Title

Durable Airtightness in Single-Family Dwellings: Field Measurements and Analysis:

Authors

Chan, Wanyu R
Walker, Iain S.
Sherman, Max H.

Publication Date

2015-06-01

LBNL-

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Durable Airtightness in Single-Family Dwellings: Field Measurements and Analysis

Wanyu R. Chan*, Iain S. Walker, and Max H. Sherman

Environmental Energy Technologies Division

June, 2015

Disclaimer

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, [Building Technologies Program] or [Federal Energy Management Program], of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Durable Airtightness in Single-Family Dwellings: Field Measurements and Analysis

Wanyu R. Chan[*], Iain S. Walker, and Max H. Sherman

Energy Technologies Area
Lawrence Berkeley National Laboratory
One Cyclotron Road, Mail Stop 90R2121, Berkeley, CA 94720, USA
[*] Corresponding author: wrchan@lbl.gov

Abstract

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. We presented a comparison of air leakage measurements collected in November 2013 through 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. The air leakage increased in all but one of the new homes, with a mean increase of about 25%. The weatherized homes also showed an increase in the mean air leakage (12%). We performed a regression analysis to describe the relationship between prior and current measurements in terms of normalized leakage (NL). The best estimate of the aging factor predicts a 15% increase in NL over ten years. Further analysis using ResDB data (LBNL's Residential Diagnostic Database) showed the expected changes in air leakage if aging were modeled. These results imply that we should examine the causes of increased leakage and methods to avoid them. This increase in leakage with time should be accounted for in long-term population-wide energy savings estimates, such as those used in ratings or energy savings programs.
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. In 2012, 16% of new single-family homes in the U.S. were Energy Star certified (USEPA 2013), where the requirement for envelope air leakage is 3 to 6 ACH_{50} (air change rates at 50 Pa) depending on the climate zone (USEPA 2011). Most homes have demonstrated improved levels of airtightness through testing shortly after construction (Chan et al 2013a), 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.

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 can explain increase in air leakage with house age. New homes built with 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). Over time, the deterioration of air sealant applied around windows and doors, joints between building components, may cause air leakage.

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 for homes that were first tested when new. Homes to be recruited in this category were restricted to those without 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. In addition, data from the LBNL Residential Diagnostic Database (ResDB) (Chan et al 2013a) were analyzed, to see if any increases in air leakage related to how long after a home was constructed at the time of testing could be discerned over a much broader range of homes and climates.

2. Methods

2.1. Field Sampling

We collaborated with two organizations 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. Both organizations had access to homes that prior air leakage measurements were made. Southface tested 17 homes that were built between 2001 and 2003 from Atlanta and its surrounding neighborhoods of Alpharetta, Cumming, and Decatur. CAPAI 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 present), caulking, weatherstripping, use of spray foam and mastic at the different building components were also available in some of the homes. The field technician reported that work in the weatherized homes typically include doors/windows upgrade, insulation of floor or ceiling, and duct sealing and/or insulation.

2.2. Data Analysis

All prior measurements of air leakage were air flows from single-point depressurization test at a pressure difference of 50 Pa, Q_{50} (m^3/s). The new homes were tested following the RESNET (2012) test protocol, and the weatherized homes were tested post-weatherization following a testing procedure specified by the Weatherization Assistance Program (Energy OutWest 2005). Because building codes, such as the IECC (2012), commonly use Air Changes per Hour at 50 Pa, ACH_{50} (h^{-1}), as the air leakage metric, we converted air leakage by dividing Q_{50} by the house volume. House volume, V (m^3), was estimated by multiplying the floor area by the ceiling height.

The new air leakage measurements for this study included both depressurization and pressurization, and were multi-point, with differential pressures ranging between ±30 to ±60 Pa. The leakage coefficient, C ($m^3/s\text{-}Pa^n$) and pressure exponent, n (-), were fitted to the depressurization test results using Equation 1. Pressurization and depressurization results often differ due to valving action in some building leaks (Walker et al 2013). Only the depressurization data were used because the prior air leakage data were measured from depressurization tests.

$$Q = C \times \Delta P^n \tag{1}$$

where Q (m^3/s) is the air flow through the blower door at a differential pressure ΔP (Pa). Q_{50} was calculated using the fitted C and n in Equation 1 at ΔP = 50 Pa. The Q_{50} values for both prior and new tests were converted to effective leakage area at 4 Pa (ELA_4) and normalized leakage (NL) for calculation of the aging factor. This conversion was performed to allow comparison to other data from ResDB that are in the form of NL.

$$\mathrm{NL} = 1000\left(\frac{\mathrm{ELA}_4}{\mathrm{FA}}\right)\left(\frac{\mathrm{H}}{2.5\ \mathrm{m}}\right)^{0.3}$$
$$\text{where} \qquad \mathrm{ELA}_4 = \sqrt{\frac{\rho}{2(4\ \mathrm{Pa})}}\,Q_{50}\left(\frac{4\ \mathrm{Pa}}{50\ \mathrm{Pa}}\right)^{n} \tag{2}$$

where ρ is the air density (1.2 kg/m^3) and H (m) is the house eave height.

Without consideration of aging factor, Equation 3 describes the relationship between NL and house characteristics, based on a regression analysis of 134,000 single-family detached homes in U.S. (Chan et al 2013a):

$$\ln(\mathrm{NL}_0) = \beta_a \mathrm{FA} + \beta_h \mathrm{H} + \overleftrightarrow{\beta_y} \cdot \overleftrightarrow{I_{YR}} + \overleftrightarrow{\beta_{CZ}} \cdot \overleftrightarrow{I_{CZ}} + \beta_{LI} I_{LI} + \beta_e I_E + \overleftrightarrow{\beta_f} \cdot \overleftrightarrow{I_{FD}} + \overleftrightarrow{\beta_d} \cdot \overleftrightarrow{I_{DT}} + \varepsilon \tag{3}$$

where β's are the fitted coefficients from the regression, FA (m^2) is the house floor area, H (m) is the house eave height, and I's are indicator variables (i.e. 0 or 1) to describe other characteristics of the house: year built (YR), climate zone (CZ), weatherization program (LI), energy efficient homes (E), foundation type (FD), and duct location (DT). The fitted coefficients of year built $\overleftrightarrow{\beta_y}$, climate zone $\overleftrightarrow{\beta_{CZ}}$, foundation type $\overleftrightarrow{\beta_f}$, and duct location $\overleftrightarrow{\beta_d}$ are vector values because there are multiple categories associated with each of the parameter, and $\overleftrightarrow{I}$ *'s* are the corresponding unit vectors indicating which bin or category the house is in. There are six year-built categories to describe homes built before 1960 to homes built after 2000, twelve climate zone categories, three floor types (slab, conditioned basement/unvented crawlspace, unconditioned basement/vented crawlspace), and three categories used to describe duct locations (inside conditioned space, in unconditioned attic/basement, in vented crawlspace); see Chan et al (2013a) for detail descriptions of these parameters and the fitted values of the regression coefficients.

We assume that the aging factor will modify the measured air leakage as follows:

$$\ln(NL_t) = \ln(NL_0) + \beta_t T \tag{4}$$

where T (years) is the age of the house when air leakage is measured. The objective of this analysis is to determine the value of β_t from the 34 homes where both values of NL_0 (i.e. NL measured at T = 0) and NL_t were known. The parameters NL_0 and NL_t in Equation 4 are log-transformed because values of NL typically follow a lognormal distribution. For the 17 homes that were weatherized, NL_0 refers to the measurement post-weatherization.

We also applied this additional term $\beta_t T$ to a subset of ResDB data to see the implications of accounting for aging explicitly to a boarder set of homes. ResDB represents a wider range of some house characteristics (e.g., year built and location) than the data collected in this study. Among the 134,000 data points in ResDB, about two-third of the data were added to the database prior to 2011 when house age at testing (i.e., T) was not entered in ResDB. Among the one-third of the data that was added to ResDB more recently, T and/or year built was missing in over half of the data, so the remaining 21,300 data points were available to observe the aging effects. The selected homes represent 22 states, where the majority was from Minnesota (64%), Georgia (14%), and California (8%). The selected homes were built between 1900 and 2010, with a fairly uniform number of homes built from each decade. For these 21,300 homes, we first used Equation 3 to calculate the value of NL_0. We then applied Equation 4 to determine if this additional aging term $\beta_t T$ helps explain the difference between NL_0 calculated using Equation 3 that did not account for aging, and NL_t that was measured. We determined this by examining if the resulted value of β_t is positive at the 95% confidence interval (CI), which would suggest that air leakage increases with age. Finally, the value of β_t calculated from the 34 homes is applied to the 21,300 homes from ResDB to explain the implications of considering aging explicitly when predicting air leakage.

3. Descriptions of Sampled Homes

3.1. Home Characteristics

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 average 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.

Table 2 shows the characteristics of the homes sampled by CAPAI. The homes are smaller in size, with a mean floor area of 130 m^2 (about 1400 ft^2), and all of them are single story.

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 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

There are differences between the two group of homes that may have implications to air leakage. For example, there are leakage pathways in homes built with a crawlspace that will not be present in homes built on slab or with a finished basement. Table 2 shows that crawlspace is a common foundation type among the weatherized homes (11 of 17) sampled by CAPAI, but it is less common among the newer homes (4 of 17) tested by Southface (Table 1). Duct leakage may add to the overall air leakage measured during a blower door test. Most of the newer homes (15 of 17) are heated by forced-air furnace and cooled by centralized air-conditioning. 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. Forced-air furnace is also the most common heating equipment among the weatherized homes (13 of 17), but a small number of them (3 of 17) use electric baseboard instead that will not have duct leakage. Homes that do not have a cooling system, or ones that use wall/window air conditioner or evaporative cooler, also eliminate the potential contribution from duct leakage.

3.2. Air Leakage Measurements

We analyzed the air leakage data in terms of ACH_{50} and NL. Figure 1 shows the change in ACH_{50} 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 ACH_{50} with a mean change of 25%. The weatherized homes also show a positive change in the mean, but it is lower at 12%. There are roughly equal numbers of weatherized homes that show positive and negative changes in ACH_{50}, but the magnitude of change tend to be greater for homes that had a positive change (+35%) than negative change (-13%). Measurement uncertainties, as a result of differences in testing conditions and the test method used, likely explained why some of the homes appeared to have improved airtightness over time. But overall, both sets of data suggest that there is an increase in ACH_{50}.

Because we are comparing multi-point ACH_{50} values to ACH_{50} values from prior single-point testing, we examined the new data to see if there was a difference between determining ACH_{50} estimated from the fitted values of *C* and *n* (Equation 1) and the ACH_{50} calculated from the single air flow measurement at 50 Pa. The differences in ACH_{50} calculated from the single-point and multi-point measurements were all within +/-3%, indicating that the reliance on single-point testing results does not introduce any significant biases.

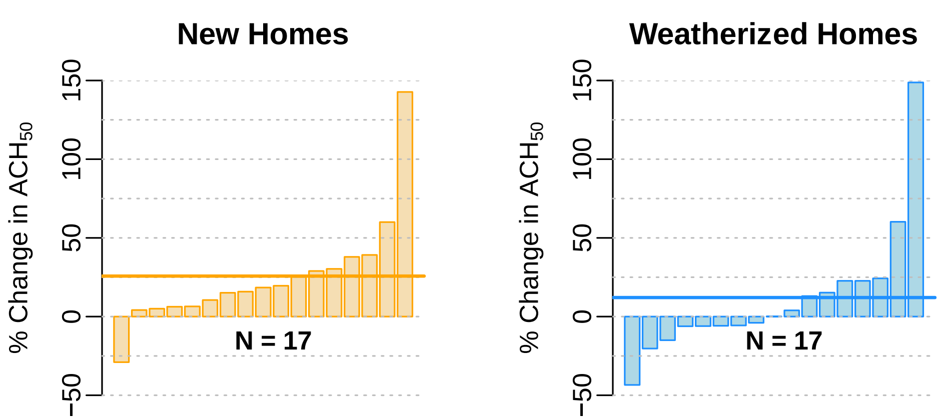

Figure 1 Percentage change in ACH_{50} calculated with respect to the prior values measured in 2001-2003 for the new homes, and 2007-2008 for the weatherized homes. The horizontal lines indicate the mean percentage change.

Distributions of NL for the two groups of homes are shown in Figure 2. Both data sets show an increase in the mean NL: 13% for the new homes, and 8% for the weatherized homes. There are increases in other statistics as well such that the boxplot of NL_t show an upward shift relative to NL_0 in both cases.

As expected, the new homes had slightly lower NL than the weatherized homes that are older in age. It is surprising, however, that the 5th and 95th percentile NL of the new homes span a wider range in values than the weatherized homes. The expectation is when homes were built to a targeted level of airtightness, the measured air leakage would should fall within a narrower range. Closer examination of the new homes data suggests that the most leaky (House N9) and the tightest (N12) measurements are potential outliers, determined by the log-transformed values having an absolute score >3 using the median absolute difference (MAD) method (RSC 2001). None of the other NL distributions shown in Figure 2 contain outliers according to this criterion. Prior blower door test reports did not record any detailed information that could explain the extreme values that were measured at N9 and N12, nor did the field technician who performed the new tests observe anything unusual at those houses. Referring to Table 1, however, there are certain characteristics of these homes that may explain the high NL calculated for N9 (small size, unconditioned basement), and the low NL calculated for N12 (large size, slab foundation). The change in mean NL_t from mean NL_0 is 21% if the two potential outliers (N9 and N13) were excluded, which is a larger change than the 13% if all data were included.

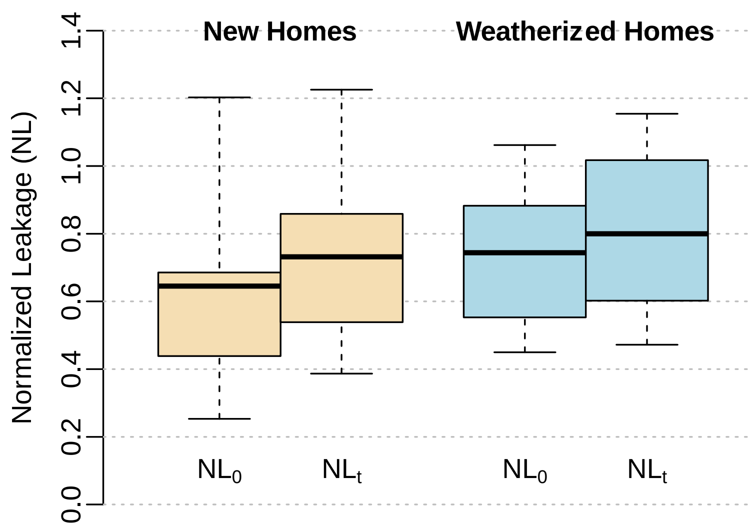

Figure 2 Comparison of NL measured when houses were new or immediately after weatherization (NL_0), and from more recent measurements (NL_t). The boxplot shows interquartile range (25th to 75th percentile), and the mean value. The whiskers extend to 5th and 95th percentiles.

4. Regression Analysis

4.1. Estimate of Aging Factor

Using both the new homes and the weatherized homes, the regression between the change in log-transformed NL as a function of the years between measurements (Equation 4) gives β_t =

0.015 per year. Table 3 shows the results of the linear regression, and also an additional analysis if four potential outliers were excluded from the analysis, as shown in Figure 3. In addition to the two potential outliers discussed before (N9 and N12), two other homes were identified (W12 and W16) that had a change in log-transformed NL substantially differ from the rest of the sample data. Again, this was determined by the same criterion as having an absolute score >3 using the MAD method. Table 3 shows that the estimated β_t is insensitive to the presence of potential outliers (value change from 0.015 to 0.014), but the total variance explained by the model as measured by R^2 will improve from 0.19 to 0.40 if the outliers were excluded.

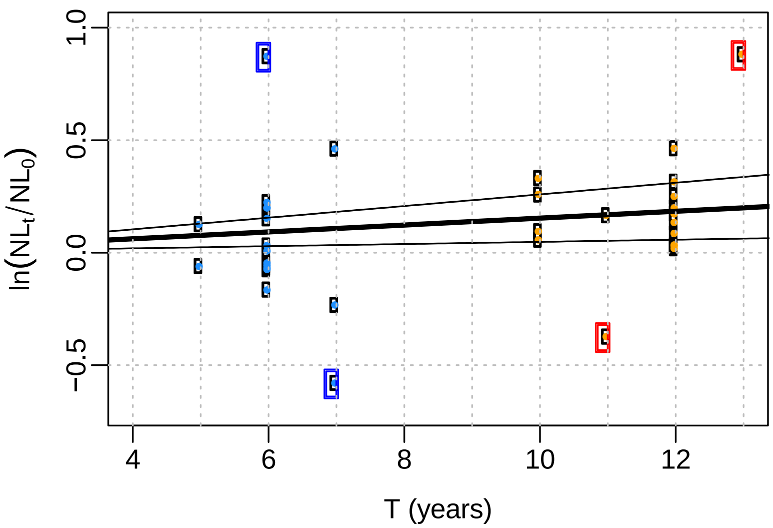

Figure 3 Relationship of the change in log-transformed NL and years between measurements. Data from new homes are in orange, and the weatherized homes are in blue. Potential outliers are indicated by double-circle. The bold line is the best-fit regression line using all data. The other two lines show 95% CI of predictions.

Table 3 Aging factor β_t fitted using linear regressison.

	β_t (year^{-1})	Std. Error	95% CI	p-value	R^2
All data (N = 34)	0.0153	0.0052	0.005, 0.026	5.65e-3	0.186
Excluding 4 potential outliers (see Fig. 3)	0.0142	0.0031	0.008, 0.021	9.28e-5	0.395

The regression results suggest that the estimated change in NL in ten years is about 15% (95% CI: 5%, 30%). One of the key assumptions of this analysis is that the two types of homes, which differed vastly in characteristics and locations, can be treated as a single group of data. If Equation 4 is modified to treat the two types of homes as each having a different β_t, the revised regression gives β_t = 0.017 per year (std. error = 0.0059) for the new homes, and β_t = 0.010 per year (std. error = 0.011) for the weatherized homes. The overall model fit will remain largely unchanged (R^2 = 0.17), but estimates of β_t become more uncertain, particularly for the weatherized homes, where the predicted β_t no longer exclude zero at 95% CI (-0.013, 0.033). This suggests that because of large variability in the change of NL among the weatherized homes, larger sample size is needed to quantify the value of β_t.

4.2. Analysis using data from ResDB

To observe whether air leakage tend to increase with age, Equation 4 was applied separately to groups of homes from ResDB that were built within five years of one another: 1901–1905, 1906–1910, … 2006–2010. Regression analysis was performed on each subgroup of homes to obtain an estimate of β_t. Each subgroup is made up of at least 100 homes.

Figure 4 shows that the increase in air leakage with age is the highest for homes that were built between 2001 and 2010, were air leakage measurements were taken typically four years after construction. Estimates of β_t were lower for homes that were built between 1991 and 2000, and were even lower for homes built between 1981 and 1990. No effect of aging was observed for homes that were built before 1980, where majority of the homes were at least 30 years old when tested. Based on this observation, it appears that aging may be occurring initially and not indefinitely. The regression analysis was repeated using fewer subgroups where year built were separated by ten years apart instead of five years. The same results were obtained, where estimate of β_t = 0.047 (95% CI: 0.041, 0.053) for homes built between 2001 and 2010, β_t = 0.012 (95% CI: 0.0094, 0.014) for homes built between 1991 and 2000, and β_t = 0.002 (95% CI: 0.0006, 0.004) for homes built between 1981 and 1990.

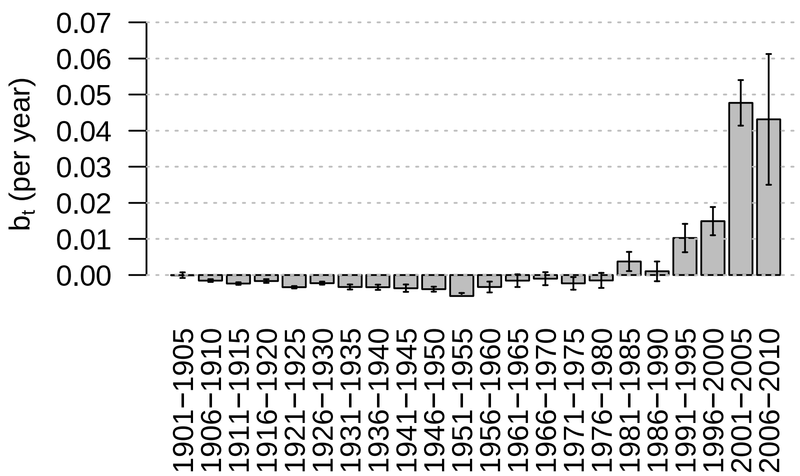

Figure 4 Aging factor β_t estimated for homes built in different years between 1901 and 2010 from ResDB. The error bar shows 95% CI of the predicted value.

Introducing an aging factor of β_t = 0.015 per year as observed from this study to the ResDB data would change the regression coefficients from the values published in Chan et al (2013a). In particular, the change would occur to the year-built coefficients $\overleftrightarrow{\beta_y}$ because year-built and house age at testing are correlated parameters. Table 4 shows the change in $\overleftrightarrow{\beta_y}$ for homes built in six year-built categories when applied to the subset of 21,300 homes, assuming aging to occur only in the initial 10, 20, or 30 years, and if all other coefficients in Equation 3 remained the same.

Figure 5 shows predicted NL assuming with and without aging for houses built in 1980s, 1990s, 2010s, as time progress from 1985 to 2015. These predictions show that if aging were ignored, the resulted year-built coefficients overestimate the difference in air leakage between newer and older homes that can be explained by improvements in construction practices. For example, the ResDB model fit without considering aging suggests that homes built in 2000s had air leakage 40% lower than similar homes built in 1980s. If aging were included in the model, the apparent improvements in airtightness between the 2000s and 1980s homes would be reduced to 12 to 31%, depending on our assumption of how long aging is modeled to last. In other words, at least some of apparent improvements in airtightness of the homes built more recently in ResDB comparing with those built in earlier decades may be because the newer homes were tested predominantly when new, whereas some of the older homes were tested some years after construction and aging had occurred. However, at this point, there is insufficient data to support the determination of how long aging continues. The longer aging is assumed to continue, the smaller is the calculated improvement in airtightness of homes built recently compared to older homes.

Table 4 Changes in year-built coefficients β_y (Equation 3) if aging were assumed to occur within the initial 10, 20, or 30 years after construction.

Year-built	**No Aging**	**Including Aging, where β_t = 0.015 (year^{-1})**		
	β_y (95% CI)	**β_y: 10yr cap**	**β_y: 20yr cap**	**β_y: 30yr cap**
Before 1960	-0.46 (-0.45, -0.47)	-0.62 (-0.61, -0.63)	-0.77 (-0.76, -0.78)	-0.92 (-0.91, -0.94)
1960–1969	-0.48 (-0.44, -0.51)	-0.63 (-0.59, -0.67)	-0.78 (-0.75, -0.82)	-0.94 (-0.90, -0.97)
1970–1979	-0.54 (-0.51, -0.57)	-0.70 (-0.66, -0.73)	-0.85 (-0.82, -0.88)	-1.00 (-0.97, -1.03)
1980–1989	-0.60 (-0.57, -0.63)	-0.75 (-0.72, -0.78)	-0.90 (-0.87, -0.93)	-0.99 (-0.96, -1.02)
1990–1999	-0.73 (-0.70, -0.75)	-0.82 (-0.80, -0.85)	-0.88 (-0.85, -0.90)	-0.88 (-0.85, -0.90)
2000–2011	-1.11 (-1.11, -1.12)	-1.12 (-1.11, -1.12)	-1.12 (-1.11, -1.12)	-1.12 (-1.11, -1.12)

Another potentially misleading conclusion if aging is ignored is that comparison of the air leakage of new and older homes would exaggerate the difference in their airtightness over time. In 2005, for example, a new construction would appear to have air leakage 40% less than home built in 1980s that has similar characteristics. If aging only occurred in the initial 10 years following construction, then the difference between these two homes built would narrow to 30% by 2015. If aging continues to occur in the next 10 years that follow, then the revised model predicts only 20% difference in their air leakage value. If aging is ignored, the difference in air leakage between homes built from different years does not change with time, and would remain at 40% regardless when the comparison is made. The predictions shown in Figure 5 assumed that aging occurred at the same rate of β_t for all homes. However, if aging only occurred among the newer 2000s homes but not the 1980s homes because the older homes simply did not use any airtightening strategies to be begin with, then the predicted differences between these two groups of homes would be narrowed further. For example, by 2015, the 2000 homes are expected to have air leakage 20% lower than the 1980s homes, if only the 2000s homes have aged. This prediction is less than the 30% calculated if aging were applied to all homes for the initial 10 years.

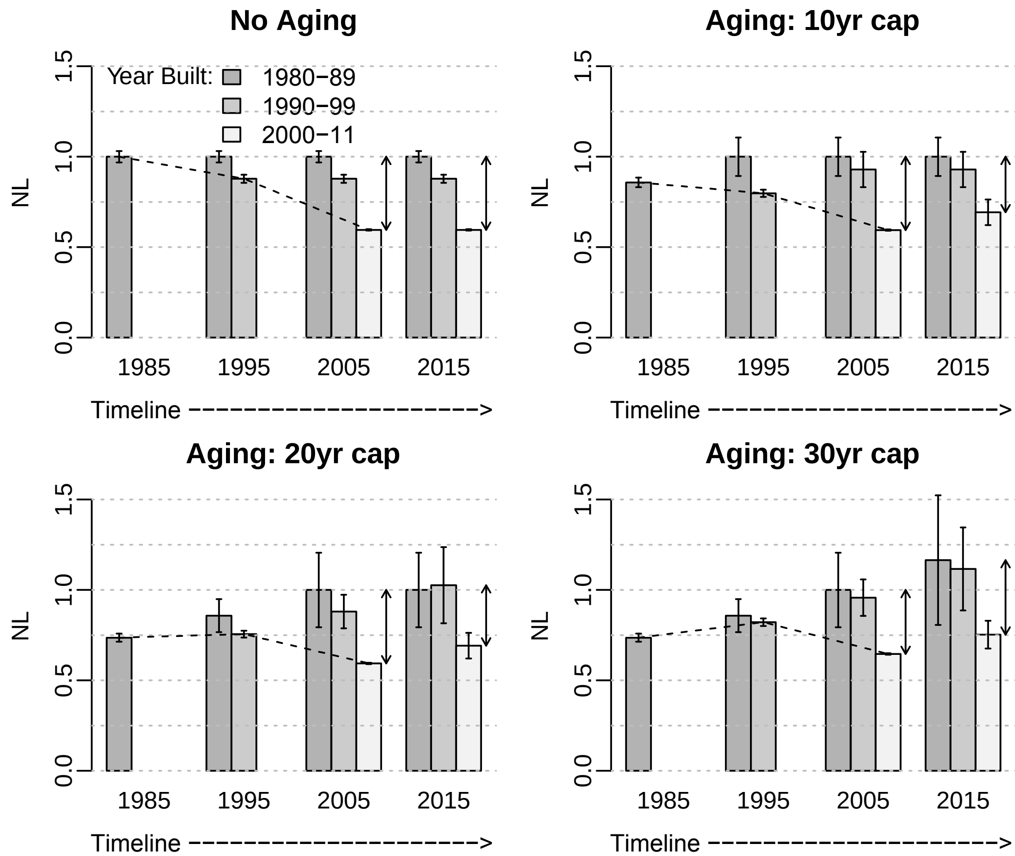

Figure 5 Predicted NL with or without aging using a subset of ResDB as time progress. The dotted line indicates the predicted change in NL for houses built in the three year built categories when new. The two arrows show the predicted difference in NL for the three categories of homes in 2005 and 2015. The error bar shows 95% CI of the predicted NL. Values of NL are all normalized to the 2005 prediction for houses built in 1980s.

5. Discussion

Estimates of the aging factor β_t from the blower door measurements collected in this study and data from ResDB both suggest that the air leakage of US single-family detached homes tend to increase as they age. The increase in NL is about 15% (95% CI: 5% to 30%) over ten years from the blower door data collected by this study. Subsequent analysis of the ResDB data also found indications that air leakage increases with age for houses built as early as 1980 or 1990. A higher β_t was found for homes in ResDB that were tested relatively soon after they were built between 2001 and 2010. This implies that the increase in air leakage likely occurred soon after the homes were built, but the trend did not appear to continue over time. Another plausible explanation is that only newer homes showed aging because of the airtightening strategies applied in these homes, which did not exist in older homes before there was attention paid to reduce air leakage. If proven true, then there may be significant challenges for energy efficient new homes to continue to be low energy over time as air leakage increases with age.

The overall increase in air leakage due to aging is likely to exceed the 15% observed from the data collected by this study if aging were to continue beyond the initial ten years. Figure 5 illustrated the changes in air leakage that may result if aging continued for longer. The resulted increase in air infiltration will cause a notable rise in heating and cooling energy of homes. Changes in air leakage will impact the performance of other components of the homes as well. For example, maintaining thermal comfort at times of peak heating or cooling needs can become much more challenging over time. It is important to realize that building envelope is also a time variable factor to consider, similar to other building components that may require repair over time. The US housing stock is growing older. Data from the American Housing Survey (AHS 2014) reveal that the median age of an owner-occupied home was 37 years old in the 2013 national survey, which is 10 years older than the median age reported in 1993. Strategies that promote durable airtightness can have substantial impact to the overall energy efficiency of the residential housing stock.

There are a number of external factors that our regression analysis did not consider. For example, the agreement between repeated measurements of air leakage may be impacted by difference in weather conditions (Antretter et al 2007) during the blower door test. Since all blower door tests performed most recently from the 34 homes occurred in the winter months, seasonal differences might have affected our finding, though there is insufficient data to determine the magnitude of this potential bias. The ResDB data does not contain repeated measurements from the same homes. Rather, influence of house age on air leakage measurements were observed from a group of homes with similar year-built but were tested at different ages. Difference in measurement protocol, equipment, data acquisition and processing can also introduce uncertainties when comparing air leakage results. Uncertainties from our estimates of NL_0 based on prior work (Chan et al 2013a) further add to the uncertainty of this analysis. But considering the diversity of data sources that contributed this data, and the variety of homes in terms of geographical location, construction type, and other characteristics, we expected that these sources of uncertainties mostly add noise to our predictions of the aging factor.

It is also important to note that the analysis of the weatherization homes included “old” sealing from the time the houses were built, as well as “new” seals from the weatherization itself. We might expect that the old leakage is beyond the aging period and thus the aging effect we see is only from the seals added at the weatherization. Typically weatherization reduces leakage by 25% (Chan et al 2013b). Thus, the aging effect we observed in this study among the weatherized homes may appear smaller because the “new” seals only represent a small fraction of the leakage. More data on the durability of airtightness improvements by weatherization is important for the cost saving evaluation of the program.

Preliminary analyses using a subset of the ResDB data suggest that the aging effect is not constant but decreases over time. More air leakage data will need to be collected periodically as a house age to better understand how this process is occurring over time. There are substantial challenges to obtain repeated measurements of air leakage, including getting access to suitable homes and willing participants, knowledge about any home improvement work performed between tests, and ability to replicate blower door tests under the same conditions. In recent years, requirements on air leakage by building codes can mean that the test data of new homes may become more available for future study to refer to as baseline. Since maintaining airtightness is an important strategy to achieve long-term energy savings, better understanding of the factors that may impact airtightness durability, such as construction methods, materials, occupant behaviors, and environmental conditions, are needed.

6. Conclusions

Repeated blower door measurements from 34 single-family homes measured by this study show an increase in air leakage of about 15% in ten years. More field data is necessary to robustly determine the size of the aging effect and if there are trends with region or other factors. 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. Nevertheless our results indicate that simulations and forecasts made using the as-built airtightness levels are likely underestimating the life-cycle impact of air infiltration. As-built airtightness levels should probably be derated accordingly.

References

AHS. National Summary Tables, American Housing Survey, US Department of Housing and Urban Development and US Census Bureau, Washington, DC, 2014. http://www.census.gov/programs-surveys/ahs/data.html

Antretter F, Karagiozis A, TenWolde A, Holm A. “Effects of air leakage of residential buildings in mixed and cold climates”, Thermal Performance of the Exterior Envelopes of Buildings X Conference Proceedings, Clearwater Beach, FL, December 2-7, 2007.

ASTM. E779-10 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. ASTM International, Conshohocken, PA, 2010.

Chan WR, Joh J, Sherman MH. “Analysis of air leakage measurements of US houses”, Energy and Buildings. 2013a 66 pp616–625.

Chan WR, Sherman MH. “Improving building envelope and duct airtightness of US dwellings – the current state of energy retrofits”, 3rd TightVent Workshop on Building and Ductwork Airtightness, Air Infiltration and Ventilation Centre, Washington DC, April 18-19, 2013b.

Energy OutWest. Weatherization Field Manual: Best Practices for the Weatherization Assistance Program. Energy OutWest, Pullman, WA, 2004. http://www.commerce.wa.gov/documents/hip-weatherization-energy-out-west-field-guide.pdf

IECC. International Energy Conversation Code. International Code Council, 2012.

Kim AK, Shaw CY. “Seasonal variation in airtightness of two detached houses”, Measured Air Leakage of Buildings: A Symposium, Issue 904, American Society for Testing and Materials, 1986 pp17-32.

Proskiw G. “The variation of airtightness of wood-frame houses over an 11-year period”, Thermal Performance of the Exterior Envelopes of Buildings VII Conference Proceedings. Clearwater Beach, FL, December 6-10, 1998.

RESNET. Standard for Performance Testing and Work Scope: Enclosure and Air Distribution Leakage Testing. Chapter 8, RESNET Standard. Residential Energy Services Network, Inc., Oceanside, CA, 2012. http://www.resnet.us/standards/DRAFT_Chapter_8_July_22.pdf

RSC. “Robust statistic: a method of coping with outliners”, Technical Brief No.6, Analytical Methods Committee, Royal Society of Chemistry, London, 2001.

USEPA. ENERGY STAR Certified New Homes Market Indices for States. 2013. http://www.energystar.gov/index.cfm?fuseaction=qhmi.showHomesMarketIndex

USEPA. ENERGY STAR Qualified Homes, Version 3 (Rev. 03) National Program Requirements. 2011. http://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/NationalProgramRequirements_v3.pdf

Walker IS, Sherman MH, Joh J, Chan WR. “Applying a large datasets to developing a better understanding of air leakage measurements in homes”, International Journal of Ventilation 2013 11 pp323-338.

Acknowledgements

Support for this work was provided by the U.S. Dept. of Energy Building America Program, Office of Energy Efficiency and Renewable Energy under DOE Contract DE-AC02-05CH11231; by the U.S. Dept. of Housing and Urban Development, Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070; by the U.S. Environmental Protection Agency Indoor Environments Division through Interagency Agreement DW-89-92322201-0; and by the California Energy Commission through Contract 500-09-042.

We want to thank all the homeowners who participated in this study for their time and cooperation. We also want to acknowledge the field team who performed this work, led by Eyu-Jin Kim at Southface Energy Institute, and Hans Berg at Community Action Partnership of Idaho (CAPAI).