Sick Building Syndrome Re-emergence in Massachusetts: Air-tight Homes, Uninformed Occupants

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Abstract

Since July of 2014, approximately 14,500 new single-family homes in Massachusetts have been constructed with airtight building shells measuring under three Air Changes per Hour at negative 50 Pascal pressure difference (ACH_{50}) to meet the standards of the state-mandated 2012 and 2015 International Energy Conservation Codes. The evidence is clear and plentiful that buildings this tight can be subject to Sick Building Syndrome and can contribute to the ill health of the building's occupants, including increased rates of asthma, respiratory issues, chronic inflammation, chronic fatigue, and allergies, as well as a decline in sleep quality, cognitive function, and decision-making abilities. Low ventilation rates in buildings are also correlated with moisture damage, dust mites, and mold growth. It has even been suggested that low ventilation rates can contribute to an increased risk of cancer and heart disease. Therefore, these new energy codes also mandate that each house needs a continuously operating mechanical ventilation system that is designed to bring in the proper amount of air from the outdoors.

This study utilized a mail survey sent to a sample of the occupants of single-family homes in Massachusetts that were built to these new airtightness and ventilation requirements. The survey was designed to gauge whether these homes have ventilation systems, if the systems are being used, if the occupants understand why the systems need to be operating, and if the occupants understand how to operate the systems. The survey sample was small (n=31) which resulted in a fairly high maximum margin of error of 17.6%. These data are, therefore, not very precise. Regardless of the fairly low precision, the results show that a significant percentage (at 95% confidence) of the occupants living in Massachusetts in homes built under these new standards report either that they don't have a ventilation system (13.3%); they could not find the system even after looking for it (26.6%); they did not know their home required a ventilation system for proper indoor air quality until they received the survey (45.2%) they have a ventilation system that is controlled in a way that does not meet code (16.7%); or they did not know how to turn the system on and off (71%).

The study concludes that a significant percentage of homes built to the 2012 or 2015 IECC standards in Massachusetts effectively have ventilation rates well below the code requirements and accepted ventilation standards due to the absence, inoperability, and/or improper control of a whole-house mechanical ventilation system. The occupants of these homes are likely to be subject to increased risk of Sick Building Syndrome symptoms and other negative health effects that are correlated with low ventilation rates. It appears that a significant educational campaign is necessary to educate the occupants of this new style of construction about the importance of each home's mechanical ventilation system. It also appears that enforcement of the existing ventilation code needs to be improved.

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Background

Introduction

In July 2014, the Commonwealth of Massachusetts formally adopted the 2012 International Energy Conservation Code (IECC) for residential new construction (Commonwealth of Massachusetts, 2014). There were many changes in this energy code compared to the previously enforced 2009 IECC, but perhaps the most aggressive change was an updated mandatory building tightness requirement in which all new homes need to be pressure-tested and measure at fewer than three (3) Air Changes Per Hour at negative 50 Pascal (ACH_{50})[1]. The previous building tightness requirement called for a measurement under $7ACH_{50}$ (International Code Council, Inc., 2011), meaning that the adoption of the updated code requires buildings' envelopes to be more than twice as airtight as was previously allowed based on cubic feet per minute of air leakage as tested by a blower door. ~~Said another way~~In effect, the maximum allowable volume of outdoor air entering a code-compliant building has been reduced by 57% compared with the previous code requirement.

It is well-documented that tighter building envelopes are effective in reducing heat loss and heat gain to and from the outdoor air, thus improving the energy efficiency of a building. A total conversion of America's current residential buildings to airtight mechanically-ventilated buildings would result in an estimated energy savings of $22 billion (Logue et. al, 2013). However, there are many documented negative consequences of outdoor air exchange rates as low as this current code requires. These consequences can include elevated exposure to indoor air pollutants [ref], increased rates of asthma and other respiratory issues [ref], increased incidence of allergies[ref], chronic fatigue[ref], increased risk of mold and dust mites[ref], a decline in cognitive ability[ref], and even a potentially elevated risk of certain types of cancer[ref].

After the 1973 United States oil embargo, many buildings were constructed around the world at a tightness level similar to this new wave of construction in Massachusetts. These aforementioned symptoms became associated among people who lived or spent significant time

[1] For readers familiar with natural air changes: $7ACH_{50}$ converts roughly to 0.41 ACHn and $3ACH_{50}$ converts roughly to 0.18ACHn in Massachusetts. However, this is an imperfect conversion as ACHn depends on weather conditions while blower door testing utilizes a weather-blind standard reference pressure.

in these buildings and the collection of symptoms became known as “Sick Building Syndrome” (Riesenberg and Arehart-Treichel, 1986).

Sick Building Syndrome and other associated symptoms can be reduced or eliminated in an airtight building by installing and using a mechanical ventilation system in the house. This has been demonstrated by many studies. A mechanical ventilation system could be a “balanced” system such as a Heat Recovery Ventilator that both supplies and exhausts air to and from the home. It could also be a simple exhaust fan that continuously draws indoor air out of the house and replaces it with outdoor air that is drawn through gaps and cracks in the house’s building shell. It is common knowledge within the industry that using one or more bathroom exhaust fans with special controls as the whole-house mechanical ventilation system is by far the most common strategy to meet the code requirement in Massachusetts. This should be no surprise, as the installed cost of a Heat Recovery Ventilator typically ranges from $1600 to $2600 (Minnesota Sustainable Housing Initiative, 2018), while exhaust fans that meet the minimum standards of the 2012 or 2015 IECC are widely available for around $150. Given that a “normal” bathroom exhaust fan is ordinarily required, its further service as a whole house ventilation system is achieved, in effect, at zero additional installation cost.

~~and have no effective installation cost because a “normal” bathroom exhaust fan would have needed to be installed in its place anyways.~~

The 2012 and 2015 IECC construction strategy, which can be summarized with the axiom “build tight, ventilate right,”~~,~~ does appear to be an excellent strategy for improving energy efficiency. This strategy has also been demonstrated to maintain and even improve indoor air quality when a proper mechanical ventilation system is designed, installed, and operated ~~properly~~effectively. Multiple studies have demonstrated that this is the case [ref]. However, it appears that the “build tight, ventilate right” strategy may have a serious flaw. ~~The potential flaw is that~~ P~~p~~roper indoor air quality in these newly constructed buildings is dependent on the proper installation, use, and maintenance of a mechanical ventilation system – most often a single bathroom exhaust fan. If the ventilation system is not functioning properly, a house will then be left with a ventilation rate that is low enough to have negative human health implications.

This study was designed to provide data in order to better understand the incidence of this potential flaw. It utilizes a mail survey sent to the addresses of homes built under the 2012 or 2015 IECC energy codes. The mail survey was designed to provide data that would result in understanding if these homes have ventilation systems, if the occupants understand that they have ventilation systems, if the occupants are using the ventilation systems, if the occupants understand why they have ventilation systems, and if the ventilation requirements in the building code are being properly followed and enforced.

Massachusetts was one of the first states to enforce the "build tight, ventilate right" construction strategy in its building code. Four years later, the state can now serve as an excellent case study for the challenges of its widespread implementation. As of August 2017, the 2012 IECC, or an even more strict code, has been written into law in the states of CA, NV, OR, WA, TX, FL, DC, MD, DE, NY, and VT (US Department of Energy, 2017)[2]. Though this study focuses specifically on the Commonwealth of Massachusetts, it is highly likely that the results are pertinent to all other states that have adopted building codes with airtightness and mechanical ventilation requirements. Additional states are likely to adopt such codes ~~like these~~ in ~~the~~ future ~~in~~ pursuit of energy usage reduction and greenhouse gas emissions reduction goals.

The Link between Ventilation Rates and Human Health

Indoor air quality is very important for human health. This has been well documented by many studies over many decades. The average American spends 87% of their time in the indoor environment, ~~and they~~ spending 69% of their time in a residence (Klepeis et al., 2001). There are many potential sources of indoor air pollution including toxics from building materials, finishes, furniture, carpets and flooring, insulation, household cleaning products, personal care products, heating and cooling equipment, and many others. Some common and important indoor air pollutants include volatile organic chemicals (VOCs), such as Formaldehyde, as well as Carbon Monoxide, Carbon Dioxide, Lead, NO2, Radon, particulate matter, biological contaminants like molds and dust mites, and many other emerging contaminants of concern such

[2] Some states have amended these codes so that the building tightness requirement is not so aggressive. Other states, not listed, may also have large populations of air-tight homes built through energy efficiency programs.

as plasticizers and flame retardants (Environmental Protection Agency, 2018a). The Environmental Protection Agency (2018a) ~~says that~~states: "If too little outdoor air enters indoors, pollutants can accumulate to levels that can pose health and comfort problems. Unless buildings are built with special mechanical means of ventilation, those designed and constructed to minimize the amount of outdoor air that can "leak" in and out may have higher indoor pollutant levels." A large variety of studies back this finding and in many cases have directly shown strong correlations between low ventilation rates in buildings and negative human health outcomes.

Jantunen et al. (2011) modeled the effects of indoor air quality on cardiovascular disease, allergies, respiratory symptoms, allergies, acute toxication, and COPD. The categories of pollutants examined were fine particulate matter, building dampness, bio-aerosols, radon, carbon monoxide, and VOCs. The researchers removed indoor tobacco smoke from this analysis, as it can be ~~confoundedly~~ complicated and ~~would have~~ dominate~~d~~ the results. The result of the analysis was an estimate that approximately two million years of healthy life are lost annually due to sub-optimal indoor air quality in Europe alone, which accounts for 3% of Europe's total annual years of healthy life lost from burden of disease. In a similar analysis, Logue et al. (2011) estimated the impact of indoor air pollution in the United States residential sector and found that sub-optimal indoor air quality causes approximately one to three days of disability-adjusted life to be lost per person per year on average.

Sundell et al. (2011), a multi-disciplinary group, reviewed 27 peer-reviewed scientific papers and found that the papers consistently showed an association between low ventilation rates and negative human health outcomes among occupants. In particular, they report that the data show correlations between low ventilation rates and inflammation, respiratory infections, asthma symptoms, and short-term sick leave. They also found consistency with studies showing the correlation between ventilation rates and the incidence of dust mites.

Wargocki et al. (2002), a multi-disciplinary group, reviewed 105 peer-reviewed scientific papers in an attempt to research and consolidate the available information on the link between ventilation rates and health in the indoor environment. They excluded 61 papers from the study for many reasons~~--~~; most commonly that the researcher did not control appropriately for co-factors. After reviewing the remaining 44 papers, the committee concluded, as a consensus, that:

"The literature shows a strong association between ventilation and comfort (as indicated by perceived air quality) and health (as indicated by Sick Building Syndrome symptoms, inflammation, infections, asthma, allergy, short-term sick leave). It also indicates that there is an association between ventilation rate and productivity (as indicated by performance of office work)" (Wargocki et al., 2002, p. 125). The study also concludes that "The literature indicates that outdoor air rates below 25 L/s[3] per person[4] in offices increase the risk of Sick Building Syndrome symptoms, increase short-term sick leave, and decrease productivity" (p. 125).

In 1999, Seppanen, Fisk, and Mendell reviewed data from 20 studies testing the association of indoor ventilation rates and human health outcomes in over 30,000 subjects. They found that "Almost all studies found that ventilation rates below 10 L/s per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes" (Page 226).

Oie et al (1999) studied the health of a cohort of 172 newborns, while also testing the homes that these newborns lived in to measure ventilation rates and sources of pollution. The study showed a significant link between low ventilation rates and increased incidence of bronchial obstruction among the children and suggests that children are at particular risk of the respiratory effects of poor indoor air quality. A study by Norback et al. (2015) of the health of 600 nursing home residents suggests that the elderly are also subject to an elevated risk of respiratory issues as a result of low ventilation rates. These studies demonstrate that homes with low ventilation rates could be even more dangerous for certain types of occupants.

Allen et al. (2016) studied the effects of CO2 levels, VOC levels, and ventilation rates on the cognitive performance of workers. They utilized a double-blind study in which a group of office workers from many industries worked from a laboratory-controlled environment for a week. At the end of each day, the workers completed a standardized cognitive performance simulation. The researchers varied CO2 levels, VOC levels, and ventilation rates each day and found that higher cognitive performance was correlated independently with lower CO2

[3] Liters per second

[4] Ventilation rates per person such as "L/s per person" can only be achieved with mechanical ventilation systems. These units are not directly convertible or comparable to the natural air infiltration rate of a house, which is quite variable over time with changing weather conditions. The ventilation rates presented in studies like this one cannot be compared directly to a house with a 3ACH50 leakage rate and no mechanical ventilation. These studies are presented to demonstrate the direct correlation between ventilation rates and occupant health.

concentrations, lower VOC concentrations, and higher ventilation rates compared with their cognitive performance after working a day in an environment with CO2 concentrations, VOC concentrations, and a ventilation rate designed to represent the "typical" working environment ($P<.0001$ for each variable).

The studies presented above have all directly measured human health markers as they correlate with ventilation rates. Beyond the studies described in this section, there are also many additional studies that show correlations between ventilation rates and the concentrations of the known human health hazards in indoor air, without directly measuring the health impacts on occupants.

For example, a significant correlation between ventilation rates and CO_2 concentrations has been well established for decades, and is still consistently shown to be significant,[5] even outside of the laboratory, by recent real-world studies such as Leivo et. al (2017) and Thomsen et. al (2016). A study by Satish et. al (2012) showed a significant correlation between higher measured indoor CO_2 concentrations and poorer decision-making performance. Given that CO_2 concentrations are correlated with ventilation rates and CO_2 concentrations are also correlated with lower decision-making performance, it would be a very reasonable hypothesis that ventilation rates can be directly correlated with decision-making performance. It is, therefore, not a surprise that two years after Satish et. al demonstrated the effect of CO2 concentrations on decision-making, Maddalena et. al (2014) showed a direct relationship between lower ventilation rates and lower decision-making ability in a laboratory-controlled office setting utilizing a controlled CO2 input. This finding was then substantiated by Allen et. al (2015) in the cognitive performance study described above. Synthesizing multiple studies presents strong evidence of potential ventilation-related human health impacts that have not yet been studied directly.

For example, no studies have yet directly linked ventilation rates to long-term health effects such as cancer. Such a study would be extremely difficult to conduct given the timeframe that would be required to study these long-term health effects and the large number of variables to be controlled for. However, Parathasarthy et. al (2011) worked with Lawrence Berkeley National Laboratory to review the existing literature to understand which VOCs have been found

[5] Though both of these studies also show that there are other significant factors that influence CO2 concentrations, including the number of occupants and the occupancy rate.

in concerning concentrations inside buildings and which also have the physical properties that would allow mechanical ventilation to dilute them. They then grouped the VOCs by importance based on their health impacts and ability to be ventilated. Ten VOCs ~~were listed~~appeared on "List-A". List-A includes only compounds that both exceed more than one toxicity (cancer, non-cancer, reproductive) or odor/pungency threshold, and were also found to have the physical characteristics to be affected by ventilation rates.

Among these ten List-A VOCs is Formaldehyde. A~~There is an a~~bundant~~ce of~~ literature link~~sing~~ Formaldehyde exposure in buildings to cancer development. Formaldehyde is classified by the United States EPA as a "known carcinogen" (National Resource Council, 2014). Given that Formaldehyde is a known carcinogen, has been found in buildings in concentrations above the threshold for increased risk of cancer, and is subject to dilution by increased ventilation rates, it is a very reasonable hypothesis that ventilation rates correlate with cancer risk. Potential causality between low ventilation rates and disease could be established in a similar manner for many pollutants and many diseases in lieu of any direct evidence, though direct health studies are certainly more convincing. Reviewing the literature, there appears to be a research need for these types of studies and syntheses.

The primary difficulty in studying correlations between ventilation rates and the concentrations of indoor air pollutants in a real-world setting is that the source of the indoor air pollutants is always an important variable that is not easily measured or controlled for outside of a laboratory setting. There are many recent studies that have shown the significant indoor air quality improvements of "green buildings" vs. traditional buildings, but there are often too many different variables between the groups of buildings to confidently attribute the indoor air quality improvements to the addition of mechanical ventilation alone. For example, most "green buildings" standards such as LEED also have building materials requirements that could significantly change the types of pollutant sources found within the home compared with standard construction. The health impacts of indoor air will always be partly attributable to the source of the pollutants and partly attributable to the ventilation rate which would dilute those source concentrations. It is very difficult to separate these two factors in a study design or data analysis.

New, Under-Studied, and Emerging Chemicals

There are a wide variety of chemicals located inside houses in which the health effects are under-studied. For example, one of the primary strategies that many builders are using to meet the new building airtightness requirement is the use of spray foam insulation. As of the writing of this report, spray foam is typically composed primarily of polyurethane, but the components of spray foams vary by manufacturer and have varied over time. These spray foams are often marketed as simply polyurethane, but always also contain a proprietary blend of other chemicals including flame retardants and blowing agents (Environmental Protection Agency, 2017b). The State of California has recently pursued a legislative change that would remove methylene diphenyl diisocyanates from spray foam blends used in the state, citing an emerging link between this chemical and respiratory issues (Hogue, 2017). The list of potentially concerning chemicals used in proprietary spray foam blends may be long and under-studied. In all blends, it is known that isocyanates remain in the spray foam after installation and it is not clear how much and under what conditions the spray foam will off-gas the isocyanates into the indoor air (Environmental Protection Agency, 2017b). Isocyanates in indoor air have been linked to a variety of respiratory issues (Environmental Protection Agency, 2017b). The United States Environmental Protection Agency (2018) says that "The potential for off-gassing of volatile chemicals from spray polyurethane foam is not fully understood and is an area where more research is needed."

When the 2012 IECC was adopted in Massachusetts, a new Fire Code was also adopted. One major change in this Fire Code was that the subfloor above all basements was required to meet more strict fire resistance standards. The Code standard could be met either by adding sheetrock to the ceiling of the basement or coating the subfloor with a certified flame retardant. Adding sheetrock to the basement ceiling is a logistical nightmare in most buildings, due to the presence of ductwork, plumbing, and wiring running along the floor joists and subfloor, so coating the entire subfloor in a flame retardant has become very common. These flame retardants are generally patented with unknown ingredients. The subfloor is just one example of the major increase of flame retardants in homes. The United States Environmental Protection Agency (2017a) says that "Americans are often exposed to flame retardant chemicals in their daily lives. The chemicals are widely used in products such as household furniture, textiles, and electronic equipment. Many flame retardant chemicals can persist in the environment, and

studies have shown that some may be hazardous to people and animals." They follow that they are currently assessing the health impact of a variety of popular flame retardants. The health effects and relationship with ventilation rates for all flame retardants are currently under-studied.

Spray Foam and flame retardants are just two examples of many potential indoor air pollutants that are under-studied. Parathasarthy et. al (2011) identified ten different VOCs with significant cause for concern in the indoor environment that also have the physical properties to be affected by ventilation rates. This list of potential chemicals of concern is likely growing as new chemicals and products are invented, as codes and standards evolve, and as household needs change. The chemical landscape of the indoor environment is constantly changing and should be expected to continue changing. It is a paradox that the ventilation standard may need to be constantly studied and adjusted to properly ventilate changing pollutant sources in homes, while the constantly changing pollutant sources make it very difficult to directly study the impacts of ventilation rates on human health over time. There appears to be a strong research need for using alternative methods to demonstrate the relationship between ventilation rates and human health. Synthesis studies that separately assess the concentrations of certain pollutants in homes, assess how those concentrations are expected to impact human health, and assess how ventilation rates effect those concentrations may be one very promising avenue.

The Effectiveness of Mechanical Ventilation Systems in Tight Houses

The studies described above present clear evidence that many negative human health outcomes correlate with lower ventilation rates. It is clear that a house needs ventilation air to maintain adequate indoor air quality. Natural air infiltration alone is not a reliable source of ventilation, particularly in buildings that are constructed to be airtight. Natural infiltration is dependent on the pressure difference between the inside and outside of the house, which is constantly changing due to weather and indoor activities (Building Energy Codes Program, 2011). If there is no pressure difference between the inside and outside of the house, such as a weather condition with no wind and in which the temperature inside is exactly the same as the temperature outside, there will be no natural infiltration, regardless of how tightly the building was constructed (Building Energy Codes Program, 2011). This means that natural ventilation

can be very erratic. There is often more ventilation air entering than is needed and sometimes less ventilation air than is needed. Further, operable windows cannot be relied on for ventilation. Offermann (2009) found that 32% of his sample of 1,515 California new homes did not ever use their operable windows. He found that window use was especially infrequent in cooler climates and especially during the coldest months. The Massachusetts climate is significantly colder than California climates, so it appears to be a reasonable hypothesis that the use of windows in Massachusetts during the winter would be even lower than this California study's estimate.

Offermann (2009) performed a field study in conjunction with the California Energy Commission to examine ventilation rates and behaviors in 108 new California homes with a mean tested ventilation rate of 4.8ACH_{50}. As a reminder, Massachusetts new homes need to measure at less than 3ACH_{50}, which is significantly tighter than the homes in this study. The homes in this study receive, roughly, more than a 50% higher volume of outdoor air than a new Massachusetts home would, absent a mechanical ventilation system. The large majority of the homes included in this study did not have a mechanical ventilation system, as the California Energy Code at the time allowed for the use of operable windows to supplement the natural ventilation rate. Offermann did onsite tracer gas measurements in multiple seasons in order to estimate the actual ventilation rate of these houses under typical operating conditions (homeowners were allowed to open and close windows as they normally would) and found that 67% of the homes were significantly under-ventilated based on the California Building Code. He found that 98% of the homes had formaldehyde levels that exceeded guidelines for cancer. A significant number of homes also exceeded guidelines for the presence of acetaldehyde and five different VOCs, including chloroform and benzene. Twenty-eight percent of the households reported experiencing at least one physical symptom consistent with sick building syndrome when they were in the house that they do not typically experience when away from the house.

Francisco et al. (2017) performed a randomized trial on 81 houses that were undergoing weatherization. Half of the houses, the control group, were weatherized until the building's airtightness reached a level that is approximately 8ACH_{50}[6]. They then stopped air sealing any further and did not add a mechanical ventilation system. The other half, the test group, were

[6] These buildings received, roughly, a 166% higher volume of outdoor air than a new Massahcusetts home would in the absence of a mechanical ventilation system.

weatherized until they reached a level that was approximately $8ACH_{50}$ and then were equipped with a mechanical ventilation system, which was typically an automatically-controlled bathroom exhaust fan. The mean natural leakage rate did not differ significantly between the two groups either before or after weatherization. Baseline air quality measurements and health surveys were taken both before and after the weatherization in all houses. Both groups had significant improvements in many air quality measurements compared to their pre-weatherization measurements. However, the mechanically-ventilated group had significantly larger reductions in moisture, VOCs, radon at the first story of the building, CO2 concentrations, and incidence of headaches in children compared to the group without mechanical ventilation.

Fisk, Mirer, and Mendell (2009) used regression analysis to study the impact of ventilation rates on Sick Building Syndrome symptoms. One interesting finding is that as the ventilation rate increased from 10 to 25 L/s per person in an office building, the relative prevalence of Sick Building Syndrome symptoms decreased by an average of 29%.

Feoldvary et. al (2017) studied the indoor air quality effects of weatherizing three multifamily buildings in Slovakia. Three separate identical pairs of multifamily buildings for a total of six buildings were studied. Of each pair, one building was weatherized and the other was not. All buildings were naturally ventilated both before and after the weatherization. The weatherized buildings did not have a mechanical ventilation system installed as part of the updates. After the update, the weatherized buildings were measured to have significantly lower ventilation rates than the control group. When comparing the pairs of buildings, they found that the weatherized buildings had significantly higher levels of CO_2 and VOCs including Formaldehyde. There was also a higher occurrence of occupants reporting Sick Building Syndrome symptoms in the weatherized group.

Noris et al. (2013) performed a study on 16 apartment buildings in California that underwent weatherization and a variety of other renovations aimed to improve energy efficiency and indoor environmental quality. Eight units had continuously-operating heat recovery ventilators installed, and eight units did not have any continuous mechanical ventilation system installed. Measured levels of CO_2, Acetaldehyde, and VOC were significantly lower than the baseline measurements after the retrofit for all test homes. However, the measured levels were

lower in the ventilated group compared with the non-ventilated group. The study's authors were able to conclude that "IEQ[7] improved more in apartments with continuous balanced mechanical ventilation systems installed compared to apartments without continuous mechanical ventilation. In general, larger percent increases in ventilation rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources." (Noris et al., 2013, p. 177)

Sundell et al. (2011), a multi-disciplinary group, reviewed 27 peer-reviewed scientific papers and found that the papers consistently showed that Sick Building Syndrome symptoms are reduced as mechanical ventilation rates are increased.

Wilson et al. (2013) studied 248 households in Boston, New York, and Chicago that were undergoing "energy efficient renovations" which included tightening the building envelope and the installation of a mechanical ventilation system by a trained professional. Using surveys over a three year period, the researchers discovered with high significance that occupants improved in overall health and had a reduction in sinusitis, hypertension, and asthma symptoms.

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Strøm-Tejsen et al. (2016) studied a group of 16 students in dormitories in Denmark. They installed inaudible ventilation fans in the dorms and had the students fill out a questionnaire each morning while the researchers varied whether the ventilation fan was turned on or off. They found, with significance, that when the students slept in a room with a ventilation fan vs. a room without one [don't you mean: "with a ventilation fan in operation, vs a room in which the fan was switched off?"], the student reported better mental clarity and sleep quality on the following day. Students wore sleep monitors during the experiment and the data from the monitors showed a significant improvement in sleep quality when the ventilation fan was in operation.

The literature is clear that ventilation systems can be effective at diluting certain pollutants and that the "build tight, ventilate right" methodology is capable of, at the very least, doing no harm to indoor air quality compared with the typical construction methodology of a

[7] Indoor Air Quality

fairly leaky building. The evidence even seems to suggest that this methodology can result in an indoor environment with superior air quality when implemented correctly.

What Can Go Wrong?

Despite the demonstrated effectiveness of properly-functioning whole-house mechanical ventilation systems in maintaining proper indoor air quality, there are many ways in which a ventilation system that passes inspection may not actually be "properly functioning" and can be insufficient to effectively ventilate a home. For one example, the ventilation system could have simply been never turned on or could have been turned off by an uneducated resident. In a 2009 survey of California homeowners living in airtight homes with mechanical ventilation systems, 22% did not have the ventilation system explained to them when they bought or moved into the house, 37% said that they did not understand how the system works, and 17% said that they did not understand how to operate the system properly (Offermann, 2009, p. 214).

Also, ventilation systems can fail and the resident may not notice or be educated enough to know that it failed. There are multiple studies showing high failure rates and high rates of improper installations in ventilation systems, particularly heat recovery ventilators. For example, Davis (1998) did performance testing on nine recently-installed "balanced" ventilation systems in new houses in the Southeast United States. He found that all nine had at least one design or installation issue that was reducing its effectiveness. Hill (1999) studied 60 airtight houses with Heat Recovery Ventilators in the United States and Canada, including site visits to test the equipment and phone interviews to gauge the resident's understanding of the system. He found that 12% of the systems were not operational due to a failed component and 17% had blocked air intakes. Only 32% of residents in his sample had read the manual for their ventilation system. 26% reported that they had indoor air quality issues during the phone interview and of those, 60% were found to have a ventilation rate below the accepted ventilation standard.

Francisco et al. (2017) inadvertently found that the use of exhaust-based mechanical ventilation systems can significantly increase radon levels in the basement, likely because the negative pressure created by the ventilation system draws additional gases from the soil than would have naturally entered the basement's air. Forty-two homes were weatherized and had exhaust mechanical ventilation systems installed on the first floor. The concentrations of radon

in the basements rose by a mean of 30% compared to measurements taken before the updates. However, the concentrations of radon fell on the first-story, where the ventilation system was located, by approximately 30% compared to their respective pre-weatherization measurements. This study illustrates both the ability of an exhaust system to draw soil gases into the home at an enhanced rate and also the ventilation system's ability to dilute the pollutant when it reaches the living area of the home. However, in houses with living areas in the basement, those areas may be subject to significantly higher radon concentrations with the use of an exhaust mechanical ventilation system located on the upper floors.

These studies demonstrate that there can be issues with ventilation systems in real-world applications. There are a variety of pathways to failure for ventilation systems, including equipment failure, poor installation and/or system design, an uneducated occupant that turns the system off or changes its settings, or a ventilation system that is functioning properly but has unintended and unforeseen consequences

How Well Do Exhaust Fans Ventilate a House?

There are a variety of potential issues with the use of an exhaust-only system as a whole-house mechanical ventilation system. A U.S. Department of Energy publication says of exhaust ventilation systems: "While these systems are very simple and low cost, they have some significant limitations, and there are situations where exhaust-only strategies are not appropriate" (Aldrich, 2014 p24).

Rudd and Bergey (2014) worked with the University of Texas to construct and study two nearly identical detached houses. The houses had identical dimensions and layouts but used different materials to test different levels of contamination. Both of the houses had identical energy recovery ventilators and identical bathroom exhaust fans installed. The researchers then measured air quality for multiple 12-hour periods using different ventilation systems for both houses. When the exhaust fan was used as ventilation system in both homes, they found an average of 70% higher concentrations of particulate matter and 57% higher concentrations of VOCs, including a significant increase in Formaldehyde levels compared with measurements when using the Energy Recovery Ventilators. Measured VOCs were found to b be significantly

higher when using the exhaust ventilation system compared to not using a ventilation system at all in both houses (37% and 18% increases respectively). [!!!] They suggest that this increase was likely due to the change in the pathway of make-up air. For example, spot measurements suggest that the 37% increase in VOCs in one building was likely because the ventilation system was drawing air from the attic into the main area of the house, which would not otherwise happen at a significant volume without the assistance of the exhaust ventilation fan. They also found that ventilation was significantly less uniform throughout the different areas of the house when the exhaust fan was used compared with an energy recovery ventilator, meaning that certain rooms had significantly higher pollutant loads than others.

Studies finding that single-point exhaust ventilation systems do not ventilate a house as evenly as a balanced and distributed ventilation system have now been replicated many times. Rudd and Lstiburek (2000) used tracer gas[8] and different ventilation systems in a test house. The testing showed that a single exhaust-only bathroom fan can potentially remove tracer gases from a house effectively and evenly, but only under certain conditions. The researchers found that if a bedroom door were shut and if the central air handling unit was not operating often, the bedroom could be more than 50% under-ventilated compared to the rest of the house. Hendron et al. (2006) performed a similar study using tracer gas and an exhaust-only ventilation system and found similar results; when doors were closed and the central air handler was not running often, ventilation could be uneven throughout the house. One bedroom with a closed door was even found to have a longer "age of air" than the air in the main area of the house by a factor of 2.5. CARB (2007) performed yet another tracer gas study in a Massachusetts house with an exhaust-only ventilation fan and found that the age of air inside a bedroom with a closed door can be more than double the main area of the house.

Another major uncertainty is whether ventilation systems are being set correctly in the field. For example, it is unclear whether they are being installed correctly consistently so that the airflow settings are actually translating into the desired ventilation rate and are not being reduced by leakage, friction, or blockages from a poor install. Therefore, a Massachusetts field study in

[8] Tracer Gas is an inert gas that can be created in a known concentration by researchers inside the house. The ppm can then subsequently be measured using sensors. It is used as a proxy that represents the physical behavior of many indoor air pollutants.

which existing ventilation system rates and air quality throughout the house under existing and normal operating conditions are tested is highly recommended to better understand this potential issue. Other states and communities outside of Massachusetts have also adopted similar energy codes, and the recommendations of this study likely apply to these other markets as well.

Methods

Background Research

The first phase of this project was to conduct a ~~strong~~ thorough review of the relevant literature regarding the correlations between human health and ventilation rates in buildings. The literature that was found to be relevant has been summarized in the Background section of this report. The literature regarding indoor air quality, ventilation, and human health is very large and spans many decades. The literature review done for this study was by no means comprehensive, though a strong effort was made to find the most relevant studies, understand them well, and describe them accurately and succinctly. The literature was found to be missing data regarding the actual in-service rate of ventilation systems and some important aspects of occupants', builders', and inspectors' behavior when a ventilation system is forced into a home by way of a state-mandated building code. The second phase of this project was, therefore, to design and implement a study to provide some of this important data with a focus on new residential construction in Massachusetts.

Study Design

The goal of the study design was to test a variety of null hypotheses regarding whole-house mechanical ventilation systems in Massachusetts homes built to either the 2012 IECC or 2015 IECC energy codes. There were multiple null hypotheses being tested. They include:

- 100% of the Massachusetts homes required by law to have a whole-house mechanical ventilation system had one installed.
- 100% of the occupants of these homes understand that the whole-house mechanical ventilation system is required to operate to maintain reasonable indoor air quality.

- 100% of the whole-house mechanical ventilation systems in these homes are being used by the occupant.
- 100% of the occupants of these homes understand how to operate their whole-house mechanical ventilation system.

To test these null hypotheses, a mail survey was developed to be sent to the occupants of 240 different single-family homes throughout Massachusetts. The survey package included an introductory page, a specially-made guide to locating and identifying a whole-house mechanical ventilation system, and a two-page 12-question multiple choice survey. The survey package is shown in Appendix A.

The sample of homes to be used in the study was developed using real estate search engines. Many of these search engines allow the application of advanced search filters to search for only homes that have been advertised and/or sold through their website that have a particular construction year. The sample developed includes only houses with a construction date of 2016 or 2017 in towns that adopted the "base" 2012 IECC energy code in July, 2014. Houses with construction dates that fell within the second half of 2014 and all of 2015 were excluded because some builders acquired building permits for future projects just before July 2014 so that the projects could "lock-in" the old code, rather than comply with the new one. This study leaves a conservative 1.5-year gap to be sure that there was an extremely low probability that a home built under that circumstance would be included in the study. The sample also includes only houses with a construction date in the second half of 2017 in towns that have adopted the Massachusetts Stretch Energy Code[9]. The use of only homes constructed during this period ensures that all homes used in the sample were subject to the $3ACH_{50}$ airtightness standard and were subject to the requirement of a whole-house mechanical ventilation system. The sample is

[9] Many Massachusetts municipalities use the "Stretch" energy code rather than the 2012 or 2015 IECC "base" energy codes. The Stretch Code is a Massachusetts-only variation to the energy code that was intended to be stricter than the base code. However, the Stretch Code, confusingly, was less strict than the base code due to legislative lag during the period of July 2014 through August 2016 before the Stretch Code formally adopted the tightness and mechanical ventilation requirements of the 2015 IECC. Using only Q3 and Q4 2017 houses in Stretch Code communities was a conservative measure that allowed for these communities to be represented in the sample without any significant chance of erroneously including a home without the mechanical ventilation requirement in the sample. The September 2017 update of Massachusetts DOER's "Stretch Code Adoption, by Community" document (Massachusetts Department of Energy Resources, 2017) was used to determine Stretch Code adoption. In reality, most Stretch Code homes from 2014 or later did actually have a mechanical ventilation requirement, by way of the "New Homes with Energy Star" rebate program which was extremely popular for Stretch Code homes, but this study aimed to be conservative.

designed in a way that it is highly improbable that a survey was sent to a home that was not subject to the aforementioned energy code requirements. [excellent!]

Using U.S. Census data for housing permits issued in Massachusetts by year for buildings with less than five units, it is estimated that there have been approximately 14,500 single-family homes constructed in the Commonwealth under the 2012 IECC or 2015 IECC Energy Codes to date (U.S. Census Bureau, 2018)[10]. This does not include homes that were built airtight before the implementation of this code, such as homes in which the builder pursued ENERGY STAR certification, a rebate through the New Homes with Energy Star program, homes with a low Home Energy Rating score, and/or homes in pursuit of the federal Energy Efficient New Homes Tax Credit. It also does not include multi-family housing or houses that have undergone weatherization. It also does not include houses built under the 2009 IECC-referenced Stretch Code. Therefore, this estimate of ~~effected~~ affected homes is almost certainly significantly underestimated. The population of single-family homes affected by the airtightness and ventilation requirements of the IECC is expected to grow by approximately 8,000 to 8,500 annually in Massachusetts assuming that the current rate of construction reflected in U.S. Census data continues.

The only search attributes of homes listed on real estate websites that were screened for inclusion in the sample were the construction year, the municipality, and at least one actual image of the exterior of the house confirming that it was a single-family home or duplex. When selecting the homes for the sample, the researcher was prepared to eliminate any home in which the images indicated that the house was not new construction.[11] However, no homes needed to be excluded for this reason. The researcher was also prepared to eliminate any home in which the "Sold" date differed from the "Construction" date by any more than six months. This was

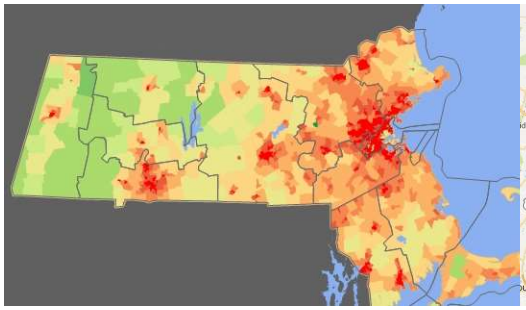
[10] The total number of issued permits for Q3 and Q4 of 2014, all of 2015, and all of 2016 was multiplied by 69.5% and the resulting number was subtracted from the total to remove all homes that were subject to the Massachusetts Stretch Code during these time periods. The Stretch Code, confusingly, lagged behind the basic energy code during this period and did not necessarily require a building shell as tight as the 2012 IECC or 2015 IECC and did not explicitly require mechanical ventilation. This calculation was based on an estimate from Massachusetts DOER as of September 2017 that 69.5% of the state's population resides in Stretch Code communities (Massachusetts Department of Energy Resources, 2017).

[11] The approximate ge of a house can, of course, not be understood by a picture. This was meant to be a double check on top of an already reliable method of advanced filtering based on construction date. Exterior features or landscaping that looked other than brand new would have triggered further investigation.

another conservative measure taken to be sure that the construction date shown on the real-estate website for any included house was accurate and not a database error.

The sample was then stratified by municipality in a way that attempted to mimic a heat map of population density in Massachusetts. The sample design incorporated as many different municipalities as possible, while keeping within the spirit of population density imitation. The sample of 240 homes included homes from 149 different municipalities. The maximum number of homes located in any one particular town was five. The only search attributes of homes used in the sample that were recorded were the address and town. The researcher had no personal knowledge about any of the homes used in the sample other than their age, location, and the image(s) shown on the real estate site. The researcher was prepared to, but never needed to, exclude any home from the sample in which he had any previous knowledge about.

A heat map of population density in Massachusetts is shown below in Figure 1 for comparison with Figure 2, which is a heat map that was generated using the zip codes of this study's sample population.



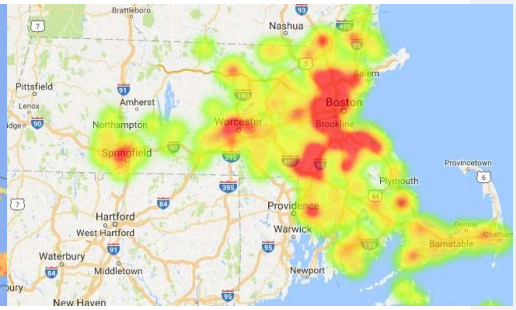


Figure 1: Popı Figure 2: Heat Map of House Locations Used in Survey Sample Data)

Admittedly, stratifying the sample population using population density is not a perfect method to represent the overall population. For example, it is not clear if the population density of a municipality in Massachusetts in 2010 correlates well with the number of new homes constructed in that municipality in recent years. After careful thought, it was simply not possible to create a sample population that was perfectly stratified in every way to newly-constructed Massachusetts homes due to the lack of data and a relatively small, but actively growing total population that only includes houses constructed in

recent years. sStratification by municipality and population density were used in order to limit the effects of any one particular town inspector, builder, or aspects of local culture on the survey results. By stratifying this way, the survey results could be confidently understood to, at the very least, represent many different areas of the state. A high percentage of responses to any survey question, therefore, could not possibly represent only an issue localized to one particular municipality or builder. The main goal of this study was to assess whether the aforementioned potential issues regarding ventilation systems might be common enough throughout Massachusetts to warrant further action by responsible parties, not necessarily to gather results that represent the overall sample population with strong precision. Such a study would be much more expensive and time-consuming than the scope of this research allowed.

Data Collection

The survey was sent to the addresses on the sample list in a postmarked envelope using the United States Postal Service. Each envelope was addressed to "Postal Customer". Inside each envelope were the introductory letter, the guide to locating the mechanical ventilation system, and the survey. Another postmarked envelope with the return address pre-filled was included. The introductory letter instructed the recipient, if they chose to participate, to read and follow the guide to locating their system and subsequently complete the survey. They were instructed to insert the survey into the pre-filled envelope to return it to the researcher's address. Both the introductory letter and the survey itself informed the occupants that their anonymity would be maintained. The researcher's address was used as the return address for the return envelope so that respondents did not have to fill their own return address in and could remain anonymous. As completed surveys were returned, responses were tabulated in Microsoft Excel and the results were kept organized by respondent in order to potentially conduct multivariate analyses.

Types of Error

The survey design had many potential sources of error to mitigate. One potential source of error was a survey recipient responding that they do not believe that they have a whole-house ventilation system, when in truth the house did have one but they could not locate or identify it. Another potential source of error was an occupant responding that they believe that they do have

a whole-house ventilation system, when in reality they had misunderstood and were thinking about a different piece of equipment. One example of a piece of equipment that could conceivably be mistaken for a whole-house ventilation system is a bathroom exhaust fan without advanced controls, which is required in all bathrooms for moisture removal, but would not be considered a whole-house ventilation system. In response to these two anticipated issues, the survey included a page dedicated to describing common whole-house mechanical ventilation systems with pictures. This page can be seen in Appendix A. This page was important in reducing the chance of erroneous survey results that could have potentially resulted from a homeowner/resident that was truly uninformed about their whole-house mechanical ventilation system. Even with the inclusion of this descriptive page, there is still some probability of an erroneous survey result could come from a confused respondent.

Another potential source of error was an occupant that responded that they understood some aspect of their system but they actually did not. In a study of 60 homeowners living in homes with Heat Recovery Ventilators, Hill (1999) found that 77% of respondents reported that they understood their ventilation system. However, of the respondents who reported strong understanding, 60% were found to have substandard ventilation levels in their house and 55% had systems that were found to be unbalanced. In the same study, 81% of respondents reported that they regularly clean their ventilation system. However, of those respondents, 42% were found to have systems with dirty filters, cores, or cabinets and 17% had systems with blocked air intakes. Given these results, it is clear that an occupant's assessment of their own understanding might be inadequate on the topic of ventilation. Positive survey results for questions regarding occupants' understanding in this study are, therefore, subject to potential error, though questions were worded in a way which made them as specific as possible in order to limit the effect of this potential source of error.

Another flaw of the survey design is that it was possible that occupants living in a home included in the sample do not speak English or would otherwise have had difficulty comprehending the survey, which could be considered a reasonably complex topic. It is intuitive that a survey recipient ~~that~~ who was not literate in English would simply not attempt to fill it out and return the survey, but it is not clear how this potential source of error would impact the results. U.S. Census Data suggests that 22.7% of Massachusetts residents speak a language other

than English at home (U.S. Census Bureau, 2017). It is reasonable to hypothesize that the population of Massachusetts homeowners/renters that do not ~~fluently~~ speak fluent English might be at additional risk of not understanding their ventilation system. This is a reasonable hypothesis since the majority of builders, inspectors, and architects working in Massachusetts are primarily English-speaking and may have been less likely to communicate the airtightness of the house and the importance of the ventilation system to their buyer if the buyer did not speak the same primary language. If this hypothesis was found to be true, this study's results might significantly under-represent the proportion of occupants that have not been educated about their ventilation system and/or do not use it. The fact that the Massachusetts population contains people with a variety of different primary languages could prove to be a significant and tricky issue regarding education on ventilation systems. Incorporating other languages into this study design was prohibitively expensive within the study's budget, but is recommended for any future replication of this study.

Finally, it could potentially be more likely that survey recipients that were previously not aware that they had a ventilation system would have completed and returned the survey. This might be true because the survey package could have been more interesting and informative to those recipients compared to one that previously understood that their house has a ventilation system and already understood its purpose. If this were the case, the data would be over-representing those who were less educated about their systems. It was not possible to avoid this potential source of error within this study's budget and design.

These potential sources of error certainly had some chance to skew the results, and, therefore, limit the predictive power of the data. Despite these shortcomings, this data is still very valuable because the survey's primary purpose was to discover whether some hypothesized issues are actually occurring, not to determine the incidence rates with high precision. The primary null hypothesis can be summarized as "100% of Massachusetts homeowners/residents that reside in a single-family structure built under the 2012 IECC or more recent energy code have a whole-house ventilation system, are aware that they have one, understand why it is important, understand how to operate it, and currently use it appropriately." Data showing any number of exceptions to this null hypothesis that cannot be reasonably explained by the potential

error sources and fall outside the survey's margin of error should, therefore, be considered significant and would allow for rejection of the null hypothesis.

Results and Discussion

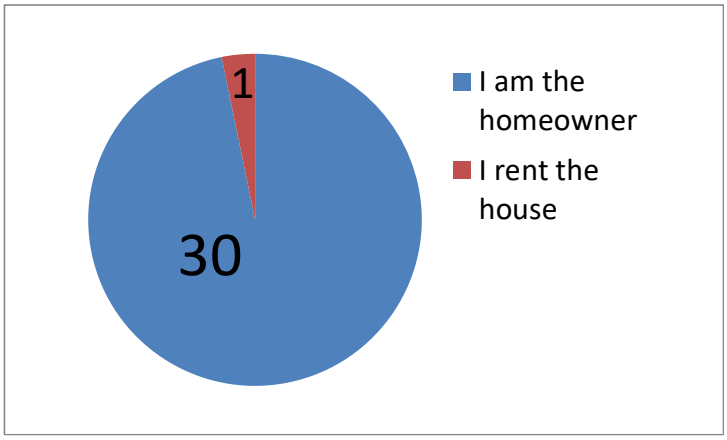
The survey received 31 responses. This was a response rate of 12.9% of the survey's 240 recipients. The sample is relatively small, particularly when compared to the total estimated affected population size of 14,500 houses. The maximum margin of error for this survey at a 95% confidence interval is 17.8%. A margin of error could be calculated individually for each question's responses, and if calculated this way would likely show improved precision for almost all questions. It did not appear that such a statistical analysis would provide any additional value to this discussion however, as achieving high precision is not a goal of this study. Due to the small sample size and the potential for survey bias error it seems most appropriate to use a conservative statistical approach to extrapolating these results to the overall population.

The relatively high margin of error limits the ability of this survey's results to be extrapolated to the overall population with precision. However, even when using the most conservative result within the maximum margin of error throughout the analysis, many of the survey's results are still very powerful and sufficient to test the study's hypotheses. This survey was, therefore, successful in its goal of generating data that indicates with confidence whether ventilation systems are being used and understood throughout Massachusetts new homes. This study serves as somewhat of a "proof of concept". It could be replicated in the future with a much higher sample size to generate data that could also be viewed as a reasonably precise representation of the overall population. Such a larger replication might be desired to better understand the scale of the issues and to better design and target solutions.

Survey Responses

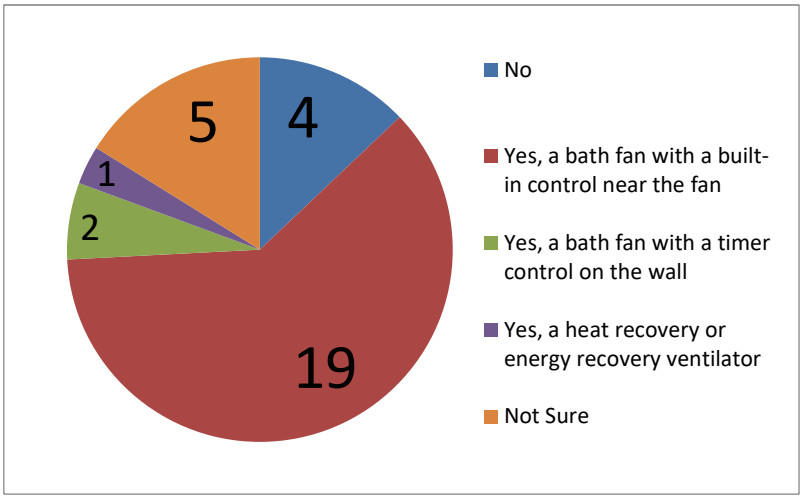
Each question that was asked in the survey is included below. Each survey question is stated below exactly as it was written in the survey, and all responses are reported exactly as they were written on the survey. The results of each survey question are shown below, with a short discussion of each result.

1) Do you own or rent the house?



The survey primarily captured homeowners, with only one renter responding. This question was intended to properly characterize the survey recipients and to understand if there was any difference in the knowledge of homeowners vs. renters in regards to attributes of their ventilation systems and knowledge regarding the systems. Due to the very low response rate of renters, this comparison cannot be made with significance. However, the knowledge that these survey responses are almost entirely from homeowners is a useful lens through which to view the responses to the following questions.

2) Does your house have a whole-house mechanical ventilation system?



One major finding from this survey is that a total of twenty-nine percent (29% (n=9)) of respondents reported either that they do not have a ventilation system, or that they do not know if they have one. Even after receiving a manual designed to help the homeowner locate their whole-house mechanical ventilation system, twenty-nine percent were not able to confidently report that they do indeed have one.

Twelve point nine percent (12.9% (n=4)) reported not even having a ventilation system. This means that their house is insufficiently ventilated by all measures: codes, standards, and relevant scientific studies. This is also evidence that ventilation codes are not being enforced properly. Sixteen point one percent (16.1% (n=5)) reported being "not sure" if they have a ventilation system. It is of note that fifty six percent (56% (n=5)) of the respondents who either do not have a ventilation system or do not know

whether they have a ventilation system also included a handwritten note in the margin of their survey indicating that they looked for it, but could not find a system. Such details were not prompted by the multiple-choice survey questions. It, therefore, appears unlikely that these responses were due to a homeowner who ~~that~~ simply failed to look for a system.

Even if these homeowners do actually have a ventilation system, but simply could not find it, it is not clear if the system is functioning. It is also intuitive that a homeowner who does not know if they even have a ventilation system will certainly not perform maintenance on it or replace it upon failure [not necessarily; this could be bundled with other services performed by a third party (handyman); but I agree with your intuition] . It is possible that some proportion of these homes do have functioning ventilation systems, but it would only be a matter of time before the unit fails due to negligence and the house would then enter a state of insufficient ventilation.

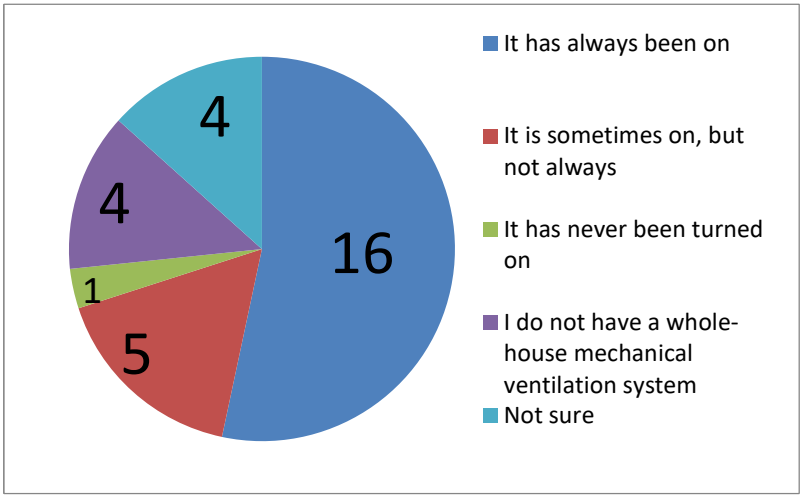
As stated in the background section of this paper above, there is strong evidence that homes built to the Massachusetts code's tightness standards without a functioning ventilation system can have a variety of negative human health impacts. The result of this survey question is, therefore, evidence that a significant percentage of homes built under the 2012 IECC or a more strict code in Massachusetts are currently at risk of exhibiting Sick Building Syndrome and other negative consequences of low ventilation rates.

Multivariate analysis showed that ninety five percent (95% (n=21)) of respondents with ~~that have~~ a ventilation system have a bathroom exhaust fan. This result will not surprise anyone ~~that~~ workings in the construction industry, but provides strong data to show clearly that automatically controlled bathroom exhaust fans are the dominant choice for a ventilation system in Massachusetts. Only one home with a heat recovery ventilator was captured in this survey.

It is also of note that six point five percent (6.5% ; ~~(~~n=2~~)~~) of respondents reported having a bathroom fan with a timer located on the wall. These systems are actually

illegal, as the Massachusetts Amendments to the IECC 2012 and 2015 state specifically that the ventilation system needs to be "continuously operating" (State Board of Building Regulations and Standards, 2016). There is very little precision in this survey result due to the low number of responses and the survey's high margin of error, but it is still an interesting finding that might spur an additional hypothesis to be tested by a survey with a higher sample size and tighter margin of error.

3) How often has your whole-house mechanical ventilation system been "on" since you have lived in the house?



Multivariate analysis showed that of the respondents who reported that they do have a ventilation system, Twenty-two point seven percent (22.7% (n=5)) reported having ventilation systems that are "Sometimes, but not always on." This does not include one of the respondents with a bathroom exhaust fan wired to a wall-timer, as that particular respondent reported that "It has never been turned on." However, that respondent's system is now almost certainly operating "sometimes, but not always" effectively making this percentage twenty-seven point two (27.2% (n=6)). The Massachusetts Energy Code explicitly states that mechanical ventilation must be

"continuously operating" (State Board of Building Regulations and Standards, 2016). These systems, therefore, are not up to code. A space was left on the survey page after this particular response choice which asked the recipient to "please describe." All five respondents included a description. The results are shown below:

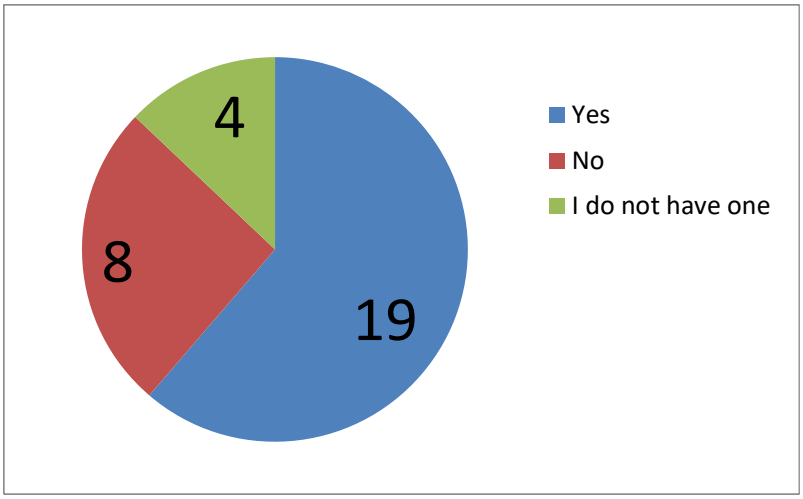
- "It is only on 3 of 7 days of the week."
- "Occasionally shuts off automatically."
- "It runs periodically, several times per day."
- "Fan ventilates every night from 12am to 8am."
- Motion Sensor.

These responses are quite confusing, as all but one of these five respondents reported that their ventilation system is a bathroom exhaust fan with controls near the fan. The most popular models of bathroom exhaust fans with built-in timer controls are designed to be run continuously and do not easily allow for intermittent control. It appears likely that these responses represent either that their ventilation system was wired incorrectly, an external timer was added, or that these respondents answered that their bathroom exhaust fan had built-in controls but should have answered that it had controls "on the wall." It may also be that the homeowner is manually controlling the system. A field study would be very useful to help determine the cause of this significant percentage of ventilation systems operating intermittently.

It is clear that these systems do not meet code, but it is less clear how well each of these ventilation systems functions and if the residents of these houses should be considered at significantly elevated risk of Sick Building Syndrome and associated issues. There appears to be a lack of studies demonstrating the relationship between intermittent ventilation systems (and their infinite number of different potential schedules) with the indoor air quality of these homes. It seems to be a reasonable hypothesis that these homes would demonstrate elevated levels of pollutants during the "off" periods and would dilute the pollutants during the "on" periods (assuming a sufficiently high ventilation rate), but constant mechanical ventilation rates have been used in nearly all studies that directly measured human health markers as correlated with

ventilation rates so this relationship is unclear and almost certainly different for each different schedule.

4) **Before receiving this letter, did you know that your house has a whole-house mechanical ventilation system?**



Twenty-five point eight percent (25.8% (n=8)) of respondents reported that they did not know that they had a whole-house ventilation system until receiving the survey package sent for this study. Multivariate analysis showed that this was the answer selected by all of the respondents who answered that they were "not sure" if they had a ventilation system. Multivariate analysis showed that of the respondents who were able to report confidently that

they do have a ventilation system, thirteen point six percent (13.6% (n=3)) did not know that they had one until receiving the survey package.

The results of this question show that there is a significant lack of understanding about the existence of mechanical ventilation systems among the owners of airtight homes in Massachusetts. These results also suggest that some survey recipients that did not previously know they had a ventilation system successfully learned about its' existence from this mailing. This finding suggests that a mailing may be an effective tool to educate some existing homeowners about their ventilation systems. A replication of this study with a higher targeted sample size would not only achieve higher precision, but it appears that it could also act to improve awareness for some percentage the recipients. This study design can be effectively used both to learn more about these issues and help to solve them simultaneously.

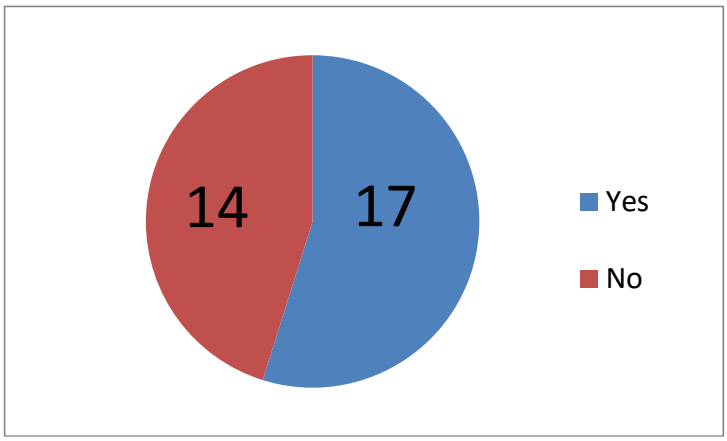
5) Before receiving this letter, which of the following did you know how to accomplish? (Select all that apply)

Response	n	% of total
Turn the whole-house ventilation system on and off	9	29.0%
Change the system's timer settings	5	16.1%
Change the system's airflow settings	2	6.5%
Perform proper maintenance on the system	2	6.5%

It is clear from the survey that a significant number of homeowners do not understand how to operate their ventilation systems. This is demonstrated most clearly by only twenty-nine percent (29% (n=8)) knowing how to turn their systems on and off. It is also significant that very few (n=2) respondents know how to change the airflow and timer settings of their system. This indicates that of those homeowners who know that they have a system only understand that it exists and are not capable of operating it. It therefore appears that the ventilation rates in these houses are primarily at the mercy of whoever originally programmed the system's settings. There appears to be a strong need for a field study which tests the settings of ventilation systems to understand if the proper settings are being used.

The question regarding "proper maintenance" was included primarily for respondents that have a heat recovery ventilator because these systems have significant maintenance requirements. "Proper maintenance" is certainly not clear for a bathroom exhaust fan, as there is little maintenance to be done other than basic cleaning. This is a tricky and unfocused question for a homeowner with a bathroom fan ventilation system. There was only one respondent that reported having a heat recovery ventilator, so the results from this portion of the question are not significant.

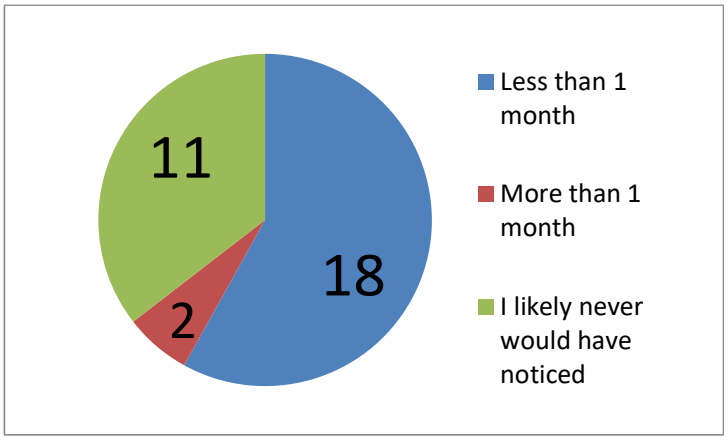
6) Before receiving this letter, did you know that your house needs a whole-house mechanical ventilation system operating to maintain proper indoor air quality?



Forty-five point two percent (45.2% (n=14)) did not know that their house needs a ventilation system to maintain proper indoor air quality before receiving the survey package. This result is another clear and significant example that homeowners lack understanding about their ventilation systems. Multivariate analysis showed that twelve percent (12% (n=2)) of the homeowners who reported that they knew that they had a whole-house ventilation system reported that they did not understand its purpose. This survey result very clearly displays that a significant number of Massachusetts

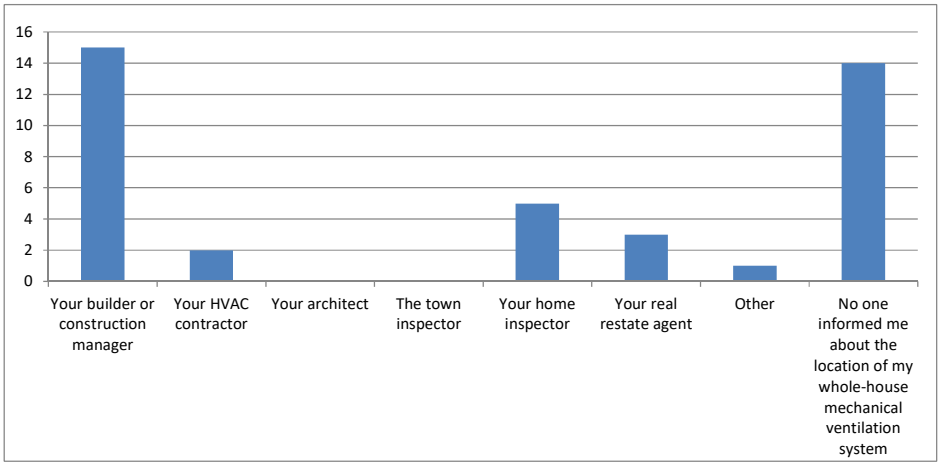
homeowners lack education about the need for mechanical ventilation systems in their homes.

7) **Before receiving this letter, how long do you think that it would have taken you to notice if your ventilation system stopped working?**



Multivariate analysis shows that the respondents who reported that they "likely never would have noticed" if the ventilation system failed are primarily the same respondents that reported either that they do not have a ventilation system or were not sure if they have one. However, of those that reported that they do have a ventilation system, nine percent (9% (n=2)) also reported that they likely would have never noticed if it failed. A survey replication with more samples and higher precision would help to better understand the likelihood that an occupant with a ventilation system would notice in a reasonable timeframe after it fails.

8) **If you were informed about the location of your whole-house mechanical ventilation system upon moving into the house, please check the box next to the source of this information.**

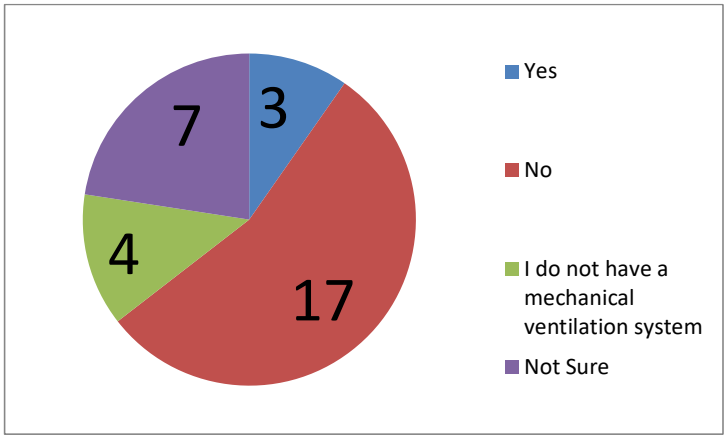


This question was intended to understand which actors have been successfully educating homeowners about their ventilation systems and which actors have not. The results of this question could be helpful when designing a strategy to improve education regarding ventilation systems. Multivariate analysis showed that of the homeowners who responded that they understand that they have a ventilation system, most were informed by their builder or a construction manager (68.2%, n=15). It should be noted that three of these respondents wrote in the margin of the survey, without being asked, that they only learned about the ventilation system

from their builder after asking why it was not shutting off. Builders and their managers seem to be the most effective leverage points to improve homeowner awareness and education, as they have shown to be an effective educational channel for a significant number of respondents. However, the three respondents ~~that~~ who were not taught about their ventilation system until asking about it combined with the fourteen respondents that were never informed by their builder about the need for a ventilation system (total of 61.6%, n=16) show that there is significant room for improvement in builders' educating their homebuyers about these systems. Real estate agents and home inspectors might be other important actors to target, as they tend to have direct contact with a homebuyer, but were only a source of ventilation system education for 9.7% (n=3) and 16.1% (n=5) of respondents respectively. It is also a reasonable hypothesis that properly educated real estate agents and home inspectors would be one major key to ensuring that a new homeowner is educated about the ventilation system when any of these homes are re-sold, as the builder would likely be removed from the process at that point.

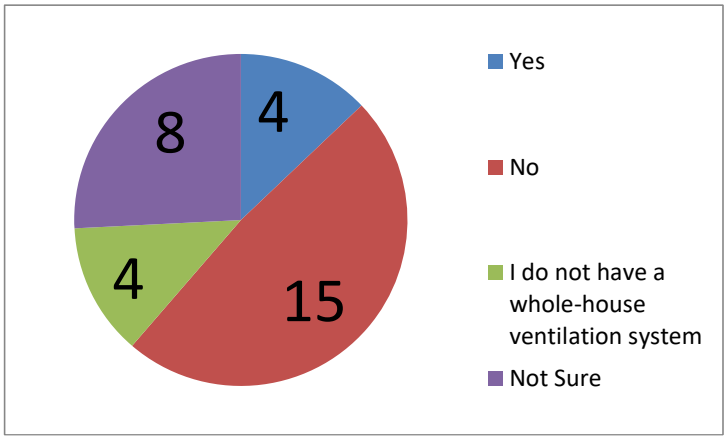
The one respondent who selected "Other" wrote that a Home Energy Rater was the source of information.

9) Upon moving in to the house, did your whole-house ventilation system have a label on the system or its controls that clearly identified it as your whole-house ventilation system?



The Massachusetts amendments to the 2012 and 2015 IECC Energy Code state that "Ventilation controls shall be labeled with regard to their function, unless the function is obvious." (State Board of Building Regulations and Standards, 2016). This requirement of the Code was designed to make homeowners aware of their ventilation system. The results of this survey question clearly indicate that this code requirement is not being followed or enforced, as multivariate analysis showed that only thirteen point six percent (13.6% (n=3)) of the respondents who reported that they do have a ventilation system reported that the controls were labeled when they moved into the house. One major leverage point for improvement of the in-service rate of ventilation systems in Massachusetts may be stronger enforcement of this Code requirement.

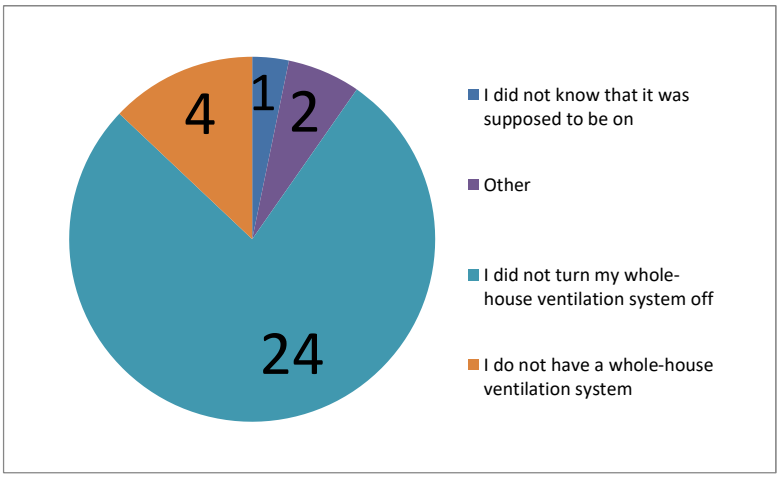
10) Upon moving in to the house, were you provided with a document including information on the design, operation, and maintenance of the whole-house ventilation system?



The Massachusetts amendments to the 2012 and 2015 IECC Energy Code state that "The owner and the occupant of the dwelling shall be provided with information on the ventilation design and systems installed, as well as instructions on the proper operation and maintenance of the ventilation systems" (State Board of Building Regulations and Standards, 2016). This Code requirement was designed to make homeowners aware of their ventilation system and educate

them on how to properly operate and maintain it. The results of this survey question clearly indicate that this Code requirement is not being followed or enforced, as multivariate analysis showed that only eighteen point two (18.2% (n=4)) of the respondents who reported that they do have a ventilation system reported receiving such a document. One major leverage point for improvement of the in-service rate of ventilation systems in Massachusetts may be stronger enforcement of this Code requirement.

11) If you turned your whole-house ventilation system off, please describe why you decided to turn it off (Select all that apply)



Multivariate analysis showed that thirteen point six percent (13.6% (n=3)) of respondents that reported having a ventilation system intentionally turned their ventilation systems off. One of these respondents was the same respondent that reported using the ventilation system for only three out of seven days. The respondent's answer to this question was "I believe it is not good to run it 24/7 – should be shut off occasionally." Another said that "I do not run the ventilation system when using Heat or AC (Winter/Summer)." The third respondent reported that they did not know that it was supposed to be on. These respondents each demonstrate a lack of

understanding of the role that their ventilation system is meant to play in their home and represents a home that likely has low ventilation rates at least some of the time and an elevated risk of Sick Building Syndrome and associated symptoms amongst the building's occupants.

12) Compared to your previous residence, are any of the following statements true? (Select all that apply)

Response	n	% of Total
Someone living in this house has noticed an increase in the symptoms of allergies	1	3.3%
Someone living in this house has noticed an increase in asthma or another respiratory symptom	0	0.0%
Someone living in this house has noticed a decrease in sleep quality	3	10%
Someone living in this house has noticed increased fatigue when inside the house	3	10%
Someone living in this house has noticed generally poor air quality	0	0.0%
There seems to be more moisture inside the house (Condensation on windows and windowsills, etc.)	3	10%
There has been mold growth on building materials inside the house	1	3.3%
None of the above	21	70.0%

This question was designed to utilize multivariate analysis to explore potential correlations between respondents' reporting that they do not have a functioning ventilation system with some of the known symptoms of a house with low ventilation rates. The wording of this question asks the respondent to compare their current home to their previous residence, which, admittedly, means that there are significant unknown variables regarding the respondents' previous residence that would ideally be controlled for. These response choices are also

somewhat subjective. The responses to this question are, therefore, limited in their predictive power. There was no way to design a properly-controlled and objective question that could allow an understanding of the correlation between these symptoms and the presence of a mechanical ventilation system within the context of this small survey study. This question was asked in the spirit of a "Pilot Study" in order to potentially achieve results that might lead to the development of additional hypotheses and perhaps subsequent studies that would be better controlled and have a higher sample size. One respondent did not answer this question (total n = 30).

With those limitations in mind, there are a few interesting findings to report. First, thirty percent (30% (n=9) reported an increase of at least one of these building or health-related symptoms compared with their previous home. Of those nine respondents, three reported that they do not know if they have a ventilation system, two reported that they do not have a ventilation system, one reported that their system does not operate continuously because it is wired to a motion sensor, and one had a ventilation system that was turned off until the homeowner received the survey package. The other two reported having functioning ventilation system; one has a bathroom fan with a built-in timer and the other has a heat recovery ventilator. In total, multivariate analysis showed that of the respondents reporting at least one of these symptoms, seventy-seven point six (77.6% (n=7)) do not have a ventilation system, do not know if they have a system, were not operating their system previously, or have a system that does not operate continuously.

It is interesting that three respondents reported an increase in fatigue when inside their house compared with their previous home. One of these respondents also reported a reduction in sleep quality, and that respondent reported that they do not know if they have a ventilation system. Another respondent reported that they did not have a ventilation system and the third respondent had never turned their ventilation system on until receiving the survey package. There are some key variables that would need to be controlled for to draw any conclusions about this potential correlation. However, it is interesting that of the only three respondents, who reported increased fatigue in the house, one definitely was not using their ventilation system and the two could not confirm that they had one. There are no definitive conclusions that can be

drawn from this data alone, but this result and its description might help to inform the development of a hypothesis which could be tested in a future study.

It is also interesting that three respondents reported that someone in the home has had a reduction in sleep quality in their new house compared with their previous home. Of course, there are many variables, such as noise and lifestyle changes, that would need to be controlled for to draw any conclusions about this potential correlation. However, it is interesting that one of these three respondents reported that they did not know if they had a ventilation system and another reported that their ventilation system "occasionally shuts off automatically." The third reported having a functioning bathroom exhaust fan with a built-in timer control. There are no conclusions that can be drawn from this data alone, but this result and its description might help to inform the development of a hypothesis which could be tested in a future study.

Three respondents reported that there seems to be more moisture inside the house than their previous home. One of these three respondents reported that they did not know if they had a ventilation system, one reported that their ventilation system "occasionally shuts off automatically" because it is wired to a motion sensor, and the other reported having a functioning heat recovery ventilator. New homes do tend to have more moisture than older homes, as building components like the framing and concrete release their moisture content into the indoor air over time. However, with a properly functioning ventilation system, this excess moisture content should be ventilated and should not be noticeable to a homeowner. The sources of excess moisture (showers, cooking, basement leaks etc.), as well as the use of bathroom and kitchen exhaust fans for spot moisture ventilation would need to be controlled for in order to understand this potential correlation with significance. There are no conclusions that can be drawn from this data alone, but this result and its description might help to inform the development of a hypothesis which could be tested in a future study.

One final interesting finding is that there was one respondent who reported that they are "not sure" if they have a mechanical ventilation system and also reported an increase in the symptoms of allergies, a decrease in sleep quality, and an increase in fatigue in their new house compared with their previous home.

General Discussion

The survey's results show that a total of forty-five point two (45.2% (n=14)) of respondents either do not have a ventilation system, do not have a system that meets code, or aren't sure whether they have a system. Within the conservative 17.6% maximum margin of error of this survey and using the very conservative estimate of 14,500 currently-affected houses, it appears that there may be 4,002 to 9,048 homes in Massachusetts that currently fall into one of these categories. U.S. Census data for Massachusetts suggests that approximately 2.4 people live in the average single-family home in the state (U.S. Census Bureau, 2017). Therefore there may, conservatively, be somewhere between 9,604 and 21,715 people living in these airtight houses without a ventilation system that is up to standards. Studies suggest that these people may be subject to a variety of health issues from living in a building with such a low effective ventilation rate. The data is very clear that homeowners lack understanding about their ventilation system, but the data also show that homeowners are not the only ones who need to be educated. It appears that builders are not always installing ventilation systems that meet the State Code and are not always properly educating the buyers of the homes they construct. It also appears that town building inspectors are not always enforcing ventilation systems that meet the code.

This study's data suggest that the $3ACH_{50}$ airtightness and whole-house mechanical ventilation system requirements were adopted in the state's building code without sufficiently investing in educational campaigns to ensure the use and understanding of the ventilation system among buildings' occupants. Given Massachusetts' climate goals and its adoption schedule of increasingly strict energy codes moving forward, it seems very unlikely that the code requirements of an airtight building shell with a mechanical ventilation system will be relaxed in the foreseeable future. Therefore, it seems that there should be a significant educational campaign focused on improving the education of the conservatively-estimated 35,000 people currently living in homes constructed under these codes. It also seems that there should be a significant educational campaign targeted in a way that ensures the education of the estimated 20,000 additional people that will become occupants of airtight mechanically-ventilated homes in Massachusetts during each year.

The cost of the survey, not including the value of labor time, was approximately $2.00 per survey package. At a response rate of 12.9%, the cost per returned survey was approximately

$15.50. In order to achieve a maximum margin of error of 5% at 95% confidence, a replication of this study would need to receive 384 survey responses. Therefore, the cost to replicate this survey with high precision would be approximately $6,000, not including labor costs. This cost could likely be reduced due to efficiencies of scale. There would also be a significant increase in cost if a replication intends to also include non-English speaking occupants into the survey sample. This cost was beyond the budget of this self-funded graduate capstone project, but seems to be a relatively very low cost to a larger organization, such as the Commonwealth of Massachusetts, to better understand these important issues. It is, therefore, recommended that state and other public or private organizations that are involved with the energy code adoption and/or enforcement pursue a larger and more precise study, which they could then use to inform the optimal design of a significant educational campaign. As demonstrated by the respondents who learned about their ventilation system and its function after receiving this study's survey package, such a replication would also simultaneously serve as an educational tool for some percentage of the targeted building occupants.

It should be noted that homes built to the 2012 and 2015 IECC are not the only homes in Massachusetts that have low natural ventilation rates and whole-house mechanical ventilation systems. There are also a very significant number of homes that were constructed before July 2014 in this fashion, in order to meet the requirements of ENERGY STAR, the New Homes with Energy Star Rebate Program, and/or the federal Energy Efficient Homes Tax Credit. Many homes were constructed from July 2014 through January 2017 in communities that used the "Stretch" Energy Code rather than the "Base" Energy Code, which did not have an implicit $3ACH_{50}$ requirement, but required a certain Home Energy Rating Score (HERS) to be achieved. Tightening the building envelope was one popular method to reduce the HERS score and meet this code. All estimates of the total number of homes that are airtight and use mechanical ventilation systems are significantly underestimated in this report because only homes that fell under the 2012 or 2015 IECC were included. However, an effective educational campaign would need to incorporate these other homes as well. A replication of this study should be performed for these other populations of airtight mechanically-ventilated homes in Massachusetts.

Conclusion

The new energy code strategy of "build tight and ventilate right" has the chance to bring the benefits of airtight, well-ventilated homes into the mainstream in Massachusetts and beyond. However, the strategy also has the potential to create human health and building longevity issues that could ruin the reputation of energy-efficient construction if mechanical ventilation isn't properly implemented with consistency. This study shows that a significant number of homes built under the 2012 or 2015 IECC in Massachusetts do not have a functioning ventilation system. A significant number of homes have a ventilation system that does not meet code. A significant number of homeowners are unaware that they have a ventilation system. A significant number of homeowners are unaware of why they need a ventilation system to operate continuously in their airtight house. A significant number of homeowners do not know how to operate their ventilation system. Building Code requirements meant to improve occupants' education, such as giving the occupant an information manual for the ventilation system and the labeling of ventilation controls are not being followed or enforced.

There are also many potential ventilation issues that can be encountered, even with a ventilation system that meets the code, which could not be captured in this study. The primary recommendations are to replicate this study with a higher sample size, replicate this study for other populations of airtight homes such as those that went through the New Homes with Energy Star rebate program, perform a field study to understand the incidence rates of improper settings and poor installations, and to pursue a significant educational campaign aimed at the existing and future occupants of these homes. An educational campaign might include some combination of a targeted mailer, the use of common advertising media such newspapers and the Internet, a targeted program utilizing field representatives to personally test systems and educate occupants, or perhaps changes to the building code. For example, one simple code change that may be effective would be to require that a standardized "Warning" label be affixed to a permanent location such as the home's main circuit breaker which states something to the effect of: "This home was built airtight to energy efficient standards. A continuously operating ventilation system is required to maintain proper indoor air quality." [Why not go a step further, adding "…and thereby minimize potential respiratory and other health risks?"]

With proper education to builders, inspectors, and homeowners, these issues can be overcome and the new era of Massachusetts homes following the "build tight and ventilate right" methodology can be energy efficient while also promoting the health of occupants. However, if the necessity of mechanical ventilation in these homes is not brought to light with a very significant educational campaign, this generation of houses could impact the health of the people occupying them and gain the reputation as dangerous to live in. [Really minor esthetic point: good that you're landing with a major, parting comment; unfortunate that your final sentence ends with a preposition.]

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Appendix A – The Survey Package

Dear Homeowner/Resident,

I am a Harvard University Student conducting research on new homes for a Masters' Capstone Project. You are receiving this survey because your new home was built airtight due to strict Massachusetts State energy codes. These energy codes require that your home was built with a whole-house mechanical ventilation system that brings fresh air into the house. Homes built to these new airtightness standards need to have a mechanical ventilation system operating at all times or the house's air quality will suffer. **Research has linked airtight buildings without mechanical ventilation to increased rates of asthma, respiratory infections, and allergies, as well as a decrease in brain function. There is even evidence that a lack of ventilation in a home could increase the risk of certain types of cancer. Research has also shown that these buildings are very prone to mold growth and moisture damage.**

The purpose of this survey is to understand if these new airtight homes have mechanical ventilation systems, if the systems are being used, and if the residents of the homes like you understand the systems.

I would very much appreciate if you could please fill out this very short two-page multiple-choice survey. A postmarked envelope has been included to return your responses. Your confidentiality and anonymity will be maintained. You are not being asked to include your name or address in your response, and your response will be anonymous. Your address was selected using a database of new homes and no effort was made to identify you.

The following page includes pictures and descriptions of the most common whole-house ventilation systems in order to help you find and identify your system if you do not already know. Please review this page and look for your ventilation system before completing the survey. If you do not have a whole-house mechanical ventilation system, or are not sure if you have one, please still complete the survey.

Thank you!

Jason Morse

Graduate Student, Sustainability Program

Harvard University

Types of Whole-House Mechanical Ventilation Systems

Bathroom Fan with Timer Controls

Often builders will install a special bathroom fan in at least one of the bathrooms that can also act as your whole-house mechanical ventilation system. Common trade names for these systems are the "Panasonic Whispergreen" and the "Broan Ultragreen". These fans are quiet, but you should be able to hear the fan running constantly if you listen closely. You will not be able to turn the fan off by using the switch on the wall, though using the switch might make the fan run faster or slower.

If you are not sure, you can verify that this is your whole-house mechanical ventilation system by pulling back the faceplate and looking inside the fan. If the fan is meant to be a whole-house mechanical ventilation unit, it will have a control box near the fan that looks something like the picture to the right →

It is possible that the timer control was placed on the wall instead of near the fan. If so, the timer would have the option of programming a daily or weekly schedule for the fan and will look something like one of the controls shown below:

All bathrooms should have a bathroom exhaust fan, but not all bathroom fans function as a whole-house mechanical ventilation system. If you do not see one of these controls pictured to the left, your fan is likely not a whole-house ventilation fan and is only meant to remove odors and moisture from your bathroom. If the fan is controlled by a simple switch or a countdown timer (shown below) that does not allow you to program the fan's schedule daily or weekly, the fan is NOT your whole-house mechanical ventilation system.

Heat Recovery and Energy Recovery Ventilators

Your house might also have a Heat Recovery Ventilator or an Energy Recovery Ventilator. It would likely be located in the basement, a mechanical closet, or possibly in an attic space and would look something like the picture to the right. There would likely be a marking somewhere on the outside of the unit describing it as either a "Heat Recovery Ventilator" or an "Energy Recovery Ventilator"

Please check the box next to the most appropriate answer.

- ☐ I understand that my participation in this survey is purely for research purposes, and that my confidentiality and anonymity will be maintained

1) Do you own or rent the house?

- ☐ I am the homeowner
- ☐ I rent the house

2) Does your house have a whole-house mechanical ventilation system?

- ☐ No
- ☐ Yes, a bath fan with a built-in control near the fan
- ☐ Yes, a bath fan with a timer control on the wall
- ☐ Yes, a heat recovery or energy recovery ventilator
- ☐ Yes, Other (Please Describe): _____
- ☐ Not sure

3) How often has your whole-house mechanical ventilation system been "on" since you have lived in the house?

- ☐ It has always been on
- ☐ It is sometimes on, but not always (Please Describe): _____
- ☐ It has never been turned on
- ☐ I do not have a whole-house mechanical ventilation system
- ☐ Not sure

4) Before receiving this letter, did you know that your house has a whole-house mechanical ventilation system?

- ☐ Yes
- ☐ No
- ☐ I do not have one

5) Before receiving this letter, which of the following did you know how to accomplish? (Select all that apply)

- ☐ Turn the whole-house ventilation system on and off
- ☐ Change the system's timer settings
- ☐ Change the system's airflow settings

- ☐ Perform proper maintenance on the system

6) **Before receiving this letter, did you know that your house needs a whole-house mechanical ventilation system operating to maintain proper indoor air quality?**

- ☐ Yes
- ☐ No

7) **Before receiving this letter, how long do you think that it would have taken you to notice if your ventilation system stopped working?**

- ☐ Less than 1 month
- ☐ More than 1 month
- ☐ I likely never would have noticed

8) **If you were informed about the location of your whole-house mechanical ventilation system upon moving into the house, please check the box next to the source of this information.**

- ☐ Your builder or a construction manager
- ☐ Your HVAC Contractor
- ☐ Your architect
- ☐ The town inspector
- ☐ Your home inspector
- ☐ Your real estate agent
- ☐ Other (Please describe) _____
- ☐ No one informed me about the location of my whole-house mechanical ventilation system

9) **Upon moving in to the house, did your whole-house ventilation system have a label on the system or its controls that clearly identified it as your whole-house ventilation system?**

- ☐ Yes
- ☐ No
- ☐ I do not have a whole-house mechanical ventilation system
- ☐ Not Sure

10) **Upon moving in to the house, were you provided with a document including information on the design, operation, and maintenance of the whole-house ventilation system?**

- ☐ Yes
- ☐ No
- ☐ I do not have a whole-house mechanical ventilation system
- ☐ Not Sure

11) **If you turned your whole-house ventilation system off, please describe why you decided to turn it off (Select all that apply)**

- ☐ I did not know that it was supposed to be on
- ☐ It was too noisy
- ☐ I believed that it was wasting energy
- ☐ Other (Please Describe): _____

- ☐ I did not turn my whole-house ventilation system off
- ☐ I do not have a whole-house mechanical ventilation system

12) Compared to your previous residence, are any of the following statements true? (Select all that apply)

- ☐ Someone living in this house has noticed an increase in the symptoms of allergies
- ☐ Someone living in this house has noticed an increase in asthma or another respiratory symptom
- ☐ Someone living in this house has noticed a decrease in sleep quality
- ☐ Someone living in this house has noticed increased fatigue when inside the house
- ☐ Someone living in this house has noticed generally poor air quality
- ☐ There seems to be more moisture inside the house (Condensation on windows and windowsills, etc.)
- ☐ There has been mold growth on building materials inside the house
- ☐ None of the above

Thank you for your participation

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Jason--

This is a Capstone for which you and the Sustainability Program should be justifiably proud. You succeeded wonderfully at completing what you originally proposed, and then kept going. The resulting capstone has much to its credit:

- Importance including significant potential for avoiding major health risks currently incurred,
- High relevance at local, state, and national levels,
- Thorough review of extensive literatures and inclusion of additional sources, such as Census data,
- Superbly organized and written text,
- Well-designed survey,
- Effective analysis of results, including appropriate multi-variate statistics enabling error analysis, and interpretation of their meaning.
- Solid conclusions and recommendations.

Unlike most of my Capstone reviews, my only edits here were miniscule and can be readily dispatched in minutes -- e.g. page numbering (big whoop!).

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With more time, a few further steps would make this high altitude accomplishment approach stratospheric levels. Though neither expected, nor necessary for your final Capstone submission, these might include:

- Further addressing of points raised by your citation of Francisco et al, 2017, particularly the nature of increased radon exposure associated with heat recovery ventilation in basements; any additional toxicants for which such ventilation might increase risk to occupants?
- Mentioning legal liability issues that may open up, given higher likelihood of lawsuits for plaintiffs claiming damages from sick building syndrome, where clear guidelines regarding ventilation were never provided.
- In light of overlap with Hill's (1999) findings, more discussion of the unique value contribution of your work would be helpful.
- Development of a graphic, if not quantitative, model that unpacks the relative contributions to sick building syndrome of inadequate ventilation, in decreasing magnitude of impact.

Final upshot: Bravo, well done! Capstone project grade: A

Best,

Rick