PNNL-28337

Pacific Northwest NATIONAL LABORATORY

Envelope Air Tightness for Sleeping and Dwelling Units

Technical Brief

December 2018

R Hart
M Tyler

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Contents

Background

This study was conducted by Pacific Northwest National Laboratory (PNNL) in support of the U.S. Department of Energy (DOE) Building Energy Codes Program (BECP). BECP was founded in 1993 in response to the *Energy Policy Act of 1992*, and fulfills several key functions specified under federal statute and related to building energy codes. Section 307 of ECPA, as amended, requires DOE to periodically review the technical and economic basis of the voluntary building energy codes, such as the International Energy Conservation Code (IECC) and Standard 90.1, and participate in the industry process for review and modification, including seeking adoption of all technologically feasible and economically justified energy efficiency measures. (42 U.S.C. 6836(b)) Section 304(a) of ECPA, as amended, also directs DOE to review published editions of the IECC and Standard 90.1, and issue a determination as to whether the revised edition would increase energy efficiency in residential and commercial buildings, respectively.

PNNL supports this mission by evaluating concepts being considered for future code updates, conducting technical reviews and analysis of potential changes and their associated impacts, including energy savings analysis, cost-effectiveness analysis, and providing guidance on how changes can be more readily adopted by states and localities. This helps to ensure successful implementation of advancing technologies, construction practices, and related industry standards, and encourages building practices that are proven affordable and efficient.

This technical brief represents a compilation of relevant information on a specified concept. An overview of the concept is presented, followed by supporting technical analysis, related research and recommended code language. Additional context may also be provided, such as known consideration in previous model code development, state code proceedings, or incorporation in existing codes or standards. Each brief is intended as a resource for interested and affected stakeholders, particularly those charged with considering impacts of proposed code updates. Further technical assistance may be available from PNNL to adapt content to the needs of individual states or municipalities, such as specific building types, climate weightings, or utility rates.

Learn more at www.energycodes.gov.

1.0 Envelope Air Tightness for Sleeping and Dwelling Units

Air leakage can be a significant source of energy waste in buildings, contributing to higher heating and cooling costs for building owners and occupants, and increasing risk related to comfort and durability. Air tightness testing can result in more attention to air barrier sealing and significantly reduced building leakage. Currently, the residential energy code requires air tightness testing for residential buildings three stories and less in height to ensure proper tightness and a controlled indoor environment. However, in the commercial energy code there is no testing requirement for residential buildings four stories or more in height (e.g., apartments, dormitories, hotel guest rooms). Industry standards affecting these buildings have historically relied upon visual verification, as well as material and assembly requirements. Providing adequate control over air leakage can also allow many benefits, including reduced HVAC equipment sizing, better building pressurization, and energy savings due to reduced heating and cooling of infiltrated outside air. In moist climates, ensuring lower leakage through testing can also result in better humidity control and reduced risk of durability issues.

1.1 Summary

This technical brief investigates the potential benefits of air leakage testing in residential buildings covered by the commercial energy code and outlines an approach that could be applied based on building type, use, size, and climate zone.

- Testing thresholds are organized by residential and institutional building occupancies (Group R[1] and I[2] building occupancies) and based on cost-effectiveness analysis relying on industry-accepted methods.
- The testing requirement is currently an optional path for commercial buildings in the International Energy Conservation Code (IECC) and ASHRAE Standard 90.1, where whole-building air-leakage testing is allowed as a means of meeting air leakage requirements, and with a maximum leakage limit of 0.40 cfm/ft^2 (2.0 L/s · m^2) at 0.3 in. w.g. (75 Pa). In the residential code, all residential buildings three stories and lower must currently be tested at 3 or 5 air changes per hour (ACH) at 0.2 in. w.g. (50 Pa).
- As outlined, individual dwelling units could be tested on a sampling basis. The minimum requirement is where residential units are separately tested using a lower cost, unguarded, single blower door approach. If a whole building test is desired instead, this is already provided for as an option in the main charging paragraph.

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[1] **Residential Group R:** uses intended for sleeping purposes. Group R is divided into four sub groups: **R-1** occupants are transient in nature; **R-2** occupancies containing sleeping units or more than two dwelling units where the occupants are more permanent in nature; **R-3** one and two family dwelling, or adult and child care facilities that provide accommodation for five or fewer persons of any age for less than 24 hours; **R-4** are intended for occupancy as residential care/assisted living facilities including more than five but not more than sixteen occupants, excluding staff.

[2] **Institutional Group I:** uses intended in which people are cared for or live in a supervised environment, having physical limitations because of health or age are harbored for medical treatment or other care or treatment or in which the liberty of the occupants is restricted. Group I is divided into four sub groups: **I-1** houses more than 16 persons, on a 24 hour basis, who because of age, mental disability or other reasons, live in a supervised residential environment that provides personal care services. The occupants are capable of responding to an emergency situation without physical assistance from staff; **I-2** buildings are used for medical, surgical, psychiatric, nursing or custodial care on a 24 hr basis of more than five persons who are not capable of self-preservation (Less than five people shall be considered an R-3); **I-3** is inhabited by more than five persons who are under restraint or security and is occupied by persons who are generally incapable of self-preservation due to security measures not under the occupant's control.

- A maximum leakage rate of 0.30 cfm/ft^2 (1.5 L/s · m^2) at 0.2 in. w.g. (50 Pa) is specified for all climate zones. This tests is at a pressure differential of 0.2 inch w.g. (50 Pa), which is a more traditional residential testing pressure, and is intended to generally align with existing single-family metrics. It matches a test at 0.40 cfm/ft^2 (1.5 L/s · m^2) at 0.3 in. w.g. (75 Pa), the current alternative commercial test limit.

Air barrier testing saves energy by reducing infiltration of outside air into and out of the building. Most of the time, outside air is hotter or colder than the comfort temperature being maintained in the residence by the heating and cooling systems. Therefore, reducing the infiltration will reduce energy use for heating and cooling. The measure would require that blower door testing be applied to a sample of units in a multiple unit residential construction project. The equipment and staff required are the same as are needed in current air leakage testing required under the residential energy code.

1.2 Technical Considerations

How does the proposed measure compare to what's required in current codes?

Compared to existing standards, the proposed rate of 0.20 cfm/ft^2 at 50 Pa for certain climates is a leakier standard than the 3ACH50 requirement in the residential code (IECC). Similarly the rate 0.30 cfm/ft^2 at 50 Pa is leakier than the 5ACH50 climate zone 1 and 2 residential requirement. Yet, both result in similar per-unit airflow leakage compared to detached residential, as mid- to high-rise residential units are typically much smaller than single family detached homes. Figure 1 compares the ACH50 equivalent of the enclosure testing for different sizes of apartments and homes. Figure 1 also compares test leakage at the two different testing thresholds. The apartment leakage is reduced to 75% of the tested allowance, because in an unguarded test about 25% of the leakage is expected to be through interior walls to adjacent apartments. Test leakage is typically higher than actual wind-driven leakage.

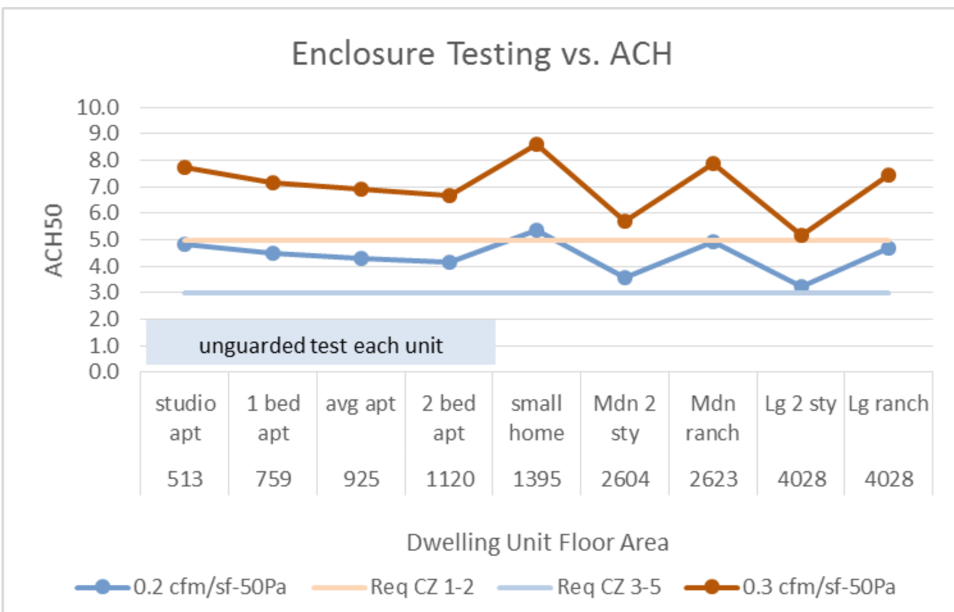

Figure 1. Comparative ACH of different tests in apartments and homes

Figure 2 shows the actual test leakage air volume in cfm that would occur with different testing protocols. Because the apartments are smaller, they have a reduced leakage volume per unit compared to the detached houses. Figure 3 shows how individual unit apartment unguarded test results (prefix t-) are higher than actual exterior leakage (prefix ex) and what the relationship is to detached home ACH savings.

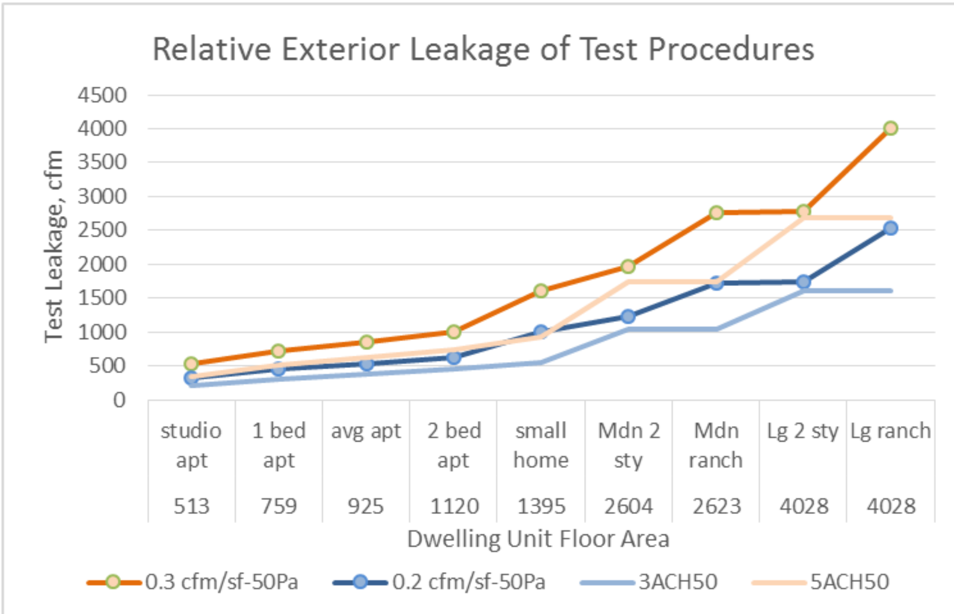

Figure 2. Comparative airflow leakage savings of different sized apartments and homes

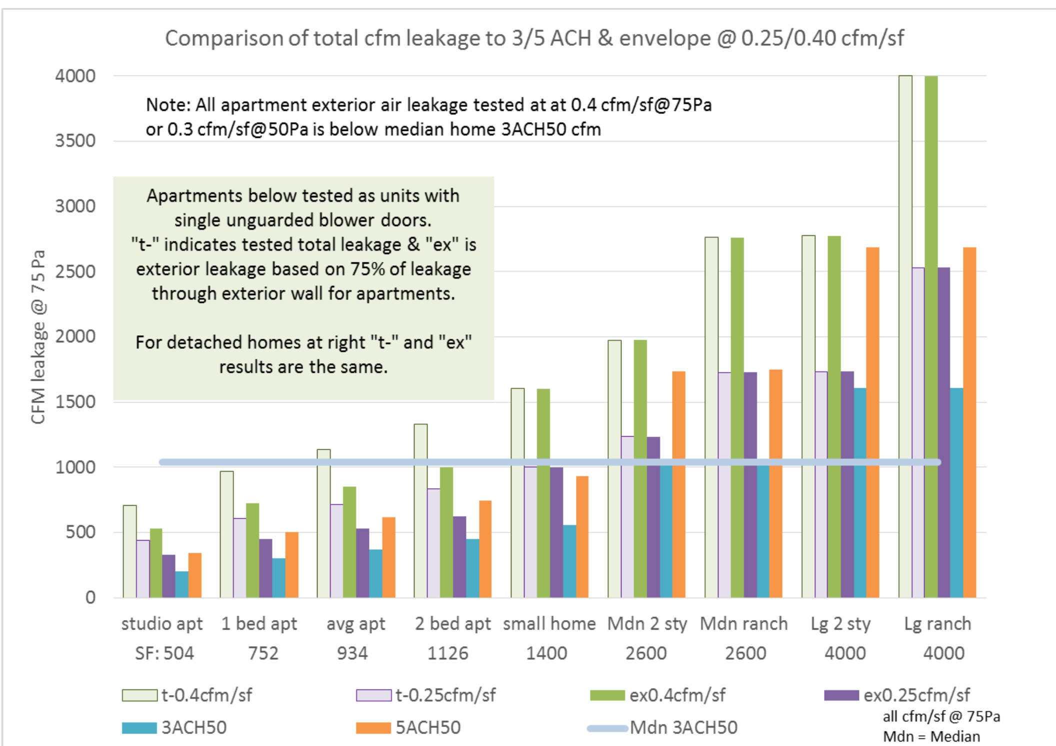

Figure 3. Comparative airflow leakage savings of different sized apartments and homes

Why is building leakage testing superior to other approaches?

While it is important that the materials and assemblies have limited leakage, specification by individual materials and assemblies does not necessarily equate to an air-tight building. Recent research (Wiss 2014) shows that 40% of buildings constructed without an envelope consultant have air leakage exceeding the current optional test standard of 0.40 cfm/ft^2 at 75 Pa, while buildings with envelope consultants had leakage below 0.25 cfm/ft^2 at 75 Pa. Requiring testing will ensure that the goal of this section of the code—limiting unintended air infiltration in buildings—is achieved.

What strategies are considered to minimize compliance burdens in the field?

To manage testing cost, a testing approach is introduced that requires only 20% of the units (with a seven-unit minimum) to be tested in the building. The testing method is also an unguarded test of individual units that reduces cost significantly compared to whole building testing or guarded unit testing. To motivate high-quality air sealing, additional testing of an additional 20% of the units would be required if any unit exceeds the leakage limit. Then the weighted average of tested units is used for comparison to the required leakage limit. While the testing requirement is slightly less stringent than the residential code, it matches current optional commercial requirements and is an improvement over the current condition of no testing requirements in the commercial code. It also provides a more reasonable target than air changes per hour for these units, which are typically smaller and have less total leakage than detached residences.

Are there existing codes and standards that require similar testing measures?

This measure is similar to the residential air leakage provisions in the 2018 IECC in that it also requires the use of ASTM E 779. The measure is similar to air leakage testing that is required by the State of Washington and City of Seattle commercial building energy codes as well as procedures followed by the U.S. Department of Defense for testing of commercial buildings. The City of Seattle requirements have been in place since 2009 and hundreds of commercial buildings have been tested under that code, including many large buildings.

1.3 Energy and Cost Impacts

Energy Savings: An analysis of energy impact shows that annual energy cost savings from increased envelope air tightness ranges from $6.64 to $44.02 per thousand square feet of floor area in mid-rise apartment buildings (in climate zones where testing is recommended).

Cost Impact: The proposed measure would carry an incremental cost of construction, particularly in new commercial and high-rise multifamily buildings where a sample of unguarded tests would now be required. Air barrier contractors commonly report that the cost of individual unit air leakage testing is about $350. For residential units using a 20% sampling method, that translates to $70 per unit. As demand for air leakage testing in commercial buildings increases, more companies are expected to enter the market to provide these services, as evidenced in areas where similar code provisions have been implemented. The testing required can be achieved with the same staff and equipment used for single family dwelling unit testing that is currently required in the residential energy codes.

Cost-effectiveness: PNNL performed a cost-effectiveness analysis to identify the net impacts associated with the measure using the established DOE methodology (Hart and Liu 2015). Results of the cost-effectiveness analysis indicate that the average savings-to-investment ratio (SIR) and simple payback (SPP) for unguarded dwelling unit testing with a limit of 0.30 cfm/ft^2 (1.5 L/s · m^2) at a pressure differential of 0.2 inch water gauge (50 Pa) in mid-rise apartment buildings were:

- SIR: 7.8; cost-effective if greater than 1.0
- SPP: 5.3 years; cost-effective if less than 40 year life

A measure is cost-effective when the SIR is greater than 1.0, indicating that the present value of savings is greater than the incremental cost. The cost for individual unguarded unit testing is expected to be significantly lower than the cost for whole building testing, especially with the sampling protocol provided. Results of the cost-effectiveness analysis were taken into account when developing the sample code language presented in the next section (i.e., the recommended language only targets building types and climate zones where the testing requirement was determined to be cost-effective).

More detail on the cost analysis is also presented in the Appendix.

1.4 Sample Code Language

In the suggested code language, testing is shown in climate zones where cost-effective.

- In non-excepted climate zones, an envelope testing limit of 0.30 cfm/ft^2 (1.5 L/s · m^2) of the *testing unit enclosure area* at a pressure differential of 0.2 inch w.g. (50 Pa), which matches the current commercial optional testing limit of current standard of 0.40 cfm/ft^2 at 75 Pa and is similar to the warm climate limit of 5ACH50 in the residential energy code.
- Exceptions are provided for climate zone 2B where air barriers are not required and in climate zones 3C and 5C where testing was not found to be currently cost-effective. Existing compliance options associated with air barrier materials or assemblies are retained for buildings that do not have a specified testing requirement.
- In addition, some clarifications are necessary, including referenced areas in each of the paths and addition of defined terms. For example, a definition of *testing unit enclosure area* is added to support compartmental single unit testing.

Changes to the 2018 IECC required to implement this measure are shown. Similar changes could be made to ASHRAE standard 90.1.

Existing definitions –

DWELLING UNIT. A single unit providing complete independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking and sanitation.

SLEEPING UNIT. A room or space in which people sleep, that can include permanent provisions for living, eating, and either sanitation or kitchen facilities but not both. Such rooms and spaces that are part of a dwelling unit are not *sleeping units*.

Add the following definition:

TESTING UNIT ENCLOSURE AREA: The area sum of all the boundary surfaces that define the *dwelling unit*, *sleeping unit*, or common *conditioned space* including top/ceiling, bottom/floor, and all side walls. This does not include interior partition walls within the *dwelling unit*, *sleeping unit*, or common *conditioned space*. Wall height shall be measured from the finished floor of the *conditioned space* to the finished floor or roof/ceiling air barrier above.

Modify Sections C402.5 and C402.5.1 as follows and add section C402.5.1.3:
Italicize defined terms as shown in the following sections:

C402.5 Air leakage—thermal envelope (Mandatory). The *building thermal envelope* ~~of buildings~~ shall comply with Sections C402.5.1 through C402.5.8, or the *building thermal envelope* shall be tested in accordance with ASTM E 779 at a pressure differential of 0.3 inch water gauge (75 Pa) or an equivalent method approved by the code official and deemed to comply with the provisions of this section when the tested air leakage rate of the building thermal envelope is not greater than 0.40 cfm/ft^2 (2.0 $L/s \cdot m^2$). Where compliance is based on such testing, the building shall also comply with Sections C402.5.5, C402.5.6, and C402.5.7.

C402.5.1 Air barriers. A *continuous air barrier* shall be provided throughout the *building thermal envelope*. The *continuous air barrier~~s~~* shall ~~be permitted to~~ be located on the inside or outside of the *building thermal envelope*, located within the assemblies composing the *building thermal envelope*, or any combination thereof. The air barrier shall comply with Sections C402.5.1.1 and C402.5.1.2.

Exception: Air barriers are not required in buildings located in *Climate Zone* 2B.

No changes to sections C402.5.1.1

C402.5.1.2 Air barrier compliance ~~options~~. A *continuous air barrier* for the opaque building envelope shall comply with the following:

1. Buildings or portions of buildings including group R and group I occupancy shall meet the provisions of Section C402.5.1.2.3.

   Exception to item 1: Buildings in climate zones 2B, 3C, and 5C.
2. Buildings or portions of buildings including group R and group I occupancy in climate zones 3C and 5C shall meet the provisions of Section C402.5.1.2.1 or C402.5.1.2.2.
3. Buildings or portions of buildings of other than group R and group I occupancy shall meet the provisions of Section C402.5.1.2.1 or C402.5.1.2.2.

No changes to sections C402.5.1.2.1 & C402.5.1.2.2

C402.5.1.2.3 Dwelling and Sleeping Unit Enclosure Testing. The *building thermal envelope* shall be tested in accordance with ASTM E 779, RESNET/ICC 380, ASTM E1827 or an equivalent method *approved* by the code official. The measured air leakage shall not exceed 0.30

cfm/ft^2 (1.5 L/s · m^2) of the *testing unit enclosure area* at a pressure differential of 0.2 inch water gauge (50 Pa). Where multiple *dwelling units* or *sleeping units* or other occupiable conditioned spaces are contained within one *building thermal envelope*, each unit shall be considered an individual testing unit and the building air leakage shall be the weighted average of all testing unit results, weighted by each testing unit's *testing unit enclosure area*. Units shall be tested separately with an unguarded blower door test as follows:

1. Where buildings have fewer than eight testing units, each testing unit shall be tested.
2. For buildings with eight or more testing units the greater of seven units or 20 percent of the testing units in the building shall be tested including a top floor unit, a ground floor unit, and a unit with the largest *testing unit enclosure area*. Where any tested unit exceeds the maximum air leakage rate, an additional 20 percent of units shall be tested, including a mixture of testing unit types and locations.

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Appendix

Cost-effectiveness Analysis Detail

Purpose: Determine cost-effectiveness of unguarded air barrier testing for residential dwelling units and sleeping units in apartment buildings and hotels.

Basis of Analysis

Simulation of change in leakage from 1.0 cfm/sf to 0.4 cfm/sf for the mid-rise apartment prototype building using the EnergyPlus™ energy simulation software.

The cost-effectiveness analysis is conducted according to the DOE cost-effectiveness methodology.[1] The long-term economic impacts for two cases are determined:

- Publicly-owned Buildings: Based on the established FEMP method[2] (Scenario 1)
- Privately-owned Buildings: Based on the 90.1-2019 *Scalar* Method.[3] (Scenario 3)

DOE prototypes[4] for mid-rise apartments are simulated in EnergyPlus.

40.0-year measure life is the accepted value designated by the ASHRAE Standard 90.1 (SSPC 90.1) code development and consensus committee for analysis of building envelope measures.

Scenario 1 factors

Electric uniform present value (UPV) factor[5] with 3% discount and EIA energy escalation for present value (PV) savings: 25.09

Blended Fossil UPV factor with 3% discount and EIA energy escalation for PV savings: 27.25

In Scenario 1, measures are found cost-effective when the savings-to-investment ratio (SIR) ≥ 1.0.

Scenario 3 factors

(90.1-2019) Scalar threshold :	Electric	22.1	24%	**Blended**
	Fossil	25.2	76%	**24.5**

In Scenario 3, measures are found cost-effective when the simple payback ≤ the scalar threshold.

[1] Hart R and B Liu. 2015. *Methodology for Evaluating Cost-effectiveness of Commercial Energy Code Changes*. Pacific Northwest National Laboratory for U.S. Department of Energy; Energy Efficiency & Renewable Energy. PNNL-23923, Rev1. https://www.energycodes.gov/development/commercial/methodology.

[2] Fuller S and S Petersen. *Life-Cycle Costing Manual for the Federal Energy Management Program*. NIST, U.S. Department of Commerce, 1995. http://fire.nist.gov/bfrlpubs/build96/PDF/b96121.pdf.

[3] Based on the approach and factors established by the ASHRAE Standard 90.1 project committee for 90.1-2019.

[4] Details on building prototypes available at: https://www.energycodes.gov/commercial-prototype-building-models.

[5] Lavappa P and J Kneifel. *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-2018: Annual Supplement to NIST Handbook 135*, 2018. https://nvlpubs.nist.gov/nistpubs/ir/2018/NIST.IR.85-3273-33.pdf.

Energy Prices

Residential sector pricing is appropriate for most dwelling and sleeping units. These are used in Scenario 1, while the commercial prices selected by the ASHRAE 90.1 committee are used in Scenario 3.

Residential prices are sourced from EIA data for the 12-month period from November 2017 to October 2018. Heating prices are weighted by typical sector fuel use weighting for natural gas and oil, resulting in a blended fossil fuel price expressed in $ per therm. UPV factors for the Scenario 1 analysis account for both fuel escalation and present value discounting. For heating, they are weighted for the fuel mix. UPV 30-year factors are adjusted to a 40-year life by applying the equivalent year 1-30 net discount rate for the 30-year UPV to years 31-40:

Energy Type			**Unit Price**		**Weight**	**UPV,30**	**UPV,40**
Natural Gas	10.55	$/ kCuFt	$1.0169	$/therm	87.7%	22.75	22.75
Heating Oil	3.01	$/ gal	$2.1700	$/therm	12.3%	28.67	28.67
Blended Fossil Rate			**$1.1588**	**$/therm**		23.48	**27.25**
Electricity			**$0.1290**	**$/kWh**		21.45	**25.09**

Energy Savings

Based on the results of the EnergyPlus analysis, the results based on floor area are as follows:

Annual Energy Savings, per 1000 square foot of floor area Mid-rise apartment						
Climate	Prices for Scenario 1					Scenario 3
Zone	kWh	therm	Elec $	Gas $	Total $	Total $
1A	150.4	0.0	$19.41	$0.00	$19.41	$15.99
1B	122.3	0.0	$15.79	$0.00	$15.78	$13.00
2A	67.4	0.9	$8.70	$1.05	$9.76	$8.06
2B	268.5	1.1	$34.66	$1.29	$35.94	$29.63
3A	41.7	9.3	$5.39	$10.74	$16.12	$13.52
3B	54.2	2.4	$6.99	$2.76	$9.75	$8.10
3C	-7.2	0.8	-$0.92	$0.89	-$0.04	-$0.01
4A	32.5	21.9	$4.20	$25.37	$29.57	$24.91
4B	11.9	5.5	$1.54	$6.35	$7.89	$6.64
4C	-33.3	10.9	-$4.29	$12.57	$8.28	$7.10
5A	2.6	32.4	$0.34	$37.50	$37.84	$31.99
5B	-4.0	12.7	-$0.52	$14.76	$14.24	$12.06
5C	-41.1	6.3	-$5.30	$7.25	$1.95	$1.76
6A	14.2	43.4	$1.84	$50.26	$52.10	$44.02
6B	-7.2	26.1	-$0.93	$30.29	$29.35	$24.85
7	-10.3	33.1	-$1.33	$38.32	$36.99	$31.31
8	-35.4	20.0	-$4.57	$23.14	$18.58	$15.81
				Average	$20.21	$16.98

Cost-effectiveness

The cost-effectiveness is evaluated using Scenario 1 for the public sector and Scenario 3 for the private sector.[1] For Scenario 1, the SIR indicates a measure is cost-effective when greater than 1.0. In Scenario 3, the simple payback (cost/annual savings) is compared to a scalar threshold that includes commercial discount rates and loan costs. When the payback is less than the threshold, a measure is considered cost-effective. The scalar threshold for blended savings over a 40-year measure life is 24.5 years. Results are shown only when testing is required in the measure.

Climate Zone	Scenario 1 PV of Savings	Net LCC Savings	SIR PV sav / Cost	Scenario 3 annual Savings	Scenario 3 payback years	Both Scenarios Pass?
1A	$455	$385	6.5	$15.99	4.4	Yes
1B	$370	$300	5.3	$13.00	5.4	Yes
2A	$231	$161	3.3	$8.06	8.7	Yes
3A	$399	$329	5.7	$13.52	5.2	Yes
3B	$234	$164	3.3	$8.10	8.6	Yes
4A	$744	$674	10.6	$24.91	2.8	Yes
4B	$198	$128	2.8	$6.64	10.5	Yes
4C	$219	$149	3.1	$7.10	9.9	Yes
5A	$962	$892	13.7	$31.99	2.2	Yes
5B	$363	$293	5.2	$12.06	5.8	Yes
6A	$1,322	$1,252	18.9	$44.02	1.6	Yes
6B	$749	$679	10.7	$24.85	2.8	Yes
7	$944	$874	13.5	$31.31	2.2	Yes
8	$482	$412	6.9	$15.81	4.4	Yes
Scenario 3 discounted payback threshold for 40 year life is						**24.5**

Conclusions

Air barrier testing is cost-effective in most climates for dwelling units and sleeping units. Costs are reduced when individual unguarded unit testing is used rather than whole building testing.
Air barrier testing is recommended for dwelling units and sleeping units in climates where it is cost-effective.

[1] Hart R and B Liu. 2015. *Methodology for Evaluating Cost-Effectiveness of Commercial Energy Code Changes*. Pacific Northwest National Laboratory for U.S. Department of Energy; Energy Efficiency & Renewable Energy, August 2015. https://www.energycodes.gov/development/commercial/methodology.

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