Literature Review: Energy Savings with Acceptable IAQ through Air Flow Control in Residential Retrofit

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Partnership for Advanced Residential Retrofit

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Literature Review:

Energy Savings with Acceptable IAQ through Air Flow Control in Residential Retrofit

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Definitions

BA	Building America
CFIS	Central fan integrated supply
DALY	Disability Adjusted Life Year
DNPH	Formaldehyde-2,4-dinitrophenylhydrazone
ERV	Energy recovery ventilator
HUD	U.S. Department of Housing and Urban Development
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PARR	Partnership for Advanced Residential Retrofit
PM	Particulate matter
SHS	Secondhand tobacco smoke
TVOC	Total volatile organic compounds
WAP	National Weatherization Assistance Program

Executive Summary

This report summarizes the findings of prior research relevant to the Building America project “Energy Savings with Acceptable IAQ through Air Flow Control in Residential Retrofit” and considers the potential impact of presented evidence on proposed study design. The project will attempt to demonstrate a methodology for reducing the energy required to maintain acceptable indoor air quality (IAQ) in existing residential homes using a systems approach to controlling various air streams. The Partnership for Advanced Residential Retrofit (PARR) will study approximately 20 treatment homes and 20 control homes over 24 months to evaluate the proposed approach.

There is a substantial base of literature on the energy and IAQ benefits of air sealing, but it is not as simple as more is better. By interfering with natural infiltration in specific areas, air sealing creates complex dynamics between air flows of a home that can benefit or not benefit occupants from an IAQ perspective. Air sealing and duct sealing may also be a contractor’s best tools for source control by limiting IAQ contaminants from undesirable places, such as garages and foundation areas; however, this interaction is complex, contaminant-specific, and dependent on multiple site variables.

From the perspective of energy savings, air sealing and insulation are often viewed as the most important components of any retrofit or low-energy construction strategy. However, even 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.

There is a more limited amount of literature comparing the IAQ impacts of different types of ventilation, especially in occupied or older homes, but enough research has been conducted on new homes to provide a solid foundation. In general, supply ventilation may reduce the entry of ground-source contaminants and exhaust ventilation may be preferred for occupant-generated contaminants. However, the optimal ventilation strategy may depend on the nature of the contaminants, the characteristics of the structure and its occupants, and geography.

Unsurprisingly, ventilation energy impacts are also situation-specific. As different ventilation strategies affect air flows 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 almost certainly necessary in most situations. Most research has shown minimal energy penalties associated with correctly designed and operated ventilation systems.

The current project will attempt to synthesize these findings into a whole-home approach to residential retrofit that balances and optimizes three air streams – ventilation, infiltration, and conditioning system flows – with the competing priorities of maximum energy savings, maximum IAQ, minimum cost, and maximum transferability to the retrofit marketplace.

1 Project Background

The goal of this Building America (BA) project is to reduce the ventilation energy used to assure acceptable indoor air quality (IAQ) in existing residential homes by using a systems approach to controlling the three contributing air streams: ventilation, infiltration, and conditioning system flows. The savings will be associated with ventilation strategy, infiltration control, conditioning system flow rate, and duct leakage control to ensure acceptable IAQ without negatively impacting combustion safety. Key success factors include: (1) minimizing fan-driven ventilation air volume, (2) controlling infiltration from undesirable sources, and (3) reducing duct system losses in areas that produce no IAQ benefit.

The Partnership for Advanced Residential Retrofit (PARR) will study a minimum of 20 treatment homes and 20 control homes over 24 months to evaluate the proper systems approach. Baseline testing on all homes will be conducted for 3-4 weeks each in groups of 10. Following this baseline period, each set of treatment and control houses will be tested for 6-8 weeks. The entire post-intervention sampling is expected to last for 12-18 months.

This literature review follows two separate information-gathering events, an Expert Meeting and a Practitioner Meeting, both held in early 2016 in Chicago, IL. This review continues the discussion of prior research raised at those meetings as well as questions that were proposed for potential future study. This project hopes to build off of the knowledge base presented here, specifically by applying many different kinds of best practices in a holistic, systems approach to optimizing residential retrofit energy use and IAQ in a relatively large sample of existing homes in the Midwest.

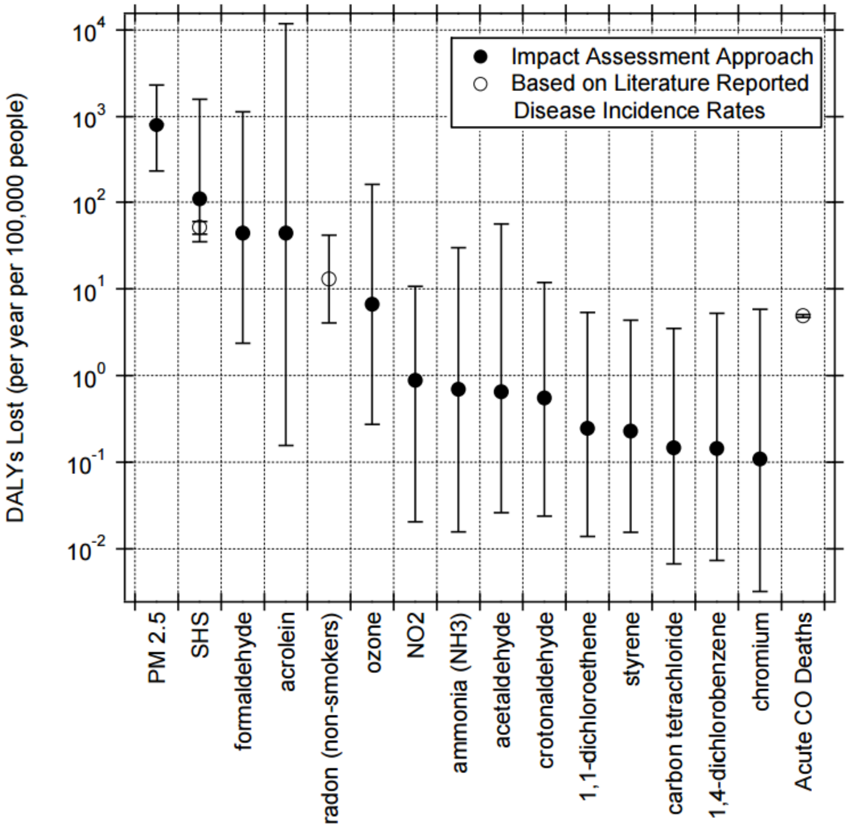
2 IAQ Control

The authors of this review selected a limited amount of prior research based on a narrow interest in IAQ, residential retrofits, measurements performed in actual homes, and cold climate regions. Specifically, PARR reviewed work on the effects of different ventilation systems on IAQ.

2.1 Primary IAQ Contaminants of Interest

An important starting point for this review was LBNL's 2011 study, *Why We Ventilate* (Logue et al., 2011). This summary report provides a foundation for understanding which contaminants pose significant health threats and require attention in a residential retrofit context. Using a unique methodology, the authors estimated Disability Adjusted Life Year (DALY) metrics for 15 potential household pollutants (Figure 1). This indicator attempts to combine human mortality and morbidity associated with a substance into a measure of years of life lost due to death, reduced health, or disability.

Figure 1: Estimated DALYs of chronic air pollutant inhalation in U.S. residences



As apparent from Figure 1, the study concluded that on average, the IAQ contaminants most responsible for harm to human health are PM2.5, secondhand tobacco smoke (SHS), formaldehyde, acrolein, radon, and ozone. PM2.5 can take many forms; particles 10 microns in size can include bacteria, mold spores, and dust mites, while tobacco smoke, soot, smog, and viruses can all be less than 1 micron (Rudd & Bergey, 2014). Logue et al. (2011) concludes with a number of considerations:

- Localized exhaust ventilation (kitchen fans, bath fans) is likely the best option for removing point-source contaminants such as acrolein or moisture in bathrooms.
    - However, there are common issues with occupant usage, including consistency and perception (Less et al., 2015 and Stratton & Singer, 2014).
- Although PM2.5 is often generated indoors by combustion appliances, supply ventilation may not be appropriate in all cases for controlling PM2.5 concentration through dilution, since in many areas outdoor air is higher in PM2.5 than indoor air.
- One possible solution to this PM2.5 dilemma is to filter incoming ventilation air or filter all indoor areas regardless of ventilation strategy. However, this solution may come at a cost (both equipment and energy).
- Source control may be the most effective method for controlling more widely distributed point-source contaminants such as formaldehyde.

The current PARR study seeks to combine multiple best practices in both source control and ventilation to create an optimized, whole-building approach to IAQ control. This is supported by a wide range of research reporting weaknesses in the ability of certain types of ventilation to single-handedly reduce most types of contaminants. In addition, ventilation systems intended to serve as an IAQ catch-all often have flaws which prevent them from performing as planned.

For example, Less et al. (2015) analyzed IAQ in 24 homes in California that were either new or had recently undergone a deep retrofit. The authors found “numerous observed faults in complex mechanical ventilation systems” and several “design flaws.” Designed with airtightness in mind, the homes had a median leakage rate of 2.8 air changes per hour at 50 Pa. Although this combination resulted in very high small particle concentrations in the sample homes without filtration systems, the airtightness and use of low-emitting construction and interior materials allowed most homes to achieve “acceptable and even exceptional IAQ” despite problems in the design and operation of mechanical ventilation systems (Less et al., 2015).

Like ventilation, air sealing alone cannot adequately control IAQ, and can intensify contaminant issues without proper ventilation. However, certain types of air sealing on the envelope may be more effective at limiting contaminants than others. For example, 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 air flows 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 crawlspaces, unfinished basements, attics, or other foundation areas.

Ventilation and air sealing are not the only common retrofit measures which can significantly impact IAQ. Duct sealing should be a primary concern from an IAQ standpoint for two reasons: One, ducts are often located in areas with poor IAQ such as unfinished basements, crawlspaces, or attics, and two, excessive duct leakage can lead to uneven pressure throughout a home. Such imbalances could result in issues with drafting 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 and Puttagunta, 2011).

2.2 Findings of the National WAP Evaluation

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 other people and organizations (Tonn et al., 2014). 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 five indoor environmental quality parameters, including carbon monoxide, radon, formaldehyde, temperature/humidity, and moisture (Pigg et al., 2014).

Table 1 shows the results for radon, formaldehyde, and humidity (expressed as dew point temperature). For radon, the results are for the lowest living level of the house; this was usually the first floor but in some homes this was a basement. Table 1 shows the changes in contaminant levels. Overall, net changes were small but statistically significant. Radon increased on average 0.1 pCi/l in the treatment group and decreased by 0.3 pCi/l in the control group.

Table 1. Net change in contaminant levels (with 90% confidence intervals).

	Sample size		Change (Post – Pre)					
	Treatment	Control	Treatment		Control		Net (treat – ctrl)	
Radon, pCi/l	285	162	+0.1	±0.1	-0.3	±0.2	+0.4	±0.2
Formaldehyde, ppb	63	56	+3.5	±1.6	+1.9	±1.5	+1.6	±1.1
Dew-point temp, ºC	295	175	+0.1	±0.4	-0.6	±0.3	+0.7	±0.3

Average indoor temperature increased by about 0.1 ºC in the treatment group and decreased by about 0.1 ºC in the control group. Most homes had little CO, with nearly 60% never reaching 5 ppm at any point during monitoring and nearly 80% never exceeding 9 ppm. Malfunctioning furnaces and ovens and attached garages were identified as causes of high CO. Weatherization activities sometimes rectified a CO issue, such as by replacing a furnace.

This study also weighed the possible impacts of ventilation on radon levels, although it admitted that “radon entry into homes is an extremely complicated process.” While it is possible that increased ventilation through mechanical means potentially reduces radon concentrations by forcing the exchange of indoor out 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.

Depressurization can occur naturally through stack effects, wind effects, or changes in barometric pressure. Radon is removed via mechanical or natural ventilation, and there is a positive correlation between the air tightness of homes and radon levels (Pigg et al., 2014). The combination of different pressure and ventilation effects on a home, whether intentional or natural, plus differences in home construction, location, and occupant behavior, equate to “highly idiosyncratic” and hard-to-predict patterns of radon concentration.

2.3 Other Research Investigating IAQ Contaminants of Interest

A concurrent study, measured the impact of exhaust-only ventilation on radon and humidity in 18 homes in Colorado, Iowa, Minnesota and Ohio (Pigg, 2014). Like the National WAP Evaluation cited above, radon was monitored continuously on the lowest living level and humidity was recorded at a thermostat. The authors concluded that when exhaust-only ventilation was applied to any sample home, radon concentration had either declined or remained the same in all cases, and on average, ventilation reduced the level of radon by 12% ±7%.

As no homes showed elevated levels of radon after the application of exhaust-only ventilation, this suggests 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. Similar, but smaller, effects were observed on relative humidity, which decreased by a statistically significant 1.7% ± 1.2% with ventilation. However, such changes made no observable impact on general humidity levels in the home (Pigg, 2014).

A recent study sponsored by U.S. HUD examined the differences in several IAQ metrics and occupant health outcomes between low-income homes with and without ventilation (Francisco et al., 2015). No homes began the study with automated mechanical ventilation and a baseline was established in each. One group of homes was made compliant with the ASHRAE 62-1989 standard, where natural infiltration served as the main ventilation method. The other group received exhaust-only ventilation per the ASHRAE 62.2-2010 standard. Table 2 shows the IAQ results pre- and post-weatherization for both ventilation standards

Table 2: IAQ measurements before and after weatherization by ventilation standard

Contaminant group	N	Pre-Wx GM	Post-Wx GM	% Change	P (within group)
Formaldehyde, ppb					
All homes	71	28	23	-18%	0.002**
62-1989	30	31	25	-19%	0.019**
62.2-2010	41	26	21	-19%	0.041**
p between groups					0.723
TVOCs, ppb					
All homes	68	163	134	-18%	0.180
62-1989	31	124	124	0%	0.989
62.2-2010	37	204	142	-30%	0.041**
p between groups					0.209
Basement radon, pCi/l					
All homes	51	2.6	3.0	15%	0.330
62-1989	23	3.0	2.9	-3%	0.888
62.2-2010	28	2.4	3.1	29%	0.073*
p between groups					0.266
1st floor radon, pCi/l					

All homes	46	1.8	1.4	-22%	0.143
62-1989	21	1.7	1.6	-6%	0.824
62.2-2010	25	1.9	1.3	-32%	0.067*
p between groups					0.304
Carbon Dioxide, ppm					
All homes	66	914	797	-13%	0.005**
62-1989	29	888	810	-9%	0.266
62.2-2010	37	936	787	-16%	0.004**
p between groups					0.399

**Marginally significant at $0.05 \le p < 0.1$. **Significant at $p < 0.05$*

Homes receiving the ASHRAE 62.2-2010 ventilation standard experienced significantly lower formaldehyde, total volatile organic compounds, and carbon dioxide levels. Radon levels increased in the basement but decreased on the first floor. Homes in the ASHRAE 62-1989 group saw no significant changes except for formaldehyde, which decreased the same amount as the 62.2-2010 group. The difference between the two ventilation groups was not statistically significant for any of the contaminants.

A 2014 study of various IAQ contaminants in 10 new high performance homes in a humid climate analyzed the impact of ventilation system flow rates on pollutant concentrations (Martin et al., 2014). Multiple types of ventilation were tested, including an originally-installed central fan integrated supply (CFIS) ventilation system that delivered 35cfm of outside air during heating and cooling, and a retrofitted continuous exhaust system approximating the ASHRAE 62.2-2010 standard at 60cfm.

Two contaminants, acetaldehyde and nitrogen dioxide, responded to increased ventilation in either form by decreasing in concentration throughout the living spaces. However, formaldehyde and VOCs did not respond to increased ventilation as clearly. This relationship was more variable, and in several homes both increased significantly under the continuous exhaust ventilation test condition. The authors' reasoning is consistent with other studies, hypothesizing that exhaust ventilation "pull[s] make-up air through the building envelope and increas[es] emission rates of any solvents or other volatile chemicals contained in the materials" throughout the structure. In addition, in order to maintain indoor temperature set points during the testing period, homes under the continuous exhaust ventilation system required approximately 9% more energy use on average.

A similar 2007 NREL study also compared the impacts of single-point exhaust ventilation and CFIS ventilation but from the perspective of indoor air mixing (Rudd et al., 2007). Although IAQ contaminants were not measured, it is inferred that uniform fresh air dilution or indoor air removal benefits occupants by reducing concentration of and exposure to harmful pollutants. The study found that when interior doors were closed, the more distributed the ventilation system (i.e. supply ventilation through the air handling and central duct system), the better the mixing. As point-source exhaust systems, such as intermittent bath fans or continuous exhaust systems, pull air from one point, closed interior doors or very low natural air replacement due to tight building construction interfere with air flow through the building and restrict mixing in certain areas.

The authors also discovered that opening doors greatly increased air mixing under the exhaust test condition, as did the addition of transfer grilles, but open doors were more effective. It should be noted that these observations took place in new homes of above-average envelope tightness, which likely played into the measurement of air mixing in a significant way. In an average home under normal occupancy conditions, there would be more natural infiltration and more variability in mixing due to occupant behavior.

A more recent study prepared for NREL took this concept one step further by analyzing not only air mixing and air exchange rates between different living spaces, but also several IAQ contaminants (Rudd & Bergey, 2014). The study compared the air exchange rate and IAQ impacts of single-point exhaust ventilation, CFIS ventilation, and balanced energy recovery ventilation (ERV) against a baseline condition of no ventilation, closed interior doors, and no central fan in two new, unoccupied homes in Texas. Consistent with the Rudd et al. (2007) study, exhaust-only ventilation did the least of all the test scenarios to force air changes between zones, and balanced ERV performed best.

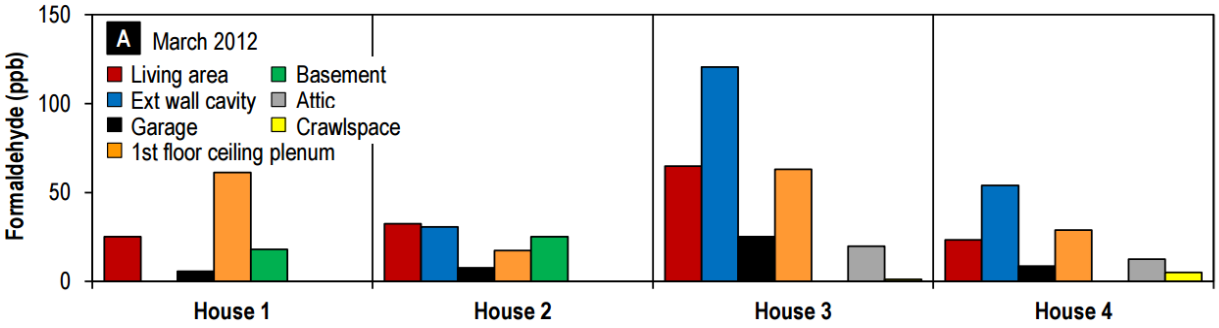
In terms of reducing small particulate matter, exhaust-only also performed the worst, and all other test conditions – including the baseline – showed a 52%-85% reduction in small particles over exhaust only. The CFIS condition performed the best and the authors attribute this to filtration by recirculating air through the central air distribution system. Similarly, the CFIS and ERV conditions decreased the overall concentrations of total volatile organic compounds (TVOC) on average 47% and 57%, respectively, over the exhaust-only condition. This is consistent with the reasoning that exhaust-only systems pull air from unknown places potentially containing as many IAQ contaminants as the indoor air they are intended to ventilate.

Again, a limitation of these studies is the nature of the homes tested. The fact that the sample homes were tight, with doors closed, and with no occupants but with assumed contaminant distributions potentially amplified the relative benefits of supply vs. exhaust ventilation.

Finally, a 2013 ORNL study focusing on formaldehyde in new homes measured contaminant levels across several seasons and found large fluctuations due to temperature-induced off-gassing from interior and exterior construction wood products (Hun, Jackson, & Shrestha, 2013). Figure 2 shows how even in relatively similar homes, IAQ contaminants such as formaldehyde can vary dramatically in extent and location. Note that the homes sampled were unoccupied and unfurnished; thus, the source of nearly all the formaldehyde was pressed-wood products used in construction and concentrations would be higher with furniture present.

In the four homes examined, exhaust ventilation had very little impact on reducing indoor formaldehyde concentrations, but supply ventilation and gas-phase filtration were effective. The study concludes that this is likely due to exhaust ventilation’s depressurizing effects, which creates airflow that moves contaminants from exterior walls and other construction materials into occupied spaces. Supply ventilation, by diluting indoor contaminants with fresh, outside air, does not create this problem, but does create notable pressurizing effects. However, cost constraints on ventilation systems in general make supply ventilation unlikely to compete with simple bath fans in many homes – particularly in retrofits.

Figure 2: Formaldehyde concentrations (DNPH) in various locations in four homes



3 Energy Impacts of Common IAQ Control Measures

Residential buildings are estimated to consume up to 23% of the country's annual source energy, and a greater 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). The authors reviewed several major studies for consistency and their ability to inform the current project.

3.1 Air Sealing and Energy Savings

When Puttagunta and Faakye (2014) summarized the energy impacts air sealing, they concluded that "airtightness is more important than the overall thermal resistance of the building envelope." This is supported by modeling analyses performed Logue et al. (2013), which estimated the energy impacts of various air sealing standards, and then extrapolated the impacts to the entire US residential housing stock. The authors found that even retrofit program-average envelope tightening, such as a 20-30% reduction in air leakage through basic air sealing techniques, would have large impacts on US energy consumption, up to 0.72 quads reduced annually.

Interestingly, climate zone 5 often shows the largest energy benefits from envelope tightening, perhaps due to the region's cold winters and hot summers which result in both large heating and cooling loads in homes (Logue et al., 2013). Similarly, the US Environmental Protection Agency (EPA) estimated through modeling that moderate air sealing, combined with adding insulation in attics and other spaces, can lead to a 15% reduction in heating and cooling energy use in most US homes, with some of the largest benefits in climate zone 5 (US EPA 2016).

Not all types of air sealing are equal in terms of energy savings. For example, Lstiburek (2014) says "holes up high leak more air than holes down low," and suggests that air sealing performed near the top of a structure curtails contaminants entering near the bottom, even if the bottom remains relatively unsealed, "like a hot air balloon" (Lstiburek, 2014). The literature discussed in the previous section seems to generally support this, but with a number of important caveats.

Another major component of the *National Retrospective Evaluation of the Weatherization Assistance Program* focused solely on the energy impacts of WAP actions in single family homes (Tonn et al., 2014 & Blasnik et al., 2014). The study reported that for single family site-built homes heated by natural gas or electricity, air sealing was attributed with providing “the largest fraction of program savings” out of all measures. For homes heated with natural gas, air sealing contributed on average 50 therms saved, or 28% of the total gas savings per home. In electric-heated homes, air sealing represented 43% of total electric savings in an average home (Blasnik et al., 2014).

3.2 Duct Sealing and Energy Savings

Like air sealing, the potential for energy savings through duct sealing is nuanced but large. A somewhat older study analyzing the effectiveness of the pressure pan technique in a relatively large sample of existing Arkansas homes found that duct tightness had substantial impacts on overall home energy use (Davis and Roberson, 1993). The average sample home had an initial duct leakage rate of 621 CFM50, which the authors reduced by 74% using only $39.65 in materials, leading to an average household reduction in energy consumption of 20%. This is consistent with a more recent information piece from US EPA estimating that on average, duct leakage is responsible for heating and cooling system efficiency losses of up to 20% (US EPA, 2009).

Somewhat consistent with these findings, Palmiter and Francisco (1994) implemented a 70% reduction in duct system leakage in six homes and found an average 16% reduction in energy use associated with space heating. Cummings et al. (1994) performed similar retrofits (total cost was $200) on 24 homes and found an average 18% energy reduction. Puttagunta and Faakye (2014) suggest that in terms of reducing energy losses, the most critical location to seal ducts is around the air handler, where air pressures are highest, and all permanent connections must be sealed with an appropriate type of mastic. Another area of high loss is ducts placed outdoors or outside of the home’s thermal boundary; these also represent potential contaminant entry points (Walker et al., 1996).

Duct sealing appeared to have less of an impact in WAP homes, contributing only 4% of total natural gas savings in homes heated by gas. In those homes, air sealing, heating system replacement, attic insulation, and wall insulation made up over 80% of the gas savings on average. It should be noted that duct sealing was performed in only 40% of WAP homes (Blasnik et al., 2014).

3.3 Ventilation Energy Use

Ventilation applications in retrofits or new construction are typically associated with increased energy consumption. This is because a simple exhaust-only ventilation system not only uses electricity to power fan motors, but also removes conditioned air from the structure. Incoming air, whether controlled (through supply ventilation) or uncontrolled (though infiltration), then requires cooling or heating to replace the lost air. For example, the same WAP evaluation discussed in the sections above found that “ventilation improvements, such as the installation of an exhaust fan in a tighter home, were estimated to increase gas use by 20 therms on average” (Blasnik et al., 2014). An increase in electricity consumption should also be expected.

Similarly, the same study by Logue et al. (2013) referenced earlier modeled the energy impact of bringing the large numbers of homes into compliance with ASHRAE 62.2 and found that energy consumption per home would only increase by 1% on average. The authors caution, however, that many mechanical ventilation systems are improperly installed or operated (this is expanded on in previous sections), and even slight oversizing dramatically increases the energy penalty associated with ventilation. In general, the type of ventilation, the sizing, and several other conditions in the home determine the actual energy consumption of the system.

Another study that used modeling analysis to estimate the energy impacts of ventilation in US DOE Challenge Homes (very tight envelopes) found that homes ventilating to just 75% of the ASHRAE 62.2-2013 standard (a condition roughly equivalent to the ASHRAE 62.2-2010 standard) used 10% less energy for space conditioning than if at 100% of the standard (Martin, 2014). Also, operating at 50% of the 2013 standard saved 15% of space conditioning energy. The author does not suggest these conditions as potential real-life measures, but rather performs the analysis to show the relationship between ventilation and energy consumption. The study then compares these test conditions to ERV and exhaust-only systems and finds that energy penalties are overall small. Also, exhaust-only ventilation in very tight homes was associated with increased energy consumption over ERV systems.

4 Conclusion

4.1 Summary

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. Future research has the opportunity to build upon an established understanding of the physics, engineering, and chemistry of air flows, heat transfer, contaminant exchange, and construction practices by layering real-time observations of occupant behavior, the actual working conditions of older homes, and the knowledge and abilities of tradespeople making a living off of the industry.

Several studies referenced in this review alluded to the goals of the current project as priorities 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 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.

There is abundant literature on the energy and IAQ benefits of air sealing, however it is not as simple a case as more is better. By interfering with natural infiltration in specific areas, air sealing creates a complex dynamic between air flows 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 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. When it comes to protecting against interior pollution sources, such as furniture or occupant behaviors, air sealing may have limited or even detrimental effects.

Ventilation is another critical retrofit component impacting pressure balancing and IAQ. There is a more limited amount of literature comparing the IAQ impacts of different types of ventilation, but enough quality research has been conducted to draw several reasonably solid conclusions. In general, supply ventilation may reduce the entry of ground-source contaminants 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. However, the optimal ventilation strategy may depend on the nature of the contaminants, the characteristics of the structure and its occupants, and geography.

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. Often representing up to half of a retrofit measure package’s attributable energy savings, air sealing must also be performed with a critical eye toward IAQ and air flow 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. For example, knowledge of the particulars of static pressure, system efficiency, and air flow requirements may not be widespread, and more training is needed (Edwards, Baker, & Graham, 2015).

Ventilation energy impacts are also situation-specific. As different ventilation strategies affect air flows 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, like duct sealing, gaps exist in product, installation, and operational knowledge (Less et al., 2015).

The current project team will synthesize these findings into a whole-home approach to residential retrofits that balances and optimizes three air streams – ventilation, infiltration, and conditioning system flows – with the competing priorities of maximum energy savings, maximum IAQ, minimum cost, and maximum transferability to the retrofit marketplace.

4.2 Recommendations

The project team plans to incorporate the major findings of this review in the following ways:

- There are a number of different indoor air contaminants to be concerned about, but most important are small particulates, formaldehyde, radon, moisture, and several point-source generated pollutants such as acrolein. Steps will be taken to design the test plan around as many of these as possible, taking into consideration their particular measurement requirements and other study parameters.

- Air sealing has different impacts on different contaminants. However, ventilation also interacts with air sealing to produce different outcomes for each contaminant. The team will consider each contaminant individually and attempt 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. Given the variety of housing configurations and conditions, the team will select a range of housing types but will attempt to match control and treatment homes as closely as possible to gain appropriate counterfactual scenarios.

- The literature shows differing impacts between exhaust and supply ventilation depending on the contaminant. However, much of the existing field work 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 trades-work that is reflective of market conditions is imperative.

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