL for as-is, 1.9 (±1.26) pi/CL for exhaust, and 1.92 (±1.30) pi/CL for supply. No statistical significance was found between as-is and exhaust (p=0.76) and as-is and supply (p=0.50). Figure 19 shows the spread of radon readings in the basement and living room, respectively, for the normally sampled homes.

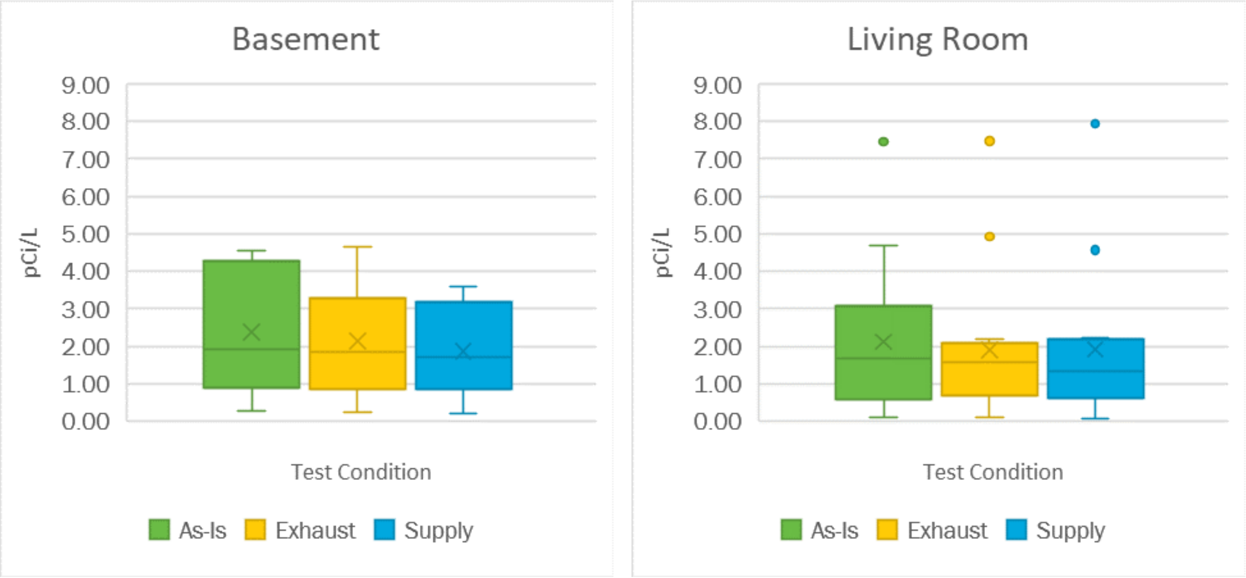


Figure 19. Phase 2 radon readings in the basement [n=8] (left) and the living room [n=13] (right)

The exhaust/as-is [n=12 (basement), 18 (living room)] and supply/as-is [n=9 (basement), 15 (living room)] ratios for radon were calculated for all homes and are illustrated in Figure 20. Both the exhaust and supply ventilation strategies demonstrated an ability to mitigate radon at the basement and in the living room. For the basement, the average exhaust/as-is ratio was 0.9 (± 0.06) and the average supply/as-is ratio was 0.86 (± 0.15). For the living room, the average exhaust/as-is ratio was 0.89 (± 0.106) and the average supply/as-is ratio was 0.92 (± 0.18). While no statistical significance was found between the ratio metrics for the basement (p=0.68) [n=9] or the living room (p=0.99) [n=15], the 95% confidence interval for the average ratio of exhaust/as-is for both the basement and the living room was under 1, which means that the exhaust ventilation reduction was statistically significant (p=0.006 for the basement; p=0.037 for the living room from regression analysis). Reductions from supply ventilation were statistically significant in the basement at the 90% confidence level (p=0.061) but were not significant in the living room (p=0.339). These results suggest that exhaust or supply ventilation do not increase radon levels significantly and may in fact reduce them slightly.

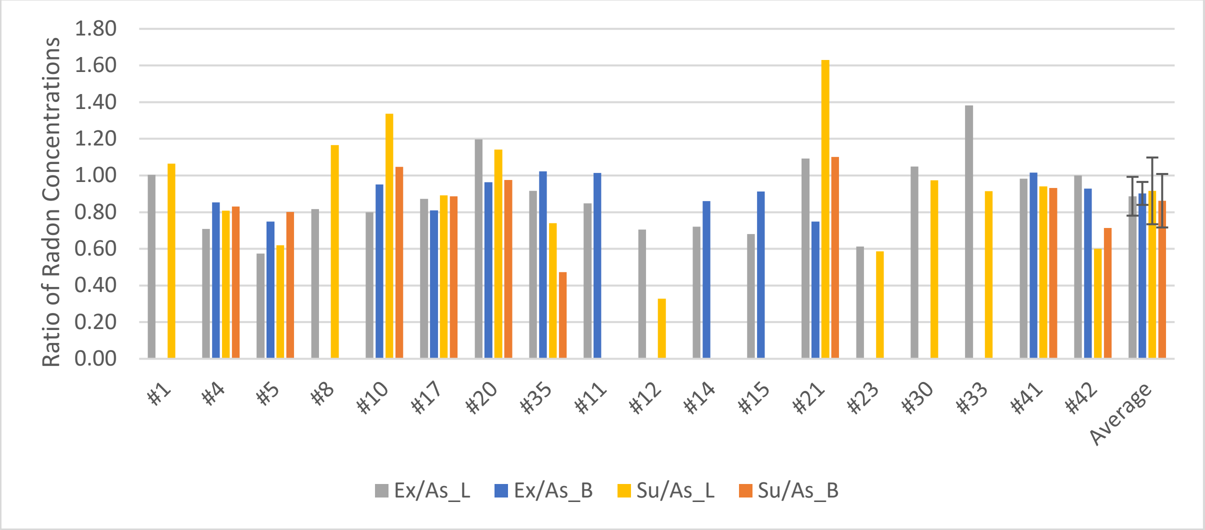


Figure 20. Phase 2 ratio of radon at basement and living room for exhaust/as-is and supply/as-is

4.4.1.5 $PM_{2.5}$

Particulate matter was evaluated using the ratio of the indoor $PM_{2.5}$ median to outdoor $PM_{2.5}$ median (referred to as "adjusted indoor $PM_{2.5}$ median"). The median was used to minimize data skew due to short-term events. $PM_{2.5}$ was sampled from both the living room and the exterior of the home. No readings were taken from homes #41 and #42 due to a sensor failure. Because of the use of the ratio of medians, sample-wide averages are based on the geometric mean.

The geometric mean of the ratio of the adjusted indoor $PM_{2.5}$ median to outdoor $PM_{2.5}$ median across the normally sampled homes [n=11] was 0.27 (±0.33) for as-is, 0.24 (±0.29) for exhaust, and 0.33 (±0.26) for supply. No statistical significance was found between as-is and exhaust (p=0.97) and as-is and supply (p=0.61). Figure 21 shows the spread of adjusted indoor readings for the normally sampled homes.

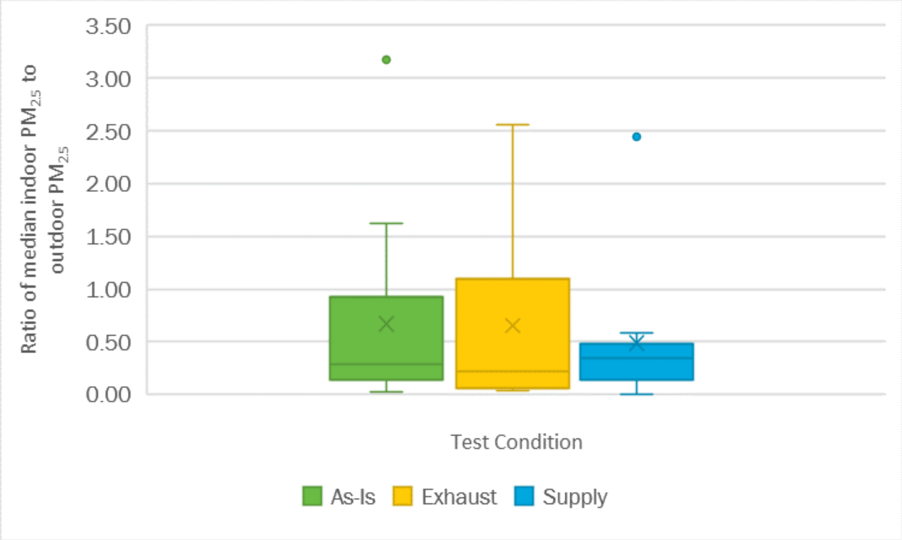


Figure 21. Phase 2 ratios of median indoor $PM_{2.5}$ to median outdoor $PM_{2.5}$ [n=11]

The ratio of adjusted indoor $PM_{2.5}$ median for exhaust/as-is [n=16] and supply/as-is [n=13] was calculated for all homes and is illustrated in Figure 22. Adjusted for outside particulate matter, both ventilation strategies demonstrated an ability to reduce $PM_{2.5}$ over as-is with the exhaust/as-is geometric mean being 0.71 (±0.33) and supply/as-is geometric mean being 0.73 (±0.46). However, these reductions are not statistically significant. Additionally, no statistical significance was found between exhaust/as-is and supply/as-is (p=0.65) [n=13]. This suggests that adding supply or exhaust ventilation does not increase $PM_{2.5}$ levels significantly compared to as-is. Of course, this conclusion is based on central Illinois' air quality, and other locations with varying outdoor air quality $PM_{2.5}$ levels may see different results.

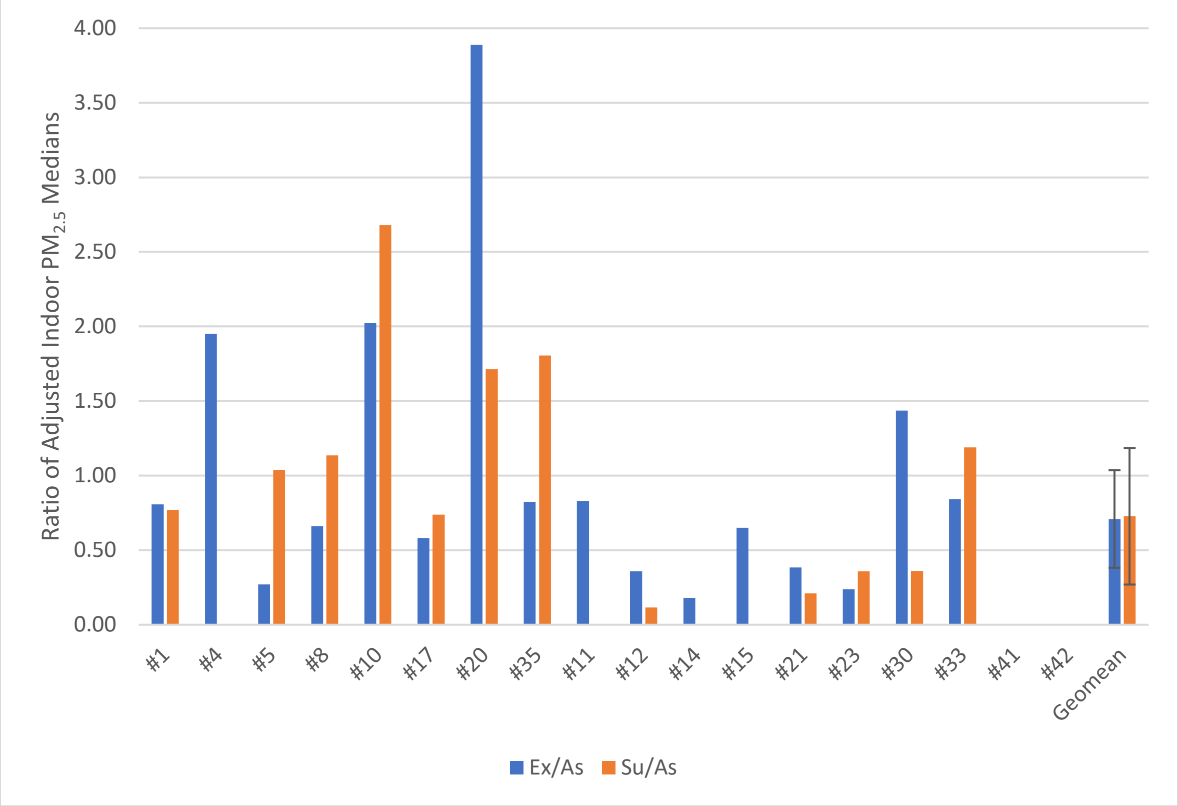


Figure 22. Phase 2 ratio of adjusted indoor $PM_{2.5}$ medians for exhaust/as-is and supply/as-is [n=18]

4.4.1.6 Moisture Balance

The outside temperature of homes #33 and #12 (supply condition only) were too warm to calculate moisture balance. During the supply condition for house #1, an exceptional condition related to moisture balance occurred, which is discussed further in Appendix G as a case study. The supply condition for house #1 is excluded from the statistical analyses, but for illustrative purposes, we include it in Figure 23 below.

The average moisture balance across all normally sampled homes with sufficient data in the necessary temperature range of 0°–15°C (32°–59°F) [n=11] was 405.6 (±137.1) Pa for as-is, 393.7 (±131.9) Pa for exhaust, and 377.4 (± 132.2) Pa for supply. No statistical significance was found between as-is and exhaust (p=0.89) and as-is and supply (p=0.74). Figure 23 shows the spread of moisture balance for the normally sampled homes. Two homes had a moisture balance greater than 810 Pa in at least one testing period, meeting the ISO 13788 definition of a damp home. In one of these homes, the moisture balance dropped to 342 Pa post-retrofit, demonstrating a substantial improvement in moisture in the home. The other home was over 810 Pa post-retrofit, but data were insufficient pre-retrofit to estimate a moisture balance and an estimate of the effects of the retrofit cannot be made.

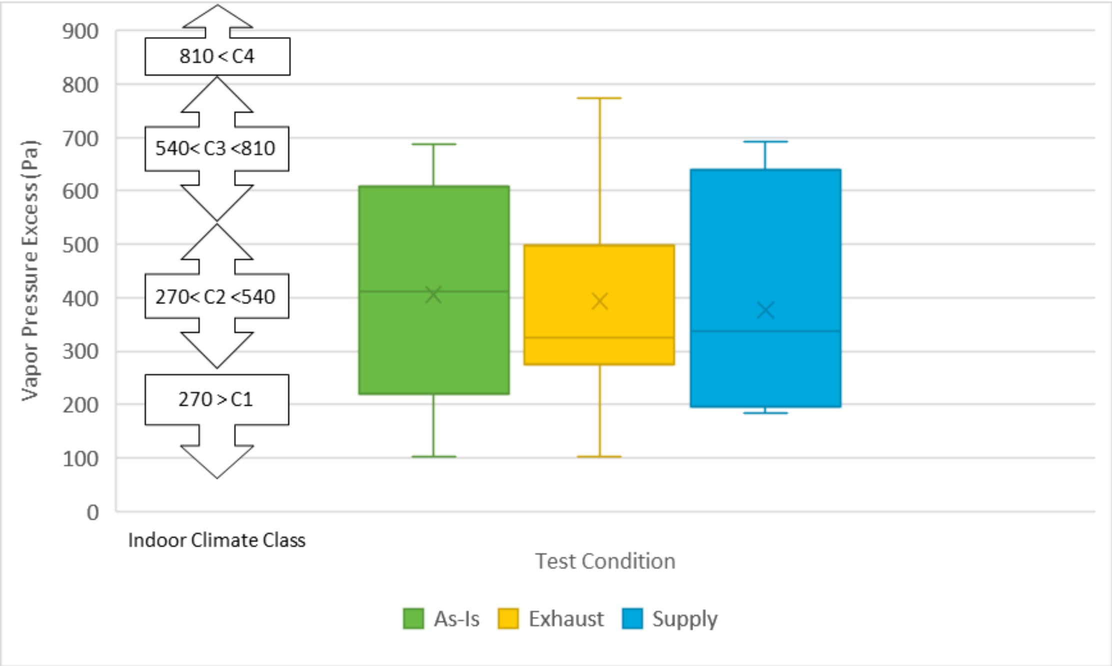


Figure 23. Phase 2 moisture balance readings [n=11]

The ratio of moisture balances for exhaust/as-is [n=17] and supply/as-is [n=12] was calculated for all homes and is illustrated in Figure 24.[5] The average ratio for exhaust/as-is was 0.97 (±0.103) and 1.01 (±0.32) for supply/as-is. No statistical significance was found between the ratio metrics (p=0.99) [n=12].

---

[5] House #1 su/as ratio is not included in the su/as ratio average and is for illustrative purposes only.

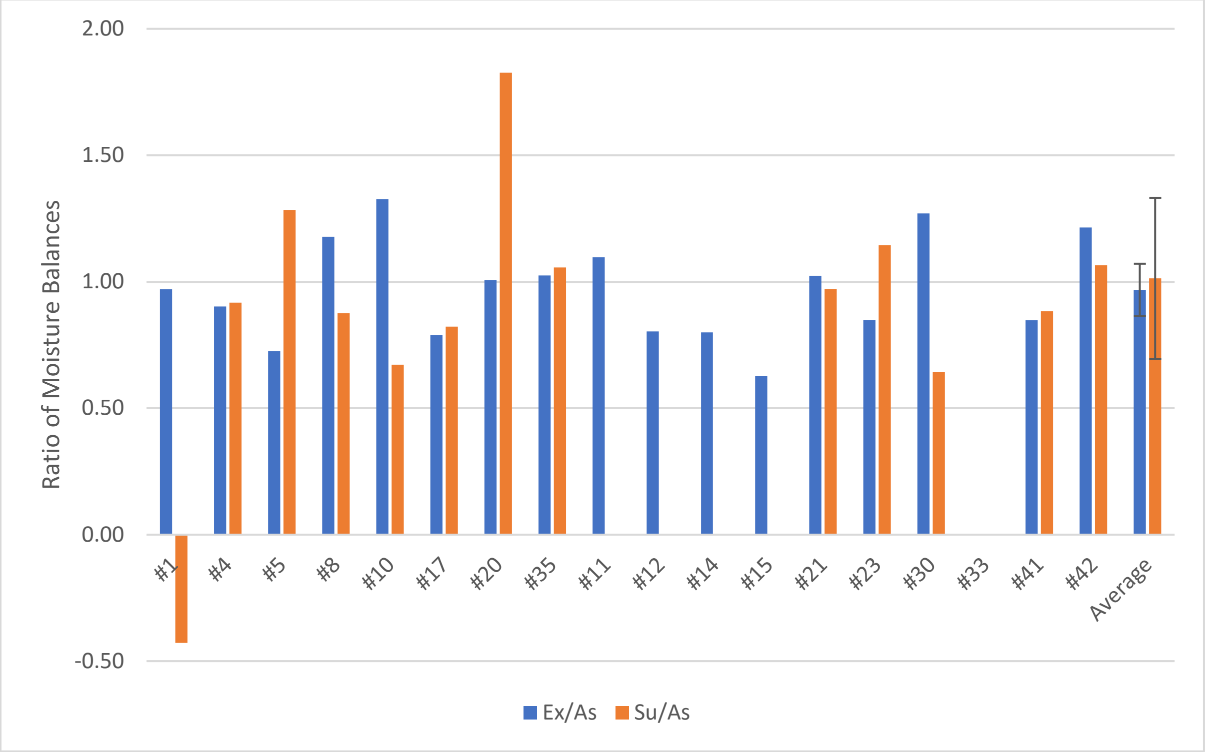


Figure 24. Phase 2 ratio of moisture balance for exhaust/as-is and supply/as-is [n=18]

4.4.1.7 Summary

Figure 25 summarizes the exhaust/as-is and supply/as-is distributions for the full sample of homes, with 95% confidence intervals. This reflects the individual contaminant discussions previously but allows the findings across contaminants to be viewed easily.

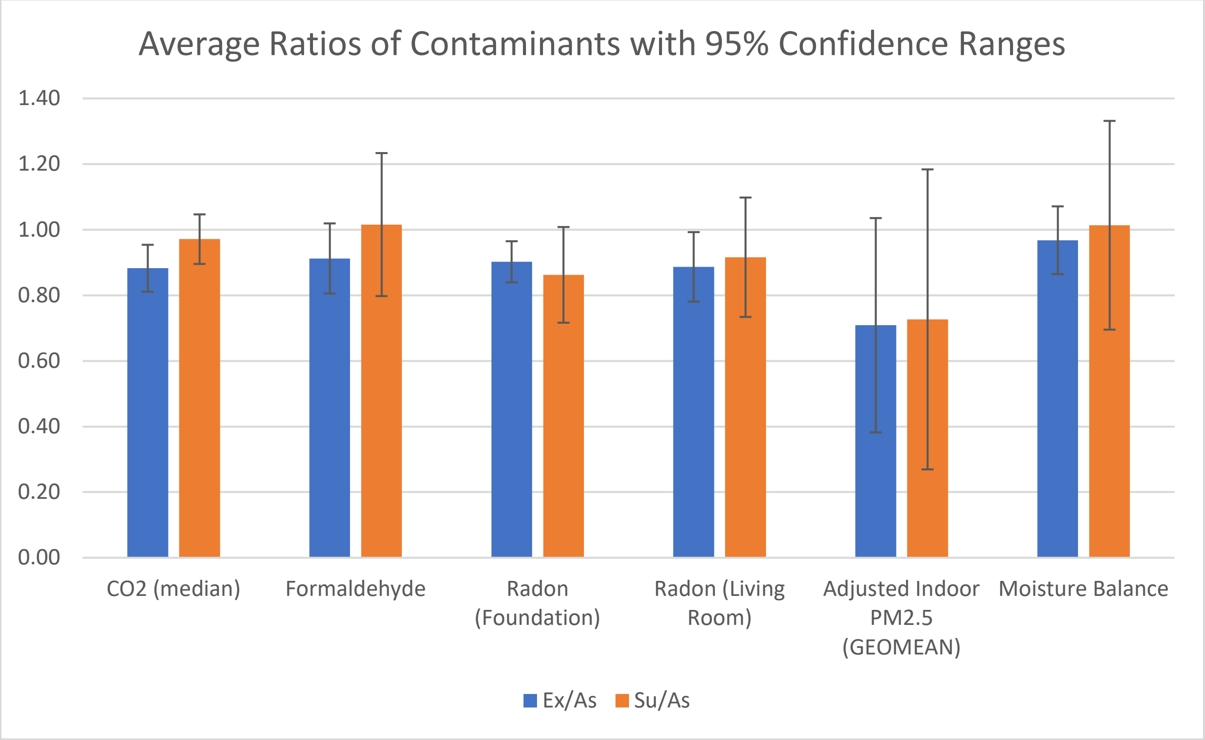


Figure 25. Phase 2 average ratios of contaminants in exhaust/as-is and supply/as-is conditions

4.4.1.8 Impact of Air Exchange on Contaminants During Normal Household Operation

A regression analysis was performed between ACH50 and the contaminant levels during the as-is test condition. Because of the small sample size and the potential for outliers to influence the results, a robust regression was used to account for outliers that could skew the results. It can be especially important for small samples, such as in this study. No statistical significance was found for median CO_2 (p=0.376) [n=18], radon (basement) (p=0.194) [n=12], or radon (living room) (p=0.294) [n=18]. The relationship between ACH50 and moisture balance was statistically significant at the 90% confidence level (p=0.052) [n=17], with homes becoming dryer as ACH50 increases (negative correlation). Statistical significance was found at the 95% confidence level for adjusted indoor $PM_{2.5}$ median (p=0.028) [n=16], with adjusted $PM_{2.5}$ increasing as ACH50 increases (positive correlation). A robust regression could not be run for formaldehyde because of the sample-wide low values.

5 Discussion

5.1 Indoor Air Quality Impacts and Guidance

The monitoring in the two phases of this research measured formaldehyde, $PM_{2.5}$, and radon because they are ubiquitous in housing and because they have significant adverse health effects. We also measured CO_2 because it is an indirect surrogate for the ability of a home's ventilation to dilute contaminants with outdoor air. Table 7 summarizes the concentration guidelines for the measured contaminants.

Table 7. IAQ Guidelines for Selected Contaminants

Contaminant	Guideline	Source	Notes
$PM_{2.5}$	12 µg/m^3 (annual)	EPA National Ambient Air Quality Standards	Applies to outdoor air
	35 µg/m^3 (24-hr)		
	10 µg/m^3 (annual)	WHO Air Quality Guideline	
	25 µg/m^3 (24-hr)		
CO_2	5000 ppm	OSHA	Permissible Exposure Limit, 8-hr TWA
Formaldehyde	See Table 9. Adopted Formaldehyde Exposure Limits for Various Agencies		
Radon	4 pCi/L	EPA	Action level
	2.7 pCi/L	WHO	Reference level

The following sections describe in further detail the documented health impacts of each of these contaminants.

5.1.1 $PM_{2.5}$

$PM_{2.5}$ is an airborne dust composed of very small inhalable particles that penetrate deep into the lungs. The particles have diameters that are generally 2.5 micrometers and smaller, which is about 30 times smaller than a human hair. In outdoor air, most particles are formed from complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, factories, automobiles, and other sources. In indoor air, particles can be emitted from cooking, combustion activities (including burning of candles, use of fireplaces, and use of unvented space heaters or kerosene heaters), cigarette smoking, and other activities. (U.S. EPA 2020) Most primary $PM_{2.5}$ emissions are from human-made sources,

Concentrations of $PM_{2.5}$ are expressed as micrograms of dust per cubic meter of air (µg/m^3). The National Ambient Air Quality Standard for $PM_{2.5}$ is 12 µg/m^3 as an annual average and 35 µg/m^3 as a 24-hour average. The annual standard is designed to protect against health effects associated with both long- and short- term exposure to $PM_{2.5}$. The current annual standard has been in place since 2012, and the 24-hour average has been in place since 2006. In April 2020, EPA decided to leave these numbers unchanged. WHO has established slightly lower limits for outdoor air (10 µg/m^3 as an annual average and 25 µg/m^3 as a 24-hour average). For indoor air, there is no legal limit and no WHO recommendation. One researcher reported an average indoor air concentration of $PM_{2.5}$ to be 15.9 µg/m^3 (Logue et al. 2012), providing some guidance on an expected baseline in residential homes.

An authoritative review of toxicity for $PM_{2.5}$ is available from the U.S. EPA's 2019 *Integrated Science Assessment for Particulate Matter*. According to EPA, recent epidemiologic studies also constitute strong evidence for a causal relationship between short-term $PM_{2.5}$ exposure and asthma exacerbation, chronic obstructive pulmonary disease (COPD) exacerbation, and combined respiratory-related diseases. These studies include emergency department visits and hospital admissions. The consistent, positive associations observed for asthma and COPD emergency department visits and hospital admissions have been shown in multiple studies. The studies used different ways to control for the potential confounding effects of weather (e.g., temperature). The relationship has also been supported by evidence of increased symptoms and medication use (U.S. EPA 2019).

Figure 26 summarizes the harmful effects of $PM_{2.5}$ exposure, clearly showing that asthma and other health problems are related to $PM_{2.5}$ exposure. Ultrafine particles were not included in this study.

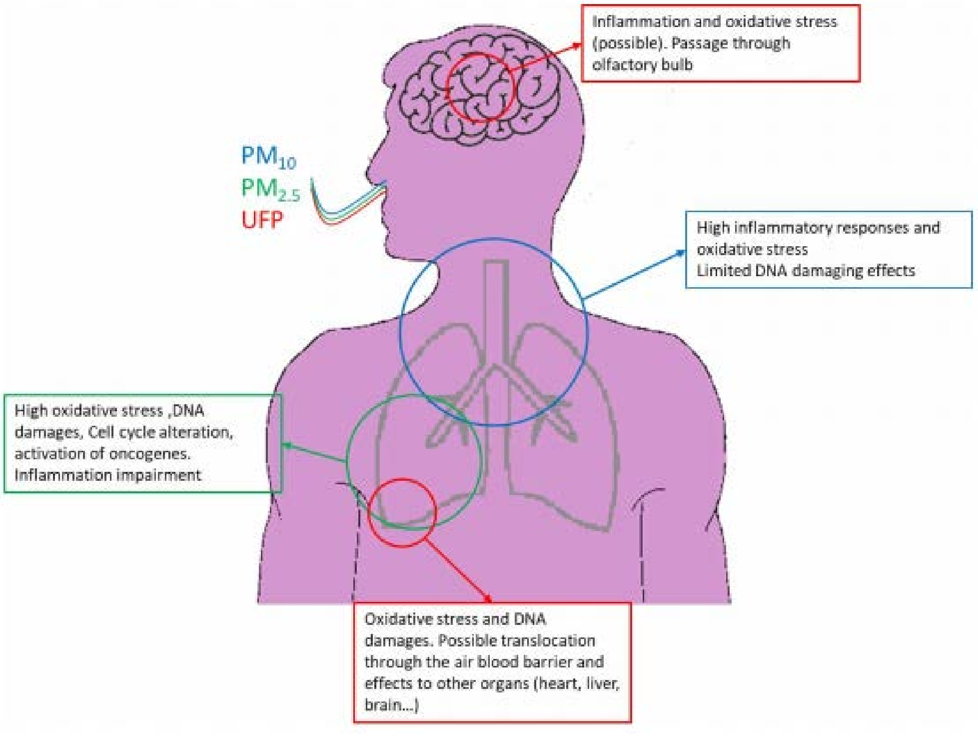


Figure 26. Health effects of $PM_{2.5}$ exposure

Source: Int. J. Mol. Sci. 2020, 21, 2489; doi:10.3390/ijms21072489

5.1.1.1 Other Adverse Health Impacts of $PM_{2.5}$

$PM_{2.5}$ has been linked to many other adverse health outcomes. For example, $PM_{2.5}$ exposure has been causally linked to cardiovascular-related emergency department visits and hospital admissions, ischemic heart disease and heart failure, and cardiovascular-related mortality. The cardiovascular effects are supported by animal studies as well. Animal toxicological studies also provide evidence for nervous system effects, including neuroinflammation and oxidative stress, neurodegeneration, cognitive effects, and effects on neurodevelopment. Other studies support associations with changes in brain morphology (shape), cognitive decrements, and dementia. There is also preliminary evidence of an association with autism.

EPA also determined that there is likely to be a causal association between $PM_{2.5}$ exposure and lung cancer, even in people who have never smoked. EPA concluded that there is a causal relationship between long-term $PM_{2.5}$ exposure and total (nonaccidental) mortality, including studies showing that increases in life expectancy are due to decreases in long-term exposure (U.S. EPA 2019; U.S. EPA 2016).

5.1.2 Carbon Dioxide (CO_2)

CO_2 is a product of combustion, fermentation, and respiration. Humans breathe in oxygen and exhale CO_2, a colorless, odorless, and nonflammable gas. CO_2 not only displaces oxygen, but also has its own toxicity (Permentier 2017). Most attention recently has been devoted to the increase in CO_2 levels as a result of greenhouse gas emissions. Average outdoor CO_2 levels were 316 ppm in 1958 and have since risen to 406 ppm as recently as 2017 (Scripps Institute of Oceanography, cited in Jones 2017).

One recent study showed that relative to 600 ppm, at 1,000 ppm CO_2, moderate and statistically significant decrements in decision-making occurred. At 2,500 ppm, large and statistically significant reductions occurred in seven scales of decision-making performance (Satish et al. 2012).

CO_2 has often been used as a surrogate measure of the amount of fresh air introduced into homes, because breathing can cause it to build up in indoor spaces. Today, outdoor air levels are typically between 350 to 500 ppm. The Occupational Safety and Health Administration has established an 8-hour time-weighted average for healthy workers of 5,000 ppm; some industrial operations have shown CO_2 levels that are immediately dangerous to life and health (30,000 ppm) (Smith et al. 1988), although such levels are not seen in the home environment.

Although there is no legal limit for indoor residential CO_2 concentrations, traditionally levels above 1,000 ppm have been regarded as one sign of possibly inadequate outdoor air supply. In 2010, ASHRAE stated, "maintaining a steady-state CO_2 concentration in a space no greater than about 700 ppm above outdoor air levels [approximately 1,000 ppm] will indicate that a substantial majority of visitors entering a space will be satisfied with respect to human bioeffluents (body odor)" (ASHRAE Standard 62.1-2010, 37). However, more recent versions of the ASHRAE standard do not state that CO_2 alone should be used as a surrogate for good IAQ (Persily 2021).

5.1.3 Formaldehyde

Formaldehyde toxicity has been reviewed extensively and has focused primarily on cancer and respiratory sensitization. Formaldehyde can be commonly found in the environment due to natural processes, like forest fires, and is released into the air via industrial emissions, incineration, and fuel combustion. Some volatile organic chemicals (VOCs) can react with ozone in the air to produce formaldehyde (CARB 2020). In homes, formaldehyde is commonly found in household products, as it is widely used in composite wood products that have resins containing formaldehyde, and in building materials and insulation, glues, permanent press fabrics, paints, lacquers, and other coatings, shampoos, soaps, hair care products, body washes, and nail polish. Some green building standards call for using building materials that comply with the California Air Resources Board requirements, which require no added formaldehyde during the manufacturing process (Enterprise 2020).

Formaldehyde exposure has been linked to many adverse health effects, including cancer through DNA reactivity, gene mutation, chromosomal breakage, aneuploidy (an abnormal number of chromosomes), epigenetic effects, glutathione depletion (glutathione is an antioxidant that repairs cell damage), oxidative stress, and proliferation of cells. The National Toxicology Program (NTP) at the U.S. Department of Health and Human Services states that formaldehyde is a "known carcinogen, based on sufficient evidence of carcinogenicity from studies in humans and supporting data on mechanisms of carcinogenesis." (NTP 2014)[6]

Another study showed that formaldehyde from wood products in homes is associated with an adverse immune response, measured by elevated circulating IgG and IgE autoantibodies (autoantibodies attack one's own proteins) and a decrease in T-cells (Thrasher et al. 1987). The study also found that long-term exposure to formaldehyde is associated with genetic changes in patients who were exposed in the workplace, and in residents of mobile homes or of homes containing particleboard subflooring, suggesting that the hypersensitivity associated with formaldehyde may be why asthma and other health complaints are also associated with formaldehyde exposure (Thrasher et al. 1990).

Chronic childhood exposure is especially important, because children can be expected to spend more time in the home environment for more cumulative years compared to adults, and may be more vulnerable due to smaller lung / alveoli size. A study showed that increased formaldehyde is associated with greater negative impacts on lung function in children compared to adults in the same household. The same study showed that decreased lung function in children at concentrations as low as 30 ppb was more pronounced in those with asthma, as measured by peak expiratory flow rate. Between 60 and 120 ppb, there was a greater prevalence of diagnosed asthma and chronic bronchitis in children, but not adults (Krzyzanowski et al. 1990).

Another study reported that formaldehyde-specific antibodies (IgE) and respiratory symptoms improved when children transferred from school buildings shown to have formaldehyde

---

[6] The most recent report on formaldehyde is at http://ntp.niehs.nih.gov/ntp/roc/content/profiles/formaldehyde.pdf.

concentrations of 40–75 ppb to school buildings with lower concentrations of 23–29 ppb (Wantke et al. 1996). Yet another study showed increased sensitization associated with formaldehyde in children's homes that had a median value of at least 12 ppb (Garrett et al. 1999). Table 8 summarizes some of these health effects.

Table 8. Health Effects of Formaldehyde in Children in the Home Environment

Health Outcome	Study Authors and Date	Formaldehyde Measured in the Home	Effects Studied on Children Living in the Home	Concentration at Which Effects Were Observed (ppb)
Sensitization: Asthma and atopy; increased allergy; increased asthma-like symptoms	Garrett, et al. (1999)	Yes	Yes	28 3% increase in risk of asthma for every 8.1 ppb
Pulmonary function; 10% reduction in peak expiratory flow rates	Krzyzanowski, et al. (1990)	Yes	Yes	27 ppb
Reproductive and developmental effects; increased risk of spontaneous abortion (SAB)	Taskinen, et al. (1999)	No	No	26
Eye irritation, burning eyes	Ritchie and Lehnen (1987)	Yes	Yes	50
Eye irritation, burning eyes	Hanrahan, et al. (1984)	Yes	Some teenagers	70
Increased asthma incidents	Rumchev, et al. (2002)	Yes	Yes	33

For chronic, non-cancer health effects, California has adopted a chronic reference exposure level of 7 ppb to address nasal obstruction and discomfort, lower airway discomfort, and eye irritation (Cal EPA 2014). Other agencies have adopted exposure limits for indoor air, although none are legally enforceable, as shown in Table 9.

Table 9. Adopted Formaldehyde Exposure Limits for Various Agencies

Agency/Organization	Exposure Limit (ppb)
WHO Indoor Guideline	80
NIOSH Recommended Exposure Limit (Workplace)	16
FEMA (specification for trailers used in disaster recoveries)	16
ATSDR Minimum Risk Level	8
California (non-cancer)	7

5.1.4 Radon

Radon is a radioactive carcinogen that is responsible for approximately 21,000 deaths—15% of the total lung-cancer deaths annually—in the United States (NRC 1999). Reports on radon health effects have concluded that lung cancer rates increase with increasing cumulative radon exposure (Lubin et al. 1997; Krewski et al. 2006). The current EPA action level for radon in the United States, established in 1986, is 4 pCi/L. The World Health Organization established a reference level of 2.7 pCi/L in 2009. WHO also reported that the population attributable fraction of lung cancer from radon was between 2% and 12%, which accounted for the annual premature deaths of at least 1,234 people in France and 1,896 people in Germany (Zeeb 2011).

5.2 Applicability of Findings

Concerns about IAQ and health impact energy efficiency programs.

IAQ concerns have been cited by some programs as reasons to not air seal homes (Manual, 2011). Other programs, such as DOE’s Weatherization Assistance Program, address the issue by allowing for expenditures on health and safety and requiring certain health and safety measures such as ventilation.

> *“Just wanted to comment on how comfortable my house is this winter. Even in the sub-zero temperatures, I’ve had the thermostat down all winter and haven’t had to touch it.”*
>
> *- Message from Treatment homeowner sent February 2021*

This study included two phases. The first, which was conducted in partnership with contractors who include IAQ considerations in their work and explored further opportunities to integrate IAQ and energy efficiency into retrofit projects, explored whether implementation of a systematic approach to airflow management in homes could lead to maintaining both energy savings and IAQ. All homes in the project were required to receive ventilation that complied with ASHRAE Standard 62.2-2016. Otherwise, homes were either treated “as normal” by participating contractors (control homes) or with additional measures (treatment homes). The results found few statistically significant impacts on IAQ of energy retrofits in either group. This lack of statistical significance can be viewed positively, as evidence that it is possible to conduct comprehensive energy efficiency retrofits without negatively impacting IAQ. To the extent that there were statistically significant impacts on IAQ, they showed that IAQ improved following retrofit. A limitation to this phase of the study is that the contractors that participated were a self-selecting sample who already implemented some measures that considered IAQ, and so we cannot draw conclusions from the data on how the approach may have improved IAQ relative to a more basic level of measures. Although energy reductions were not as high as anticipated, the study does support the notion that both energy and IAQ can be improved, leading to good outcomes in both.

The second phase explored differential impacts of supply versus exhaust ventilation strategies on IAQ. There has been substantial controversy regarding whether one approach is superior. The results showed that neither strategy negatively impacted IAQ across measured contaminants, and that some contaminants were reduced more by exhaust ventilation and some were reduced more by supply ventilation. However, most results were not statistically significant given the limited sample size. Those improvements that were statistically significant were primarily for exhaust ventilation. The results reinforce that ventilation does benefit IAQ and suggests that the choice of strategy may depend on the primary contaminant(s) of interest, though more study is needed to conclusively determine the extent to which exhaust or supply ventilation impacts specific contaminants.

5.3 Technology Transfer

The project team conducted direct outreach and contractor training to five leading home performance auditors and installation contractors covering the enhanced energy and IAQ measures for Phase 1, and supply ventilation implementation for Phase 2. In addition, team members shared information on the project in several venues. GTI provided a project update to attendees at a ComEd/Nicor Gas seminar, "High-Performance Homes: Evolution and Innovation" in Des Plaines, Illinois, and introduced the project to a group of Chicagoland Passive House practitioners. GTI also briefed its Emerging Technology Program membership on Phase 1 preliminary findings at one of its biannual meetings. The Emerging Technology Program is a membership-based utility collaborative that works to accelerate the commercialization and adoption of energy-efficient technologies.

GTI and the University of Illinois at Urbana-Champaign shared aspects of the project at a Home Performance Coalition conference, and MEEA presented a poster at the American Council for an Energy-Efficient Economy National Conference on Energy Efficiency as a Resource. Preliminary results were also shared as a conference session for the Energy Efficient Building Association. In addition, the project findings will inform ongoing training efforts conducted at the University of Illinois. The University of Illinois Indoor Climate Research and Training group maintains a state-of-the-art training center and administers the training program for the Illinois Home Weatherization Assistance Program, which provides weatherization services to low-income Illinois residents and households.

One of the motivations for Phase 1 of this project was to provide data to support a greater focus on IAQ within home energy retrofits, and to refute the perception that there is an inherent trade-off between IAQ and energy performance. Unfortunately, we found during execution of the Phase 1 research that there are several market barriers that need to be overcome before contractors would incorporate the enhanced energy retrofit protocol into their everyday business models. The treatment home measures can be costly and, depending on the home, complicated. Despite getting buy-in from contractors early on, the enhanced diagnostics and analytical protocol involving duct leakage testing, air handler flow testing, and zonal pressure diagnostics proved difficult for contractors to apply in the field. The project team ended up taking on this responsibility to ensure successful execution and remove it as a barrier for recruiting.

On a positive note, the project discovered that some recommended practices such as rim joist sealing and air sealing at attached garages are being implemented by some advanced contractors. We also found that energy efficiency program incentives play a large role in uptake of retrofit measures. It would be beneficial if energy measures with potential to improve IAQ were consistently incentivized in home retrofit programs. Perhaps most simply, given the findings related to duct sealing and moisture balance, programs can recommend that visible ductwork be sealed in unfinished basements when home performance contractors encounter unsealed ducts that are easily accessible. This could be a prescriptive program recommendation.

Phase 2 demonstrated that supply ventilation implementation faces market barriers in existing home retrofits. Home Performance contractors may be uncomfortable retrofitting supply ventilation systems without bringing in a separate HVAC contractor, increasing costs and scheduling complexity. New construction or retrofits where the HVAC system was being replaced would not face this issue. In general, retrofits that may be performed by a single trade have a market advantage over those that require coordination from multiple trades. From this perspective, exhaust ventilation strategies were easier for the home performance contractors in this study to implement. Further work should be done to study the potential of added benefits of balanced ventilation with both supply and exhaust approaches in residential retrofits.

6 Conclusions and Recommendations

This project aimed to evaluate the potential to successfully balance energy savings and IAQ in residential retrofits (Phase 1), determine the extent to which a systematic approach could easily be integrated into contractors' business models (Phase 1), and assess the relative impacts of different ventilation strategies on IAQ metrics (Phase 2). Both phases included a relatively small number of homes, and larger studies are needed to confirm the results presented here and gain a deeper understanding of the impacts on specific IAQ contaminants.

In the Phase 1 homes, there were no statistically significant changes in indoor contaminant levels as a result of retrofits, which means that the retrofits were not associated with poorer IAQ. This was true regardless of whether the homes were treated with an aim toward meeting all project criteria or with the only additional intervention beyond normal practice being the installation of ventilation at a flow rate that complies with ASHRAE Standard 62.2. Given that the contractors who participated were already implementing some measures that are beyond basic practice (such as performing air sealing at the foundation level instead of focusing primarily on the attic), this finding suggests that it is possible to implement comprehensive energy efficiency measures without compromising IAQ. While we cannot assess the impacts relative to more basic practice, this supports the success of the approach taken in the study. With modest gains in building air tightness achieved in this study, further work may also be necessary to quantify impacts on IAQ with tighter enclosures.

Duct leakage improvements were found to be statistically significant with respect to reductions in the moisture load of homes. The metric used in this study included both duct leakage to indoors and outdoors. Because most ducts in sample homes are located in the foundation space, air leaks may be an important transport mechanism for soil moisture, and air sealing may reduce the entry of this moisture into the home. The research supports the finding that prescriptive duct sealing coupled with foundation sealing in unfinished foundation levels can improve moisture balance and IAQ.

Regarding contractor adoption, the fact that partnering contractors were already implementing improved practices shows that it is feasible for contractors to integrate these practices into a successful business. However, the contractors indicated they could not feasibly implement the additional diagnostics required by the study beyond what they were already conducting. Therefore, for these additional diagnostics to be broadly implemented, it is likely that they would need to become standard practice and/or required by programs, which would also carry increased assessment costs. Additionally, more research is needed to understand how contractors can be trained to discuss and ultimately sell IAQ upgrades as part of home performance services.

In Phase 2 homes, there were no statistically significant differences in contaminant impacts between supply and exhaust ventilation. Compared to no ventilation, both approaches showed reductions in contaminant levels for all contaminants, though most of these reductions were not statistically significant. The only two statistically significant reductions compared to no ventilation were for exhaust ventilation, for CO_2 and radon. Given the results of this study, weatherization and utility energy efficiency programs can be confident that as long as contractors provide some kind of mechanical ventilation, there is no risk of adversely affecting IAQ by doing too much air sealing, insulation, or other energy efficiency measures.

References

Aldrich, R., and S. Puttagunta. 2011. *Measure Guideline: Sealing and Insulating Ducts in Existing Homes*. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Building Technologies Program, KNDJ-0-40342-01.

ASHRAE. 2010. “Ventilation for Acceptable Indoor Air Quality.” ANSI/AHSRAE Standard 62.1-2010.

Blasnik, M., G. Dalhoff, S. Pigg, A. Mendyk, D. Carroll, and F. Ucar. 2014. *National Weatherization Assistance Program Impact Evaluation: Energy Impacts for Single Family Homes*. Oak Ridge National Laboratory. ORNL/TM-2015/13. Oak Ridge, TN.

Brand, L., S. Yee, and J. Baker. 2015. *Improving Gas Furnace Performance: A Field and Laboratory Study at End of Life*. Prepared for NREL under subcontract KNDJ-0-40346-03. https://www.nrel.gov/docs/fy15osti/63702.pdf

California Air Resources Board (CARB). 2020. “Formaldehyde.” Last updated May 1, 2020. https://ww2.arb.ca.gov/resources/fact-sheets/formaldehyde

California Environmental Protection Agency (Cal EPA). 2014. “Appendix D. Individual Acute, 8-Hour, and Chronic Reference Exposure Level Summaries.” *Technical Support Document for the Derivation of Noncancer Reference Exposure Levels*.

Chitwood, R., and L. Harriman. 2012. *Measured Home Performance*. Version 2.0, Chapter 9.

Collignan, B., and E. Powaga. 2019. “Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration.” *Journal of Environmental Radioactivity*. https://doi.org/10.1016/j.jenvrad.2017.11.023

Cummings, J., J. Tooley, M. Moyer, and R. Dunsmore. 1994. “Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes*.” Proceedings of the ACEEE Summer Study 1994* 9: 65–76.

Davis, B., and M. Roberson. 1993. “Using the ‘pressure pan’ technique to prioritize duct sealing efforts: A study of 18 Arkansas homes.” *Energy and Buildings* 20.1: 57–63.

Edwards, S., J. Baker, and M. Graham. 2015. *HVAC SAVE: A Case Study in the Next Evolution of Residential Quality Installation Programs*. Midwest Energy Efficiency Alliance White Paper.

Enterprise. N.d. “Materials, Section 6.4.” 2020 Enterprise Green Communities Criteria: The Standard for Sustainable Futures. Accessed Feb 10, 2021. https://www.greencommunitiesonline.org/materials

Francisco, P., D. Jacobs, L. Targos, S. Dixon, J. Breysse, B. Rose, H. Dawson, S. Nall, D. Phillips, and S. Cali, 2017. “Ventilation, Indoor Air Quality and Health Outcomes in Home Weatherization.” *Indoor Air* (2):463–477. https://doi.org/10.1111/ina.12325

Francisco, P. W., D. E. Jacobs, L. Targos, S. L. Dixon, J. Breysse, W. Rose, and S. Cali. (2017). "Ventilation, indoor air quality, and health in homes undergoing weatherization." *Indoor Air*., 27(2): 463–477. https://doi.org/10.1111/ina.12325

Garrett, M. H., M. A. Hooper, B. M. Hooper, P. R. Rayment, and M. J. Abramson. 1999. "Increased risk of allergy in children due to formaldehyde exposure in homes." *Allergy* 54(4): 330–337. https://doi.org/10.1034/j.1398-9995.1999.00763.x

Hanrahan, L. P., K. A. Dally, H. A. Anderson, M. S. Kanarek, and J. Rankin. 1984 "Formaldehyde vapor in mobile homes: a cross sectional survey of concentrations and irritant effects." *Am J Public Health* 74(9): 1026–7.

Hubbard, L. M., B. Bolker, R. H. Socolow, D. J. Dickerhoff, and R. B. Mosley. 1988. In: Proceedings of the 1988 Symposium on Radon and Radon Reduction Technology.

Hun, D., M. Jackson, and S. Shrestha. 2013. *Optimization of Ventilation Energy Demands and Indoor Air Quality in the ZEBRAlliance Homes*. Oak Ridge National Laboratory. Oak Ridge, TN. https://www.osti.gov/servlets/purl/1221074

ISO. 2001. *ISO Standard 13788, Hygrothermal Performance of Building Components and Building Elements—Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation—Calculation Methods*. International Organization for Standardization. http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=22203

Jacobs, D. E., and M. S. Smith. 1988 "Exposures to carbon dioxide in the poultry processing industry." *American Industrial Hygiene Association Journal*. 49(12): 624–629. https://doi.org/10.1080/15298668891380358

Krewski D., J. H. Lubin., J. M. Zielinski, M. Alavanja, V. S. Catalan, R. W. Field, J. B. Klotz, et al. 2006. "A combined analysis of North American case-control studies of residential radon and lung cancer." *J Toxicol Environ Health A*. 69(7): 533–597. https://doi.org/10.1080/15287390500260945

Krzyzanowski, M., J. J. Quackenboss, and M. D. Lebowitz. 1990. "Chronic respiratory effects of indoor formaldehyde exposure." *Environ Res* 52(2): 117–125. https://doi.org/10.1016/s0013-9351(05)80247-6

Less, B., N. Mullen, B. Singer, and I. Walker. 2015. "Indoor air quality in 24 California residences designed as high-performance homes." *Science and Technology for the Built Environment* 21(1), 14–24.

Logue, J., M. Sherman, P. Price, and B. Singer. 2011. *Why We Ventilate*. Lawrence Berkeley National Laboratory report. LBNL-5093, Berkeley, CA.

Logue, J. M., P. N. Price, M. H. Sherman, and B. C. Singer. 2012. "A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences." *Environ Health Perspect* 120: 216–222.

Logue, J., M. Sherman, I. Walker, and B. Singer. 2013. “Energy impacts of envelope tightening and mechanical ventilation for the US residential sector.” *Energy and Buildings* 65: 281–291.

Lubin, J. H., and J. D. Boice Jr. 1997. “Lung cancer risk from residential radon: meta-analysis of eight epidemiologic studies.” *J. Natl. Cancer Inst*. 89, 49–57.

Manual, J. 2011. “Avoiding Health Pitfalls of Home Energy-Efficiency Retrofits.” *Environ Health Perspect* 119(2): A76–A79.

Martin, E. 2014. *Impact of Residential Mechanical Ventilation on Energy Cost and Humidity Control*. Building Science Corporation, Florida Solar Energy Center/BA-PIRC, IBACOS.

Merrin, Z., P. Francisco, D. Bohac, J.A. Quinnell, C. Olson. 2018 “An evaluation of strategies to reduce transport of pollutants from garages to homes.” *Science and Technology for the Built Environment* 24(2): 198–208. https://doi.org/10.1080/23744731.2017.1417664

National Research Council (NRC). 1999. *Health Effects of Exposure to Radon: BEIR VI*. The National Academies Press. Washington, D.C. https://doi.org/10.17226/5499

National Toxicology Program (NTP). 2014. *Report on Carcinogens, Thirteenth Edition*. U.S. Department of Health and Human Services, Public Health Service. Research Triangle Park, NC. http://ntp.niehs.nih.gov/pubhealth/roc/roc13/

Nitschke, I., M. Clarkin, T. Brennan, et al. 1989. *Preliminary results from the New York State radon protection demonstration program*. Camroden Associates. USA.

Palmiter, L., and P. W. Francisco. 1994. “Measured Efficiency of Forced-Air Distribution Systems in 24 Homes.” *Proc. Of the 1994 ACEEE Summer Study*. Pacific Grove, CA.

Parker, D. S., J. R. Sherwin, R. A. Raustad, and D. B. Shirey III. 1997. “Impact of Evaporator Coil Airflow in Residential Air-Conditioning Systems.” *ASHRAE Transactions* 103: 395–405.

Permentier, K., S. Vercammen, S. Soetaert, and C. Schellemans. 2017. “Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department.” *Int J Emerg Med*; 10:14. https://doi.org/10.1186/s12245-017-0142-y

Persily, A. K. 2021. “Don’t blame standard 62.1 for 1,000 ppm CO2.” *ASHRAE Journal*, 63(2), 74–75.

Pigg, S. 2014. *National Weatherization Assistance Program Impact Evaluation: Impact of Exhaust-Only Ventilation on Indoor Radon and Humidity – A Field Investigation*. Oak Ridge National Laboratory, ORNL/TM-2014/367. Oak Ridge, TN.

Pigg, S., D. Cautley, P. Francisco, B. Hawkins, and T. Brennan. 2014. *Weatherization and Indoor Air Quality: Measured Impacts in Single-family Homes under the Weatherization Assistance Program*. Oak Ridge National Laboratory, ORNL/TM-2014/170. Oak Ridge, TN.

Ritchie, I. M., and R. G. Lehnen. 1987. “Formaldehyde-related health complaints of residents living in mobile and conventional homes.” *Am J Public Health* 77(3): 323–328.

Rose, W. B., P. W. Francisco, and Z. Merrin. 2015. *Low-Cost Radon Reduction Pilot Study*. Prepared for NREL under subcontract KNDJ-0-40346-04.

Rudd, A. 2014. *Air Leakage and Air Transfer Between Garage and Living Space*. National Renewable Energy Laboratory. DOE/GO-102014-4489. Golden, CO.

Rudd, A., and D. Bergey. 2014. *Ventilation System Effectiveness and Tested Indoor Air Quality Impacts*. National Renewable Energy Laboratory. NREL/SR-5500-61128. Golden, CO.

Rumchev, K. B., J. T. Spickett, M. K. Bulsara, M. R. Phillips, and S. M. Stick. 2002. "Domestic exposure to formaldehyde significantly increases the risk of asthma in young children." *Eur Respir J* 20(2): 403–408.

Satish, U., M. J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W. J. Fisk. 2012. "Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance." *Environ Health Perspect* 120: 1671–1677. http://dx.doi.org/10.1289/ehp.1104789

Scripps Institute of Oceanography. 2017. Cited in Nicola Jones, "How the World Passed a Carbon Threshold and Why it Matters." Yale School of the Environment. https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters

Steck, D. J. 2005. "Residential Radon Risk Assessment: How well is it working in a high radon region?" Physics Department, St. John's University. Collegeville, MN. Presented at *AARST Proceedings of the 2005 International Radon Symposium.*

Taskinen, H. K., P. Kyyrönen, M. Sallmén, S. V. Virtanen, T. A. Liukkonen, O. Huida, M. L. Lindbohm, and A. Anttila. 1999 "Reduced fertility among female wood workers exposed to formaldehyde." *Am J Ind Med*. 36(1): 206–212.

Thrasher, J. D., A. Broughton, and R. Madison. 1990. "Immune activation and autoantibodies in humans with long-term inhalation exposure to formaldehyde." *Arch Environ Health* 45(4): 217–223. http://dx.doi.org/10.1080/00039896.1990.9940805

Thrasher, J. D., A. Wojdani, G. Cheung, and G. Heuser. 1987. "Evidence for formaldehyde antibodies and altered cellular immunity in subjects exposed to formaldehyde in mobile homes." *Arch Environ Health* 42(6): 347–350.

Tonn, B., D. Carroll, S. Pigg, M. Blasnik, G. Dalhoff, J. Berger, and I. Bensch. 2014. *Weatherization Works-Summary of Findings from the Retrospective Evaluation of the US Department of Energy's Weatherization Assistance Program*. Oak Ridge National Laboratory ORNL/TM-2014/338. Oak Ridge, TN.

U.S. Census Bureau. 2019. *2019 National Housing Unit Characteristics*. American Housing Survey (AHS) for the United States. https://www.census.gov/programs-surveys/ahs.html

U.S. Department of Energy (U.S. DOE). 2000. *Air Sealing*, Technology Fact Sheet.

U.S. Environmental Protection Agency (U.S. EPA). 2016. *Integrated Science Assessment for Oxides of Nitrogen -- Health Criteria*. EPA/600/R-15/068. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

U.S. EPA. 2019. *Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2019)*. U.S. Environmental Protection Agency. EPA/600/R-19/188. Washington, D.C. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

U.S EPA. 2020. "Particulate Matter (PM) Basics." Particulate Matter (PM) Pollution. Last modified October 1, 2020. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

U.S EPA. 2020. "Indoor Particulate Matter." Indoor Air Quality (IAQ). Last modified October 9, 2020. https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter#Levels_in_Homes

Wantke, F., C. M. Demmer, P. Tappler, M. Gotz, and R. Jarisch. 1996. "Exposure to gaseous formaldehyde induces IgE-mediated sensitization to formaldehyde in school-children." *Clin Exp Allergy* 26(3): 276–280.

Widder, S., E. Martin, D. Chasar, J. McIlvaine, B. Amos, and K. Fonorow. 2017. Comparative Performance of Two Ventilation Strategies in a Hot-Humid Climate. https://doi.org/10.2172/1344329

Zeeb, H. 2011. "Indoor radon and lung cancer." In *Environmental burden of disease associated with inadequate housing: A method guide to the quantification of health impacts of selected housing risks in the WHO European Region*, edited by M. Braubach, D.E. Jacobs, and D. Ormandy. World Health Organization.

Bibliography

Andrews, J. W. 2000. “Reducing Measurement Uncertainties in Duct Leakage Testing.” *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings* 1: 113–27.

ATSDR. 2010. “Addendum to the Toxicological Profile for Formaldehyde Agency for Toxic Substances and Disease Registry.” *Division of Toxicology and Environmental Medicine*, Atlanta, GA.

Aydin, C., and B. Ozerdem. 2006. “Air Leakage Measurement and Analysis in Duct Systems.” *Energy and Buildings* 38, 3: 207–13. doi:10.1016/j.enbuild.2005.05.010.

Carrié, F. R., A. Bossaer, J. V. Andersson, P. Wouters, and M. W. Liddament. 2000. “Duct Leakage in European Buildings: Status and Perspectives.” *Energy and Buildings* 32, 3: 235–43. doi:10.1016/S0378-7788(00)00049-9.

Erinjeri, J. J., N. M. Witriol, and M. Katz. 2009. “Measurement of Return Leaks in Residential Buildings in North Louisiana.” *Journal of Building Physics* 32, 3: 261–80. doi:10.1177/1744259108093094.

Fisk, W. J., D. Faulkner, and D. P. Sullivan. 2005. “An Evaluation of Three Commercially Available Technologies for Real-Time Measurement of Rates of Outdoor Airflow into HVAC Systems.” *ASHRAE Transactions* 111, 2: 443–55.

Francisco, P. W., and L. Palmiter. 2007. “Thermal Characterization and Duct Losses of Belly Spaces in Manufactured Homes.” *ASHRAE Transactions* 113, 2: 81–89.

Francisco, P. W., L. Palmiter, and B. Davis. 2003.“Insights into Improved Ways to Measure Residential Duct Leakage.” *ASHRAE 2003 Winter Meeting CD*, Chicago, IL. 479–89.

Francisco, P.W., L. Palmiter, E. Kruse, B. Davis, and I. S. Walker. 2004. “Evaluation of Two New Duct Leakage Measurement Methods in 51 Homes.” *ASHRAE Transactions* 110 PART II: 727–40.

Hales, D., A. Gordon, and M. Lubliner. 2003. “Duct Leakage in New Washington State Residences: Findings and Conclusions.” *ASHRAE Transactions* 109 PART 2: 393–402.

Hun, D., M. Jackson, and S. Shrestha. 2013. *Optimization of Ventilation Energy Demands and Indoor Air Quality in the ZEBRAlliance Homes*. Oak Ridge National Laboratory report ORNL/TM-2013/275. Oak Ridge, TN.

Lindgren, S. 1984. “Sealing Ventilation Ducts.” *Batiment International, Building Research & Practice* 17, 3 (1984): 174–77.

Lstiburek, J. 2014. *Measure Guideline: Guide to Attic Air Sealing*. National Renewable Energy Laboratory. DOE/GO-102014-4484. Golden, CO.

Martin, E., B. Amos, J. McIlvaine, D. Chasar, S. Widder, and K. Fonorow. 2014. "Measured Cooling Season Results Relating the Impact of Mechanical Ventilation on Energy, Comfort, and Indoor Air Quality in Humid Climates." *Proceedings of the 2014 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA.

Nabinger, S., and A. Persily. 2011. "Impacts of Airtightening Retrofits on Ventilation Rates and Energy Consumption in a Manufactured Home." *Energy and Buildings* 43, 11: 3059–67. doi:10.1016/j.enbuild.2011.07.027.

Puttagunta, S., and O. Faakye. 2014. *Taking the Challenge at Singer Village: A Cold Climate Zero Energy Ready Home*. U.S. Department of Energy. DOE/GO-102014-45216935.

Rudd, A., A. Townsend, B. Hendron, R. Anderson, D. Barley, and E. Hancock. 2007. "Field Test of Room-to-Room Distribution of Outside Air with Two Residential Ventilation Systems." *Proceedings of the 2007 IAQ Conference*, Baltimore, MD.

Sherman, M., and I. Walker. 2012. *Philosophy and approaches for airtightness requirements in the USA*. Lawrence Berkeley National Laboratory. LBNL-5713E. Berkeley, CA.

State of California. 2001. *Prioritization of Toxic Air Contaminants - Children's Environmental Health Protection Act*., Formaldehyde. https://oehha.ca.gov/air/report/document-available-prioritization-toxic-air-contaminants-childrens-environmental-health

Stratton, J., and B. Singer. 2014. *Addressing Kitchen Contaminants for Healthy, Low-Energy Homes*. Lawrence Berkeley National Laboratory. LBNL-6547E. Berkeley, CA.

U.S. EPA. 2009. "Duct Sealing." EPA 430-F-09-050. Brochure accessed online at https://www.energystar.gov/ia/products/heat_cool/ducts/DuctSealingBrochure04.pdf?9d1f-8c89

U.S. EPA. 2015. "Methodology for Estimated Energy Savings from Cost-Effective Air Sealing and Insulating." Webpage accessed at https://www.energystar.gov/saveathome/seal_insulate/methodology

Walker, I., M. Modera, A. Tuluca, and I. Graham. 1996. "Energy effectiveness of duct sealing and insulation in two multifamily buildings." *Proceedings of the ACEEE Summer Study 1996*.

Appendix A. Expert and Practitioner Meeting Contributors

Table A-1. Expert Meeting Attendees

Name	Organization
Eric Werling	DOE
Brett Singer	Lawrence Berkeley National Laboratory
Rick Chitwood	Chitwood Energy Management
Dan Cautley	Seventhwave
Jonathan Wilson	National Center for Healthy Housing
Dick Kornbluth	Dick Kornbluth, LLC
Dave Jacobs	National Center for Healthy Housing
Dave Bohac	MN Center for Energy and Environment
Larry Brand	GTI
Paul Francisco	ISTC
Bill Rose	ISTC
Will Baker	MEEA
Mark Milby	MEEA

Table A-2. Practitioner Workshop Attendees

Name	Organization	Organization Type
Kevin Johnston	AAA Northgate	Local contractor
Ron Markus	BCMW	Community action agency
Joe Konopacki	Insight Property Services	Local contractor
Stacey Rothgeb	NREL	Project supervisor
Rob Schildgen	Priority Energy	Local contractor
Brian Kumer	Thermal Imaging Services	Local contractor
Bob Junius	DCEO	State weatherization agency
Jeremy O'Brien	BPI	Trainer
Amy Destache	CLEAResult	Utility program implementer
Larry Brand	GTI	PARR team member
Paul Francisco	ISTC	PARR team member
Bill Rose	ISTC	PARR team member
Will Baker	MEEA	PARR team member
Mark Milby	MEEA	PARR team member
Kelsey Horton	MEEA	PARR team member

Appendix B. Equipment Table

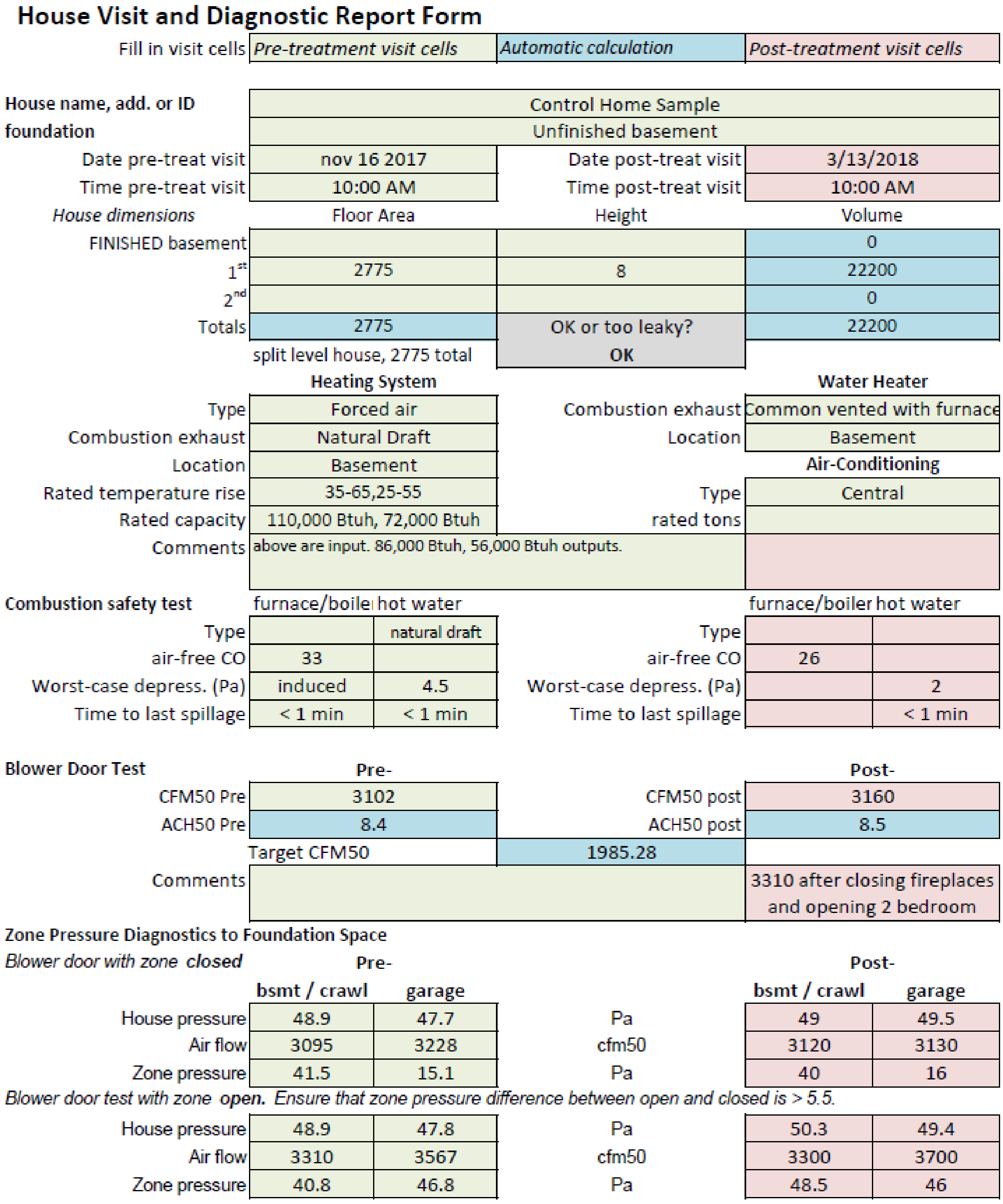
Contaminant Measurement	**Equipment Needed**	**Sample Interval**	**Information**
CO_2	Telaire 7001 monitor	continuous	Central location. ±50 ppm accuracy
	HOBO logger Onset CTV-A	1 hour interval	Long term. ± 4.5% accuracy
HCHO	Passive badges	1 week integrated	Short term. Central location. ± 25% accuracy
Radon	Passive electrets Radelec E, S chamber	1 week integrated	Short Term. Central location plus basement. ±1.4 pCi/L accuracy
Humidity	HOBO logger UX100-011	1 hour interval	Long term. Central location plus basement. ±0.38°F accuracy
$PM_{2.5}$	TSI DustTrak 8530		Where used, long term. ± 5% accuracy
Energy Measurement	**Equipment Needed**	**Measurement Type**	**Other**
Fan state (Ventilation, HVAC)	Onset UXX90-001	state	±1 Minute per Month
Furnace consumption	Onset CTV-A	Time-of-use	± 4.5% accuracy
Air handler run time	Onset CTV-A	Time-of-use	± 4.5% accuracy
Plenum temperature	Onset TMC6-HE	Continuous	±0.25° @ 20°C (±0.45° @ 68°F)
Plenum temperature	Omega TT-K-40-25	Continuous	Wiring for thermocouples
Airflow Measurement	**Equipment Needed**	**Status**	**Other**
Infiltration	Blower door		Includes zone pressure measurement. 0.9% of pressure reading or 0.12 Pa accuracy
Mechanical ventilation	Exhaust fan flow meter	Primary	±10% accuracy
	Duct blaster	If needed	±3% accuracy
Duct leakage	Duct blaster	Primary	±3% accuracy
	Delta-Q	If needed	
Forced-air system flow rate	Duct blaster	Primary	±3% accuracy
	TrueFlow	If needed	+/- 5% accuracy

Appendix C. Phase 1 Data Collection Sequence and Site Visit Data Collection Form

Phase 1 data collection procedure:

1. Collect general information about the test site. After the homeowner of the test site signed the participant agreement, the research team would visit the test site and have a visual inspection to determine whether the test home was appropriate for the study. If yes, all the general information obtained was recorded on a data collection form, which was prepared in advance (see below).
2. Conduct the blower door and zone pressure diagnostic tests. Record the test results on the data collection form.
3. Measure the air handler flow rates and conduct the duct leakage tests. Record the results on the data collection form.
4. Conduct combustion safety tests.
5. Measure the flow rates of all the exhaust fans.
6. Deploy the radon electrets and the formaldehyde badge. Fill the Chain of Custody form for the formaldehyde sampler, and the electret deployment form.
7. Install all the remaining monitoring instruments, which included temperature/relative humidity data loggers, CO_2 sensor, state sensors for exhaust fans, furnace blower-fan, furnace gas valve (in heating season), and/or a current sensor for the air conditioner (in cooling season). The data loggers used were launched in advance before the research team left the lab for the test site.
8. Place reminder signs on the outside surfaces of each exhaust fan, furnace, and/or air conditioner.
9. Instruct the residents to keep windows closed throughout testing periods. Clean up and make an appointment with the homeowner for the research team's next visit.
10. Collect the radon electrets and formaldehyde sampler after one week of their deployment. Complete the electret deployment form and the Chain of Custody form for the formaldehyde sampler. Ship out the sealed formaldehyde sampler to the SGS lab in New York for analysis. Read the electrets and calculate the radon levels in lab.
11. A contractor would start the retrofit work for the home after at least 3 weeks of the instrument deployment.
12. Repeat (2)–(10) except (8) after the retrofit was completed.
13. Collect all the remaining instruments at least three weeks after the retrofit was completed. Download the data from each data logger to a computer for processing.
14. Following the visit, process the raw data and generate a report for the homeowner.

A sample data collection form from a Control home in Phase 1 is shown below.



House Visit and Diagnostic Report Form

Fill in visit cells	*Pre-treatment visit cells*	*Automatic calculation*	*Post-treatment visit cells*

House name, add. or ID	Control Home Sample		
foundation	Unfinished basement		
Date pre-treat visit	nov 16 2017	Date post-treat visit	3/13/2018
Time pre-treat visit	10:00 AM	Time post-treat visit	10:00 AM
House dimensions	Floor Area	Height	Volume
FINISHED basement			0
1st	2775	8	22200
2nd			0
Totals	2775	OK or too leaky?	22200
	split level house, 2775 total	**OK**	
	Heating System		**Water Heater**
Type	Forced air	Combustion exhaust	Common vented with furnace
Combustion exhaust	Natural Draft	Location	Basement
Location	Basement		**Air-Conditioning**
Rated temperature rise	35-65,25-55	Type	Central
Rated capacity	110,000 Btuh, 72,000 Btuh	rated tons	
Comments	above are input. 86,000 Btuh, 56,000 Btuh outputs.		

Combustion safety test	furnace/boile	hot water		furnace/boiler	hot water
Type		natural draft	Type		
air-free CO	33		air-free CO	26	
Worst-case depress. (Pa)	induced	4.5	Worst-case depress. (Pa)		2
Time to last spillage	< 1 min	< 1 min	Time to last spillage		< 1 min

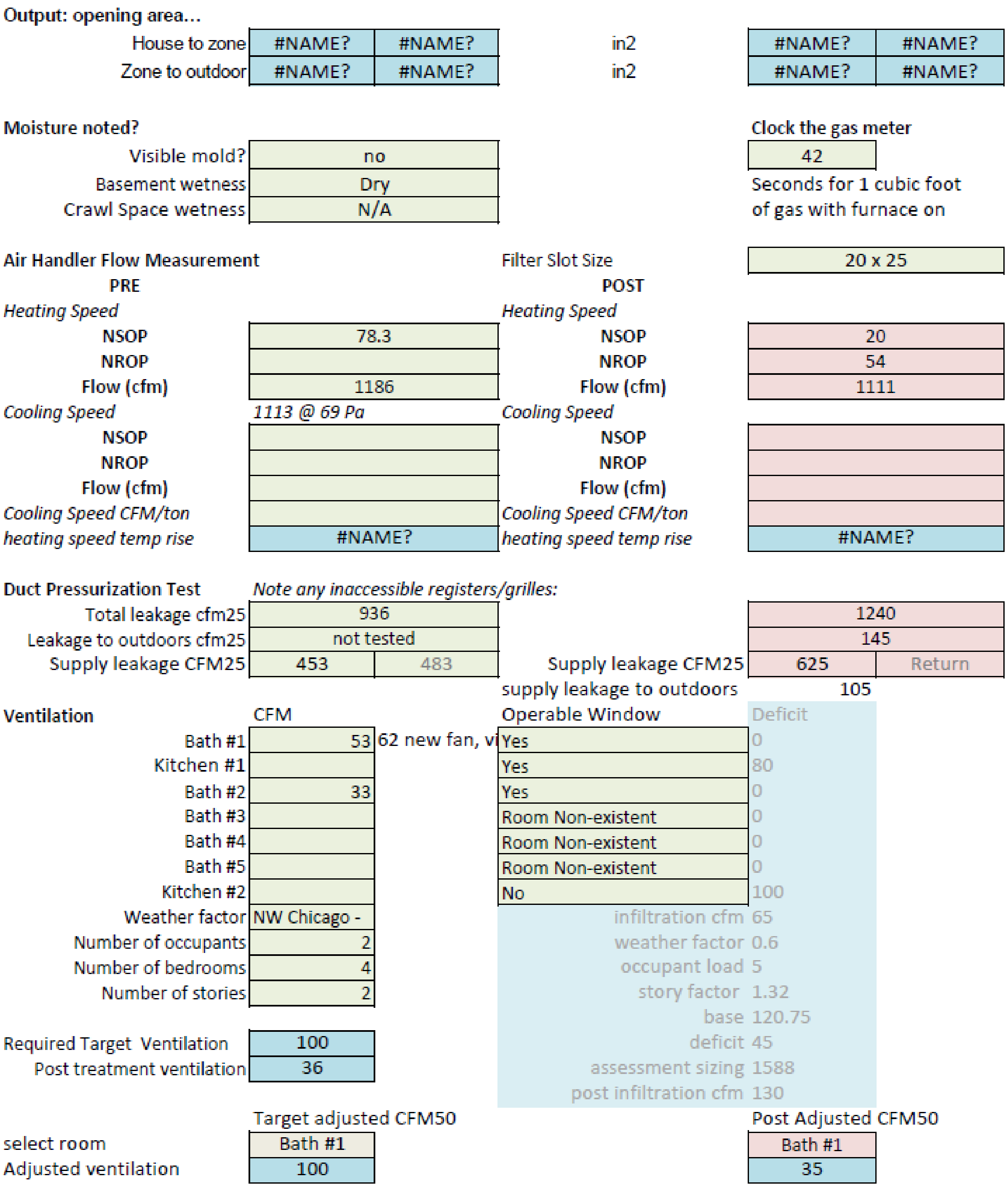
Blower Door Test	**Pre-**		**Post-**
CFM50 Pre	3102	CFM50 post	3160
ACH50 Pre	8.4	ACH50 post	8.5
	Target CFM50	1985.28	
Comments			3310 after closing fireplaces and opening 2 bedroom

Zone Pressure Diagnostics to Foundation Space

Blower door with zone ***closed***	**Pre-**			**Post-**	
	bsmt / crawl	**garage**		**bsmt / crawl**	**garage**
House pressure	48.9	47.7	Pa	49	49.5
Air flow	3095	3228	cfm50	3120	3130
Zone pressure	41.5	15.1	Pa	40	16

Blower door test with zone ***open.*** *Ensure that zone pressure difference between open and closed is > 5.5.*

House pressure	48.9	47.8	Pa	50.3	49.4
Air flow	3310	3567	cfm50	3300	3700
Zone pressure	40.8	46.8	Pa	48.5	46



Output: opening area...

House to zone	#NAME?	#NAME?	in2	#NAME?	#NAME?
Zone to outdoor	#NAME?	#NAME?	in2	#NAME?	#NAME?

Moisture noted?		**Clock the gas meter**
Visible mold?	no	42
Basement wetness	Dry	Seconds for 1 cubic foot
Crawl Space wetness	N/A	of gas with furnace on

Air Handler Flow Measurement		Filter Slot Size	20 x 25
PRE		**POST**	
Heating Speed		*Heating Speed*	
NSOP	78.3	**NSOP**	20
NROP		**NROP**	54
Flow (cfm)	1186	**Flow (cfm)**	1111
Cooling Speed	*1113 @ 69 Pa*	*Cooling Speed*	
NSOP		**NSOP**	
NROP		**NROP**	
Flow (cfm)		**Flow (cfm)**	
Cooling Speed CFM/ton		*Cooling Speed CFM/ton*	
heating speed temp rise	#NAME?	*heating speed temp rise*	#NAME?

Duct Pressurization Test	*Note any inaccessible registers/grilles:*				
Total leakage cfm25	936			1240	
Leakage to outdoors cfm25	not tested			145	
Supply leakage CFM25	453	483	Supply leakage CFM25	625	Return
			supply leakage to outdoors	105	

Ventilation	CFM		Operable Window	Deficit
Bath #1	53	62 new fan, vi	Yes	0
Kitchen #1			Yes	80
Bath #2	33		Yes	0
Bath #3			Room Non-existent	0
Bath #4			Room Non-existent	0
Bath #5			Room Non-existent	0
Kitchen #2			No	100
Weather factor	NW Chicago -		infiltration cfm	65
Number of occupants	2		weather factor	0.6
Number of bedrooms	4		occupant load	5
Number of stories	2		story factor	1.32
			base	120.75
Required Target Ventilation	100		deficit	45
Post treatment ventilation	36		assessment sizing	1588
			post infiltration cfm	130

	Target adjusted CFM50	Post Adjusted CFM50
select room	Bath #1	Bath #1
Adjusted ventilation	100	35

Instrumentation All serial numbers are serial numbers of the loggers (not equipment)

Living space	Serial Number		Serial Number
T/RH	20028457	*stays in place to end of measurement period*	
CO2	MicroDAQ	*stays in place to end of measurement period*	
Particulates		*Not all homes receive particulate counters*	

State logger *Install state loggers on exhaust devices where feasible*

bath fan		dryer	
20061833	serial no. of logger	20045084	serial no. of logger
20061871			

Furnace		
Gas valve logger SN#	20061884	*stays in place to end of measurement period*
Blower fan logger SN#	20061872	

Foundation	T/RH sensor placed in basement or crawl space	
T/RH	20028451	*stays in place to end of measurement period*

Formaldehyde sensors in living space only

Radon samplers in living space and basement

Formaldehyde and radon samplers require exact date and time (nearest hour) for placement and retrieval.

Living space	Pre-intervention		Post-intervention
Date/time of placement	11/16/2017 10:42	Date/time of placement	
Formaldehyde	AS230252	Formaldehyde	
Radon sampler	SHK 482, 323	Radon sampler	
Date/time of retrieval		Date/time of retrieval	

Basement/crawl space

Radon samplers require exact date and time (nearest hour) for placement and retrieval.

Date/time of placement	11/16/2017 10:42	
Radon sampler	SHK 196,199	
Date/time of retrieval		

If additional formaldehyde and radon samplers are used

Date/time of placement		Date/time of placement	
Formaldehyde		Formaldehyde	
Radon sampler		Radon sampler	
Location		Location	
Date/time of retrieval		Date/time of retrieval	

Date/time of placement		Date/time of placement	
Formaldehyde		Formaldehyde	
Radon sampler		Radon sampler	
Location		Location	
Date/time of retrieval		Date/time of retrieval	

Appendix D. Phase 2 Data Collection Sequence

1. Collect general information about the test site. After the homeowner of the test site signed the participant agreement, the research team would visit the test site and have a visual inspection to determine whether the test home was appropriate for the study or not. If yes, all the general information obtained was recorded on a data collection form.
2. Perform a blower door test and record the resulting CFM50 on the data collection form. Measure the flow rates of all the bathroom exhaust fans and the kitchen range hood (if there was one) and collect all other ventilation information. Then input all the collected data into a spreadsheet on a laptop computer to calculate the required ventilation according to ASHRAE Standard 62.2. If the required ventilation was equal to or greater than 30 cfm, then the home was eligible for the study. Otherwise, the home was ineligible, and the test would not proceed for the home.
3. Install all the monitoring instruments, which included temperature/RH data loggers and radon sensors in the living room and in the basement (if there was a basement), CO_2 sensor (in the living room), and $PM_{2.5}$ sensors (in the living room and outside). The data loggers used were launched in advance before the research team left the lab for the test site.
4. Deploy the formaldehyde sampler and fill its ID# and open time on the Chain of Custody form. **The As-is Ventilation Test Week started.**
5. Instruct the residents to keep windows closed throughout all the testing periods and use the ventilation devices, such as bathroom fans and kitchen range hood, as they were normally used. Make an appointment with the homeowner for the research team’s next visit on the same day of the next week.
6. Collect the formaldehyde sampler after the one week As-is Ventilation Test. **The As-is Ventilation Test Week completed.** Fill the close time of the formaldehyde sampler on the Chain of Custody form. Put the sampler in its silver bag and then place the bag in a freezer.
7. Turn on one or more bathroom exhaust fan(s) to make the total exhaust flow rate equal to or very close to the required ventilation obtained in Step (2). Tape the fan’s switch(es) with blue tape to prevent someone from switching off the fan(s) accidentally.
8. Deploy a new formaldehyde sampler and fill its ID# and open time on the Chain of Custody form. **The Exhaust-Only Ventilation Test Week started.** Make an appointment with the homeowner for the research team’s next visit on the same day of the next week.
9. A contractor would install an AirCycler supply system in the home during the first two weeks. The ventilation flowrate of the supply system was measured with Nailor 36FMSD Flow Measuring Stations and/or an ACIN FlowFinder. The AirCycler running time was set to 0 right after the installation was completed.

10. Collect the second formaldehyde sampler after the one week Exhaust-Only Ventilation Test. **The Exhaust-Only Ventilation Test Week completed.** Fill the close time of the formaldehyde sampler on the Chain of Custody form. Put the sampler in its silver bag and then place the bag in a freezer.
11. Remove the blue tape on the bathroom exhaust fan's switch(es) and turn the fan(s) off.
12. Set the running time of the AirCycler system, Ts, to:

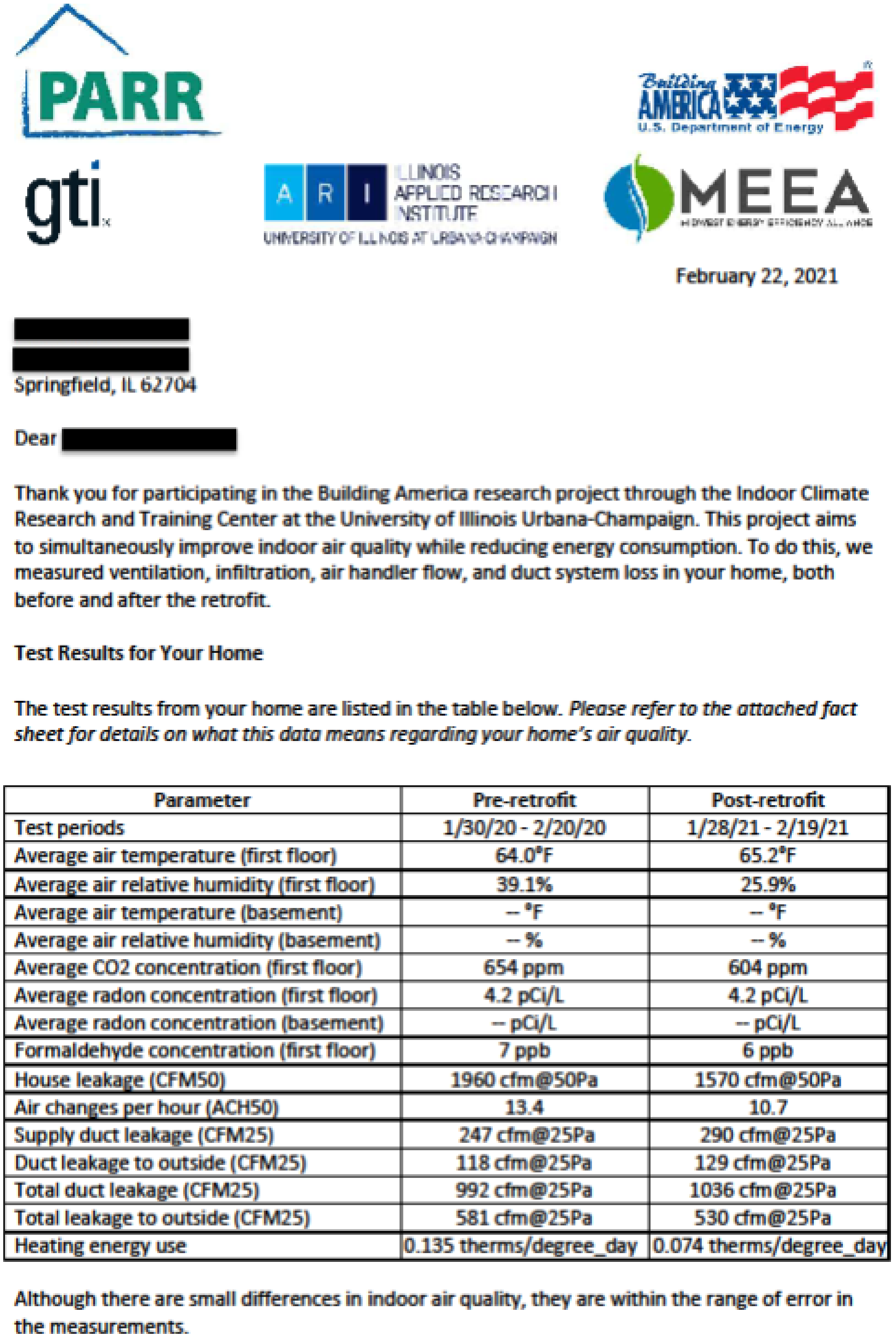
Equation 2. AirCycler system run-time

$$T_s = \frac{Q_r}{Q_s} \times 60$$

where Qr is the required ventilation determined in Step 2, and Qs is the actual flowrate of the AirCycler supply system measured in Step 9. Ts is the running time in minutes per hour set for the AirCycler supply. If the calculated Ts was greater than 60, then let Ts equal 60 minutes/hour.

13. Deploy a new formaldehyde sampler and fill its ID# and open time on the Chain of Custody form. **The Supply-Only Ventilation Test Week started.** Make an appointment with the homeowner for the research team's next visit on the same day of the next week.
14. Collect the third formaldehyde sampler after the one week Supply-Only Ventilation Test. **The Supply-Only Ventilation Test Week completed.** Fill the close time of the formaldehyde sampler on the Chain of Custody form. Put the sampler in its silver bag.
15. Collect all monitor instruments. Set the AirCycler running time as the homeowner wished.
16. Take out the two formaldehyde samplers out of the storage freezer. Ship all the three sealed formaldehyde samplers overnight to the SGS lab in New York for analysis.
17. Download the data from each data logger to a computer for processing.
18. Process the raw data and generate a report for the homeowner.

Appendix E. Representative Phase 1 Homeowner Report



February 22, 2021

[redacted]
Springfield, IL 62704

Dear [redacted]

Thank you for participating in the Building America research project through the Indoor Climate Research and Training Center at the University of Illinois Urbana-Champaign. This project aims to simultaneously improve indoor air quality while reducing energy consumption. To do this, we measured ventilation, infiltration, air handler flow, and duct system loss in your home, both before and after the retrofit.

Test Results for Your Home

The test results from your home are listed in the table below. *Please refer to the attached fact sheet for details on what this data means regarding your home's air quality.*

Parameter	Pre-retrofit	Post-retrofit
Test periods	1/30/20 - 2/20/20	1/28/21 - 2/19/21
Average air temperature (first floor)	64.0°F	65.2°F
Average air relative humidity (first floor)	39.1%	25.9%
Average air temperature (basement)	-- °F	-- °F
Average air relative humidity (basement)	-- %	-- %
Average CO2 concentration (first floor)	654 ppm	604 ppm
Average radon concentration (first floor)	4.2 pCi/L	4.2 pCi/L
Average radon concentration (basement)	-- pCi/L	-- pCi/L
Formaldehyde concentration (first floor)	7 ppb	6 ppb
House leakage (CFM50)	1960 cfm@50Pa	1570 cfm@50Pa
Air changes per hour (ACH50)	13.4	10.7
Supply duct leakage (CFM25)	247 cfm@25Pa	290 cfm@25Pa
Duct leakage to outside (CFM25)	118 cfm@25Pa	129 cfm@25Pa
Total duct leakage (CFM25)	992 cfm@25Pa	1036 cfm@25Pa
Total leakage to outside (CFM25)	581 cfm@25Pa	530 cfm@25Pa
Heating energy use	0.135 therms/degree_day	0.074 therms/degree_day

Although there are small differences in indoor air quality, they are within the range of error in the measurements.

Figure 1. Indoor and outdoor temperatures

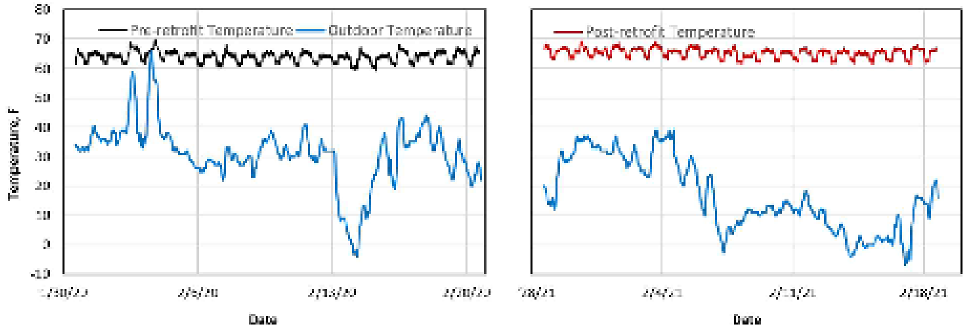


Figure 1 shows the air temperature inside your home compared to the outdoor air temperature from a nearby weather station.

Figure 2. Carbon dioxide levels before and after retrofit

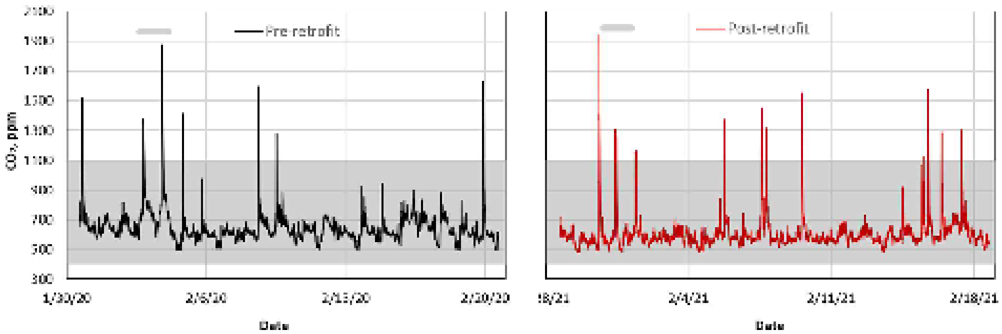


Figure 2 shows the carbon dioxide (CO_2) concentration in the living room of your home before and after the retrofit. Typical CO_2 concentrations in adequately ventilated occupied spaces is in the range of 400 to 1,100 ppm, as indicted with the shadow area. Short-term peaks can be common during periods with high occupancy or activities such as cooking or exercising. Elevated CO2 concentrations at these levels are not known to be a health risk. Your home showed moderate levels of CO2 both before and after intervention.

Figure 3. Average carbon dioxide concentration at different times of day

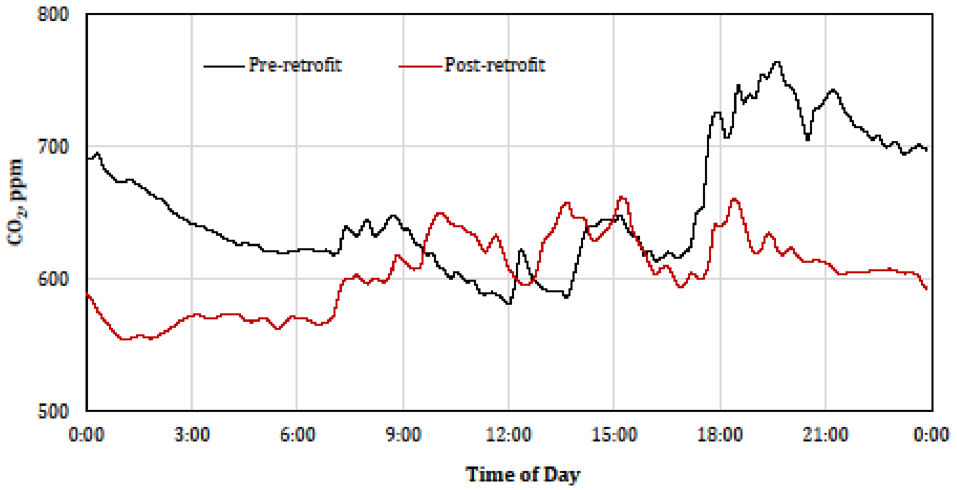


Figure 3 shows how the CO_2 concentrations in your home varied by time of day, before and after the retrofit. Post-retrofit, the CO2 levels were lower during nighttime, which indicates your home has a better ventilation with the newly installed bathroom exhaust fan even though your home became tighter from the retrofit.

This study was administered in partnership with the Gas Technology Institute and the Midwest Energy Efficiency Alliance and funded by the U.S. Department of Energy.

We are very grateful and would like to thank you again for your participation in this study. The data gathered through this study will help us visualize the linkage between residential building air quality and health to find ways to retrofit homes that reduce illness rates. Please contact Molly Graham at mgraham@mwalliance.org if you have questions or would like any additional information.

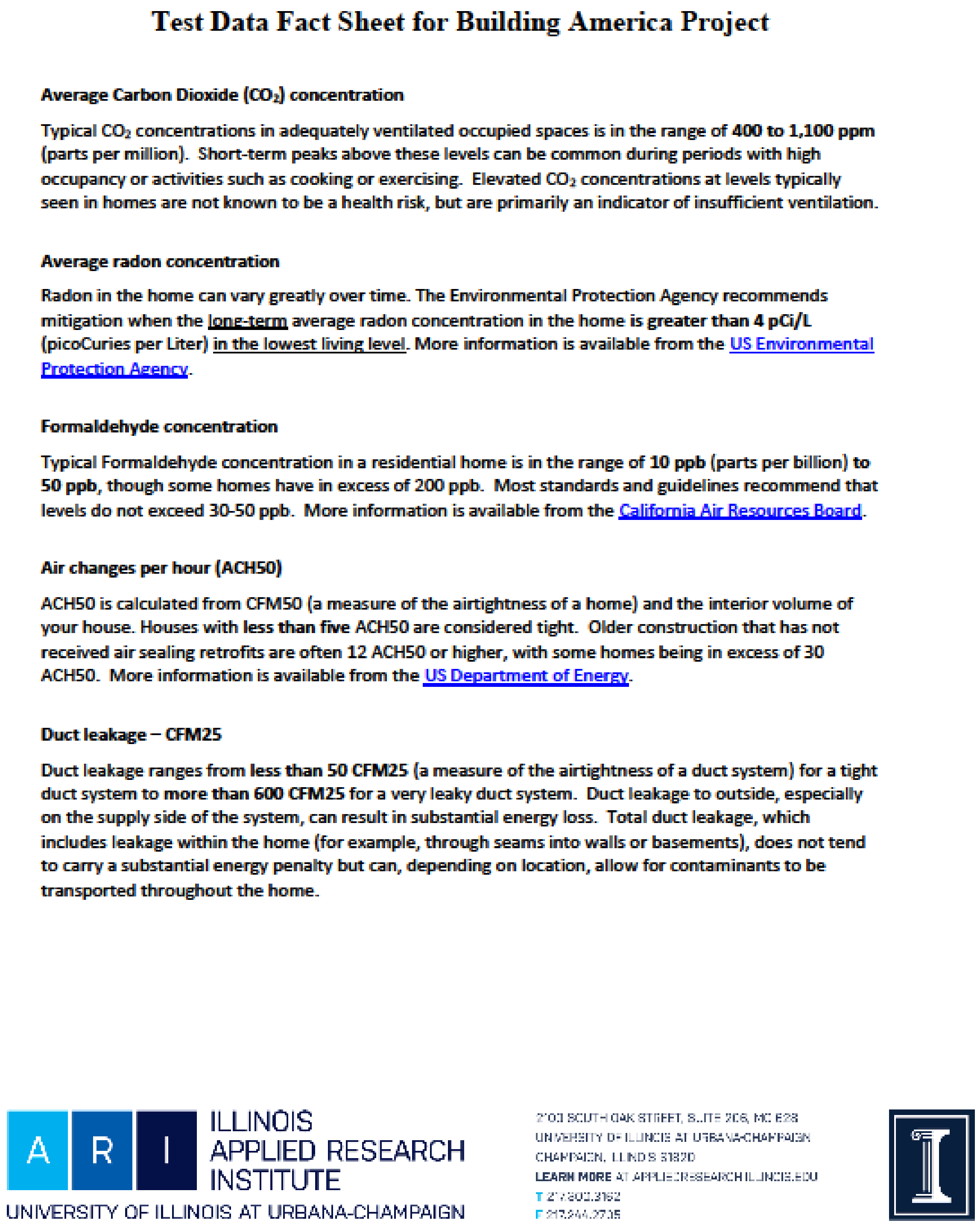
Sincerely,

[redacted]

Paul Francisco, Indoor Climate Research and Training

A R I
ILLINOIS
APPLIED RESEARCH
INSTITUTE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2100 SOUTH OAK STREET, SUITE 206, MC 629
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
CHAMPAIGN, ILLINOIS 61820
LEARN MORE AT APPLIEDRESEARCH.ILLINOIS.EDU
T 217.300.0162
F 217.244.2706



Test Data Fact Sheet for Building America Project

Average Carbon Dioxide (CO_2) concentration

Typical CO_2 concentrations in adequately ventilated occupied spaces is in the range of **400 to 1,100 ppm** (parts per million). Short-term peaks above these levels can be common during periods with high occupancy or activities such as cooking or exercising. Elevated CO_2 concentrations at levels typically seen in homes are not known to be a health risk, but are primarily an indicator of insufficient ventilation.

Average radon concentration

Radon in the home can vary greatly over time. The Environmental Protection Agency recommends mitigation when the long-term average radon concentration in the home **is greater than 4 pCi/L** (picoCuries per Liter) in the lowest living level. More information is available from the US Environmental Protection Agency.

Formaldehyde concentration

Typical Formaldehyde concentration in a residential home is in the range of **10 ppb** (parts per billion) to **50 ppb**, though some homes have in excess of 200 ppb. Most standards and guidelines recommend that levels do not exceed 30-50 ppb. More information is available from the California Air Resources Board.

Air changes per hour (ACH50)

ACH50 is calculated from CFM50 (a measure of the airtightness of a home) and the interior volume of your house. Houses with **less than five** ACH50 are considered tight. Older construction that has not received air sealing retrofits are often 12 ACH50 or higher, with some homes being in excess of 30 ACH50. More information is available from the US Department of Energy.

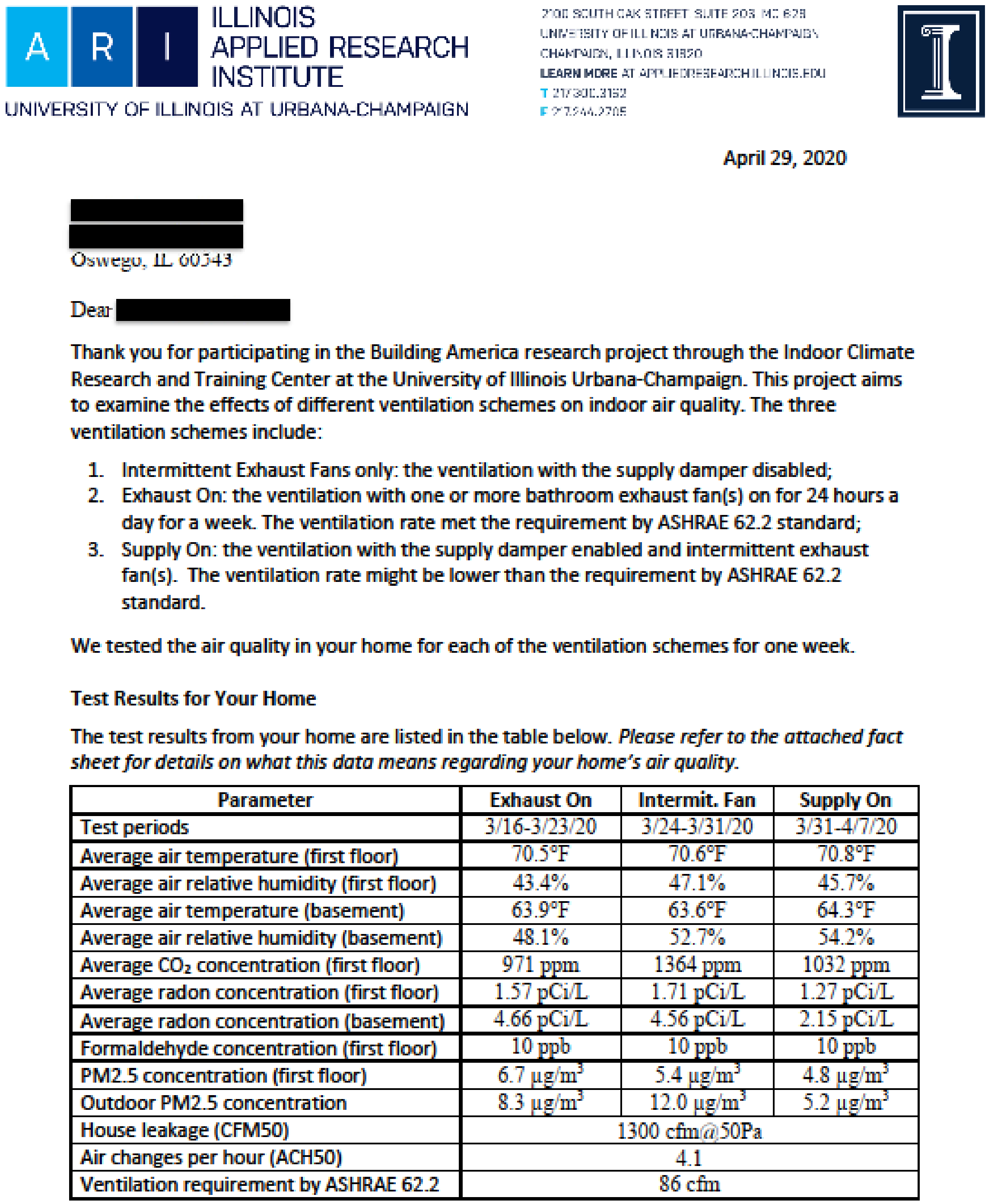
Duct leakage – CFM25

Duct leakage ranges from **less than 50 CFM25** (a measure of the airtightness of a duct system) for a tight duct system to **more than 600 CFM25** for a very leaky duct system. Duct leakage to outside, especially on the supply side of the system, can result in substantial energy loss. Total duct leakage, which includes leakage within the home (for example, through seams into walls or basements), does not tend to carry a substantial energy penalty but can, depending on location, allow for contaminants to be transported throughout the home.

ILLINOIS
APPLIED RESEARCH
INSTITUTE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2100 SOUTH OAK STREET, SUITE 206, MC 628
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
CHAMPAIGN, ILLINOIS 61820
LEARN MORE AT APPLIEDRESEARCH.ILLINOIS.EDU
T 217.300.3162
F 217.244.2705

Appendix F. Representative Phase 2 Homeowner Report



A R I ILLINOIS
APPLIED RESEARCH
INSTITUTE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2100 SOUTH OAK STREET, SUITE 203, MC 629
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
CHAMPAIGN, ILLINOIS 61820
LEARN MORE AT APPLIEDRESEARCH.ILLINOIS.EDU
T 217.300.3152
F 217.244.2705

April 29, 2020

[redacted]
Oswego, IL 60543

Dear [redacted]

Thank you for participating in the Building America research project through the Indoor Climate Research and Training Center at the University of Illinois Urbana-Champaign. This project aims to examine the effects of different ventilation schemes on indoor air quality. The three ventilation schemes include:

1. Intermittent Exhaust Fans only: the ventilation with the supply damper disabled;
2. Exhaust On: the ventilation with one or more bathroom exhaust fan(s) on for 24 hours a day for a week. The ventilation rate met the requirement by ASHRAE 62.2 standard;
3. Supply On: the ventilation with the supply damper enabled and intermittent exhaust fan(s). The ventilation rate might be lower than the requirement by ASHRAE 62.2 standard.

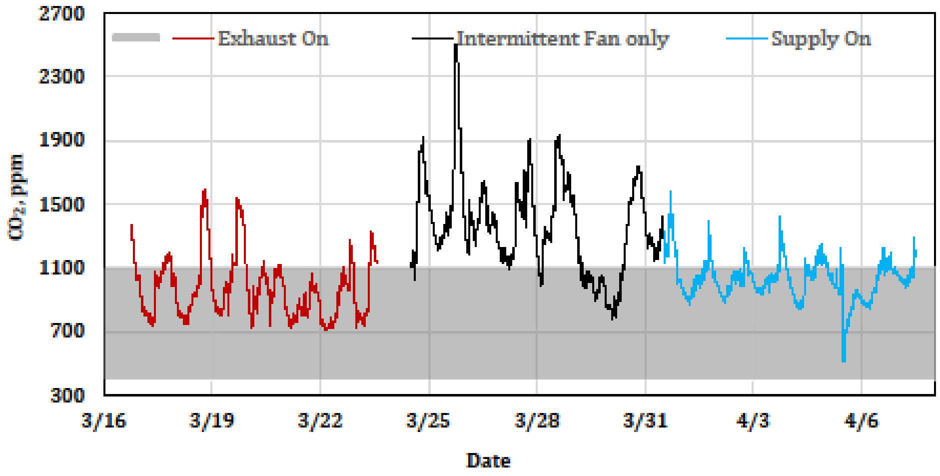
We tested the air quality in your home for each of the ventilation schemes for one week.

Test Results for Your Home

The test results from your home are listed in the table below. *Please refer to the attached fact sheet for details on what this data means regarding your home's air quality.*

Parameter	Exhaust On	Intermit. Fan	Supply On
Test periods	3/16-3/23/20	3/24-3/31/20	3/31-4/7/20
Average air temperature (first floor)	70.5°F	70.6°F	70.8°F
Average air relative humidity (first floor)	43.4%	47.1%	45.7%
Average air temperature (basement)	63.9°F	63.6°F	64.3°F
Average air relative humidity (basement)	48.1%	52.7%	54.2%
Average CO_2 concentration (first floor)	971 ppm	1364 ppm	1032 ppm
Average radon concentration (first floor)	1.57 pCi/L	1.71 pCi/L	1.27 pCi/L
Average radon concentration (basement)	4.66 pCi/L	4.56 pCi/L	2.15 pCi/L
Formaldehyde concentration (first floor)	10 ppb	10 ppb	10 ppb
PM2.5 concentration (first floor)	6.7 $\mu g/m^3$	5.4 $\mu g/m^3$	4.8 $\mu g/m^3$
Outdoor PM2.5 concentration	8.3 $\mu g/m^3$	12.0 $\mu g/m^3$	5.2 $\mu g/m^3$
House leakage (CFM50)	1300 cfm@50Pa		
Air changes per hour (ACH50)	4.1		
Ventilation requirement by ASHRAE 62.2	86 cfm		

The figure below shows the carbon dioxide (CO_2) concentration in the living room of your home during the whole three periods of the test study. Typical CO_2 concentrations in adequately ventilated occupied spaces is in the range of 400 to 1,100 ppm, as indicted with the shadow area in the figure. Elevated CO_2 concentrations above 1,100 ppm are not known to be a health risk but are an indicator of insufficient ventilation.



This study was administered in partnership with the Gas Technology Institute and the Midwest Energy Efficiency Alliance and funded by the U.S. Department of Energy.

We are very grateful and would like to thank you again for your participation in this study. The data gathered through this study will help us visualize the linkage between residential building air quality and health to find ways to ventilate homes that reduce illness rates. Please contact Kara Jonas at kjonas@mwalliance.org if you have questions or would like any additional information.

Sincerely,

[redacted]

Paul Francisco, Indoor Climate Research and Training

A R I ILLINOIS
APPLIED RESEARCH
INSTITUTE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2100 SOUTH OAK STREET, SUITE 203, MC 628
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
CHAMPAIGN, ILLINOIS 61820
LEARN MORE AT APPLIEDRESEARCH.ILLINOIS.EDU
T 217.300.3132
F 217.244.2705

Test Data Fact Sheet for Building America Project

Average Carbon Dioxide (CO_2) concentration

Typical CO_2 concentrations in adequately ventilated occupied spaces is in the range of **400 to 1,100 ppm** (parts per million). Short-term peaks above these levels can be common during periods with high occupancy or activities such as cooking or exercising. Elevated CO_2 concentrations at levels typically seen in homes are not known to be a health risk, but are primarily an indicator of insufficient ventilation.

Average radon concentration

Radon in the home can vary greatly over time. The Environmental Protection Agency recommends mitigation when the long-term average radon concentration in the home **is greater than 4 pCi/L** (picoCuries per Liter) in the lowest living level. More information is available from the US Environmental Protection Agency.

Formaldehyde concentration

Typical Formaldehyde concentration in a residential home is in the range of **10 ppb** (parts per billion) to **50 ppb**, though some homes have in excess of 200 ppb. Most standards and guidelines recommend that levels do not exceed 30-50 ppb. More information is available from the California Air Resources Board.

PM2.5

PM2.5 is airborne particulate matter with less than 2.5 microns in diameter. Typical PM2.5 concentration in a residential home is in the range of **2 to 20 μg/m³**, though sometimes PM2.5 concentrations in a home could elevate to over 40 μg/m³ when there are some indoor activities such as smoking tobacco, cooking and burning wood, candles or incense. More information is available from the California Air Resources Board.

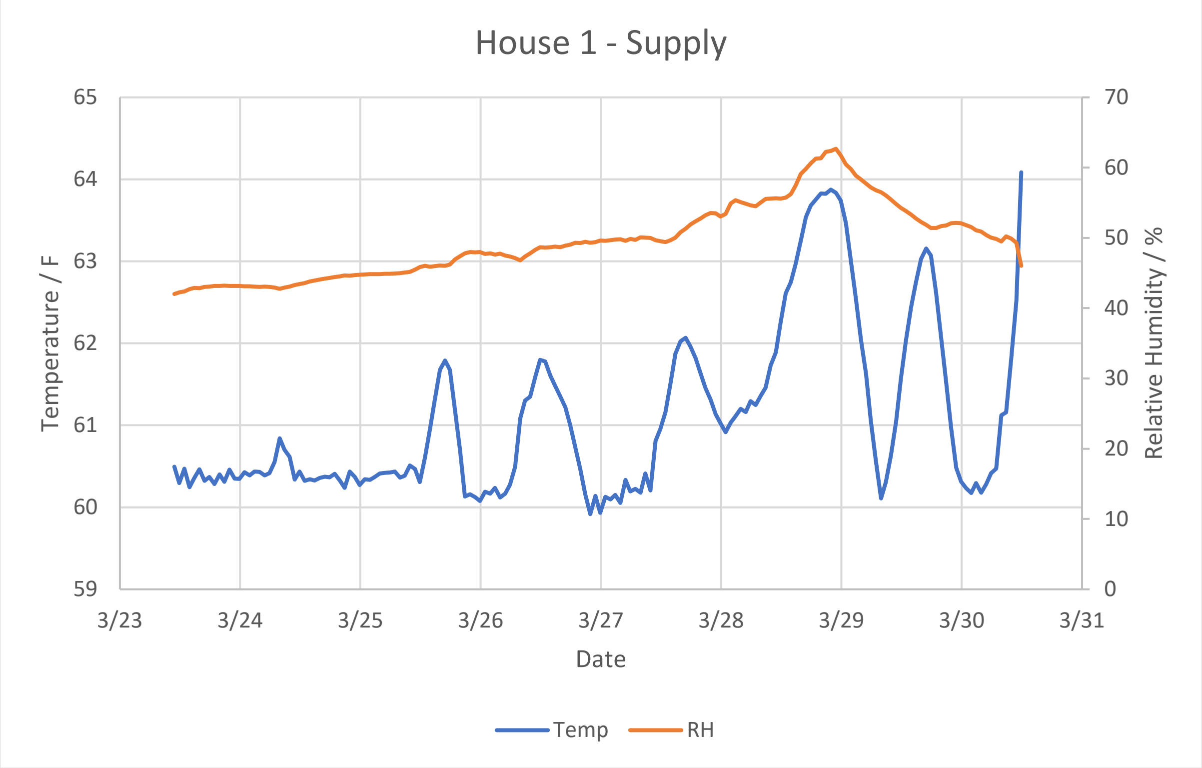
Air changes per hour (ACH50)

ACH50 is calculated from CFM50 (a measure of the airtightness of a home) and the interior volume of your house. Houses with **less than five** ACH50 are considered tight. Older construction that has not received air sealing retrofits are often 12 ACH50 or higher, with some homes being in excess of 30 ACH50. More information is available from the US Department of Energy.

A R I ILLINOIS
APPLIED RESEARCH
INSTITUTE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2100 SOUTH OAK STREET, SUITE 206, MC 629
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
CHAMPAIGN, ILLINOIS 61820
LEARN MORE AT APPLIEDRESEARCH.ILLINOIS.EDU
T 217.300.0162
F 217.244.2705

Appendix G. Phase 2: House 1 Case Study



House 1 was used as a second “weekend” home by a family of four. It appears to have remained unoccupied throughout the period in which supply ventilation was provided. The house has a downflow furnace. The house is on a crawl space, and crawl space observations showed water entry. With a strong water source such as a crawl space, higher outdoor temperatures lead to higher absolute humidity (higher vapor pressure) in the crawl. There is at least one supply duct run, which is open to the crawl space—it could not be closed by taping the kick-space register.

The graph shows indoor temperature and RH during the supply vent test period. The temperature is maintained in the low 60s Fahrenheit. During periods when the temperature rose in the afternoon, the RH also showed an increase. This is an exceptional condition. In most buildings without occupancy, the indoor vapor pressure tends to remain constant, which leads to asymmetric readings of T and RH—as temperature goes up, RH goes down.

The data can be explained as follows. When the air handler is not operating, the leaks in the supply ductwork allow the air in that ductwork to take on the crawl space humidity. When the blower operates, that humidity is discharged into the house. Higher outdoor temperatures lead to higher vapor pressure in the crawl-connected supply air, which, at the low temperatures of indoor air, appears as higher RH.

An important takeaway from this case study is the importance of ensuring that supply ventilation air may not be humidified, whether by leaky ducts in wet crawl spaces, in this case, or by mechanical humidification. Disabling a furnace-mounted humidifier requires not only shutting off electrical power but also shutting off water, given that passive evaporation from a humidifier may be significant. Without this precaution, operation of supply ventilation can result in increasing the dampness of the home when ventilation occurs without a simultaneous call for space conditioning.

Building America

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit: buildingamerica.gov

DOE/GO-102023-5783 · June 2023