DURABLE AIRTIGHTNESS IN SINGLE-FAMILY DWELLINGS: FIELD MEASUREMENTS AND ANALYSIS

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ABSTRACT

This study presents a comparison of air leakage measurements collected recently (November 2013 to March 2014) with two sets of prior data collected between 2001-2003 from 17 new homes located near Atlanta, GA, and 17 homes near Boise, ID that were weatherized in 2007-2008. The purpose of the comparison is to determine if there are changes to the airtightness of building envelopes over time. Durability of building envelope is important to new homes that are increasingly built with improved levels of airtightness. It is also important to weatherized homes such that energy savings from retrofit measures, such as air sealing, are persistent. Analysis of the multi-point depressurization data shows that the blower tests characterized the air leakage at 50 Pa pressure difference well. This is shown by good agreement between air changes per hour at 50 Pa (ACH50 or n_{50}) as measured, and as estimated from the fitted values of leakage coefficients and pressure exponents to the multi-point depressurization data. We used Student's t-test to compare the current two sets of air leakage measurements with their respective prior data. Results suggest that the mean of 6.5 ACH50 measured recently from the new homes was higher than the mean of 5.6 measured previously in 2001-2003. Calculations of the percentage change with respect to the prior ACH50 show that all but one new home show increases in ACH50. The median percentage increase in ACH50 is about 20% for new homes, but it is nearly zero for the weatherized homes. We performed a regression analysis to describe the relationship between prior and current measurements of ACH50. For the new homes, best estimate of the slope factor is approximately 1.15, meaning that the regression model predicts a 15% increase in ACH50 over ten years. On the other hand, analysis of the weatherized homes suggests no significant increase (slope factor near 1). Further analysis of the data is underway that will characterize the potential increase in air leakage among new homes using data from ResDB (LBNL's Residential Diagnostic Database). More understanding of the factors associated with building envelope durability will eventually lead to improvements in building materials and practices that are better at sustaining airtightness in the long run.

KEYWORDS

Blower door, fan pressurization measurements, air leakage, new construction, weatherization

1 INTRODUCTION

The building industry has made great progress over the past 30 years in building homes with improved airtightness. Most homes have demonstrated improved levels of airtightness through testing shortly after construction, however, little is known about how the airtightness changes with time as houses age. This is also a concern in retrofitted homes, where the energy savings from air sealing might be short-lived if the airtightness improvements are not durable.

Analysis of the LBNL Residential Diagnostic Database (ResDB, Chan et al. 2012) suggests that the air leakage of new US single-family detached homes improves at a rate of roughly 1% per year, such that the airtightness testing results when the homes are new shows that recently constructed homes are about 10% tighter than homes built ten years ago. The database has limited test results available from homes that were built in the same year, but tested at different times after construction. Analysis of these tests also showed that for homes all built within a given year, there is an increase in air leakage at about 1% per year with respect to the age of the home when the blower door test was performed. However, this result is uncertain because there are many external factors that the regression analysis cannot account for.

To better address the question of air leakage changes with time, this study performed air leakage testing in homes where a blower door test was performed approximately five to ten years ago. This study targeted two types of homes. The first category of homes were built between 2001 and 2003, and with the blower door test performed prior to occupancy. These data will reflect a potential change in air leakage after approximately ten years. Homes to be recruited in this category had not had had any major renovations. The second category of homes had undergone retrofits, with the air-sealing work and blower door test performed between 2007 and 2008.

2 METHODS

We collaborated with two subcontractors to collect air leakage measurements of single-family homes on this project: Southface Energy Institute in Atlanta, GA, and Community Action Partnership of Idaho (CAPAI) in Boise. These organizations were selected because they had access to homes in the above two categories, i.e., (i) homes built between 2001 and 2003 that were tested for air leakage when new; (ii) homes that were weatherized between 2007 and 2008. Both Southface and CAPAI were very knowledgeable about the characteristics of the homes in their area because they worked closely with builders and homeowners in their communities. Their field technicians routinely conduct blower door tests, and are comfortable with performing variations of the blower door test besides the typical single-point measurement at 50 Pa depressurization. In this study, both pressurization and depressurization tests were performed at multiple pressure points as a way to evaluate the extent to which testing conditions may influence the air leakage results.

Southface tested 17 homes that were built between 2001 and 2003 from Atlanta and its surrounding neighborhoods of Alpharetta, Cumming, and Decatur. CAPAI also tested 17 homes that participated in low-income weatherization program between 2007 and 2008 from Boise, Caldwell, Nampa, and Notus. Southface and CAPAI reached out to potential homeowners by phone and by using mailing materials. The recruitment materials and phone scripts were prepared by LBNL and approved by LBNL's Institution Review Board (IRB) for protection of human subjects. Each participant signed a consent form, and received a small financial incentive for completing the blower door test. Personal identifiable information, such as homeowner names, full street address, and phone number, were treated as secured data by Southface and CAPAI. This information is not shared with LBNL or included in any of our reporting or analyses.

Southface and CAPAI recruited homes and conducted blower door tests between November 2013 and March 2014. In addition to the blower door test, other basic information about the homes was also collected, including floor area, number of stories, number of bedrooms, year built, foundation type, presence of an attached garage, and the type of heating and cooling equipment. General descriptions about the air barrier if presence, caulking, weatherstripping, use of spray foam and mastic at the different building components were also noted in some of the homes.

3 RESULTS

3.1 Descriptions of Sampled Homes

All the 2001-2003 new homes belonged to an energy efficiency program. Table 1 shows the basic characteristics of the 17 homes recruited for this study. They are typically 275 m^2 (3000 ft^2) in floor area, ranging between 170 m^2 and 400 m^2. Most of the homes (14 of 17) are two-stories. Many of them (9 of 17) have a basement. The number of homes with finished (5 homes) and unfinished basement (4 homes) is about equal. The remaining homes are either built on slab (4 homes) or have a crawlspace (4 homes). Most of the homes (15 of 17) are heated by forced-air furnace and cooled by centralized air-conditioning. Only two homes are the exceptions, where heat pumps are used instead for heating and cooling. Due to the large size of these homes, many of them (9 of 17) have two heating and cooling systems, where one of them is in the attic, and the other is in the basement.

Table 1: House characteristics of new homes built between 2001 and 2003.

ID	City	Year Built	Floor Area (m^2)	Ceiling Height (m)	Stories	N Bed-room	Foundation	Heating/Cooling (x2 = two systems)
N1	Cumming	2001	256	3.7	2.5	4	Crawlspace (unvent)	Heat pump
N2	Cumming	2001	243	2.7	2	4	Crawlspace (unvent)	Furnace/AC
N3	Cumming	2003	305	3.0	2.5	5	Basement (cond)	Furnace/AC
N4	Cumming	2003	191	3.0	2.5	5	Slab	Furnace/AC (x2)
N5	Alpharetta	2002	287	3.0	2	4	Basement (cond)	Furnace/AC (x2)
N6	Alpharetta	2003	305	3.7	2.5	2	Basement (cond)	Furnace/AC (x2)
N7	Cumming	2001	277	3.0	2.5	4	Basement (cond)	Furnace/AC (x2)
N8	Cumming	2001	336	3.0	2	5	Basement (cond)	Furnace/AC (x2)
N9	Cumming	2002	203	3.2	2.5	5	Basement (uncond)	Furnace/AC (x2)
N10	Cumming	2003	281	3.0	2.5	3	Slab	Furnace/AC
N11	Alpharetta	2001	330	3.0	2	3	Basement (uncond)	Furnace/AC (x2)
N12	Atlanta	2001	405	3.7	1	2	Slab	Heat pump (x2)
N13	Decatur	2002	170	2.6	1	2	Crawlspace (vent)	Furnace/AC
N14	Decatur	2002	202	3.0	1	3	Slab	Furnace/AC
N15	Decatur	2002	289	2.6	2	3	Crawlspace (vent)	Furnace/AC (x2)
N16	Cumming	2002	296	3.0	2	3	Basement (uncond)	Furnace/AC
N17	Cumming	2002	281	3.0	2	4	Basement (uncond)	Furnace/AC

Table 2 shows the characteristics of the homes sampled by CAPAI. The homes were smaller in size, with a mean floor area of 130 m^2 (about 1400 ft^2), and all of them are single-story. The common foundation types are crawlspace (11 homes) and basement (6 homes). Most crawlspaces are vented (10 of 11). There are homes with conditioned basement (4 homes) and unconditioned basement (2 homes) in the dataset. Most of the houses (13 of 17) are heated by a forced-air furnace. Three of the homes use electric baseboard as the main heating equipment, and one uses a wood pellet stove. A wide range of cooling equipment was used in these homes, including centralized AC, wall AC, window AC, or an evaporative cooler (swamp cooler). There were also three homes that currently do not have a cooling system.

It was noted by the field technician that weatherization work in these homes typically include doors/windows upgrade (14 homes received doors/windows replacement or air sealing around them), insulation of floor (11 homes) or ceiling (7 homes), and duct sealing and/or insulation (9 homes).

Table 2: House characteristics of homes weatherized between 2006 and 2008.

ID	**City**	**Year Built**	**Floor Area (m^2)**	**Ceiling Height (m)**	**Stories**	**N Bed-room**	**Foundation**	**Heating/Cooling**
W1	Caldwell	1959	87	2.4	1	3	Crawlspace (vent)	Furnace/Wall AC
W2	Boise	1978	103	2.3	1	2	Crawlspace (vent)	Furnace/Evap Cool
W3	Boise	1930s	151	2.7	1	3	Crawlspace (unvent)	Furnace/AC
W4	Boise	1977	94	2.3	1	3	Crawlspace (vent)	Furnace/AC
W5	Caldwell	1960s	101	2.4	1.5	3	Crawlspace (vent)	Furnace/AC
W6	Caldwell	1951	234	2.4	1	4	Basement (cond)	Furnace/Evap Cool
W7	Caldwell	1970s	102	2.4	1	3	Crawlspace (vent)	Furnace/Widw AC
W8	Boise	1970s	99	2.3	1	2	Crawlspace (vent)	Furnace/(none)
W9	Caldwell	1967	89	2.3	1	2	Crawlspace (vent)	Elec. /(none)
W10	Caldwell	1979	116	2.3	1	2	Crawlspace (vent)	Furnace/AC
W11	Nampa	1948	114	2.2	1	2	Basement (uncond)	Furnace/Evap Cool
W12	Notus	1974	125	2.3	1	3	Basement (cond)	Elec. /Evap Cool
W13	Nampa	1927	204	2.4	1	4	Basement (cond)	Furnace/AC
W14	Boise	1900s	117	2.7	1	2	Basement (uncond)	Elec./Wall AC
W15	Boise	1968	188	2.4	1	4	Basement (cond)	Furnace/Evap Cool
W16	Boise	1960s	122	2.5	1	3	Crawlspace (vent)	Furnace/(none)
W17	Nampa	1967	181	2.3	1	4	Crawlspace (vent)	Wood/Evap Cool

3.2 Air Leakage Measurements

All prior measurements of air leakage were collected from single-point depressurization test at a pressure difference of 50 Pa. The new homes were tested following RESNET test protocol, and the weatherized homes were tested post-weatherization following testing procedure specified by the Weatherization Assistance Program. The air change rates at 50 Pa, n_{50} orACH50 (h^{-1}), were computed from the reported airflow rates at 50 Pa divided by the house volume (Equation (1)). House volume, V (m^3), is estimated by multiplying the floor area by the ceiling height.

$$\text{ACH50} = Q_{50\text{Pa}}/V \tag{1}$$

Both depressurization and pressurization measurements were collected from the two sets of homes, with differential pressures ranging between ±30 to ±60 Pa. The leakage coefficient, C (m^3/s-Pa^n) and pressure exponent, n (-), were fitted from the depressurization test results using Equation (2).

$$Q = C \times \Delta P^n \tag{2}$$

where Q (m^3/s) is the air flow through the blower door at a differential pressure ΔP (Pa).

Estimated C for new homes has a mean of 0.10 m^3/s-Pa^n (std. dev. = 0.041). For weatherized homes, C has a mean of 0.065 m^3/s-Pa^n (std. dev. = 0.019). Estimates of n for the new homes and weatherized homes have a similar mean values of 0.68 (std. dev. = 0.074) and 0.66 (std. dev. = 0.043), respectively.

The new homes have larger leakage coefficients partly because they are larger in size than the weatherized homes. Using the fitted values of C and n, estimates of ACH50 for new homes has a mean of 6.5 (std. dev. = 2.4). For weatherized homes, the estimated mean of ACH50 is 10.2 (std. dev. = 3.6). ACH50 estimated from the fitted values of C and n are essentially the same as the ACH50 calculated from the single point measurement at 50 Pa, as shown in Figure 1. The remaindering of this analysis will use the ACH50 measured at a single point of

50 Pa depressurization, which is closer to the test protocol used to collect the prior measurements.

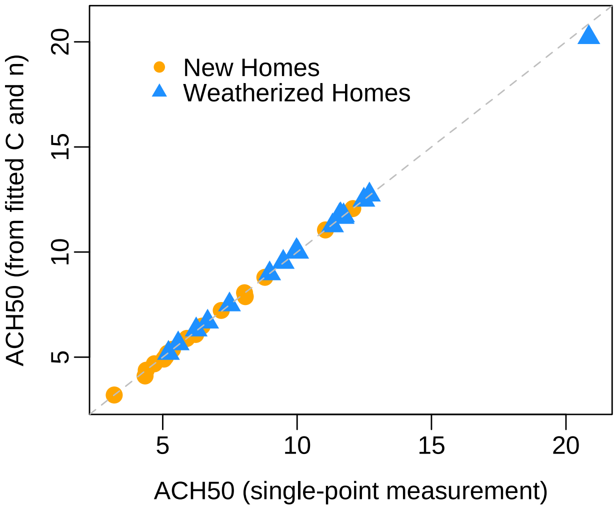

Figure 1: Comparison of the air changes per hour at 50 Pa (ACH50) in two groups of homes, calculated using a single-point measurement at 50 Pa depressurization (x-axis), and by using fitted values of *C* and *n* (y-axis).

3.3 Changes in Air Leakage

Figure 2 compares the ACH50 measured previously with the current measurements. Results from the t-test (Table 3) suggest that there is a change in ACH50 among the 2001-2003 at a 75% confidence interval (from p-value = 0.248). The confidence level improves when the ACH50 data is log-transformed that there is an increase in ACH50. On the other hand, the t-test results show no change in mean ACH50 for the weatherized homes in 2007-2008. The log-transformation has little impact on the analysis for this group of homes.

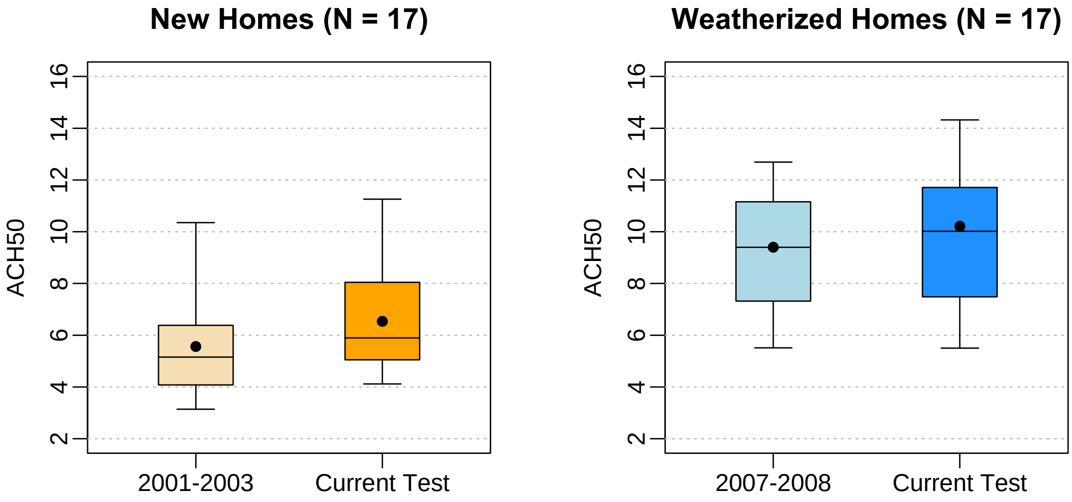

Figure 2: Comparison of the air changes per hour at 50 Pa (ACH50) in two groups of homes, where air leakage were measured previously and were repeated again recently. The boxplot shows interquartile range (25th to 75th percentile), and the median. The whiskers extend to 5th and 95th percentiles. The solid triangle shows the mean ACH50.

Table 3: Summary statistics of Student's t-test results

Dataset	**Parameter**	**Prior Test Mean ACH50**	**Current Test Mean ACH50**	**t-Test: Difference b/w Prior and Current Mean Values**	
				p-value	**95% Conf. Interval**
New Homes	ACH50	5.56	6.54	0.248	-0.71 to 2.66
New Homes	log (ACH50)	1.62	1.82	0.180	-0.10 to 0.49
Weatherized Homes	ACH50	10.21	9.40	0.460	-1.41 to 3.03
Weatherized Homes	log (ACH50)	2.27	2.20	0.577	-0.16 to 0.29

Figure 3 shows the change in ACH50 calculated from the current tests with respect to the prior tests measured in 2001-2003 for the new homes, and 2007-2008 for the weatherized homes. All but one of the new homes show an increase in ACH50. The median change is about 20%. On the other hand, there are roughly equal numbers of weatherized homes that show positive and negative changes in ACH50. The median change is nearly zero.

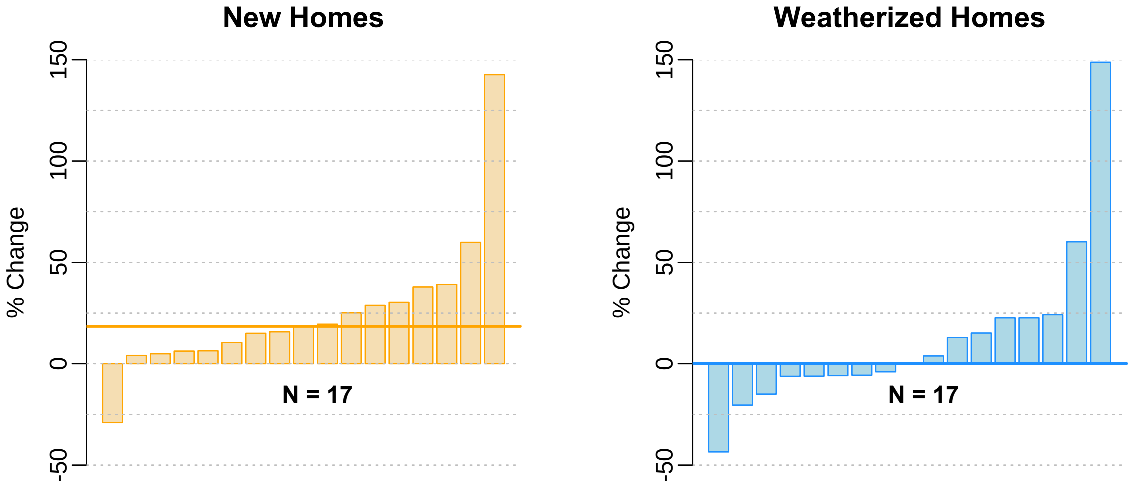

Figure 3: Percentage change in ACH50 calculated with respect to the prior values measured in 2001-2003 for the new homes, and 2007-2008 for the weatherized homes. The horizontal line indicates the median % change.

3.4 Regression Analysis

A regression analysis was preformed to describe the relationship between the ACH50 measured from the prior air leakage tests and now. The intercept was set to zero in the linear regression, as follows:

$$ACH50_{current} = a \times ACH50_{prior} \quad (3)$$

Figure 2 compares the ACH50 measured with results from the prior tests plotted on the x-axis, and results from the current tests on the y-axis. Overlaid on these figures are the results from the linear regression. Solid blue line shows the model-fit from least square estimate. The dotted blue lines shows the 95% confidence interval from the predictions. The regression results are summarized in Table 4.

For the 2001-2003 new homes, three of homes (N9, N12, and N14) indicated in Figure 4 by the "X" symbol appear to be outliners, suggesting possible abnormality with the blower door tests. If these three homes were excluded, the slope of the regression line would increase but only by a small amount. This is illustrated by the solid orange line in Figure 4. Field technicians reported problems with keeping the attic hatch door closed during the blower door test in one of these three homes (N14). N9 and N12 had the highest and lowest ACH50 estimated for this group of homes tested when new. This is perhaps an indication that their construction was unique in some ways from the rest of the group, or perhaps the data is inaccurate for some reason. Unfortunately, the prior test reports on N9 and N12 did not record any detailed information that could explain their extreme values. Excluding these three homes resulted in a slightly higher slope estimate of 1.18, instead of 1.12 (see Table 4). Based on these two estimates of the slope factor, the increase in ACH50 is about 1.15, i.e. 15% increase over ten years for these new homes.

For the weatherized homes, there was one home that showed substantial increase (W13) in ACH50, and another home that showed substantial decrease (W12) in ACH50. Table 4 shows that these two data points have negligible effect on the slope estimate. The slope estimates do not preclude zero at the 95% confidence interval. Based on this analysis, which is in agreement with the percentage change calculations presented above, we concluded that there is no significant change in the air leakage of homes that were weatherized in 2007-2008.

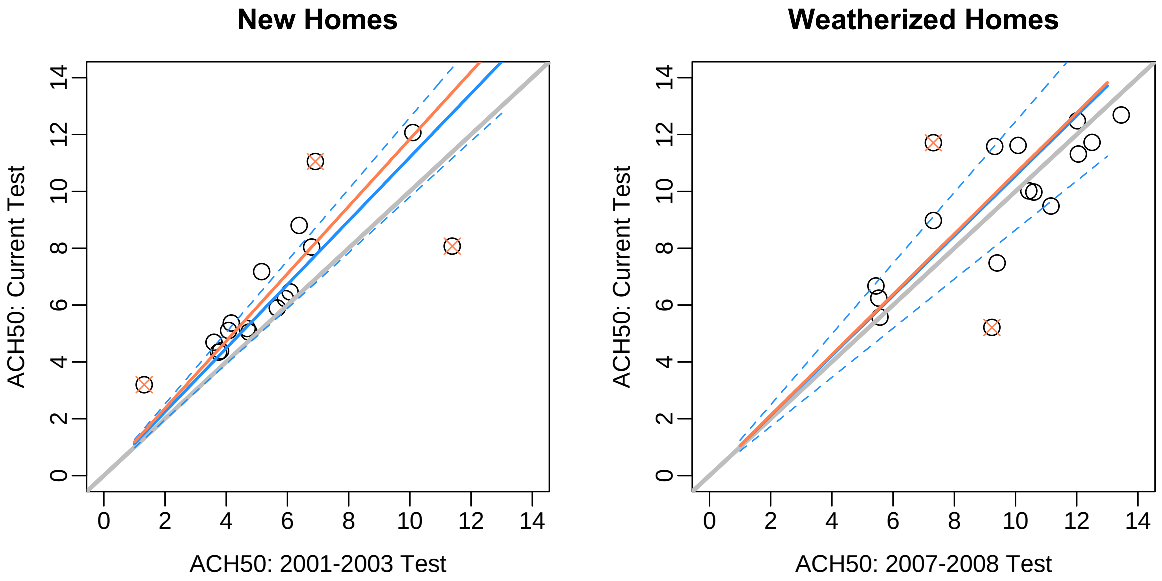

Figure 4: Comparison of the air changes per hour at 50 Pa (ACH50) in two groups of homes, where air leakage were measured previously and were repeated again recently. The boxplot shows interquartile range (25th to 75th percentile), and the median. The whiskers extend to 5th and 95th percentiles. The solid triangle shows the mean ACH50.

Table 4: Results of linear regression.

Dataset (see Figure 4 for data excluded)	Estimate of *a*	Std. Error	p-value	95% Conf. Interval	R^2
New Homes	1.12	0.066	1.17e-11	0.98 to 1.26	0.944
New Homes (excl. 3 data points)	1.18	0.031	9.60e-15	1.12 to 1.25	0.991
Weatherized Homes	1.05	0.090	2.84e-9	0.86 to 1.24	0.889
Weatherized Homes (excl. 2 data points)	1.06	0.091	1.36e-8	0.87 to 1.26	0.900

4 CONCLUSIONS

Blower door measurements in homes built between 2001 and 2003 show an increase in air leakage of about 15% in ten years. The rate of increase in air leakage observed in this study is about the same as previously analyzed in ResDB (approximately 10%), thus confirming our hypothesis that aging of the building envelope is the cause. On the other hand, effectively no increase in air leakage was observed in homes that were weatherized about six or seven years ago between 2007 and 2008. This suggests that the improvements made from weatherization were still effective. Moreover, aging appears not to occur in this later group of homes that were all built prior to 1970s.

The vastly different results from these two groups of homes suggest that the leakage sites may be different. For the weatherized homes, the joints between building components that were sealed, such as by caulking and weatherstripping around windows and doors, do not change their leakage characteristics with time. On the other hand, in new homes, the new and moist wood materials can shrink over the first several years, potentially causing leaks in the building envelope. The effect of this drying process may be similar to the relationship between air leakage and indoor humidity observed by Kim and Shaw (1986). In addition, past work by Proskiw (1998) measured the airtightness of 17 Canadian homes over an 11-year period and found leakage occurring at the floor drains, around duct penetrations and windows, even though the air barrier remained effective. The drying of wood frames leading to shrinkage and therefore gaps between building components may be one reason that could explain the leaks that were found.

Since the finding of this study is based on a small set of data from two groups of homes located near Atlanta, GA and Boise, ID. More data is needed to determine if aging of the building envelope leading to increase in air leakage is a widespread issue in the US housing stock. We plan to incorporate the measurements collected from this study with the air leakage model developed using data from ResDB. If further analysis also suggests that there is an increase in air leakage over time, then there is an opportunity for improvements in building materials and practices that can better sustain airtightness and realize the energy savings. While the change in air leakage is only about 15% over ten years based on this study, some homes experienced rather substantial increases in ACH50 (>30%). Future work to identify factors that are associated with durability issues would provide valuable information on how to improve airtightness not just test-when-new, but also in the long run.

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