Building Enclosure Airtightness Testing in Washington State – Lessons Learned about Air Barrier Systems and Large Building Testing Procedures

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ABSTRACT

Airtightness testing is the process in which the building enclosure is tested to quantify its air leakage and qualitatively identify airflow paths through the air barrier system. Testing is often performed as part of the commissioning process for the building enclosure air barrier and mechanical systems in new buildings or to identify air leakage pathways to make improvements to existing buildings.

Quantitative airtightness testing of single-family homes is fairly common and understood by the industry as hundreds of thousands of houses have been tested across North America over the past decades as part of new construction or as part of various weatherization and energy upgrade programs. Quantitative airtightness testing of larger buildings such as those in the commercial or large residential building sector is much less common in North America as the tests tend to be complicated and costly and are not required by most building codes. The only requirements for large building airtightness tests are for new US GSA and US Army Corps buildings and for large buildings built under recent Washington State and Seattle Energy Codes.

Within Washington State and Seattle, all commercial buildings and residential buildings over three stories require a whole-building airtightness test. There is a requirement in both energy codes to achieve a target airtightness test result; however, both codes have provisions that allow the code official to waive the quantitative result of a failed test if sufficient air sealing efforts have been made. This is allowing the design and construction industry time to learn how airtight newly constructed buildings are and where improvements can be made to air barrier systems and materials. The authors have been involved with many of these large building airtightness tests on both the design and testing teams. From these projects and several research studies of similar buildings we have gathered a database of Washington State enclosure airtightness values along with building types and air barrier system components. Some trends are beginning to show up in the data which suggest that certain air barrier systems may be more effective than others. Lessons learned about air barrier sealing practices and insight into airtightness testing procedures for large buildings will be shared.

INTRODUCTION

Air leakage testing is the process in which the building enclosure is quantitatively measured for leakage, typically to determine how much energy could be lost through discontinuities in the air barrier. This testing has been a part of

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residential energy audits for more than 30 years, but relatively very little quantitative testing has been done on large buildings. The US Army Corps of Engineers (USACE), General Services Administration (GSA), the state of Washington, and the city of Seattle in particular, have been at the forefront of large building testing in North America since 2009. The Washington State Energy Code (WSEC) and the Seattle Energy Code (SEC) both added provisions in the 2009 code editions that require air leakage testing for nonresidential buildings or buildings greater than five stories. Since then, the authors have tested many buildings around the greater Seattle area and have been involved with the air barrier design and review of those buildings in most cases. This paper will present the lessons learned from several years of testing larger buildings and present methods for how the industry can better coordinate airtight buildings in the future.

AIRTIGHTNESS & TESTING REQUIREMENTS

Prior to 2009, the WSEC and SEC each had language that attempted to limit air leakage, but this only amounted to requiring gaskets, weather stripping, and sealants. The 2009 editions of each code were a big leap forward, requiring an air leakage test of the entire building in most cases. However, there was no requirement to achieve any specific result, just a requirement to complete the test and report the data. The 2012 editions take things a step further, requiring specific targets for the air leakage test. Typically, leakage rates are reported as a flow rate normalized by the surface area of the tested space. The 2012 WSEC and SEC require a leakage rate in cubic feet per minute (cfm) divided by the building enclosure area in square feet. This paper will refer to such leakage rates as cfm/ft^2, and metric equivalent rates in L/s·m^2 (cubic liters per second divided by square meters).

2009 Testing Requirements

The 2009 SEC requires all buildings that are not single-family residential, regardless of how many stories, to be tested in accordance with ASTM E779 or an approved equivalent standard. This code has been in effect since November 23, 2010. There is a required target value of 0.40 cfm/ft^2 (2.03 L/s·m^2) of building enclosure area at a pressure differential of 0.3 inches of water (75 Pa)[1], but there is an exception stating that if a thorough inspection of the air barrier by a qualified third party has been conducted, the target value does not need to be achieved. The 2009 SEC also has several important modifications to ASTM E779. The 2009 SEC:

1. Allows for pressurization testing or both pressurization and depressurization testing, but does not allow depressurization testing only
2. Specifies test pressure range of 25 Pa to 80 Pa
3. Allows intentional openings in the enclosure to be sealed during the test

The 2009 WSEC is essentially the same as the 2009 SEC, except that in the WSEC the requirement to test is limited to all buildings over five stories (residential or nonresidential). The WSEC also has similar modifications to ASTM E779, but with one exception being that depressurization-only testing is allowed. Again, there is no requirement to achieve the target value of 0.40 cfm/ft^2 (2.03 L/s·m^2), just a requirement to achieve a completed test.

2012 Testing Requirements

Nonresidential buildings permitted under the 2012 edition of the SEC must be tested in the same manner as the 2009 SEC; however, these buildings now must achieve the previously specified target of 0.40 cfm/ft^2 (2.03 L/s·m^2). Any building that does not meet this requirement must be re-inspected and any leakage found must be sealed. The 2012 code gives the code official the authority to accept or reject any remedial air sealing work. Also, the definition of a residential building has changed. The 2012 SEC defines a residential building as “detached one- and two-family dwellings and multiple single-family

[1] *For this paper, all air leakage test results are listed at a reference pressure of 0.3 inches of water (75 Pa) unless otherwise noted.*

dwellings (townhouses) as well as Group R-2, R-3, and R-4 buildings three stories or less in height above grade plane."

The 2012 WSEC has essentially the same requirements as the 2012 SEC, though there are several important omissions. The WSEC does not list any modifications to ASTM E779 and also allows depressurization-only testing. The 2012 edition of WSEC has been in effect since July 1, 2013, and the 2012 SEC went into effect December 26, 2013.

TEST PROCEDURES

ASTM E779 was originally developed to provide accurate, repeatable air leakage test results in single-family homes. There are numerous testing standards of this nature in use all over the world, and they all rely in the same basic principles. Air is supplied from a calibrated fan (or fans) into a building and the building is pressurized while flow is measured. The resulting flow rate can then be normalized using the area of the building enclosure.

Testing single-family houses in this way has been done for decades and is a familiar concept to many people in the construction industry. Testing large buildings is often far more complicated and requires a more comprehensive and longer test methodology. The US Army Corps of Engineers (USACE) recognized the need for this and developed their own version of ASTM E779, which is specifically tailored to testing large buildings. The USACE actually requires all military buildings to achieve 0.25 cfm/ft^2 (1.27 L/s·m^2) or better, which is more stringent than any other past or current code requirement in North America. The USACE testing protocol also requires gathering more data over a longer period of time and testing at high pressures (0.3 inches of water) to reduce the impact of bias pressures on the test results. The WSEC and SEC also require air leakage results at 0.3 inches of water (75 Pa) instead of 0.2 inches of water (50 Pa), which is the typical requirement for most residential testing standards.

Differences between Single-Family Residential and Large Building Testing

The reasoning behind the changes to residential testing standards primarily has to do with height. Taller buildings are typically exposed to much higher wind speeds combined with a much larger stack effect. Stack pressures occur as a result of warm air rising through the building and creating large airflows and pressure differentials that can add uncertainty to air leakage test results. Stack pressure depends on the height of the building and the temperature difference between the indoors and outdoors. As the temperature difference or height increases, the stack pressure also increases. The combination of high winds and large stack pressures can create unreliable test data at lower pressures and also severely affect HVAC balancing once the building is occupied.

Aside from the difficulties associated with reliable data collection in large buildings, the testing preparation is also more difficult. There will often be multiple days of preparatory work sealing intentional openings. Also, the size of some buildings requires many fans to be set up with a complex arrangement of data cables and pressure tubes.

Challenges with Current Large Building Test Standards

While the 2009 and 2012 codes are a step in the right direction, there is still room for improvement. For example, Section 8.4 of ASTM E779 states that the indoor/outdoor temperature difference multiplied by the height of the building cannot exceed 1180 (200 metric). This is expressed as 1180 ft·°F (200 m·°C). This limit would prohibit testing for much of the year in many buildings over five stories. Another more serious concern with ASTM E779 is the language in Section 8.1 that describes how to verify a uniform interior pressure distribution. There is no mention of bottlenecks within a building (such as narrow hallways and interior doors) that could result in a lower leakage measurement than the true value, as pressure uniformity is not achieved.

Also allowing testing in one direction (pressurization only) can result in significant errors that cannot be detected unless testing in the opposite direction is also completed. Pressurization testing typically yields marginally higher leakage rates than depressurization (see pressurization and depressurization results in Table 1 below) because of outswing doors and windows that pull tight under negative pressure, but in some cases temporary seals on intentional openings can be blown off during testing, causing abnormally high results. Depending on the size of these openings, results may still appear normal to the tester if only pressurization testing is done. This is why the USACE protocol requires testing in both directions.

AIR LEAKAGE TEST RESULTS

Over the last several years the authors have conducted numerous air leakage tests on large buildings in the Seattle area. These buildings have been divided into three different usage types: residential, commercial, and institutional. Institutional in this case means it would fall under the R-2 occupancy group but is a publicly owned building.

There are many different air barrier materials and assemblies in use. For simplicity they have been divided into five main categories. Roofs and below-grade assemblies are also important components of the air barrier system, but differences are not discussed in this paper. Each category refers to the primary strategy utilized to create a continuous air barrier in the walls of the building, as follows:

1. Curtain Wall/Window Wall – The primary air barrier system is a curtain wall or window wall system that spans floor-to-floor between concrete slabs. Joints and penetrations are gasketed or filled with sealant.
2. Liquid-Applied (Exterior Air Barrier) – The surface and joints of the exterior gypsum (or wood-based) sheathing are coated with a liquid-applied membrane and sealed with sealant.
3. Sheet-Applied (Exterior Air Barrier) – The surface of the exterior gypsum sheathing is wrapped with a sheet-applied membrane (e.g. synthetic house-wraps) and sealed with tape, sealant, or self-adhered membrane at laps, penetrations, and terminations.
4. Sealed Sheathing (Exterior Air Barrier) – Similar to sheet-applied, but joints of the exterior gypsum (or wood-based) sheathing are sealed with sealant and then wrapped with sheet-applied weather-resistive barrier.
5. Storefront Glazing – The air barrier strategy consists of an aluminum-framed storefront system. The air barrier at the storefront consists of the aluminum frames, glazing gaskets, vision glass, sheet metal back pans, and perimeter sealant. Primarily used in weather-protected commercial spaces, storefront glazing tends to have lower airtightness performance than window wall or curtain wall systems.

Figure 1 *(a) Sealed sheathing, prior to sheet membrane (water resistant barrier) installation. (b) Sheet-applied air barrier sealed with tape.*

There are many other air barrier strategies, but those listed here are those most commonly utilized around the Seattle area. Also, the air barrier types shown are the primary air barrier strategy for the exterior walls. Please note that in almost any building there will be a combination of several different strategies. Figure 2 shows the distribution of buildings tested.

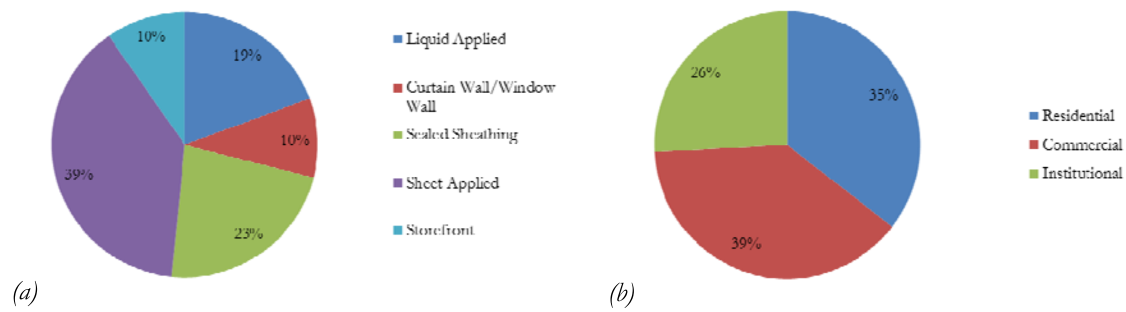

Figure 2 *Distribution of buildings tested for this paper by (a) air barrier type and (b) building type.*

Table 1 lists large and/or nonresidential tests conducted by the authors since the 2009 codes came into effect. The primary wall air barrier system is shown, along with the building type, building enclosure area, and normalized air leakage result.

Table 1. Whole-Building Air Leakage Test Data

Building Number	Primary Air Barrier Type	Enclosure Area (ft^2)	Building Type	Normalized Air Leakage (cfm/ft^2 at 75 Pa)		
				Average	Depressurization	Pressurization
1	Sealed sheathing	76,043	Institutional	0.29	0.29	0.29
2	Liquid-Applied	80,000	Commercial	0.15	0.15	0.16
3	Sheet-Applied	11,007	Commercial	0.86	-	0.86
4	Sheet-Applied	180,000	Residential	0.50	0.50	0.50
5	Liquid-Applied	52,000	Commercial	0.19	0.17	0.22
6	Sheet-Applied	8,528	Commercial	0.41	0.41	0.41
7	Sheet-Applied	5,069	Commercial	0.45	0.45	0.45
8	Sealed sheathing	104,000	Institutional	0.14	0.11	0.17
9	Sealed sheathing	79,009	Institutional	0.17	0.14	0.20
10	Liquid-Applied	62,370	Commercial	0.22	0.22	0.22
11	Liquid-Applied	26,300	Commercial	0.31	0.31	0.32
12	Sealed sheathing	69,581	Institutional	0.15	0.12	0.18
13	Sealed sheathing	62,297	Institutional	0.16	0.13	0.19
14	Sealed sheathing	93,038	Institutional	0.19	0.15	0.22
15	Sheet-Applied	70,530	Residential	0.28	0.28	0.29
16	Window Wall	159,971	Residential	0.14	0.14	-
17	Curtain Wall	12,704	Commercial	0.20	0.19	0.20
18	Sheet-Applied	7,127	Commercial	0.22	0.22	0.22
19	Storefront	8,126	Commercial	0.27	0.27	0.27
20	Window Wall	92,734	Residential	0.32	0.30	0.33
21	Liquid-Applied	82,987	Commercial/ Residential	0.25	0.23	0.26
22	Sheet-Applied	92,584	Residential	0.34	0.34	-
23	Sheet-Applied	16,503	Commercial	0.17	0.17	0.17
24	Sealed sheathing	232,844	Residential	0.21	0.20	0.21

25	Storefront	87,316	Institutional	0.26	0.25	0.26
26	Liquid-Applied	122,387	Institutional	0.15	0.15	0.15
27	Sheet Applied	79,430	Residential	0.31	0.31	0.31
28	Storefront	11,120	Commercial	0.17	0.16	0.17
29	Sheet Applied	101,353	Residential	0.30	0.27	0.32
30	Sheet Applied	72,286	Residential	0.35	0.34	0.36
31	Sheet Applied	61,410	Residential	0.36	0.33	0.39
		Average leakage Rate:	0.25 Median:	0.23	Standard deviation:	.095

RESULTS DISCUSSION

All of the tests presented here were conducted in accordance with the 2009 SEC requirements. Although there is a relatively small sample size to date (31 buildings here and growing), some important conclusions can be drawn from the data. First, it has become clear that the newly imposed airtightness target of 0.40 cfm/ft^2 (2.03 L/s·m^2) is not prohibitively difficult to achieve. The only buildings that did not meet the target were cases in which the contractor/developer did not perceive value in an airtight building or in which there was a significant discontinuity in the air barrier system.

As a case study, building 1, constructed in 2011, was tested with a result of 0.29 cfm/ft^2 (1.47 L/s·m^2). A companion building of similar design and assembly was constructed in 2012 (Building 24) by the same builder and design team. Applying the lessons learned from the test findings at the first building, it was possible for the builder to make improvements to the newer building's air barrier details, particularly at HVAC equipment and the roof parapet detailing approaches. In both buildings, a sealed sheathing (silicone sealant between joints of exterior gypsum sheathing) was used as the primary wall air barrier strategy, integrated with the rest of the building (windows, roof, below-grade areas, etc.). The newer building tested at 0.21 cfm/ft^2 at 75 Pa (1.07 L/s·m^2), a reduction of 28% from the first building at 0.29 cfm/ft^2 (1.47 L/s·m^2).

It is also worth noting that Building 4 and Building 15 were both constructed by the same developer/contractor using the same sheet applied air barrier strategy. The difference in results comes from a better understanding of air barrier detailing and having an emphasis on airtightness all the way through the design and construction phases. The contractor learned and improved from one building to the next, and the leakage was reduced by nearly 44%, from 0.50 to 0.28 cfm/ft^2 (2.54 to 1.43 L/s·m^2).

Figure 3 shows the normalized air leakage of each building as well as the square footage of the enclosure. The solid red line denotes the 0.40 cfm/ft^2 (2.03 L/s·m^2) target.

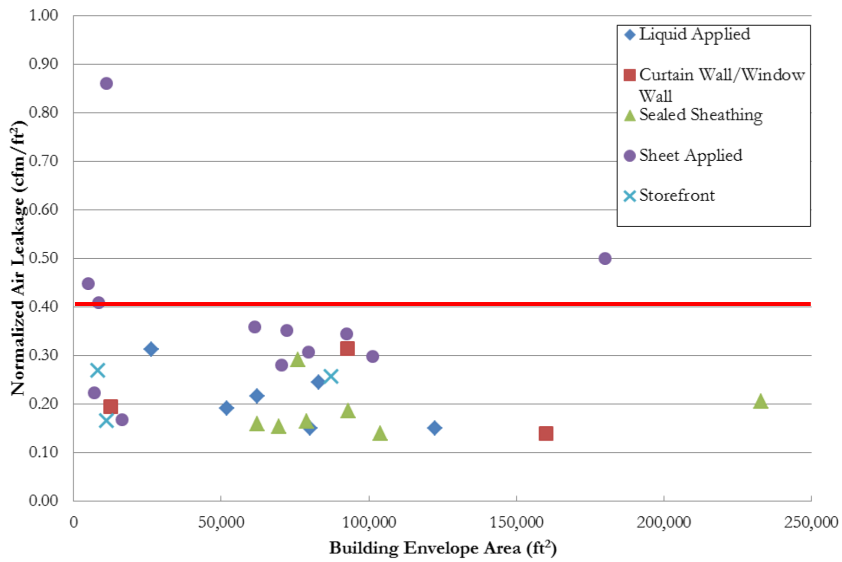

Figure 3 *Normalized Leakage Area plotted against Building Enclosure Area. Marker types denote different air barrier types.*

In general, the quality of detailing at interfaces and workmanship can have a much larger impact on the overall air leakage of a building than the air barrier type. The outlier in Figure 3 (0.86 cfm/ft², 11,007 ft²) was due to large discontinuities in the air barrier that were noted prior to the test, but not addressed. For the remaining analysis in this paper, this outlier will not be included. The only other results above 0.40 cfm/ft² (2.03 L/s·m²) were cases where the contractor and developer did not perceive value in airtightness and minimal effort was put into air sealing. Figure 4 shows the data averaged by air barrier type. Most of the tests are within 0.15 to 0.33 cfm/ft² (0.76 to 1.67 L/s·m²), and aside from a few sheet-applied systems, there is no significant difference between each air barrier type. The average of all of the results is 0.25 cfm/ft² (1.27 L/s·m²), with a median of 0.23 cfm/ft² (1.17 L/s·m²) and a standard deviation of 0.095 cfm/ft² (0.48 L/s·m²).

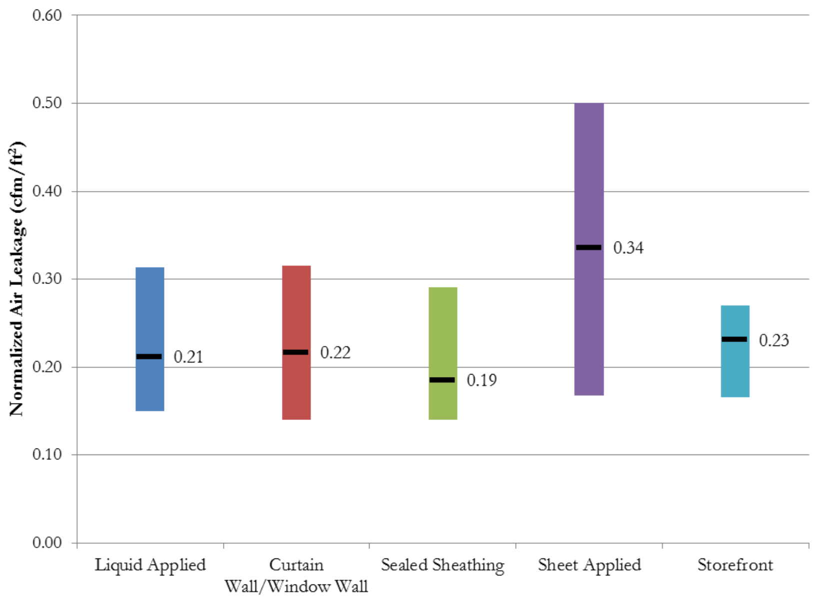

Figure 4 *Minimum, maximum, and average leakage results for each air barrier type. Average values shown as black dashes. The previously mentioned outlier has been omitted.*

There has long been the belief among mechanical system designers that large buildings are very leaky, and in some cases this is true, but currently assumptions are being made that lead to oversizing HVAC units. Passive make-up louvers are sometimes installed to compensate for this, which effectively negates all the work done to make the building airtight.

CONCLUSIONS

Air leakage testing is slowly becoming more accepted in Washington as a valuable part of the commissioning process. The Seattle building industry has been for the most part successful in meeting the challenge of building relatively airtight buildings. This paper presented results from the first two years of air leakage testing done for building code compliance by the authors. The results are promising, with all but four buildings (85% of those tested) meeting or exceeding the proposed air leakage target. Those buildings that did not meet the target have well-documented explanations for the excessive leakage. With a thorough understanding of air barriers, a qualified design team should have no trouble achieving 0.40 cfm/ft^2 (2.03 L/s·m^2) with any of the commonly used air barrier systems. In some cases, less than half of the proposed target is attainable. There is limited data available, but currently there is no indication that one primary wall air barrier strategy is far superior or inferior to others. In our experience it is the details and workmanship which are more critical to the performance of a system. The results in this paper demonstrate that to maximize the benefit from HVAC system selection and implementation and commissioning, owners, architects, HVAC designers, building enclosure designers and commissioning agents need to better communicate and coordinate early in the design development phase of the project. The knowledge that relatively airtight buildings are being built should help HVAC designers properly size equipment to meet the owner's requirements, ensuring the equipment operates properly while mitigating the negative performance that comes from over sizing HVAC equipment.

NOMENCLATURE

Air barrier - Refers to the materials and components of the building enclosure or of compartmentalizing elements that together control airflow through the assembly.

ASTM – American Society for Testing and Materials

Bias pressure - Refers to the pressure difference measured between the exterior and interior of a building when no fans are used to adjust the pressure. Bias pressure is caused by the natural driving forces of stack effect and wind.

Building enclosure - Refers to the part of a building that separates the interior environmental conditions from the exterior environmental conditions, including the control of precipitation, water vapor, air, and heat.

Cfm - cubic feet per minute (ft^3/min)

Driving forces - Refers to natural phenomena and mechanical systems that create pressure differentials and thus create airflow. This includes stack effect, wind, and ventilation equipment.

Normalized air leakage – air leakage divided by the area of the building enclosure, typically listed in units of cfm/ft^2 at a reference pressure of 0.3 inches of water (75 Pa). Multiply by 5.08 to convert to $L/s{\cdot}m^2$.

Pa – Pascal. This is the standard metric unit of pressure measurement.1 inch of water = 249 Pa

Stack effect – Refers to the natural pressures that develop across the building enclosure due to the buoyancy of warm air and the temperature differential between inside and outside the building.

REFERENCES

2009 Seattle Energy Code. 2010. Seattle: Seattle Department of Planning and Development.

2012 Seattle Energy Code – Commercial. 2014. Seattle: Seattle Department of Planning and Development.

2012 Washington State Energy Code, Commercial Provisions. 2013. Olympia: Washington State Building Code Council.

ASTM E779-10. 2010. Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. Philadelphia: American Society for Testing and Materials.

Ricketts, L., Finch, G., and Bombino, R. 2013. Air Leakage Control in Multi-Unit Residential Buildings. Vancouver: RDH Building Engineering Limited.

U.S. Army Corps of Engineers and Air Barrier Association of America. 2012. U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes. Champaign: U.S. Army Corps of Engineers.

Washington State Energy Code – 2009 Edition. 2011. Olympia: Washington State Building Code Council.