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AIVC Airtightness Workshop

3rd TightVent Workshop on Building and Ductwork Airtightness

Design, Implementation, Control and Durability: Feedback from Practice and Perspectives

Proceedings

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INIVE

Programme

Thursday 18 April 2013

Friday 19 April 2013

08:00-09:30 Session 6: Large and multi-family buildings

10:00-11:30 Session 7: Large and multi-family buildings

11:45-12:45 (13:00) Session 8: Data collection, perspectives

Thursday 18 April 2013

08:00-09:30 Session 1: Opening session

1. Welcome by AIVC (INIVE), Peter Wouters, INIVE EEIG
2. Welcome by NIBS and BETEC, USA
3. Presentation by the Department of Energy, Eric Werling, Department of Energy, USA
4. Presentation by ASHRAE, Tom Phoenix, ASHRAE, USA

Thursday 18 April 2013

10:00-11:30 Session 2: Airtightness requirements and quality issues

1. The changing requirements on airtightness in the US. Wagdy Anis, WJE Associates, USA.
2. Efforts for providing quality control regarding airtightness, Laverne Dalgleish, chair of ABAA
3. Interactions of airtightness with ventilation systems and implications on energy use. Willem de Gids, the Netherlands
4. New and retrofitted army buildings. Alexander Zhivov, USACE, USA

THE CHANGING REQUIREMENTS OF AIRTIGHTNESS IN THE US

Wagdy Anis, FAIA, LEED AP
Wiss, Janney, Elstner Associates, Inc. - USA.

ABSTRACT

Building problems such as condensation, frost, efflorescence, mold, icicle and ice dam formation, wood decay, metal corrosion, premature failure of assemblies, draftiness and discomfort, and energy loss have all been associated with the phenomenon of air leakage of building enclosures.

In 1965, at the Institute for Research in Construction, at the National Research Council of Canada, (IRC-NRC) Kirby Garden authored the Canadian Building Digest No. 72 entitled “Controlling Air Leakage is Important”. In 1977, also at IRC-NRC, Gustav Handegord, in a paper entitled “The Need For Airtightness in Buildings” concluded that air leakage through construction is the principal means by which water vapor moves to cold surfaces and is the major cause of condensation in buildings.

The Canadian Model National Building Code incorporated air barrier requirements in 1985 in Chapter 5, Environmental Separation, (without quantified maximum air permeance requirements). In 1995 the Model Code adopted 0.2 L/s*m^2 @ 75 Pa (0.004 cfm/ft^2 @ 0.3” w.g.), the air leakage rate of a sheet of 1/2” thick drywall, as the maximum air leakage rate for materials used to construct the air barrier.

In 2001 a major overhaul of the Massachusetts’ energy code was promulgated. The energy code until then had been based on ASHRAE 90.1 1989. Guided by the International Energy Conservation Code (IECC) 2000 and ASHRAE 90.1 1999, MA put in place the first advanced proprietary energy code that combined the best of both codes. It also included extensive air barrier requirements for the first time in the US, based on the Canadian example with additional requirements for compartmentalization and leakage control of stationary mechanical systems and open louvers. Massachusetts undertook a massive educational campaign introducing the new code requirements and held hundreds of public educational sessions and in-house consultations to design firms regarding the new requirements. Funding for this effort was provided by the Department of Energy Resources and the utility companies. Publications on the impact of airtightness ensued (Anis, 2001)

As a result of the Massachusetts air barrier requirements, the Air Barrier Association of America was formed in 2001 based on ISO 9000, with a mission of industry regulation, education and knowledge dissemination.

Attempts to introduce airtightness requirements using air barrier technology into ASHRAE 90.1 were triggered by a Change Proposal to amend ASHRAE 90.1-2001 to include air barrier requirements submitted by the author in 2002. A cost effectiveness study based on energy savings was performed by NIST for SSPC 90.1 committee and published as NISTIR 7238 , (Emmerich, McDowell, Anis, 2005). SSPC 90.1 included air barrier requirements in ASHRAE 90.1 2010, although a whole building airtightness compliance option is missing. The New Buildings Institute (NBI), published its Advanced Buildings Guide as “EBenchmark” in 2003 (subsequently became “Core Performance”), ASHRAE Advanced Energy Design Guides and ANSI/ASHRAE/ IES/USGBC 189.1 all included air barrier requirements. The IECC in 2012 adopted air barrier requirements that include a whole building airtightness option. The US Army Corps of Engineers in 2009 published its air barrier and whole building testing protocol and requirements with a maximum whole building air permeability of the enclosure (six-sided box) of 0.25 cfm/ft2 @ 0.3” w.g (1.25 L/s•m2 @75 Pa). Following suit, the General Services Administration (GSA), the biggest property owner in the world, published its P-100 Design Guide with whole building air testing requirements and a maximum air permeability of 0.4 cfm/ft2 @ 1.57 psf (2.0 L/s•m2 @ 75 Pa). In 2010, the tri-forces published UFC-3-101-01 Architecture , with air tightness requirements for the army, navy and air force buildings with whole building testing requirements to different criteria for the different branches of the Department of Defense (USACE and NAVFAC at 0.25 cfm/ft2 @ 1.57 psf (1.25 L/s•m2 @75 Pa) and Air Force at 0.4 cfm/ft2@1.57 psf (2.0 L/s•m2 @ 75 Pa). The International Green Construction Code (IgCC-2012) has recently been published and requires mandatory air leakage testing of whole buildings.

The requirements for whole building air tightness testing are becoming increasingly attractive to many jurisdictions. The State of Washington was the first to institute air barrier requirements with both a maximum material air leakage requirement and a whole building maximum air permeability rate with testing requirements for buildings six stories and higher. Requirements for enclosure commissioning as an option for buildings that are too difficult to test are also being considered.

INTERACTIONS OF AIRTIGHTNESS WITH VENTILATION SYSTEMS AND IMPLICATIONS ON ENERGY USE

Willem de Gids
VentGuide
The Netherlands

Abstract

Due to imperfect building envelopes air infiltration takes place. Air that infiltrates into a building has to be heated up to the comfort level. The consequence for the use of energy is clear. Many calculation procedures in regulations and standard assume a linear relation between the air tightness level of a building and the energy use due to air infiltration. Nevertheless some demand controlled ventilation systems don´t recognize the difference between outside air coming through cracks into the building and air that enters through purpose provided openings. Balanced systems however in case the purpose provided flows are really balanced, have a higher penalty for infiltration air than systems with natural air supplies.

For balanced ventilation systems all infiltrated air is also exfiltrated air, hence the energy use is bigger than for some other systems. The flows through a building in relation to the type of ventilation system and its control in relation to energy use will be discussed in this paper.

PAPER TITLE: AIR TIGHTNESS IN NEW AND RETROFITTED U.S. ARMY BUILDINGS

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ABSTRACT

During the past several years ERDC CERL has been conducting investigations to develop design/construction strategies for improving the energy efficiency, preventing mold and improving indoor air quality in newly constructed buildings and buildings undergoing major renovations. An important part of these studies was building envelope leakage tests on some existing facilities to gain understanding of the general leakiness of Army buildings and the effect of increased air tightness on the building energy consumption. Based on the results of these studies, air tightness criteria and performance requirements to new construction and major renovation projects have been developed and included into the Army design/construction strategies.

Since 2009 the US Army Corps of Engineers (USACE) implemented a requirement for air tightness in all new construction and building enclosure renovation projects. This requirement set levels of air tightness for the building enclosure at the material, assembly, and system level. Additionally, it requires that a whole building air leakage test be completed at completion of construction to verify performance of the constructed air barrier system. The current version of the Air Leakage Test Protocol for Building Envelopes developed by USACE ERDC together with Air Barrier Association of America (ABAA) and industrial partners has been published in May 2012 and can be founded on http://www.wbdg.org/pdfs/usace_airleakagetestprotocol.pdf.

This paper presents results of air tightness tests before and after new requirements were set forward. Updated results for more than 350 newly constructed and renovated large buildings air leakage tests and perform analysis in regards to, design and construction process, air barrier materials, building use, and construction types are presented. Presented data may support future decisions regarding air tightness levels to be adopted for commercial buildings.

Thursday 18 April 2013

12:30-13:45 Session 3: Characterization of products and systems

1. Airtightness of the window-wall interface in masonry brick walls. Nathan Van den Bossche and Arnold Janssens, Belgium
2. Evaluation of an Interior Air Barrier System with Dynamic Water Vapour Control in North American Climates. Stanley D. Gatland II, CertainTeed, USA
3. Airtight Curtain Wall/Window Connection Best Practice. Joerg Birkelbach, Tremco illbruck, USA
4. The Science of Rough Opening Preparation and Window Installation to Minimize Air Leakage, Sam Hagerman, Hammer and Hand, USA

Short Presentation

5. *The Science of Fluid-Applied Flashing Systems, Paul Grahovac, Prosoco, USA*

AIRTIGHTNESS OF THE WINDOW-WALL INTERFACE IN MASONRY BRICK WALLS

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ABSTRACT

In recent decades there has been an increased focus on enhanced thermal resistance of building components and as a consequence, the relative importance of airtightness on the overall energy losses of buildings has increased significantly. The construction industry requires practical information on the airtightness of individual construction elements and building envelope interfaces. A literature review on the airtightness of window-wall interfaces has shown that no experimental data are available for masonry construction. This paper offers an investigative study on the airtightness of window-wall interfaces of masonry walls, for 13 different installation methods. The results show that the selected solutions cover a wide range of airtightness levels, from 0m³/h.m up to 31m³/h.m at 50 Pa. The experiments have permitted determining that a very good performance can be obtained by using polyurethane foam and caulking, airtight membranes, polyurethane foam and plywood framing, and plaster and caulking. On the contrary, mineral fibre insulation, a partial fill with polyurethane foam and plaster without caulking should be avoided when good airtightness is required. Furthermore, a comprehensive methodology for error calculation is offered, based on error propagation of partially correlated parameters, including the effect of measurement errors, extraneous air leakage and conversion to standard boundary conditions.

KEYWORDS

airtightness, window-wall interface, brick cavity wall,

INTRODUCTION

Throughout the last few decades an increasing number of countries are enforcing energy codes and existing codes are getting stricter in respect to energy usage in homes. In addition, there has been a general increase in the price of energy (U.S. E.I.A, 2008). Airtightness is one of the defining factors in energy use in buildings. In a moderate climate such as that found in Belgium, infiltration of cold air accounts for up to 20% of overall primary energy use for code-compliant buildings (VEA, 2009). Obviously, in colder climates the more pronounced effects of infiltrating cold air in buildings will result in code requirements for improved energy efficiency and thus promote better construction practice concerning airtightness (Sherman and Chan, 2004). In general, the existing housing stock in colder climates is more airtight as compared to homes located in moderate climates (McWilliams and Sherman, 2005). One might expect that more airtight buildings are constructed over time due to stricter building codes, but an analysis by Bossaer et al. (1998) on 51 homes built before and after the implementation of the first energy building code in Belgium showed no difference in respect to airtightness. However, the energy code in Belgium only provides recommendations on airtightness in relation to HVAC-systems, contrary to that required in other countries, e.g. Norway, Sweden and the US (Limb, 2001). The average airtightness (n_{50} , the measured air volume flow at 50Pa pressure difference divided by the interior volume of the building) of detached residential buildings in Belgium in 1995 was 11.7 air changes h^{-1} (Bosaer et al., 1998; results were recalculated to meet ISO 13829:2001 requirements). A more recent study by Laverge et al. (2010) on newly built residential dwellings shows that the air leakage has decreased significantly in 15 years, and is now about 6.0 air changes h^{-1} at 50Pa pressure difference. This decrease is mainly caused by an increased awareness concerning airtightness by architects, contractors and building owners. The required level of airtightness of buildings in Belgium will most likely become stricter in the future. In 2006 the airtightness of only 1,5% of all newly built dwellings was measured, whereas in 2009 already over 7% were tested using a pressurization test (VEA, 2011). There is an urgent need for standard details at openings in buildings that would minimize air leakage at these vulnerable locations (Hens, 2011); this has become apparent from the increased number of airtightness tests that are now being carried out. It is evident that the building stock in Belgium has poor airtightness performance and from this it can be surmised that there is likewise a lack of knowledge at the designer's side in respect to achieving adequate airtightness in homes. For wood-frame construction interesting research was published by Relander et al. on different components and interfaces (Relander et al., 2010, 2011). The window-wall interface is one of the key air infiltration pathways in wood-frame construction (Relander et al., 2008). Consequently, there is a high probability that this will likewise be the situation for masonry cavity walls.

Energy concerns are not the only reason to focus on airtightness. A lack of airtightness can cause cold draughts, lower acoustical performance of the building envelope, interfere with the balance of a HVAC-system, promote interstitial condensation through exfiltrating air and surface condensation through infiltrating air. Research by Lacasse et al. (2003) even suggests that deficiencies in airtightness have an effect on the watertightness of the window-wall interface: over the course of watertigthness tests those window-wall assemblies that were less airtight achieved reduced levels of pressure equalisation that resulted in higher rates of water infiltration into the assembly.

Based on the rising demand from the building industry for standard details for airtight construction in masonry cavity walls, and the fact that window-wall interfaces can account for significant air losses, and as well, the lack of information found in literature on this topic, a research project was initiated to provide practical information on this topic. This paper reports the results of an experimental study on 13 different installation methods for windows in masonry cavity walls. Section 3 provides details on the relevant standards, the test method and experimental setup, and a thorough error analysis based on error propagation of partially correlated parameters. In section 4 the different installation methods are described using detailed sectional drawings and description, whereas the results are reported in section 5. Next to that, section 5 also comprises an analysis of window-wall interface air leakage as compared to overall building airtightness.

LITERATURE REVIEW

The typical construction method and materials of different components of the building envelope vary geographically, according to climate, natural resources and building practice employed in a particular geographical location. This paper only focuses on the window-wall interface in brick cavity masonry walls. These walls are typically representative of current building practice and consist of an inside leaf in extruded large format perforated bricks, a cavity partially or fully filled with insulation and an outer masonry veneer wall. The airtightness of the wall is secured by a layer of plaster, typically sprayed to the interior side of the interior brick wall and scoured manually. Such type of walls are characteristic of North-Western European building practice (e.g. Belgium, The Netherlands, Northern France, Great Britain). This section of the paper is comprised of an analysis of experimental data on the airtightness of window-wall interfaces as found in literature, and includes some general guidelines or estimation techniques for assessing air leakage in homes which are often used or cited. The air flow rate through an opening for an applied pressure difference is commonly expressed by the empirical power law equation (1):

$$\dot{V} = C.\Delta P^n \qquad (1)$$

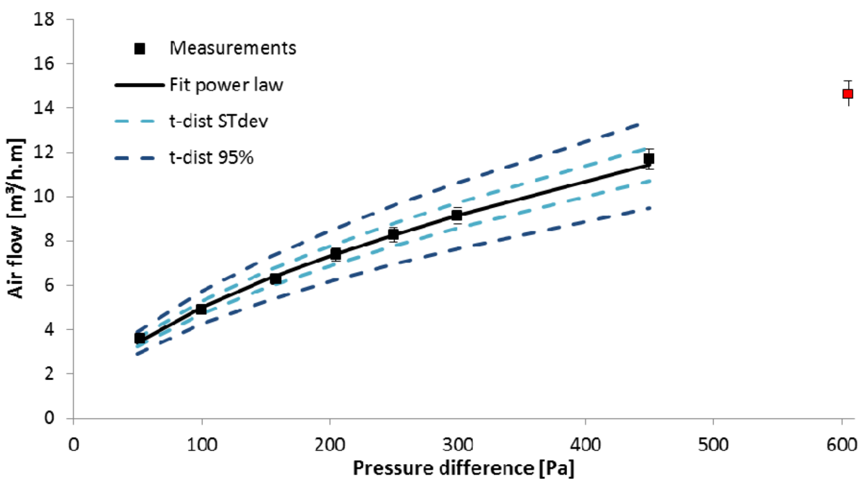
With $\dot{V}$: air flow rate (m³/h), ΔP: pressure difference (Pa), and C: flow coefficient (m³/h.Pa^n) and n: flow exponent (-). A summary of results derived from different sources can be found in Van Den Bossche et al. (2012). Most literature dealing with airtightness of window-wall interfaces originates from countries having a cold climate, and practically all reported measurements were completed on wood-frame constructions. Even though most joints have a similar width, there is a large variety in air flow rates for similar products. For example, the installation of mineral wool limits the air flow to around 1.5m³/h.m at 50Pa when placed correctly and well compressed, and ca. 5m³/h.m when installed incorrectly. Backer rods can be very airtight, and the air leakage should be below 1m³/h.m at 50Pa, whereas open cell products and self-expanding products generally perform poorly. Tapes and membranes are more airtight, between 0 and 0.31 m³/h.m at 50Pa, but also susceptible to improper installation. Polyurethane foam and sealants are practically perfectly airtight when installed correctly. The effect of a window sill on the overall performance of the window-wall interface was not evident in any of these publications, and neither was it included in this research project.

For this reason a new test series was setup, specifically devoted to masonry cavity wall construction, as described in section 4 of this paper. Before discussing the results, the issue of measuring uncertainty in air leakage measurements is first addressed.

TEST METHOD

Procedure

The test samples were measured using a standard calibrated test rig which is used on a daily basis to test the airtightness of window frames according to NBN EN 1026:2000. In absence of any specific guidelines for window-wall interfaces, the test protocol was based on the one for window frames given in NBN EN 1026: it seems reasonable to apply pressure differences corresponding to the typical product specification of windows to the window-wall interface. After three pulses at 110% of the maximum test pressure, the sequence is as follows: 50-100-150-200-250-300-450-600 Pa. The same procedure is then repeated but with negative pressures.
The window itself was non-operable, and the glazing stop was sealed on both sides (glass side and frame side) to ensure that no air was infiltrating through the window and influenced the measurements. Furthermore, smoke pencils were used to trace and visualize leakage paths in the sample. The extraneous air leakage was measured before, in between and after the tests. The experimental data reported in this paper were calculated by subtracting the first extraneous air losses from the measured air flows. If there was a slight difference in extraneous air leakage before and after the sample measurement, the lowest value of extraneous air loss was chosen to provide a conservative result. The test sequence described above was also used for quantifying the extraneous air losses, but with an airtight plate installed over the window opening (Figure 2). The plate covered 5cm of plaster around the window reveal, and was sealed to the plaster by means of a compressed closed cell neoprene backer rod and caulking. The test rig was designed to be as airtight as possible, to reduce the overall error on the results. The leakage of the test rig was adjusted by consecutive testing, but even after optimization the degree of air loss remained in a range of 0.5 – 0.6m³/h.m at 50Pa for the different measurements of extraneous leakage. As 6 out of 13 measured installation methods have an air loss ranging between 0 and 0.2m³/h.m at 50Pa, the effect of the extraneous air loss is significant. This caused quite large uncertainty intervals for results of the most airtight installation methods. The temperature, relative humidity and barometric pressure was recorded during each test, in order to convert the results to standard boundary conditions.
The error analysis was based on the calibration error of the test rig, error due to conversion to reference conditions, the chauvenet criterion, and error propagation in the power law. More details on the error analysis methodology can be found in (Van Den Bossche et al., 2012).



Air flow measurement with power law and t-distribution uncertainty interval of installation SPF-all (the red mark was rejected according to the Chauvenet-criterion).

Test specimens

In order to measure the airtightness of the window-wall interface in cavity brick walls, two test walls were built to represent different situations. The first wall was considered as common practice and was comprised of an aluminum window frame in a brick cavity wall having 8cm of polystyrene insulation and 3cm of air cavity. Note that the majority of newly built walls in Belgium incorporate an air cavity to ensure adequate drainage and easy of execution. For this specimen, two different interior finishes for the window reveal were applied: a wooden window trim (test setup A); or a layer of gypsum plaster on the reveal (test setup B). Test setups A and B were thus applied on the same wall, but have a different interior finish.
Currently in Belgium (and perhaps elsewhere in Northern Europe where homes constructed of brick masonry walls are current practice) there is a tendency to place more insulation in brick cavity walls to comply with energy standards with the expectation of reducing energy losses and thereby lowering heating costs. Extremely low energy buildings can have cavities (width of insulation plus empty cavity) up to 24cm wide in order to obtain, e.g., passive house certification. As the window frame is typically recessed about 10cm from the outer masonry plane, the installation technique should take into account the eccentric structural load of the window with regards to the inner bearing masonry wall. This eccentric load can be dealt with by mounting strong brackets at the sill, or for small to moderately sized windows by installing a plywood framework all around the window frame. Even if the window is too big and extra brackets are required at the sill, the plywood frame still offers additional benefits, such as ease of installation, rigid backing for the interior finish, and additional rigidity for the window installation. The latter technique was thus applied, also because it is currently the most common approach used in buildings certified for extremely low energy usage . The second wall was thought representative of well insulated buildings, and consisted of a wooden window frame in a brick cavity wall having 20cm of polystyrene insulation and a 2cm air cavity (setup C). For setup C it was anticipated that the performance would be independent to the type of interior finish. For both walls, the windows are 1.23m wide and 1.48m high (according to the product standard NBN EN 14351-1:2006, and representative of typical dimensions for windows in Belgium), and both walls were 1.92m by 2.02m (2m adjusted to brick module).


Figure 2a. calibration setup for measuring extraneous air leakage of the setup. Figure 2b. Installation of aluminum window frame and wood reveal.

In test setups A and B the window was installed using typical mounting brackets, whereas in setup C, given that the use of wide cavity brackets were not an option, there was a plywood framework to which to secure the window unit and that was fixed to the interior brick wall. It was anticipated that the interior finish of setup C (paint on plywood, window trim or gypsum plaster) would not affect the airtightness performance because the continuity of the airtight layer was guaranteed by the airtight plywood framework. In both test setups the horizontal projected gap between frame and wall was 2.5cm; this is a typical size and allows adequate tolerance for installation. Note that the perimeter was not exactly the same for both setups because in setup C the plywood framework at the perimeter of the window required a slightly bigger opening in the wall to obtain the same degree of tolerance. In both cases the window was recessed 10cm from the outer plane of the wall. Contrary to common practice, the joint between the exterior brick wall and the window frame was not caulked during testing. It was assumed that brickwork typically does not contribute to the airtightness due to open drains and vents in the façade. Note that the installation methods were only designed for airtightness testing; other parameters such as watertightness and thermal performance were not considered here. Consequently, no statements are made in respect to other parameters and the drawings only report the installation as it was tested. All of the different materials used to fabricate the test specimens were randomly selected and installed by professional craftsmen. Caulking and sprayed in place polyurethane foam (SP-PUR) were always left for at least one day to cure prior to testing, and plaster was permitted to cure for at least two days. Figure 2 shows the measurement of extraneous air leakage of test setup C.

In these tests, no differentiation was made between the head, jambs or sill, similar to that reported in all of the papers cited in Table 1. Furthermore, it should be noted that the results represent the air leakage along the linear interface, as well as any local deficiencies situated at the corners. For test setup A the perimeter was 5.32m and this obviously included the four (4) corners. It is likely that the corners are less airtight than the linear joints due to additional interfaces coming together and issues related to ensuring airtight installation at these locations. As the results are expressed per meter of joint length, this implies that the results presented in this paper might underestimate the air leakage for windows having a lower area to perimeter ratio given that in such instances the air leakage at the corners is more important.

INSTALLATION METHODS

The selection of the different installation methods was discussed with building practitioners, window installers and manufacturers in collaboration with the Belgian Construction Certification Association (BCCA), specifically the group working on window-wall interfaces. An overview of the installations is described in Table 2, and drawings are provided in Figure 3. In setup A, the window is installed with 10 mounting brackets (3 on each jamb, 2 on head and sill), and the interior finish consists of a wooden window trim. In test setup A seven different installation methods for the aluminium window frame were measured, with varying installation methods for a plywood window trim primarily using mineral fibre, SP-PUR and caulking. The SP-PUR used in the different installation methods is a one-component low-expansion foam with a high elastic recovery, and was applied with a foam applicator gun system. In test setup B the windows were installed in the same wall as setup A, also with 10 mounting brackets, but the interior finish consisted of gypsum plaster, a technique which is currently highly used in contemporary architectural practice. When the plaster is applied on the reveal just on to the window profile, the drying of the plaster induces a shrinkage crack at the interface (installation RP) this approach allows high air flow rates through the cracks. Such cracks are afterwards typically enlarged due to thermal movement of the window and deformation by mechanical loads (wind forces or operating forces). This can be resolved by installing a vinyl end profile for the plaster, and then placing a backer rod and caulking between the end profile and the window frame (RP stop). This technique only uses standard techniques from the building industry, and is airtight enough to be applied in passive homes. Another solution is the use of airtight membranes, equipped with a woven layer that allows plaster to adhere on the membrane. The membrane itself consisted of a polyester foil, with a pressure sensitive adhesive on one end that was adhered to the window frame, and a butyl layer on the other end that was attached to the interior brickwork.

No.	Setup	Abbreviation	Description
1	A	Empty+C	Cavity between the brick wall and window casing and trim is empty.
2	A	MF loose +C	Cavity is packed with medium density mineral fibre
3	A	MF dense +C	Cavity is packed with high density mineral fibre
4	A	SP-PUR-e +C	Cavity is partially filled with SP-PUR (exterior side)
5	A	SP-PUR-I +C	Cavity is partially filled with SP-PUR (interior side)
6	A	SP-PUR-all	Cavity is entirely filled with SP-PUR, no caulking between the window frame and the window casement
7	A	SP-PUR-all + C	Similar to No. 6 (SP-PUR-all), but with caulking between window and window trim
8	B	RP	An XPS substrate was mounted to masonry brick wall; a layer of plaster was placed onto window frame. A minor crack was induced between window frame and plaster due to drying shrinkage of plaster.
9	B	RP stop	Similar to No. 8 (RP), but instead a plaster stop profile was installed, and in between a backer rod and caulking ensured the airtightness
10	B	PR foil-e	An airtight membrane was adhered to side of window frame on one side, and on the other side to interior masonry brick wall. A thick layer of plaster connects plaster on wall to window frame.
11	B	PR foil-i	Similar to No. 10 (PR foil-e), but in this case the foil was adhered to the interior side of the window frame after the window was installed and fixed with brackets.
12	C	WF SP-PUR -all	Cavity between wooden frame and insulation and interior brick wall was filled with spray-in-place foam. Plaster was applied over SP-PUR, but shrinkage induced crack was apparent between plaster and frame.
13	C	WF SP-PUR -all +C	Similar to No. 12 (WF SP-PUR-all), but there was no crack between plaster and wood framing, e.g. by means of caulking.

Table 2: Window installation methods in test setup A, B and C.

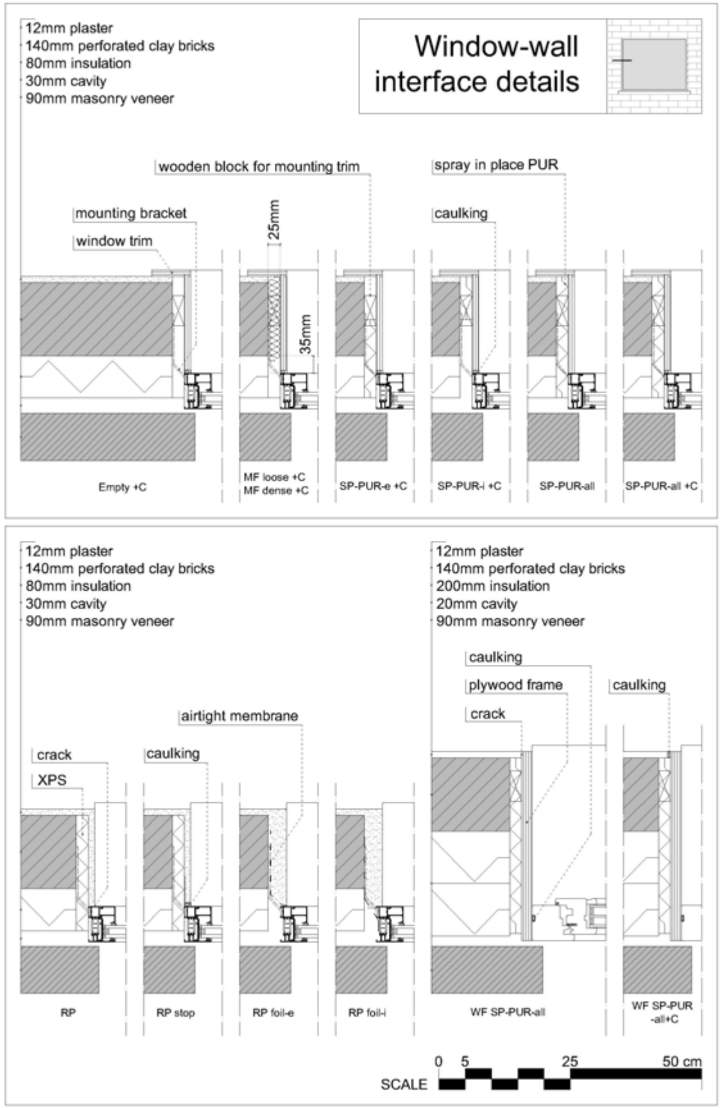


Figure 3. Window-wall interface details. Empty: no insulation in interface. C: caulking on interface with window. MF: mineral fibre insulation in interface. SP-PUR: spray-in-place polyurethane foam. e: insulation on exterior side of interface. i: insulation on interior side interface. all: interface completely filled with insulation.

RP: reveal covered with plaster. Stop: end profile for plaster is installed with caulking. Foil-i: foil adhered on interior side of window frame. Foil-e: foil adhered on side of window frame, on top of mounting brackets. WF: plywood frame is attached to window frame.

The third series of tests were done on a different wall that represented a situation for well insulated buildings (i.e. buildings having e.g. 200mm of insulation). Here the windows were installed using a plywood frame attached to the window profile: caulking was used at the corners between horizontal and vertical to ensure the airtightness. In the first test the cavity between interior brickwork and plywood was filled with SP-PUR, and plaster was applied over the SP-PUR just on to the plywood frame (WF SP-PUR-all). Due to the drying of the plaster there was also a shrinkage crack. In the second installation, the plaster was connected airtight to the wood framing by means of caulking.

RESULTS

The air leakage results through the different window-wall interface installation methods are summarized in Table 3. The leakage (V_{50}) was measured under both positive (pressure acting on the exterior side of the wall) and negative pressure, and for both values the standard deviation σ_v is reported based on the error propagation derived for the leakage coefficients as used in the power law. Table 3 also reports two air flow rates just below zero, which is obviously not possible. However, these were the results of the regression analysis, and one can easily see that a large part of the confidence interval lies above zero.

	POSITIVE		NEGATIVE		AVERAGE	
m³/h.m@50Pa	V_{50}	σ_v	V_{50}	σ_v	V_{50}	σ_v
Empty +C	**32,82**	2,04	**28,75**	2,06	**30,78**	2,06
MF loose +C	**11,29**	0,41	**11,99**	0,28	**11,64**	0,35
MF dense +C	**3,19**	0,26	**2,60**	0,21	**2,90**	0,24
SP-PUR-e +C	**1,23**	0,47	**0,90**	0,18	**1,06**	0,32
SP-PUR-i +C	**1,67**	0,19	**1,86**	0,16	**1,77**	0,18
SP-PUR-all	**1,79**	0,36	**0,94**	0,29	**1,36**	0,32
SP-PUR-all + C	**0,00**	0,28	**-0,01**	0,17	**0,00**	0,22
RP	**2,63**	0,18	**3,16**	0,29	**2,90**	0,24
RP stop	**0,08**	0,04	**0,07**	0,04	**0,08**	0,04
PR foil-e	**0,12**	0,14	**0,14**	0,13	**0,13**	0,14
PR foil-i	**0,24**	0,12	**0,13**	0,14	**0,19**	0,13
WF SP-PUR-all	**-0,03**	0,13	**0,24**	0,08	**0,10**	0,10
WF SP-PUR-all +C	**0,01**	0,09	**0,06**	0,08	**0,03**	0,08

Table 3. Air leakage of the 13 installation methods at 50 Pa.

Out of 13 tests, the air leakage of 7 samples show a higher leakage rate at positive pressure difference compared to a negative pressure difference, but only for 2 cases the error bars do not overlap. Similarly, only for two cases the flow at a negative pressure is significantly larger than the air flow at positive pressure. Conversely, based on the single-point measurements at 50Pa with smaller errors, 9 installation methods show a significantly higher air leakage for positive pressure differences, and 3 are significantly lower than the air flow at negative pressure difference. For most installations there is no obvious explanation for the difference in flow rate due to the direction of the pressure difference, except for the installations with airtight membranes where positive pressures induce ballooning of the membrane and thus higher flow rates. Note that only airtightness is reported in this paper; other aspects e.g. thermal performance may be equally important, but are not discussed here.

Test setup A

The tests showed that loose mineral fiber cannot adequately tighten the interface and consequently this resulted in significant air losses (11,64m³/h.m). Even densely packed mineral fiber still allowed quite significant air losses (2,90m³/h.m) as compared to the other installations. The use of SP-PUR performs reasonably well, even if the cavity between the interior brickwork and window trim is only partially filled. On the other hand, SP-PUR performs extremely well (0,00m³/h.m) if that cavity is completely filled and the joint between the window trim and window frame is tightened by means of a backer rod and caulking. If only the exterior side is filled (SP-PUR-e +C) air infiltrated through the joints of the brickwork. If there is SP-PUR on the interior side of the cavity, air might infiltrate through the interface of trim and frame, or through the joints of the different parts of the window trim (such as SP-PUR-i +C). SP-PUR-all was completely filled with spray in place foam, but contrary to the other installation methods, there was no caulking between trim and window which resulted in high local air flows located at the mounting brackets because the foam was unable to fill all the gaps and slits around the brackets. The results on this setup correlate quite well with the results found in literature (see Table 1) on airtightness of window-wall interfaces in wood-frame construction, although the results in this study are typically higher compared to that found in literature. This is probably because the interface in masonry construction is more irregular compared to wood frame construction. Contrary to wood, the masonry itself is not airtight which introduces a higher susceptibility to flaws and less redundancy at the interface.

Test setup B

The setup with the membrane adhered to the side of the window (PR foil-e) proved to be more airtight than the installation where the foil was installed from the interior side after the window was mounted (PR foil-i). The main locations for infiltration in both cases were the corners: for the first case the foil was folded with an overlength (at the corner the foil did not follow the perimeter; an additional 10cm was folded in order to cope with the difference in perimeter dimensions of window frame and window opening), in the second case the foil was not continuous at the corners, but locally cut for an overlap and fixed with caulking. The results on installations that rely on membranes for airtightness show good agreement with the results found in literature. One paper [22] reports high infiltration rates, but this was for poor installation quality which was not the case here.

Test setup C

Due to the drying of the plaster there was a shrinkage crack between plaster and plywood, but this only had a minor effect on the air losses. The difference in air flow between the installations with and without caulking was very small: the airtightness of the spray in place foam was also tested separately and was proved to be airtight. Both these installations could be recommended for use in passive homes. In practice, the plywood is typically covered with a gypsum board or other finishing. However, the tests done in the lab indicated the performance of the interface, regardless of the interior finish. Test results taken from the literature relating to window-wall installations using SP-PUR show similar levels of performance.

Practical implications

The interpretation of the absolute values can easily be understood by means of an example. Based on an extensive survey (Bossaer et al. 2008), one can assume that the average Flemish detached residential building has 105.0m of window-wall interface (including door to wall interface, excluding door sill, excluding garage doors), and an internal volume of 516.1m³. Figure 4 shows the share of the air loss through the different installation methods of the window-wall interface compared to the overall building air losses for a range of building airtightness levels. The legend is ranked according to the air loss, from leaky to tight (MF dense +C coincides with RP). The effect of choosing a different installation method can be found by following the black dotted lines: changing to a more airtight installation method will decrease the overall airtightness along the path of the dotted lines, depending on the original level of building airtightness. Consider a building with airtightness of $n_{50,A}$, air loss of the window-wall interface of $\dot{V}_{WWI,A}$, total length of the window-wall interfaces, L, and interior volume of the building V_b. The effect of a different window-wall interface ($\dot{V}_{WWI,B}$) can be calculated as follows:

$$n_{50,B} = n_{50,A} - \frac{\dot{V}_{WWI,A} \cdot L}{V_b} + \frac{\dot{V}_{WWI,B} \cdot L}{V_b} \qquad (12)$$

The sensitivity of the building airtightness to the window-wall interface installation method is thus quantified by the ratio L/V_b.

There are no absolute guidelines on how airtight a window-wall interface should be, or what proportion in air leakage a or a set of windows should have as compared to the overall air leakage of a building. Next to that, there is very little information on the actual airtightness of other components or interfaces in buildings with masonry cavity walls, or how significant their share is in respect to the overall air losses of the building. However, taking into account the numerous locations in a building where infiltration may occur, it seems advisable to set boundaries for the window-wall interface. For example, the air loss could be limited to 10% of the overall building leakage, which is a conservative value based on the comparative analysis of different sources of air leakage in residential buildings (Van Den Bossche, 2005). For a chosen building airtightness, it would be advisable that only the installation methods below the 10% line be used to avoid excessive air loss through the window-wall interface. Figure 4 indicates that this assumption is also feasible in practice, because for different levels of airtightness performance, a range of installation methods could comply with these requirements. The average building airtightness n_{50} of newly built detached residential buildings in Flanders is 6 air changes h^{-1}, which, if one considers the suggested 10% limit, results in a maximum air loss through the window-wall interface of 3,3m³/h.m at 50Pa. An airtightness of $3h^{-1}$ can be regarded as reasonably airtight and passive houses are very airtight ($0,6h^{-1}$). The air loss through the window-wall interface should be below respectively 1,6 m³/h.m at 50Pa and 0,33m³/h.m at 50Pa. Although these values are project-specific, they offer a reference to assess the performance of the measured installation methods. Note that this analysis was only done for an average detached residential building assuming a 10%-limit for air losses through the window-wall interface, and it is advisable to do this analysis for a project based on the actual interior volume of the building, the total length of the window-wall interfaces, and the required level of building airtightness.

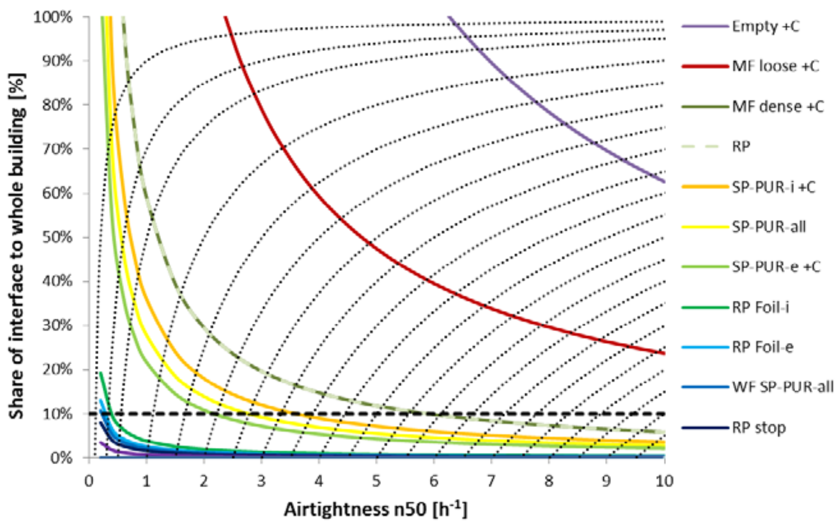


Figure 4. Proportion of air leakage through window-wall interface in relation to overall building airtightness

Based on the assumptions above, the installation methods designed as Empty +C and MF loose +C should in all instances be avoided. Whereas those methods designated as MF dense +C, RP, SP-PUR-i +C, SP-PUR-all and SP-PUR-e +C can be used for building airtightness requirements ranging between 2 and 6 h^{-1}, depending on the specific installation method. The other solutions (RP foil-e, RP foil-I, WF SP-PUR-all, RP stop, WF SP-PUR-all+C, SP-PUR-all+C) are recommended to achieve n_{50}-values below 1h^{-1} as might be used to achieve very low air leakage rates as for example passive homes.

CONCLUSIONS

For buildings in Belgium with a regular, code-compliant, thermal performance, recommendations were derived to limit the air losses through the window-wall interface: it seems advisable that these should be below 3,3m³/h.m at 50Pa. For passive houses, for which the energy loss requirements are significantly more stringent, the admissible air leakage decreases to 0,33m³/h.m. This is based on a detached residential building of average construction, for which an arbitrary limit of 10% of the total building air leakage was assumed; the overall effect will vary according to the internal volume of the building and the total length of the window-wall interface. For a specific project the effect of the window-wall interface on the overall building airtightness can easily be estimated using the results of this study.

The experimental results show reasonable correlation with the results found in literature for window-wall interfaces in wood-frame homes. No insulation or the use of loose fiber insulation to obtain adequate airtightness seems to be insufficient: the air loss was above 3,3m³/h.m (at 50Pa), whereas densely packed mineral fiber was only just below that limit. Only partially filling the cavity between the casing and the brick wall with SP-PUR is already a significant improvement, but the interior brick wall is not very airtight, and still allows some air to enter through cracks. When the entire cavity is filled with SP-PUR there is, in principle, a continuous airtight layer from wall to window frame. The performance of the installation method proved to be sensitive to errors during installation: the space behind the mounting brackets can be difficult to reach and should be completed with great care to ensure airtightness. However, such deficiencies are mitigated by installing caulking at the interface between the window casing and the window frame; in this instance, the air leakage is reduced to below 0,33m³/h.m. The results in respect to airtightness of the installation method using gypsum plaster on the reveal provided considerably higher air leakage rates than expected (2,90 m³/h.m); this is due to shrinkage cracks between the plaster and window frame. This situation was resolved either by using an end profile for the plaster with backer rod and caulking; or by applying an airtight membrane on the interface. Due to sensitivity to leakage at the window corners, the installation with a membrane adhered on the side of the window frame before installation proved to be more airtight than the case where the membrane was installed on the interior side. The solutions with end profile and membranes are sufficiently tight that these may be used when constructing very airtight buildings such as passive homes. The installation method for well insulated buildings using a plywood frame around the window was also very airtight (below 0,33m³/h.m), and this method incorporates considerable redundancy.

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PAPER TITLE
Evaluation of an Interior Air Barrier System with Dynamic Water Vapour Control in North American Climates

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N/A

ABSTRACT

A unique technical guide was developed to evaluate the performance characteristics of an interior air barrier system having dynamic water vapour control. Small and large-scale physical tests along with hygrothermal analysis were performed to investigate the engineered polymer membrane for air tightness, cavity condensation control and durability. Environmental conditions were simulated in various North American climate zones in order to predict the acceptability of the system as a dynamic interior vapour control layer and air barrier system.

The author will describe the test procedures outlined by the Canadian Construction Materials Centre (CCMC Master Format Number 07272) and the American Society for Testing and Materials (ASTM E 2357) used to evaluate the interior air barrier system for air leakage under varied air pressure differential cycles in a large-scale laboratory chamber. The material's physical properties will be presented before and after accelerated ageing and compared to more traditional materials. In addition, a detailed hygrothermal analysis over several North American climate zones will be graphically compared and discussed.

PAPER TITLE
Airtight Curtain Wall/Window Connection Best Practice

MAIN AUTHOR
Joerg Birkelbach

OTHER AUTHORS
Other authors

ABSTRACT

Energy efficiency has taken on increasing importance as fuel costs rise, the economy struggles, global warming debates become more frequent and sustainability becomes more of a mainstream imperative.

Throughout the seasons energy moves through walls, be it cool air lost to the outside during summer or warm air lost in the winter. Thermal bridging and air infiltration are two of the largest contributors of energy loss. Combined, thermal bridges and air infiltration/leakage in the envelope can account for as much as 50 percent of the heat lost in a traditional building.

The value of energy-efficient windows is lost when connectivity from window to wall is poor. Small gaps can have a huge impact in heat loss, occupant comfort and premature deteriorations.

ASHRAE, the U.S. Army Corps of Engineers and International Green Construction Code have mandated a standard air leakage performance criteria of 0.25 CFM/sq. ft. @ 75 Pascals. Meeting this standard presents a significant challenge. To do this means ensuring the integrity of the building envelope. The entire exterior wall should serve as a weather-resistant barrier to keep water and air out.

An airtight and thermal bridge-free envelope ensures that heat and consequently energy generated in a building are not wasted. All penetrations and connections throughout the building must be designed appropriate to the character of the building envelope, sealed securely and they must perform throughout the life of the building to achieve this High-Performance standard.

This presentation will describe the sequence of installation and the holistic approach used to design a superior wall system incorporating advanced materials at crucial connecting points that not only meets but exceeds these performance requirements, when tested.

An integrated design of a wall system to meet all these requirements incorporates vapor-permeable air barrier membrane, flashing membranes and a multifunctional compressed tape as an all-in-one, airtight sealing system.

The result: Air and moisture movement is controlled and the integrity of the building envelope is maintained. Heat and relatively light inside air cannot penetrate the joints and cool off there, creating condensation that can lead to the deterioration of structural components, poor indoor air quality and increased energy consumption for heating and cooling.

According to EnergyStar, effectively sealing a building envelope can result in a reduction of up to 25 percent in HVAC energy costs. Incorporating Passive House technology would result in even greater energy cost savings.

Overall, this presentation will prepare attendees to meet more stringent standards of air leakage by creating an airtight building envelope and eliminating thermal bridges, which rob buildings of energy.

The Science of Rough Opening Preparation and Window Installation to Minimize Air Leakage

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1 Abstract

Large sums of money are spent on high-performance windows with practically zero air leakage. However, traditional rough opening preparation and window installation methods and materials have been shown not to match the window performance. State-of-the-Art liquid-applied materials and related techniques demonstrate a Passive House level of performance.

2 Background

A whole-building repair contractor continuously saw the failings of peel-and-stick membranes and building wraps. Using a Systems Engineering approach, they developed and commercialized a liquid-applied system that not only solves water-damage issues but also dramatically reduces air leakage. Hammer and Hand, a high-quality Passive House builder, has adopted the technology for their projects. Zola Windows also appreciates the need for the highest-quality installation materials and methods.

The Science of Fluid-Applied Flashing Systems

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ABSTRACT

Experts predict fluid-applied flashing will replace peel-and-stick which is under scrutiny now. The fluid-applied technology was invented by a large whole-building repair contractor working with cutting-edge sealant-coating STPE material from Europe and Asia. Hurricane test chambers built for product development and testing show a window mock-up using peel-and-stick and building wrap tested at 7.01 ACH. The fluid-applied STPE system tested at 0.17 – far below the ultra-stringent Passive House standard of 0.6 ACH.

KEYWORDS

Peel-and-stick, fluid-applied, flashing.

1. INTRODUCTION

The background of this paper is the remarkable initiative taken by a building repair contractor to develop products to meet an unmet construction need. The objective is to introduce the reader to an important development in construction waterproofing and air-barrier technology.

"Five years from now, what will we look back on as an important development in building envelope construction?" The answer: **"The replacement of peel-and-stick flashing membranes with fluid-applied flashing products."** This from panel member Alex Lukachko of a leading waterproofing and air-barrier consulting company (Joe Lstiburek's Building Science Corporation) responding to an audience question at the National Institute of Building Sciences, Building Enclosure Technology and Environment Council (BETEC), December, 2011 building envelope symposium in Washington, DC.

2. TECHNOLOGY DEVELOPMENT

Age: 3 Years. Repair cladding, structural repair, repair windows, new sliding glass doors.project Repair project cost: $13 Million.

A contractor specializing in whole-building water-damage repair of multi-story structures continuously saw the failings of peel-and-stick membranes and building wraps – and testified as expert witnesses on behalf of building owners in over 85 lawsuits concerning these structures. Fearing themselves at risk because of their use of peel-and-stick, and using a Systems Engineering approach, they developed and commercialized a fluid-applied STPE system[1] that not only prevents water intrusion issues but also dramatically reduces air leakage and associated condensation.

Lockheed Martin's highly innovative stealth aircraft resulted from that company's dedication to Systems Engineering – basing design on required functionality.

Systems Engineering is not being in the business of manufacturing peel-and-stick roofing or foundation waterproofing products or spun polyolefin packaging goods and deciding to market that material as window flashing.

Rather, the approach taken for the fluid-applied STPE system was to create a "Contractor's Wish List" of features and functions to optimize constructability and building performance:

- Bonds to damp surfaces
- Immediately waterproof – withstands rain
- Fluid applied
- Adheres without a primer
- 100% solids to avoid shrinkage
- VOC Compliant – minimal odor
- Opaque when target thickness is achieved
- Can be exposed for up to 6 months
- Paintable / compatible
- Vapor permeable
- Reduces steps / saves time
- Easily repaired
- Self seals around fasteners

Then, without any preconceived technologies in mind, they scoured the globe to find the very best way to implement the functional requirements. A silicone sealant manufacturer, realizing silicone technology was not suitable, guided them to a specialist in STPE sealant chemistry. Through a close collaboration, the technology was developed and has been in continuous use since 2004. This waterproofing technology is manufactured by a significant player in the commercial air- and water-resistive barrier market that maintains a close technology support and development relationship with the original development team. The Architectural Record recognized the technology in its list of top waterproofing products of 2010.

3. CHEMISTRY

STPE stands for Silyl Terminated Poly Ether. STPE is the leading construction sealant in Europe and in Asia – including Japan where it was developed and introduced to the market over 30 years ago.

Edward M. Petrie, author of McGraw-Hill's Handbook of Adhesives and Sealants, wrote a paper[3] on STPE technology for The Adhesives and Sealant Council. He compared STPE with urethane and silicone sealants, and he used a table to indicate the STPE out-performs the others across a wide range of factors.

[Here insert the table from a separate Word file comparing STPE, Urethane, and Silicone.]

Petrie also stated: "In addition to their high performance properties, these sealants are achieving popularity due to their formulation versatility that allows the customization of viscosity and early strength development for various applications." This is why this sealant technology has been formulated to spread like a coating for flashing and air / water barrier applications.

4.	FIELD PERFORMANCE

An early multi-story project completed in 2004 was de-constructed in 2009 for the sole purpose of determining whether the materials were intact and functioning in the same way as when first installed. OAC forensic architectural and building enclosure experts of Seattle, Washington concluded the system was performing as intended, no adverse impact on any building components, all surfaces dry and in good condition, and no degradation of the products. A similar evaluation is planned for the ten-year anniversary of the installation in 2014.

5.	EXCEEDS TESTING STANDARDS

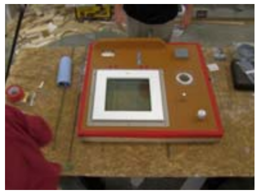
The technology has successfully passed all the tests required by the Air Barrier Association of America (ABAA Process for Approval of Air Barrier Materials, Components & Assemblies) and by the International Code Council Evaluation Service (Acceptance Criteria 212 for water-resistive barriers). The air-barrier test is run at 75 Pascals of pressure corresponding to a 25mph wind. The water-resistive test requires the coating to perform at least as well as asphalt-impregnated building paper.

The developers of the technology were not satisfied with the above-referenced national testing standards for such technology. They built the hurricane test chamber to confirm their suspicions about peel-and-stick --that even a perfectly executed assembly can leak.

They later used the chamber to demonstrate the STPE system can withstand water spray under 2,880 Pascals of pressure and racking movement corresponding to the 155mph wind-driven rain of a Category V hurricane for hours on end.

The technology is promoted as waterproofing material due to its ability to withstand a hydrostatic head. This is why the installation guidelines illustrations show them being used as sill-pan flashing and roofing underlayment – as well as for water-resistive barriers on vertical surfaces.

6.	COMPARISON TESTING



Large sums of money are spent on high-performance windows with practically zero air leakage. However, traditional rough opening preparation and window installation methods and materials do not match the window performance. State-of-the-Art fluid-applied STPE materials and related techniques demonstrate a Passive House[4] level of performance: 0.6 Air Changes per Hour (ACH) compared to Energy Star's average 4.6 ACH. Of course, if you are stopping air leakage, you are also stopping water intrusion.

Below are results of tests performed using the portable test chamber (21.25cuft) shown in Photo 4 with window installation mock-ups using 1) sheetwrap with peel-and-stick and 2) the fluid-applied STPE materials. Testing is similar to ASTM E 2357 air barrier assembly testing using a smaller mock-up.

Air Changes per Hour @ 50 Pascals = 20mph wind

- Energy Star, 5 ACH (Climate Zones 3,4)
- Passive House 0.6 ACH
- Sheetwrap & Peel-and-stick 7.01 ACH
- Fluid-applied STPE 0.17 ACH

Fluid-applied STPE at 2,880 Pascals = 155mph wind Category V hurricane: 0.53 ACH

The results are supported by the recent Karuna[5] Passive House project testing where 0.42 ACH was achieved without the STPE air-barrier system fully installed.

7. ENERGY STAR PRESCRIPTIVE REQUIREMENTS

The ENERGY STAR for Homes Version 3 Guidelines require:

- Fully sealed continuous drainage plane behind exterior cladding
- Window and door openings fully flashed
- Air sealing
- Cracks in the building envelope fully sealed
- Rough opening around windows & exterior doors sealed with caulk or foam[6]

The fluid-applied STPE Technology meets these requirements.

8. ENVIRONMENTAL

The technology complies with the most stringent air quality volatile organic compound restrictions, and it is phthalate-free. This is one of the reasons it was specified and used on "The Greenest Commercial Building in the World" – The Bullitt Center in Seattle.[7]

9. METHOD OF USE

First, an STPE joint and seam filling product is gunned out of a cartridge and spread into the joints and seams of the rough opening and into the sheathing- wall seams. Then a fluid-applied STPE waterproofing material is gunned out of a cartridge and over the entire inside surface of the rough opening (including over the previously applied joint and seam filler), and 4 -6 inches out onto the sheathing or CMU wall around the rough opening. The window is then set in the rough opening, and backer rod with STPE in a conventional sealant formulation is used to form an air and water seal around the interior perimeter of the window (this is now recommended by AAMA[8] as well). For flanged windows, the STPE fluid-applied rough-opening waterproofing material is used to flash over the flanges of the window except for drainage weeps left in the sill area. A waterproof roller-grade STPE coating is then applied to the field of the wall to satisfy code requirements for a water-resistive barrier.

Bullitt Center, Living Building Challenge, Seattle, WA

10. PROBLEMS WITH PEEL-AND-STICK

Writing in the Winter 2011 issue of the National Institute of Building Sciences' Journal of Building Enclosure Design, Editor and Building Enclosure Technology & Environment Council Chairman Wagdy Anis of Wiss, Janney Elstner consultants stated:

"Another significant event that took place at the Buildings XI International Conference was the U.S. Department of Energy (DOE)'s road mapping session,
during which stakeholders reported their ideas about prioritizing research. BETEC reported its thoughts on this to
DOE, on behalf of more than 3,000 BEC members. Ideas included:

- Evaluate the performance of some common heat air and moisture control materials.

• The durability of flashing materials ….

.

• Long-term adhesion of peel-and-stick membranes.

• Long-term performance of peel-and-stick membrane joints, vertical and horizontal, with and without term bars, shingled and reverse shingled.

Craig Wetmore, President of York Manufacturing (which sells both copper mesh through-wall flashing and peel-and-stick) provided the Flashings & Terminations Committee of the Air Barrier Association of America a paper in which he offered the following items in a critique of peel-and-stick:

- UV damage
- Flows at 140-180^{o}F
- Spray foam heat causes flow and facer damage
- Masonry cleaners harm
- Full body weight rolling
- Must replace sheets instead of repairing fishmouths
- No moisture in substrate
- No dust, fines, or dirt
- Adhesion problems
- Use primer, but VOC problems
- Primer must be dry but not too dry
- Sealant adhesion problems
- Degrades air barriers
- Flame and smoke
- 10-20 year life expectancy

Conventional rough opening preparation and window installation follows ASTM E 2112 “Standard Practice for Installation of Exterior Windows, Doors and Skylights” which does not include methods for utilizing fluid-applied STPE materials. However, the Chair of the ASTM E 2112 technical committee and the ASTM management staff have invited this author to submit a revision that will add such systems to the ones listed in the standard.

Experts have recognized the shortcomings of materials and methods referenced in ASTM E 2112 that rely on sealing off the face of the rough opening:

“Notwithstanding the advances in the performance of sealants and membrane materials, reliance upon face sealed systems has a higher risk of water penetration because of the inherent aging of the materials and loads imposed, thus reducing the overall resistance to water penetration and consequent damage.”

...the combination of wood- or steel-framed construction with windows that may leak at some point during their life cycle leads the authors to conclude that only the hot and dry hygrothermal zone may be tolerant of periodic wetting and secondary protection of the window opening is required in all other hygrothermal zones.”[9]

Designers and builders are moving quickly away from conventional materials (to prepare the rough opening and install the window) to fluid-applied STPE technology. They are doing this to avoid water intrusion and air leakage from the items previously referenced by Craig Wetmore and these additional issues identified by the contractor that developed the original STPE formulations:

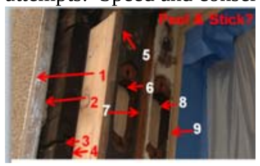
- Rotting of damp substrates behind vapor barrier coverings
- Reverse lapping
- Tenting
- Tunneling
- Difficult, laborious work
- Human error
- Adhesion failures

The conventional method requires 21 steps and creates 74 ***<u>interfaces</u>***. The title of RCI’s technical journal is **INTERFACE** for a reason.

It’s no wonder specifiers are looking for answers – given that U.S EPA’s BASE study of 100 randomly selected U.S. office buildings found that 43% of the buildings had current water leaks, and 85% had experienced previous water leaks.[10]

11. INSTALLER EXPERIENCE, AVAILABILITY, DURABILITY

Physical actions required are pulling the handle on a caulk gun to lay down a bead of material, and spreading it with a piece of flat plastic. Inexperienced workers are successful in their first attempts. Speed and conservation of material increase with experience.



The material is available at hundreds of construction supply distributors across the country.

The service temperature of a leading peel-and-stick membrane is 158 degrees F with a maximum UV exposure of 30 days. This STPE technology has been tested to 300^{o}F and may be exposed for up to six months. It does not rip or tear, and any gashes into it can quickly be repaired by re-coating**.**

12. MARKET PENETRATION

The volume of material sold and applied has dramatically increased over this recessionary period and is expected to take a larger and larger share of the market as the economy improves. This has given rise to concerns that designers and consultants failing to specify and recommend the technology may find themselves charged with failing to meet the legal standard of care: "In performing professional services, [the professional] has a duty to use that degree of care and skill which would be used by a reasonably competent [professional] providing similar services and acting in similar circumstances."[11] The technology was recently made the subject of a continuing legal education program for construction defect attorneys entitled: "Standard of Care Problems for Architects & Builders: Changing Waterproofing and Air Leakage Technology."

1. CONCLUSIONS

A pressing need to replace peel-and-stick membranes gave rise to a significant technology development effort by contractors working on real-world problems.

2. ACKNOWLEDGE-MENTS

The principals and employees of PROSOCO, Inc., Building Envelope Innovations, and Tatley-Grund Building Repair Specialists, Inc.

3. REFERENCES

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3. MS Polymers in "Hybrid" Sealants, Edward M. Petrie, The Adhesives and Sealant Council.

4. Passive House is a group of designers and builders that construct ultra-energy efficient high-end homes. The first Passive House commercial building was completed recently. The US Army Corps of Engineers has been engaging Passive House for training. www.passivehouse.us

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9. "Challenges with Using ASTM E 2112 in North American Climate Zones," Eleventh International Conference on Thermal Performance of Exterior Building Envelopes, sponsored by Building Enclosure Integration Committee of the Building Enclosure Technology & Environmental Council (BETEC) of the National Institute of Building Sciences and ASHRAE, presented at Oak Ridge National Laboratory Building Technologies Research and Integration Center.

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11. Kansas Judicial Council, Pattern Jury Instructions in Kansas, Section 123.70.

Thursday 18 April 2013

14:00-15:30 Session 4: Durability of seals – Design and quality control

1. Service Life Prediction on Sealant Materials. Joannie Chin, NIST, USA
2. Innovative Sealant Technology Provides Design Flexibility for Air Tight Joints. Andrea Wagner, Dow Corning, USA
3. Building Enclosure Commissioning – BECx -The Plan - Why, What, How, Where, Who? William R. Nash , P.E. USA
4. Performance of Duct Leakage Test Methods – When to Use Which and Why, Paul Francisco, University of Illinois, USA
5. Energy Impacts of Envelope Tightening and Mechanical Ventilation for the U.S. Residential Sector, Jennifer Logue, LBNL, USA

Short Presentation

6. *Impact of Sheathing Installation Practices on Air Barriers, Brett T. Fagan, USA*

SERVICE LIFE PREDICTION OF SEALANT MATERIALS

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To maximize energy efficiency and minimize infiltration in modern buildings, joints and openings are often filled with various types of polymeric sealant. While sealant is a critical component for building design and construction, is susceptible to damage from ultraviolet radiation, moisture, temperature changes, and applied mechanical loads. Studies have shown that 50% of commercial sealants fail within 10 years and 90% within 20 years. The test methods currently employed to assess the durability of these polymeric building materials rely on real time outdoor exposure or relative threshold testing. This presentation will focus on new approaches developed at NIST to assess service lives of polymeric products, and specifically, new test methods that allow for verified predictive models of sealant performance. The work presented is being supported by a NIST/industry consortium on sealant service life prediction and has been documented in the literature.[1,2,3]

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3. Christopher White, Kar Tean Tan, Emmett O'Brien, Hunston Donald, Joannie Chin, and R. Sam Williams "Design, Fabrication and Implementation of Thermally-Driven Outdoor Testing Devices for Building Joint Sealants", *Review of Scientific Instruments*, 82(2), 2011.

PAPER TITLE
Innovative Sealant Technology Provides Design Flexibility for Air Tight Joints

MAIN AUTHOR
Andrea Wagner

OTHER AUTHORS
Kelly Broker, Larry Carbary

ABSTRACT

Air tightness is controlled not by individual products alone, but by how those individual products come together and behave as a system. This is confirmed by the evolution of building codes from being material only based specifications to required system testing. Individual air barrier materials, especially sheet applied barriers, are able to prevent air infiltration through opaque surfaces; however, they are not able to accommodate movement imparted at control joints and interfaces with other building materials. This presentation will use data from lab testing to demonstrate how current sealants and membranes address the issues of air tightness in joints. This information will be compared to similar test results and case studies related to a newly developed sealant which has a silicone resin as its foundation in lieu of a traditional polymer. Technical data on the new sealant will be discussed along with joint design solutions, especially for sealing between traditional substrates (windows, curtainwall, etc.) and polyethylene backed air barriers. Finally, a solution for complex joints and interfaces combining the new sealant with a pre-cured silicone extrusion will be presented. Independent lab testing will be presented demonstrating the ultimate flexibility the new sealant provides the design professional in determining how best to complete a continuous air tight facade.

PAPER TITLE

Building Enclosure Commissioning – BECx -The Plan - Why , What, How , Where , Who ?

MAIN AUTHOR

William R. Nash , P.E.
Whitlock Dalrymple Poston & Associates

OTHER AUTHORS

J. Eric Peterson, P.E., Rex Cyphers P.E.

ABSTRACT

The presentation will provide discussion of the risks posed by a building enclosure and the methods of risk management that can be utilized by an Owner, Design Professional, Construction Team, Construction Manager, General Contractor. The presentation will provide details of Building Enclosure Commission process found within the National Institutes of Building Science Guideline 03 – 2012 (and 2006) and the use of ASTM Standard E 2813 – Enclosure Commissioning published in May 2012. . the presentation will detail the Enclosure Commissioning process from the Owner's Project Requirements and Basis of Design onto the phases of the design : Design Development thru Construction Documents, Building enclosure specification integration development of the BECx Plan , phased Building Enclosure design document reviews, incorporation into the project specifications of a BECx specification , Mock up specification with laboratory and field performance testing requirements with clearly stated acceptance criteria and on thru field construction , Building Enclosure training/ maintenance for the building operations personnel, - first level QC by the installing contractor , QA by the construction manager / general contractor, third party verification testing ,. Documentation and verification of the Building Enclosure field performance, the implementation of both a project nonconformance process and a 10 month warranty audit program Field Performance Testing of the Building Enclosure for the verification of the field performance of the Enclosure, Standardized testing.

The presentation discusses building enclosure commissioning (with a focus on air barriers) during design document reviews, construction document reviews, submittal and shop drawing reviews , mock up installations and field performance testing. The presentation will provide details and insights on the BECxA role in the field verification of waterproofing, air barriers, masonry, stone, metal panels, EIFS, GFRC, precast concrete, windows, curtain wall, storefront, parapets, roofing ,and the functional integration of these systems.

PAPER TITLE
Performance of Duct Leakage Test Methods – When to Use Which and Why

MAIN AUTHOR
Paul Francisco

OTHER AUTHORS

ABSTRACT

Duct leakage has been recognized for years as a major source of energy loss as well as a mechanism for pollutant transfer in buildings. As a result, substantial effort has gone into developing test methods for field measurement of duct leakage, primarily in residential buildings although the results are also applicable to many non-residential structures. Several of these methods have been incorporated into ASTM Standard E1554. Additionally, numerous standards and programs in the United States have duct airtightness testing requirements, including ASHRAE Standard 62.2, ASHRAE Standard 152, the U.S. Department of Energy's low-income weatherization assistance program (WAP), the Building Performance Institute (BPI), ACCA Standards 5QI and 12EH, and Energy Star.

Three of these test methods are the pressure pan test, the duct pressurization test, and the Delta-Q test. Each of these test methods has advantages and disadvantages. As such, which method to use depends greatly on the application.

The pressure pan test evaluates the relative leakiness of ducts and produces results in terms of pressure, not flow. Therefore it is not appropriate for applications where estimates of actual leakage flow rates are required, but is instead intended for applications where the primary goal is to assess where within a duct system major defects are located so that these defects can be quickly targeted. The fan pressurization test provides a leakage estimate but at artificial conditions. It is therefore appropriate where a specific level of duct airtightness is required and to identify those systems that do not achieve the specified level. The Delta-Q test provides leakage estimates at actual operating conditions but is sensitive to wind. It is therefore most appropriate for situations where a good estimate of energy penalty is desired, but is less suitable for demonstrating compliance with tight specifications due to the measurement uncertainty.

The pressure pan and Delta-Q tests also only provide results for leakage to outside the thermal boundary of the building. This is appropriate for energy assessments but does not address all concerns related to contaminant transport. The fan pressurization test can be done with or without a blower door operating concurrently, allowing it to produce results for leakage to outside only (if the blower door is operating) or combined leakage to inside and outside which can give a better indication of the potential for the duct system to contribute to indoor environmental quality problems.

This paper presents field-based evaluation results for each of these three test methods. Results come from several different studies in residential buildings in which multiple methods were performed at each home, allowing for comparisons between methods. The results demonstrate the benefits and drawbacks of each of the methods and provide insight into appropriate use. Specific recommendations for when to use each method are also featured.

ENERGY IMPACTS OF ENVELOPE TIGHTENING AND MECHANICAL VENTILATION FOR THE U.S. RESIDENTIAL SECTOR

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ABSTRACT

Effective residential envelope air sealing reduces infiltration and associated energy costs for thermal conditioning, yet often creates a need for mechanical ventilation to protect indoor air quality. This talk presents estimates of the potential energy savings of implementing air tightness improvements along with mechanical ventilation throughout the US housing stock. We used a physics-based model to simulate population energy impacts of varying levels of air tightness improvements and providing ventilation according to standards. There are 113 million homes in the US. We calculated the change in energy demand for each home in a nationally representative sample of 50,000 virtual homes developed from the 2009 Residential Energy Consumption Survey. Ventilation was provided as required by 2010 and proposed 2013 versions of ASHRAE Standard 62.2. Ensuring that all current homes comply with 62.2-2010 would increase residential site energy demand by 0.07 quads (0.07 exajoules (EJ)) annually at their current tightness levels. Improving air tightness of all homes at current average retrofit performance levels would decrease site energy demand by 7% or 0.7 quads (0.74 EJ) annually and upgrading all homes to be as airtight as the top 10% of similar homes would double the savings, leading to roughly $22 billion in annual savings in energy bills. We also analyzed the potential benefits of bringing the entire stock to the air tightness specifications of IECC 2012, Canada's R2000, and Passive House standards.

KEYWORDS

HVAC, weatherization, ASHRAE 62.2, retrofit, WAP

1. INTRODUCTION

The residential sector is estimated to use 10.2 quads (10.8 EJ) of site energy and 23% of the source energy annually in the U.S. (US EIA 2009). Heating and cooling accounts for an estimated 5 quads of site energy (5.3 EJ), about half of the site energy used in residences (US EIA 2005). Effective envelope air sealing reduces weather driven infiltration and annual energy costs for thermal conditioning. The impact of air sealing is a function of the initial condition of the home, the improvement in air tightness, and the local climate. Effective air sealing often leads to a requirement for mechanical ventilation to ensure acceptable indoor air quality. In recent years there has been a proliferation of federal, state and local residential retrofit programs that incorporate air sealing as a central measure to reduce energy use and associated carbon emissions. Estimates of the energy savings of air sealing and energy costs of mechanical ventilation are often based on extrapolations from simulations (Sherman and Walker 2008; Chua and Chou 2010; Mortensen, Walker et al. 2011) or comparisons of pre- and post- retrofit energy bills of homes (Schweitzer and Berry 2001; Schweitzer 2005). Matson and Sherman conducted the only previous nationwide United States modeling effort to estimate the total energy impact of infiltration and the variability in the impact (Sherman and Matson 1997). We could find no study that estimates the US population benefits of current levels of home tightening seen in retrofits or applying proposed building standards. An understanding of how the benefits of air tightness improvements vary by region, home type, starting air tightness, and other factors could improve program efficacy by focusing on homes that will provide the largest energy savings. Program value could be improved by comparing incremental benefits of increasing air sealing effectiveness (or reaching more stringent air tightness targets) against the costs of achieving these higher levels of home performance.

We developed and applied a physics based-modeling framework to address four main questions: 1) What would be the energy impact of altering the US housing stock to comply with ventilation standards? 2) What would be the energy benefit of tightening all existing homes by the average improvements seen in the low-income Weatherization Assistance Program (WAP) and non-WAP retrofit programs? 3) What would be the benefit of improving air sealing effectiveness to bring all homes to the air tightness levels currently seen in the top 10% of similar homes? and 4) What would be the energy impact of achieving various standards for absolute air tightness in all US residences?

2. METHODS

We analyzed a virtual, representative cohort of U.S. homes to estimate the energy impact of tightening building envelopes and adding mechanical ventilation for a typical meteorological year. We applied an incremental ventilation energy model (IVE) to estimate the change in energy demand due to a change in ventilation in each home in the analyzed cohort. We used a simplified airflow model along with location based weather data to determine the impact of changes in envelope and duct tightening on airflow through the home. The methods of the analysis and details of the virtual cohort are described below.

2.1 Incremental Ventilation Energy (IVE) Modeling Approach

The IVE model was described in detail and compared to a comprehensive physics-based energy, moisture and airflow model by Logue et al. (2012) and will be described briefly here. The IVE model uses the change in hourly airflow between two conditions for one home to calculate the overall change in HVAC energy use. The change in total HVAC energy used, ΔE_{HVAC}, is calculated as the sum of four contributions: changes to (1) heating (ΔE_{heat}) and (2) cooling (ΔE_{cool}), (3) changes to the energy used by the air distribution fan for a ducted, forced air system (ΔE_{blower}), and (4) changes to energy used by ventilation fans (ΔE_{fans}), as shown in Equation 1.

$$\Delta E_{HVAC} = \Delta E_{heat} + \Delta E_{cool} + \Delta E_{blower} + \Delta E_{fans} \quad (1)$$

The first three terms are all proportional to changes in airflow that occur when each piece of equipment is in use. The incremental change in heating or cooling energy is calculated for discrete time intervals using the following equations:

$$\Delta E_{heat} = max\left[\Delta t\left(\left[\dot{m}_t C_p\left(T_{set,t} - T_{out,t}\right)\right]/\varepsilon_{heat}\right), 0\right] \quad (2)$$

$$\Delta E_{cool} = \Delta E_{thermal} + \Delta E_{latent} \quad (3)$$

$$\Delta E_{thermal} = max\left[\Delta t\left(\left[\dot{m}_t C_p\left(T_{out,t} - T_{set,t}\right)\right]/\varepsilon_{cool}\right), 0\right] \quad (4)$$

$$\Delta E_{latent} = max\left[\Delta t\left(\Delta A_t * L_v * V_{cond} * \left(\rho_{water,out,t} - \rho_{water,in,t}\right)/\varepsilon_{cool}\right), 0\right] \quad (5)$$

$$\dot{m}_t = \Delta A_t * V_{cond} * \rho_{air} \quad (6)$$

The symbols in equations 2 through 6 are defined as follows:

- Δt is the time step in hours.
- $\dot{m}_t$ is the mass flow of air through the home during the time step.
- C_p (J kg^{-1} K^{-1}) is the heat capacity of air.
- $T_{set,t}$ (K) is the indoor temperature at time t (thermostat setting).
- $T_{out,t}$ (K) is the outdoor temperature at time t.
- ε_{heat} and ε_{cool} are the heating and cooling system efficiencies, respectively.
- ΔA_t (h^{-1}) is the change in the whole house air exchange rate at time step t.
- V_{cond} (m^3) is the conditioned volume of the house.
- ρ_{water} (kg m^{-3}) is the absolute humidity (the density of water vapor) in the air indoors and outdoors.
- ρ_{air} (kg m^{-3}) is the air density.
- L_v (J kg^{-1}) is the latent heat of water vaporization.

The cooling load included both sensible ($\Delta E_{thermal}$) and latent (ΔE_{latent}) components. An hourly time step allowed tracking of weather variations throughout each day in concert with meteorological data (TMY3 or Typical Meteorological Year) with the same resolution. Changes to energy demand due to an increased or decreased airflow rate were calculated every hour for a year then summed to calculate the total annual change in energy use for each home. The change in fan energy was simply the energy demand of any additional fans (ΔE_{fans}) added to move air.

The power use of a residential blower system is a function of the home conditioning system size. Since we did not have information about the sizes of the home conditioning systems and blower sizes, we used coefficients derived from residential modeling guidance to determine the impact of changes in heating and cooling energy on blower energy when ducts were present. We used coefficients derived from the modeling design manual used to assess whether new homes in California comply with the energy-efficiency elements of the state building code (CEC 2008), as shown in Equation 7. The coefficients reflect a sizing relationship between the recommended blower and heating and cooling system sizes for new California homes. The suitability of these coefficients for older systems has not been assessed. We were not able to find sufficient data to do so. We applied these coefficients for all systems that were ducted. When more than one heating system was present, we applied these coefficients to only the fraction of the heating or cooling energy that was reported to be provided by the ducted system.

$$\Delta E_{blower} = 0.023 * \Delta E_{heat} + 0.176 * \Delta E_{cool} \quad (7)$$

The IVE model was designed for use in population-level assessments of air-sealing and ventilation energy impacts, with the goal of informing policy and program planning. For this purpose, IVE can be run for many homes, with individual home specifications assigned based on documented characteristics of a home (when available) or by assigning specifications based on established relationships to characteristics that were documented.

One limitation of the model is that it does not account for the impact of ducts and duct tightening on the change in energy use. When ducts are tightened in the home, without changing the envelope, the base load energy demand will decrease. Tightening ducts increases the HVAC system efficiency and reduces the total air exchange rate of the home. Duct leakage also impacts the incremental energy demand since supply duct leakage represents a direct reduction in the system efficiency. Since the IVE does not calculate the total energy demand of the building, we cannot use it to estimate the impact of duct tightening on the home cohort. Adding the impact of duct tightening to the analysis would increase the energy savings of envelope tightening.

When applying this model to existing databases of home characteristics, we used the algorithm developed by Walker and Wilson (1998) for infiltration through the building envelope as a function of a limited number of home characteristics, outdoor weather data, and home leakage area. We used the reference method given by ASHRAE Standard 136 (1993) to combine mechanical ventilation and natural infiltration.

2.2 Virtual Cohort of Representative Homes

The Residential Energy Consumption Survey (RECS) is a survey of U.S. housing units performed by the U.S. Energy Information Agency (EIA). The RECS has been conducted every one to five years since 1979. The survey is conducted for a representative subset of the U.S. housing stock. The 2009 RECs database (US EIA 2009) contains characteristics for 12,083 homes including home location; type; number of rooms; occupancy characteristics; cooking frequency; heating and cooling equipment system types, ages and fuel type; and thermostat settings. We used the 2009 RECS database to create a virtual cohort of 50,877 homes to represent the U.S. residential housing stock. Full details of this are presented in Logue, Sherman et al. (2013).

The IVE model requires several housing parameters that are not available in the RECS; these parameters were estimated or assigned based on home characteristics that were specified in the RECS. The estimated or assigned parameters include normalized leakage of the building envelope, home size, heating and cooling system efficiencies, hourly weather conditions, and thermostat temperatures for RECS entries that did not have specified values. Chan et al. (2012) established a relationship between room number and home size. We used this same relationship to assign a house size to each home in the RECS. For each home, we used the National Solar Radiation Data Base Typical Meteorological Year (TMY) data for the weather station located closest to the IECC identified representative city for the specified climate zone for the home (NREL 2008). We used the model developed by Chan et al. (2012) to determine a normalized leakage value for each of the homes in our virtual cohort.

For each heating and cooling system in each home we assigned a system efficiency as a function of system type and age based on assignments used by the Home Energy Saver calculation engine (Mills and Energy Analysis Department 2005). Energy costs were taken from the US Energy Information Administration (USEIA 2005) reports of state costs. Costs for 2010 were used in the analysis. Most of the homes reported a heating and cooling temperature for when occupants are home, away, or sleeping. For the homes that did not report these values, the median temperature reported by the other homes was used. This default temperature setting for cooling and heating are (away: 75°F, home: 73°F, overnight: 73°F) and (away: 67°F, home: 70°F, overnight: 68°F) respectively.

2.3 Analysis Scenarios

Simulations were conducted to assess impacts of five retrofit or upgrade scenarios on the US housing stock. All scenarios included upgrades to ensure that all homes meet current ASHRAE 62.2-2010 (ASHRAE 2010) requirements, and most include envelope air tightening. Mechanical ventilation was provided either by an exhaust fan or a heat recovery ventilator (HRV). HRVs reduce the amount of heat need to condition the extra airflow, however they also require more power to operate than an exhaust fan. The six scenarios are described below:

1. Upgrade current housing stock to comply with ASHRAE 62.2.

We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan (1a) or an HRV (1b). For each scenario we reduced the required mechanical flow for each of the homes by the calculated infiltration credit using infiltration calculations in the current 2010 or proposed 2013 standards.

2. Average Tightening: Improve envelope air tightness of all homes at levels currently achieved by Weatherization Assistance Program (WAP) and non-WAP energy efficiency programs while complying with ASHRAE 62.2.

The envelope of each home was tightened using the relationship of pre- and post- retrofit homes that have participated in WAP or other energy efficiency retrofit programs. Chan et al. (2012) determined that for non-WAP energy efficiency programs, home tightening typically reduced the normalized leakage by 20% and that for WAP homes the normalized leakage was typically reduced by 30%. The WAP is for low-income homeowners; on average, WAP homes are thought to be in worse condition than non-WAP homes. For this scenario we applied the WAP level of envelope tightening to all homes that had income below 200% of the poverty limit as this is one of the WAP eligibility requirements (Garcia 2012). The remaining houses were tightened by 20% to reflect the impact of non-WAP efficiency programs. For each home the level of mechanical ventilation was adjusted to reflect the lower infiltration credit due to the tighter envelope.

3. Advanced Tightening: Tighten envelopes as necessary to ensure that each house reaches the current 90th percentile tightness for homes with similar key characteristics while complying with ASHRAE 62.2.

The Chan et al. (2012) model determines the median normalized leakage for a home with a given set of parameters. Using the characteristics of the distribution we were able to calculate the 10th percentile normalized leakage value for each home in our cohort, i.e., the tightness level met or exceeded by the 10% tightest home having a similar set of characteristics associated with air tightness. The assumption of this scenario is that the 90th percentile performance (10% most tight homes) is a level that is achievable in practice with effective air sealing retrofit work. This recognizes that even with air-sealing retrofits, air tightness likely will still vary with the age, vintage, construction style and factors related to home quality and maintenance as indicated (imperfectly) by household income. For each home the level of mechanical ventilation was adjusted to reflect the lower infiltration credit due to the tighter envelope. We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan or an HRV.

4. IECC: Tighten all homes to achieve the standards specified in the 2012 IECC standard while complying with ASHRAE 62.2

In this scenario, the envelope airtightness of each home was set to the level recommended by the 2012 IECC standard (BECP 2011): 5 air changes per hour at an induced 50 Pascal indoor-outdoor pressure difference (ACH50) for IECC climate zones CZ1 and CZ2; 3 ACH50 for all other climate zones. This is a theoretical scenario that imagines a housing stock of the future that is comprised of homes built or renovated to the 2012 standard. Mechanical ventilation was added in the same manner as the previous scenarios. We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan or an HRV.

5. R2000: Tighten all homes to achieve the standards specified in the Canadian R2000 standard while complying with ASHRAE 62.2

In this scenario, the envelope airtightness of each home was set to the level required in Canada's R2000 standard (NRC 2012): 1.5 ACH50. As with scenario 4, this considers a theoretical stock that has been built or renovated to a specific air tightness performance standard. Mechanical ventilation was added in the same manner as the previous scenarios but only HRVs were added to these homes.

6. Passive House: Tighten all homes to achieve the standards specified in the Passive House standard while complying with ASHRAE 62.2

In this scenario the envelope air tightness of each home was set to the level required the Passive House standard (PHI 2012): 0.6 ACH50. This was selected as an upper limit air tightness target. Mechanical ventilation was added in the same manner as the previous scenarios but only HRVs were added to these homes.

We specified an HRV Apparent Sensible Effectiveness (ASE) of 82%. Power consumption for the exhaust fan and HRV was calculated as a function of the required airflow based on the specifications for the Broan QDE30BL exhaust fan (on average 0.35 W/cfm) and the Amana Brand HRV150 HRV (0.9 W/cfm) (HVI 2009).

3. RESULTS

We determined the impact of the six ventilation scenarios at the U.S. and IECC climate zone levels. We estimate that making the current housing stock compliant with ASHRAE 62.2 would appreciably impact the average airflow in 45-80% of homes depending on whether an HRV or exhaust fan was used. Tightening the stock with Average and Advanced improvements would reduce the median annual average air exchange rate by up to 0.2 air changes per hour depending on the type of ventilation used. Applying increasingly strict standards could lead to an additional median reduction of up to 0.3 air changes per hour.

Table 1 shows the aggregate site and source annual impact of applying each of the ventilation scenarios to the US housing stock. Source energy demand was calculate using the reported electrical grid interconnection source energy average factor for electricity in the United States (Deru and Torcellini 2007). The table shows operating costs only; these values do not include the cost or energy to build and install the products required for these air tightness improvements (e.g., the embedded energy in materials and installed equipment, energy related to construction). The energy cost of complying with ASHRAE 62.2 is relative to the current housing stock. The savings due to tightening the envelope are relative to the existing housing stock after it complies with ASHRAE 62.2. The savings of tightening and adding the exhaust fan are relative to the stock complying with ASHRAE 62.2 using exhaust fans and the savings of tightening and adding an HRV are relative to the stock complying with ASHRAE 62.2 and using an HRV. In other words, each tightening scenario is linked to the ventilation only (no tightening) baseline with the same type of ventilation system.

The annual energy impact of bringing the entire current stock into compliance with ASHRAE 62.2 is relatively small; it would increase the annual site energy demand of the residential sector by less than 1%. Offermann (2009) showed that many installed mechanical whole house exhaust systems operate below levels required by ASHRAE 62.2. Care should be taken to meet ASHRAE 62.2, however it should be noted that exceeding the standard by requiring or using oversized fans will have energy penalties. In this work we found if we brought the current stock into compliance but installed fans in each home that provided 50% more air than needed, the cohort energy penalty for meeting ASHRAE 62.2 for exhaust only ventilation doubled and the energy penalty for HRV use increased by 50%.

Average tightening was predicted to reduce the residential energy sector demand by 0.72 quads (0.76 EJ) annually. Advanced tightening to get all homes to the level of the tightest 10% currently would achieve roughly twice the benefit of tightening at current average improvement levels. This result is scalable. Increasing the effectiveness of WAP and non-WAP retrofits to ensure that all homes reach 90th percentile air-tightness levels for homes of similar age and construction could double the energy impact of air sealing in these programs.

The final three scenarios focused on the potential benefits of air tightness standards for residential buildings. Though such standards typically focus on new construction or “down to the studs” renovations, it is useful to overlay the standards on the current stock of homes to assess their potential benefits. The Passive House tightness standard has been shown to be difficult to achieve (PHI 2012), and it can be considered as a theoretical upper limit. Thus, the result for the Passive House scenario indicated an upper bound annual energy savings from air tightening (with ventilation provided by HRVs) of roughly 2.6-2.8 quads (2.7-3.0 EJ) site energy. This is more than half of the residential sector site conditioning energy demand and a quarter of the total residential sector site energy demand. The R2000 standard would achieve 92-93% of this maximum benefit and the IECC standards would achieve 78-81% of the maximum possible benefit. Advanced tightening to get all homes to the performance level of current top 10% would achieve about half of the theoretical maximum benefit of air tightening. The cost of reaching these levels of home tightness are not explored in this work, however the estimates of annual energy and energy cost savings would be helpful in evaluating the benefits associated with various building airtightness standards and targets.

Figure 1 shows the estimated average annual impact of tightening on the total housing stock in each of the IECC climate zones. The top of the graph shows a map of the continental US IECC climate zones. Hawaii is climate zone 1 and Alaska is climate zones 7 and 8. Each bar in Figure 1 shows the total energy impact of the scenarios in the order described above, corresponding to increasing levels of air tightness. Aggregate impacts are larger in the Eastern (a) climate zones predominately due to larger populations in those areas.

Table 1. The annual increase in site energy demand, consumer energy cost, and source energy demand of the US housing stock in quads for the explored ventilation scenarios. The savings for tightening the building envelope are in comparison to the existing stock that has complied with ASHRAE 62.2. (1 Quad= 1.055 Exajoules)

	Site Energy Demand (Quads)	Energy Cost (billion$ 2010)	Source Energy Demand (Quads)
Baseline: Making Stock Comply with 62.2			
Exhaust	0.07	$1.60	0.18
HRV	0.1	$2.60	0.27
Savings compared to baseline: Average Tightening			
Exhaust	-0.72	-$11.80	-1.37
HRV	-0.72	-$11.50	-1.32
Savings compared to baseline: Advanced Tightening			
Exhaust	-1.42	-$22.90	-2.69
HRV	-1.41	-$23.20	-2.6
Savings compared to baseline: IECC Standard			
Exhaust	-2.1	-$33.80	-3.83
HRV	-2.23	-$35.00	-4.19
Savings compared to baseline: R2000 Standard			
HRV	-2.63	-$41.80	-4.78
Savings compared to baseline: Passive House Standard			
HRV	-2.86	-$45.50	-5.18

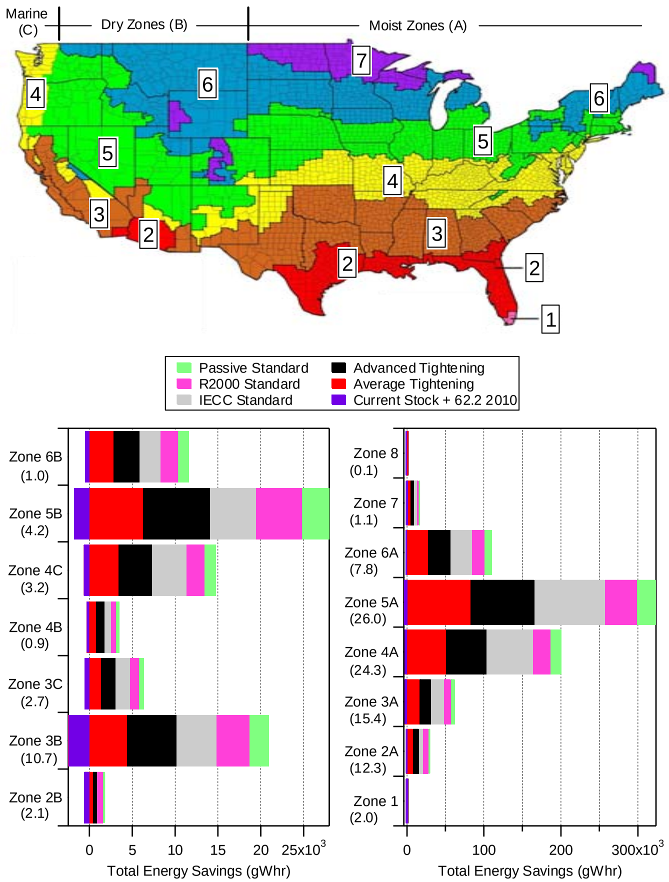

Figure 1. Impact of ventilation scenarios on change in annual residential site energy use in the US housing stock. Each bar represents the total energy impact of each ventilation scenario in each IECC climate zone. The scenarios are ordered from the least energy savings to the most. The savings for each scenario is indicated by the upper value on the colored bar, reflecting the additional benefit of implementing that scenario. In parentheses below the zone name is the number of millions of homes in the zone.

Figure 2 shows the distributions of annual site energy impacts of Average and Advanced tightening on the housing stock in each of the IECC climate zones. The distributions were made using the weighted results from the virtual cohort of representative homes analyzed for each climate zone. Since each home was assigned the mean normalized leakage for that home type, the distributions are not as wide as they would be in distributions of actual homes. Figure 2 also shows the impact of tightening the worst 10,000 homes in each climate zone (10,000 homes were tightened per climate zone). There is significant overlap for the distributions for zones 5-8. Tightening the worst 10,000 homes in zone 8 resulted in lower total energy impacts than tightening homes in zones 6B, 4A, 5A, 6A, and 7. This is because the worst 10,000 homes in climate zone 8 are, on average, tighter than the worst 10,000 homes in climate zone 7.

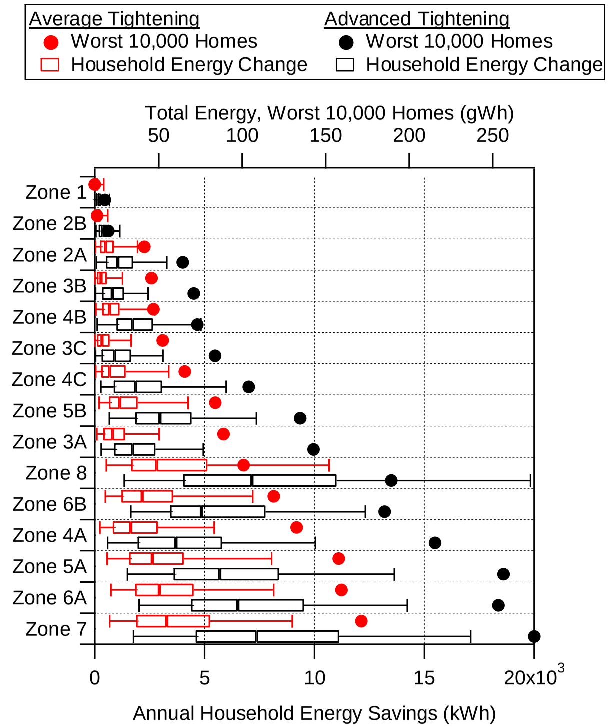

Figure 2. Impact of average and advanced tightening on change in home site energy demand by IECC climate zone. The graph shows the distribution (shown in the box-whisker plots) of home energy savings for the stock in each climate zone as well as the total energy savings from tightening the worst 10,000 homes in each climate zone (10,000 per climate zone) to the specified level.

4. CONCLUSIONS

We used a physics-based modeling approach to assess the energy impact of envelope tightening on the U.S. housing stock. Envelope tightening alone has the potential to reduce the residential sector site energy demand by 2.9 quads (3.1 EJ). However, this would require the leakage of all homes to be reduced to the level specified by the Passive House standard which is not reasonable for the existing stock. Current levels of tightening seen in WAPs and energy efficiency programs could reduce the energy demand by 0.7 quads (0.74 EJ). We estimate that advanced methods of tightening could potentially double that energy savings, achieving half of the savings that could be achieved with stock-wide application of the Passive House standard. Substantial additional energy savings are possible by improving air sealing practice to what has to be regarded as an achievable goal – to get all homes up to the current 90th percentile performance level of homes of the same type. This analysis considers the characteristics of the home that may limit air tightness and compares each home only to homes of the same age, type, and income class. There is a clear need to develop and apply the most effective methods of envelope tightening in home retrofits.

As new homes replace the existing stock, increasing tightness will reduce the energy demand of the residential sector. However these new homes will likely have higher efficiency systems for heating and cooling reducing the envelope tightness specific energy reductions to the stock. The cost of achieving progressively tighter building standards should be considered when deciding the level of air tightness required for new construction. It is considerably more difficult to reach the Passive House standard than the IECC standard and the energy benefit of doing so would be modest. The IECC 2012 captures most of the energy savings of the tightness standards explored and more aggressive tightness levels may not be worth requiring if the cost is significant. When choosing which standard to implement in each region of the country, the proposed homes location and the relative costs and benefits of reaching various tightness levels should be taken into account.

5. ACKNOWLEDGEMENTS

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PAPER TITLE
Impact of Sheathing Installation Practices on Air Barriers

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ABSTRACT

The paper will review case histories showing the as-built condition of building sheathings and their impact on the air barrier installation. Architectural drawings call out air barriers in section drawings and details, but there are no corresponding elevation drawings showing the sheathing or air barrier layers. The sheathing installation is typically left to the contractor to determine its layout and continuity.

- Review of multifamily project examples; assessment of joint conditions.
- Methods for air barrier installation at sheathing joints.
- Impact of field conditions, installation defects, and damage on air barrier installation.
- Recommendations for contractors and designers.

Thursday 18 April 2013

16:00-17:30 Session 5: Design and quality control of airtightness

1. Consideration of Envelope Airtightness in Modelling Commercial Building Energy Consumption, Lisa Chen Ng, NIST, USA
2. Leakage Reductions for Large Building Air Sealing and HVAC System Pressure Effects, David Bohac, Center for Energy and Environment, USA
3. Achieving Tight Buildings through Building Envelope Commissioning, John Runkle, Architectural Testing, USA
4. Commissioning of exterior building envelopes of large buildings for air leakage and thermal anomalies using infrared thermography and other diagnostic tools, Mario D. Gonçalves, Patenaude-Trempe Inc, Canada

Short Presentations

5. *An Airtight Shell for Effective Ducts, Tom Schneider, Building Envelope Innovations, USA*
6. *Thought Experiments for Evaluating Building Air Leakage Test Procedures. David Saum, Infiltec, USA*
7. *Optimizing Outside Pressure Taps To Reduce Wind Induced Pressure Errors. David Saum, Infiltec, USA*

CONSIDERATION OF ENVELOPE AIRTIGHTNESS IN MODELLING COMMERCIAL BUILDING ENERGY CONSUMPTION

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ABSTRACT

As various strategies for improving building envelope and HVAC equipment efficiencies are increasingly used to reduce building energy use, a greater percentage of energy loss will occur through building envelope leakage. Although the energy impacts of unintended infiltration on a building's energy use can be significant, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration and the impacts of improved airtightness. The airflow analyses capabilities of several energy simulation software tools were investigated and summarized, including whether the program calculates airflow rates or considers them to be inputs. The theory behind these calculations are summarized and evaluated for their physical soundness and accuracy. A new strategy to more accurately incorporate airflow calculations into energy software is also proposed, which is based on relationships between building infiltration rates calculated using detailed multizone airflow models and building characteristics, weather conditions, and building envelope airtightness.

KEYWORDS

Envelope airtightness, energy, infiltration, indoor air quality, commercial buildings

1. INTRODUCTION

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to maintain acceptable thermal comfort and indoor air quality (IAQ). However, the operating cost of HVAC systems is often a large percentage of the total energy cost of buildings, which constitutes 40 % of the primary energy consumed in the U.S. (DOE 2010). Due to the current emphasis on reducing energy consumption and greenhouse gas emissions, the use of energy simulation software has increased to investigate different design options and their impacts on building energy use. Since commercial building envelopes are much leakier than typically assumed (Emmerich and Persily 2011) and this leakage results in a significant energy penalty (Emmerich et al. 2007), one design option to reduce building energy use is improving building envelope airtightness. Nevertheless, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration, and therefore the impacts of improved airtightness on energy may not be fully captured.

Ng and Persily (2011) conducted a detailed comparison of the airflow capabilities of 12 of the energy simulation software surveyed by Crawley et al. (2005), which is summarized in Section 1.1 of this paper. As described below, multizone airflow modelling can be implemented in some of these programs but this approach is seldom used. Most energy simulation programs include empirical formulas to estimate building infiltration rates. However, those formulas were developed for low-rise, residential buildings and generally are not applicable in mechanically ventilated commercial buildings. Thus, a new strategy to more accurately incorporate calculations of infiltration rates into energy modelling of commercials buildings is proposed in Section 2. The new strategy is based on relationships between the building infiltration rates calculated using multizone airflow models, building characteristics, weather conditions, and envelope airtightness values. The airflow rates calculated using detailed multizone airflow modelling are compared to the infiltration rates calculated by EnergyPlus using the proposed strategy in Section 3.

1.1. Comparing airflow capabilities of energy simulation software

Table 1 summarizes the airflow capabilities of the five most widely used energy simulation software reported by Glazer (2010). A "Y" in Table 1 indicates that the energy simulation software has a particular simulation capability. An "O" indicates that the capability is optional and is not typically employed by modellers. A blank indicates that the capability is not available. All of the energy simulation software in Table 1 can account for constant infiltration rates that are not affected by changes in indoor and outdoor conditions. In some models, infiltration can be adjusted to reflect wind and stack effects. However, these adjustments for wind and stack effect are based on empirical equations for infiltration developed for low-rise residential buildings (Coblenz and Achenbach 1963; Sherman and Grimsrud 1980; Walker and Wilson 1998; ASHRAE 2005) and are not generally applicable to taller buildings or buildings with natural or mechanical ventilation systems. The effect of wind on external pressures, and thus on infiltration, can be calculated using the optional multizone airflow (pressure) network capability in EnergyPlus, DesignBuilder, or TRNSYS. When the multizone airflow (pressure) network capability is utilized, the user has the option to input wind pressure coefficients or allow the software to generate them.

Table 1: Summary of airflow and IAQ capabilities of selected energy simulation software.

	eQuest	EnergyPlus	TRNSYS	DesignBuilder	Ecotect Analysis
Infiltration					
Constant	Y	Y	Y	Y	Y
Account for wind and stack effects	Y	Y	O		Y
Multizone airflow (pressure network model)		O	O	O	
Wind pressure coefficients					
Input		O		O	
Calculated by software		O	O		

For energy simulation software that are able to simulate airflow using multizone airflow models (EnergyPlus, TRNSYS, and DesignBuilder), the capabilities are often limited and can be difficult for users to employ. The AIRFLOW NETWORK model in EnergyPlus is an early and limited version of the National Institute of Standards and Technology's (NIST) multizone airflow and contaminant transport model CONTAM (Walton and Dols 2013) with restrictions such as a single forced air system with a constant volume supply air fan. DesignBuilder implements limited capabilities of the EnergyPlus AIRFLOW NETWORK model. McDowell et al. (2003) describe a limited coupling of the multizone airflow model, CONTAM, with the transient system simulation program TRNSYS. More recently, NIST has updated the TRNSYS/CONTAM coupling to include the full multizone airflow and IAQ capabilities of CONTAM (available at http://www.bfrl.nist.gov/IAQanalysis/software/).

Gowri et al. (2009) proposed a method to account for infiltration in commercial buildings that was developed using a square medium office building and a building envelope airtightness value, such as one obtained by a pressurization test. Assuming a constant indoor-outdoor pressure difference of 4 Pa, Gowri calculated an infiltration rate to be input into EnergyPlus, using an approach that accounts for wind but not temperature effects on infiltration. In EnergyPlus, this leakage rate is then multiplied by a wind speed adjustment and a factor of 0.25 when the HVAC system is on, and 1.0 when the HVAC system is off. The method proposed by Gowri is limited because it was developed using a square building for which the wind pressure profile will be much different than for a non-square building. The method also does not account for temperature effects on infiltration, which can be important in many buildings, particularly taller buildings. Overall, the method greatly simplifies the interaction of building envelope airtightness, weather, system operation and infiltration.

The ways in which infiltration are currently accounted for in energy simulations are not necessarily based on well-developed airflow theory relating building envelope airtightness, HVAC system operation, and weather (Walton 1989). In those few energy simulation software programs where airflow can be more accurately modeled, the features are often cumbersome to employ and thus are not widely used in design. A new strategy to more accurately, but relatively simply, incorporate physically-based infiltration calculations into energy software is proposed in the next section. The proposed strategy is based on relationships developed between infiltration rates calculated by multizone airflow modelling, building characteristics, system operation, weather conditions, and building envelope airtightness. The strategy is described for implementation in EnergyPlus but is applicable to a variety of energy simulation software.

2. METHODS

The equation used to calculate infiltration in EnergyPlus is:

$$\text{Infiltration} = I_{design}\,[A + B|\Delta T| + C{\cdot}W_s + D{\cdot}W_s^2] \qquad (1)$$

where the units for infiltration and I_{design} are m^3/s•m^2, *A, B, C,* and *D* are constants, $|\Delta T|$ is the absolute indoor-outdoor temperature difference in °C, and W_s is the wind speed in m/s. Values for *A, B, C,* and *D* are recommended in the EnergyPlus user manual (DOE 2012), which are based on empirical data for low-rise residential buildings. In contrast, the authors used multizone airflow model infiltration data from several commercial building models to solve Equation (1) for *A, B, C,* and *D*. For this paper, infiltration includes the outdoor air entering through unintentional building envelope leakage only. It does not include any outdoor air entering the building through mechanical ventilation systems.

2.1. Correlating infiltration to weather (finding *A, B, C,* and *D*)

The multizone airflow modeling software, CONTAM (Walton and Dols 2013), was used to simulate the airflow in seven commercial reference buildings (DOE 2011) using weather data for Chicago. The buildings were: Full Service Restaurant, Hospital, Large Office, Medium Office, Primary School, Stand Alone Retail, and Small Hotel. Details on the building models can be found in Ng et al. (2012) and Ng et al. (2013). CONTAM-calculated infiltration rates for each building were then regressed against $|\Delta T|$ and W_s using Equation (1) to determine *A, B, C,* and *D* for each of the seven buildings. It was assumed that $A = 0$ when the HVAC system was off because when $|\Delta T|$ and W_s are zero, the system-off infiltration rate should be zero. A building envelope airtightness of 5.27 cm^2/m^2 at a reference pressure of 4 Pa was used in the CONTAM building models. In Equations (1) and (2), the units of I_{design} are m^3/s•m^2, thus the airtightness value at 4 Pa of 5.27 cm^2/m^2 used in CONTAM was converted to an EnergyPlus building envelope leakage value of 0.00137 m^3/s•m^2.

Since wind pressure is a function of the square of wind speed (Walton and Dols 2013), the CONTAM infiltration rates were also regressed against weather using Equation (2), where *C* in Equation (1) is equal to 0.

$$\text{Infiltration} = I_{design}\,[A + B|\Delta T| + D{\cdot}W_s^2] \qquad (2)$$

It was found that the calculated infiltration rates using Equation (1) and (2) were similar, thus Equation (2) was used to simplify the subsequent analyses.

Each individual building's values for *A, B,* and *D* were regressed against the building characteristics of the seven buildings, assuming $I_{design} = 0.00137$ m^3/s•m^2. The characteristics considered were: building height (*H* in m), exterior surface area to volume ratio (*SV* in m^2/m^3), and net system flow (i.e., supply air minus return air minus mechanical exhaust air) normalized by exterior surface area (F_n in m^3/s•m^2). The values for each building are listed in Table 2.

Table 2: Summary of building characteristics of seven simulated buildings.

	Full Service Restaurant	Hospital	Large Office	Medium Office	Primary School	Small Hotel	Stand Alone Retail
***H* (m)**	4.7	23.8	50.4	12	4	11.6	6.1
***SV* (m^2/m^3)**	0.17	0.11	0.09	0.18	0.34	0.23	0.24
F_n (m^3/s•m^2) × 10^{-3}	-2.6	1.0	1.3	0.56	0.02	0.50	0.21

The following relationships between the constants in Equation (2) and the building characteristics were considered:

$$A = M_A{\cdot}H + N_A{\cdot}SV + P_A{\cdot}F_n \qquad (3)$$
$$B = M_B{\cdot}H + N_B{\cdot}SV + P_B{\cdot}F_n \qquad (4)$$
$$D = M_D{\cdot}H + N_D{\cdot}SV + P_D{\cdot}F_n \qquad (5)$$

The values for *A, B,* and *D* were regressed for system-on and system-off infiltration rates. Based on the CONTAM infiltration rates and building characteristics of the seven buildings, Equations (6) through (11) were then generated to calculate *A, B,* and *D* for potential use in other buildings. As stated above, $A = 0$ when the system is off. Also, the net system flow is zero ($F_n = 0$) when the system is off.

$$A_{on} = 0.0001 \cdot H + 0.0933 \cdot SV + -47 \cdot F_n \quad (6)$$
$$B_{on} = 0.0002 \cdot H + 0.0245 \cdot SV + -5 \cdot F_n \quad (7)$$
$$D_{on} = 0.0008 \cdot H + 0.1312 \cdot SV + -28 \cdot F_n \quad (8)$$

$$A_{off} = 0 \quad (9)$$
$$B_{off} = 0.0002 \cdot H + 0.0430 \cdot SV \quad (10)$$
$$D_{off} = -0.00002 \cdot H + 0.2110 \cdot SV \quad (11)$$

Since Equations (6) through (11) were developed assuming an $I_{design} = 0.00137$ m^3/s•m^2, other I_{design} values, 0.000304 m^3/s•m^2 and 0.0054 m^3/s•m^2, were also simulated in CONTAM and EnergyPlus without changing the values of *A*, *B*, and *D*. This was done to assess the ability of a single set of *A*, *B*, and *D* to predict infiltration for a range of building envelope leakage values.

3. RESULTS

Using Equations (6) through (11), *A*, *B*, and *D* were calculated for each of the seven buildings (Table 3) and input into EnergyPlus. Hourly infiltration results were then compared between CONTAM and EnergyPlus. The mean of the CONTAM and EnergyPlus infiltration rates are listed in Table 4, along with the standard error and R^2 of the EnergyPlus infiltration rates compared with the CONTAM rates. Some R^2 values in Table 4 are negative because the relationship between infiltration, $|\Delta T|$, and W_s are not linear. The system-on and system-off standard errors and R^2 of the EnergyPlus infiltration rates listed in Table 4 indicate that CONTAM infiltration rates are predicted best for the Stand Alone Retail building. This is also shown in Figure 1, where the CONTAM vs. EnergyPlus infiltration rates fall close to a line of perfect agreement.

Table 3: Summary of *A*, *B*, and *D* of seven simulated buildings.

	Full Service Restaurant	Hospital	Large Office	Medium Office	Primary School	Small Hotel	Stand Alone Retail
***A* on**	0.1424	-0.0349	-0.0466	-0.0082	0.0310	-0.0008	0.0137
***B* on**	0.0186	0.0014	0.0040	0.0036	0.0088	0.0050	0.0059
***D* on**	0.1004	0.0049	0.0160	0.0177	0.0468	0.0256	0.0311
***A* off**	0	NA	0	0	0	NA	0
***B* off**	0.0086	NA	0.0155	0.0106	0.0154	NA	0.0119
***D* off**	0.0427	NA	0.0175	0.0437	0.0710	NA	0.0515

Note: The Hospital and Small Hotel HVAC systems are always scheduled to be on.

Table 4 shows that the Full Service Restaurant, with the system off, has the lowest R^2 value of the seven buildings, though its standard error relative to CONTAM is comparable with the other buildings. Figure 2(a) shows that for the Full Service Restaurant with the system on, the CONTAM and EnergyPlus infiltration rates are in good agreement, but for the system off (Figure 2(b)), the EnergyPlus infiltration rates are lower than the CONTAM rates. The Hospital has the largest standard error relative to CONTAM, though the mean infiltration rates are the lowest among the other buildings. Figure 3 shows that for the Hospital, the EnergyPlus infiltration rates are lower than the CONTAM rates. The Large Office, with the system on, has the lowest R^2 value of the seven buildings, and its standard error relative to CONTAM is second highest among the other buildings. In general, buildings with the lowest infiltration rates, Hospital and two offices, also have the highest standard error in relation to the CONTAM mean rate. However, the infiltration rates are relatively low for these three buildings, leading to low absolute errors in the infiltration rates.

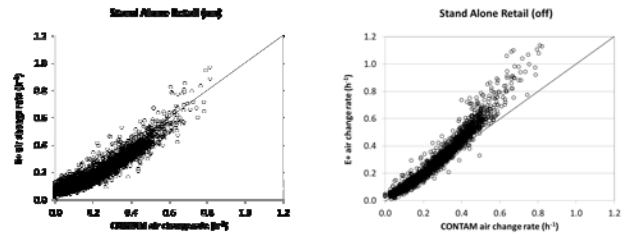

Figure 1: EnergyPlus vs. CONTAM infiltration rates for Stand Alone Retail (a) system-on and (b) system-off

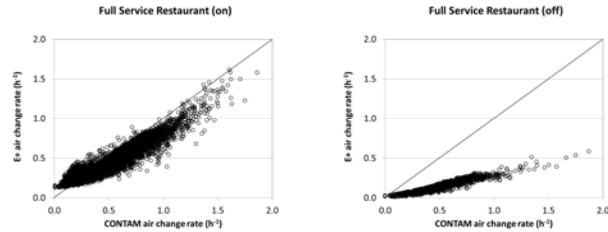

Figure 2: EnergyPlus vs. CONTAM infiltration rates for Full Service Restaurant (a) system-on and (b) system-off

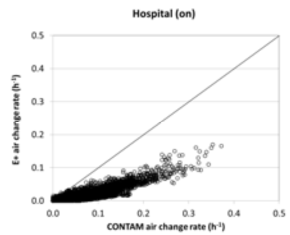

Figure 3: EnergyPlus vs. CONTAM infiltration rates for Hospital system-on

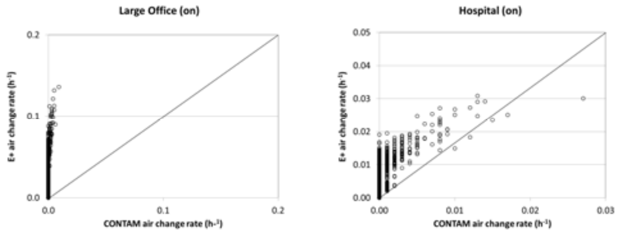

Figure 4: EnergyPlus vs. CONTAM infiltration rates for (a) Large Office system-on and (b) Hospital system-on, low I_{design} value (0.000304 $m^3/s/m^2$)

CONTAM and EnergyPlus were also simulated with I_{design} = 0.000304 $m^3/s\bullet m^2$ and 0.0054 $m^3/s\bullet m^2$, which were respectively two times lower and two times higher than the I_{design} used to develop Equations (6) through (11). For the Stand Alone Retail and Full Service Restaurant, the change in I_{design} did not affect the general trends of the EnergyPlus predictions relative to the infiltration rates predicted by CONTAM. For the Hospital, the higher I_{design} values resulted in similar results to those shown in Figure 3, for which EnergyPlus underestimated the CONTAM results. For the Hospital, the lower I_{design} value resulted in the EnergyPlus results overestimating the CONTAM results as shown in Figure 4. This was also the case for the Large Office, for the lower I_{design} value and the system on.

Table 4: Comparison of CONTAM and EnergyPlus infiltration results.

	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
System on							
CONTAM mean infiltration rate (h^{-1})	0.53	0.02	0.03	0.11	0.25	0.26	0.23
EnergyPlus mean infiltration rate (h^{-1})	0.46	0.01	0.08	0.11	0.34	0.19	0.21
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.09 (17)	0.02 (130)	0.02 (68)	0.04 (36)	0.07 (26)	0.06 (24)	0.05 (20)
R^2	0.80	-0.23	-1.74	0.83	0.31	0.61	0.83
System off							
CONTAM mean infiltration rate (h^{-1})	0.50	NA	0.14	0.27	0.29	NA	0.26
EnergyPlus mean infiltration rate (h^{-1})	0.15	NA	0.13	0.23	0.44	NA	0.29
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.08 (15)	NA	0.02 (16)	0.06 (23)	0.15 (18)	NA	0.03 (13)
R^2	-1.47	NA	0.81	0.57	-0.90	NA	0.78

Note: The Hospital and Small Hotel HVAC systems are always scheduled to be on. The standard error of EnergyPlus rates and R^2 values were based on the regression between EnergyPlus and CONTAM results.

Thus it could be concluded that using a specific I_{design} to develop relationships between infiltration, weather conditions, system operation, and building characteristics generally resulted in good agreement between CONTAM and EnergyPlus for most buildings. The buildings for which the change in I_{design} made the largest impact were those where the system pressurization tended to overcome any infiltration due to a very tight building envelope, which in this study were the Hospital and Large Office. For these two buildings, using a lower I_{design}, EnergyPlus results overestimated CONTAM results as shown in Figure 4.

4. DISCUSSION

Though modellers can account for simplified infiltration and improved envelope airtightness with current energy simulation software, the effects of weather, system operation, and envelope leakage on infiltration are either ignored or not well accounted for. Oftentimes, zero or a constant/scheduled infiltration is input into energy simulation software due to lack of understanding of how to more accurately account for infiltration. Currently, infiltration equations in energy simulation software and guidance for input variables are based largely on research for low-rise, residential buildings. However, the interaction of weather, system operation, and envelope leakage in determining infiltration rates is fundamentally related to pressure, and these physics are not typically or easily modeled in current energy simulation software. Multizone airflow modelling is the correct way to calculate infiltration, however, the current means of doing so in energy simulation programs are limited and cumbersome to implement.

The proposed strategy to incorporate the effects of weather, system operation, and envelope leakage on infiltration has been shown to be in good agreement with CONTAM simulations of several buildings of different sizes, system operation, and building envelope airtightness. The proposed strategy was also tested on buildings that were not of the seven used in developing the strategy, and those results will be reported in the future.

5. FUTURE WORK

The proposed strategy for incorporating the effects of building envelope leakage, weather, and system operation on infiltration was shown to be comparable to multizone airflow calculations for most of the buildings considered. The strategy also has potential to be useful in predicting infiltration in other buildings. Additional buildings, as well as weather and operating conditions need to be considered. In addition, further understanding and guidance on how to use the proposed strategy over a range of building envelope leakage values needs to be developed. Additional work could also involve relatively straightforward modifications to energy simulation software in order to implement the proposed strategy with better accuracy. The energy impacts of improving building envelope airtightness can then be evaluated more easily and more reliably.

6. CONCLUSIONS

Due to an increased emphasis on energy consumption and greenhouse gas emissions, the potential savings from energy efficiency measures are often analyzed using energy simulation software. However, the impact of implementing some of these measures is oftentimes incomplete because building envelope infiltration is not properly accounted for. This study summarizes the airflow analyses capabilities of the most widely used energy simulation software (eQuest, EnergyPlus, TRNSYS, DesignBuilder, and Ecotect Analysis). Many of the airflow models implemented in these software tools are inappropriate for large buildings or are limited in simulation capabilities. The proposed strategy, based on the relationship between building envelope airtightness, building characteristics, weather, and system operation, has been shown to be applicable in a variety of buildings and the results are comparable to performing multizone calculations.

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LEAKAGE REDUCTIONS FOR LARGE BUILDING AIR SEALING AND HVAC SYSTEM PRESSURE EFFECTS

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ABSTRACT

Building air leakage tests were conducted on six commercial and institutional buildings before and after air sealing work. The test protocol generally followed the requirements of ASTM E779, with additions to address the complexities of testing larger buildings. The buildings were one to three stories and were constructed between 1936 and 2007, with floor areas that ranged from 27,000 to 246,000 ft^2 (2,500 to 22,900 m^2). Before air sealing, the buildings were relatively tight with normalized air leakages that ranged from 0.15 to 0.31 cfm@75Pa/ft^2 (2.6 to 5.7 $m^3/h \cdot m^2$) using above grade envelope area and 0.09 to 0.19 cfm@75Pa/ft^2 including below grade walls and slab.

The air sealing focused on cost effective spray foam sealing of the wall/roof joints, with upgrades of exterior door weatherstripping a second priority. The sealing reduced air leakage from 6 to 18% with a median of 11%. For three of the buildings, the air sealing contractor generated the work scope and estimated the physical leakage area to be sealed. The contractor estimated air sealing was significantly greater than the measured values. The ratio of measured change in the EqLA to estimated sealed area ranged from 0.05 to 0.31.

There was a consistent and significant bias for higher leakage under pressurization than depressurization. The ratio of pressurization to depressurization tightness for the pre and post sealing measurements varied from 1.12 to 1.31 with a mean value of 1.22. Individual door tests indicated that doors with loose latches being pushed open during pressurization may have been responsible for about 17% of the increased leakage for pressurization at one of the schools.

The air tightness tests were conducted with exhaust fans, outdoor air inlets, and exhaust air outlets temporarily sealed. Single point tests were conducted after the seals were removed to compute mechanical system leakage. The normalized leakage ranged from 0.019 to 0.137 cfm@75Pa/ft^2 and increased the envelope leakage by 15% to 119%. This suggests that mechanical system air leakage can have a significant effect on building air leakage when the systems are off.

Air sealing contractors often estimate energy savings from monthly average wind pressure or wind and stack pressure models that do not include heating, ventilation, and air conditioning (HVAC) effects. Long-term building pressure monitoring indicated that HVAC operation positively pressurized many of the buildings. For one of the buildings the pressure at roof level was typically above +40Pa when the outside temperature was lower than 40F. In those situations ignoring the HVAC pressure effect results in high estimates of air infiltration and air sealing energy savings. However, there were also times when the HVAC system caused depressurization and in those situations infiltration and air sealing savings would be underestimated.

KEYWORDS
Airtightness, infiltration, commercial buildings, mechanical system leakage, HVAC pressure effect.

1. INTRODUCTION

Building architects, engineers, contractors, and facility managers tend to think of large buildings as fairly airtight and assume that envelope air leakage does not typically have a significant impact on energy use in commercial and institutional (C&I) buildings (Persily, 1988). Emmerich (2005) conducted modelling that contradicts that conventional wisdom, estimating that infiltration accounts for 33% of total heating energy use in U.S. office buildings.

Several states, including Minnesota, have recently incorporated air barrier requirements into their energy codes for new C&I buildings. In addition, the US Army Corps of Engineers (USACE) has established a performance airtightness requirement for new buildings and major retrofits of 0.25 cfm/ft^2 (1.25 $L/s \cdot m^2$) of total enclosure surface area at a pressure of 75 Pascals (USACE, 2010); and other codes or organizations have adopted a standard of 0.4 cfm/ft^2 (2.0 $L/s \cdot m^2$). However, the building stock that existed prior to this increased emphasis on envelope tightness contributes much more to overall energy use than do buildings built since these changes, and will continue to for many years, as the C&I building stock turns over slowly. Reducing air leakage energy use in existing buildings requires effective screening tools to identify buildings with a higher probability of having treatable leaks; investigation methods to identify key envelope air leakage deficiencies and/or mechanical system pressure issues; and reliable procedures to estimate cost and savings.

This project was initiated to develop and test envelope air leakage screening protocols, investigation protocols, measure the change in building leakage due to air sealing, model the effect of leakage reduction on space conditioning loads, and generate cost and savings estimation procedures. Project staff conducted air leakage investigations on 25 existing C&I buildings, including whole building air leakage tests before and after air sealing on six of those buildings. They also recorded continuous building indoor to outdoor pressure and merged it with automation system trend data to evaluate the effect of the heating, ventilation, and air conditioning (HVAC) system on building pressure. Those results are being used to develop CONTAM models (Walton, 2013) that include HVAC pressure effects. This paper presents the results of the air leakage tests and continuous pressure monitoring.

2. METHODOLOGY

The building air tightness tests generally followed the requirements of ASTM E779-10 (2010), with additions to address the complexities of testing larger buildings. The key additions to or clarifications of the test protocol are outlined below:

- **In/outdoor pressure sensors**. The average of four ground level in/outdoor pressure measurements placed on different sides of the building was used to indicate the building indoor with respect to outdoor pressure difference.
- **Baseline pressures**. Building baseline pressures were measured for at least five minutes before and after both the pressurization and depressurization tests.
- **Test pressures**. Multiple, calibrated fans were used to vary the baseline adjusted building in/outdoor pressure at 5Pa increments from approximately 15 to 75Pa. Measurements were conducted at 13 to 16 pressure levels for 60 seconds at each level.
- **Mechanical systems**. All mechanical dampers were closed and the dampers or terminations of the outside air ducts, exhaust air ducts, and exhaust fans were temporarily sealed. After the depressurization test was completed, the temporary seals were removed sequentially from the mechanical equipment while the test fans were

used to depressurize the building to a baseline adjusted pressure of approximately -75Pa. One minute of measurements were recorded at each stage of the unsealing. The measured fan flow rate and building pressure were used with the depressurization test baseline and flow exponent to compute a total building leakage for a reference pressure of 75Pa. The “envelope only” building leakage was subtracted from that value to determine the additional leakage due to the mechanical systems.

Project staff used commercially available software to record building pressure differences, record fan flow rates, control test fan speeds, graphically display the measurements, and compute air leakage values. They improved data quality by using distributed gauges to minimize tube lengths and real-time regression analysis to identify erroneous measurements.

Experienced staff or consultants conducted the building air leakage investigations with a combination of an exterior infrared (IR) survey and interior leak investigation with smoke visualization. They used the building’s HVAC system or temporary fans to pressurize the buildings for the exterior surveys (ASTM E1186-03, 2009); and conducted the investigations with a minimum inside to outside temperature difference of 18F, with no direct solar radiation on the surfaces for four to six hours prior to the survey. The results of the IR survey and experience of typical leakage sites helped guide a visual envelope leakage investigation. From the building interior a smoke puffer was used to release chemical smoke near suspected leakage sites. The velocity and volume of smoke movement indicated the relative magnitude of air leakage. The investigations typically focused on wall/roof intersections, roof elevation changes, exterior doors, mechanical system penetrations, and windows. The final step in the process was to determine code compliant methods for sealing the major envelope air leaks. Staff consulted building wall and roof air barrier details when available; and only considered sealing that required limited or no removal of building materials.

Air sealing contractors often estimate energy savings from monthly average wind pressure or wind and stack pressure models. The models do not typically include the effects of mechanical system operation on the building pressure. Pressure monitors were installed at the buildings to record one minute averages of building inside with respect to outside pressure differences at one to three interior locations. The tubes for the outdoor pressure reference exited the buildings at either the roof or ground level depending on accessibility. The monitoring periods lasted 50 to 200 days. The pressure data was converted to 15 minute averages and merged with local weather station outdoor temperature, wind speed, and wind direction data. Building automation system trend data was used to identify occupied and unoccupied operation modes. The data has been analyzed to evaluate the effect of HVAC operation on the variation in building pressure with outside temperature.

The next phase of the project is developing CONTAM models (Walton, 2013) using the building air leakage test data to establish the sum of the envelope and mechanical system leakage. The unoccupied mode data will determine the building’s neutral level to assist with assigning the vertical distribution of CONTAM envelope air leakage. Finally, analysis of the occupied mode pressure and HVAC trend data will establish the variation with outside temperature in building pressure induced by the HVAC supply and exhaust system flow rates.

3. RESULTS AND DISCUSSION

3.1. Pre-Sealing Building Tightness

The project conducted air sealing and leakage tests on two elementary schools, a middle school, a university library, a combination community library/office, and a small office building. The building IDs shown in Table 1 indicate the building type. The buildings were one to three stories tall built from 1936 to 2007, with floor areas ranging from 26,927 to 246,365 ft^2 (about 2,500 to 22,900 m^2). The pre-sealing building air tightness normalized by the above grade envelope area (i.e. five sides) ranged from 0.15 to 0.31 cfm/ft^2 (2.6 to 5.7 $m^3/h \cdot m^2$) and 0.09 to 0.19 cfm/ft^2 when normalized by the six sides area that includes below grade walls and slab (see Table 1). Both sets of values use a reference pressure of 75Pa.

Table 1: Building characteristics and pre-sealing air tightness

	Floor	Envelope Area (ft^2)		Air Leakage at 75Pa	5 Sides		6 Sides	#	Constr	
Building ID	Area (sf)	5 Sides[1]	6 Sides[2]	(cfm)	(cfm/ft^2)	($m^3/h \cdot m^2$)	(cfm/ft^2)	Stories	Year	Wall Type
Elem School TF	59,558	87,419	146,977	27,425	0.31	5.7	0.19	1	1951	Masonry & corrugated metal panel
Middle School	138,887	130,318	208,733	32,818	0.25	4.6	0.16	3	1936	Cast concrete w/CMU infill
Small Office	26,927	38,340	65,267	9,177	0.24	4.4	0.14	1	1998	EFIS tip up (3 walls) and CMU block
Univ Library	246,365	98,240	171,712	23,356	0.24	4.3	0.14	3	1967	Cast concrete w/CMU infill & brick ext
Elem School PS	60,968	84,798	145,766	17,602	0.21	3.8	0.12	1	1965	CMU w/brick exterior
Library/Office	55,407	84,558	139,965	12,321	0.15	2.6	0.09	1	2007	Steel studs & brick or stone cladding
Minimum	26,927	38,340	65,267	9,177	0.15	2.6	0.09			
Mean	98,019	87,279	146,403	20,450	0.23	4.2	0.14			
Median	60,263	86,108	146,371	20,479	0.24	4.3	0.14			
Maximum	246,365	130,318	208,733	32,818	0.31	5.7	0.19			

1 – above grade surface area
2 – includes below grade exterior walls and slab

The buildings were much tighter than expected, even though many of the buildings were older and none were required to meet a tightness standard at the time of construction. The average normalized tightness of 0.23 cfm/ft^2 (4.2 $m^3/h \cdot m^2$) was 83% less than the average value of 1.38 cfm/ft^2 reported by Emmerich (2011) for a convenience sample of 227 U.S. C&I buildings. The tightness of the leakiest of the six buildings was less than the 25th percentile of Emmerich’s database and was 25% tighter than the USACE standard. It is possible that buildings in cold climates are tighter due to greater concern for cold drafts, frozen pipes, and higher space heating costs. A previous analysis by Emmerich (2005) suggested that buildings in colder climates are generally tighter than the U.S. average. The results for these six buildings are consistent with that trend, but a larger sample is necessary to properly determine the distribution of normalized leakage and the fraction of new buildings that would be impacted by a leakage standard or existing buildings that are likely to have cost effective air sealing opportunities.

3.2. Air Sealing Leakage Reduction

The air sealing focused on cost effective spray foam sealing of the wall/roof joints, with upgrades of exterior door weatherstripping a second priority, and mechanical system penetration sealing was completed at some of the buildings. An air sealing contractor conducted the initial investigations of the three school buildings. Project staff conducted follow-up investigations and the contractor adjusted the work scope based on staff feedback. The contractor’s proposals included estimates of leakage area to be sealed and energy savings. For the three elementary and middle schools the contractor estimated that 81% of the sealing would be produced from wall/roof joint foam sealing and 15% from exterior door weatherstripping. Sealing estimates were not established for the other three buildings. For two of the buildings (*Univ. Library* and *Library/Office*) the work only included wall/roof sealing. The rooftop unit penetrations and CMU beam wall pockets near the roof were sealed for about a quarter of the *Small Office* building.

The air sealing of the three schools was completed at the bid price by the commercial contractor who specified the work. A different commercial contractor conducted the air sealing at the *Univ. Library* and *Small Office* sites on a time and materials basis. Project staff completed the limited sealing at the *Library/Office* building and costs were estimated based on the second contractors' time and materials rates. Post sealing IR scans and smoke puffer/visual investigations were completed to confirm that specified air leakage was sealed. All of the work was determined to be successful except some of the wall/roof sealing at the *Univ. Library* building which required additional exterior sealing that could not be completed prior to the post test scheduled date.

The measured change in building tightness was smaller than expected. The reduction in leakage at 75Pa (CFM75) ranged from 6% to 17% with a mean of 10% (see Table 2). The building with the highest normalized leakage had the greatest relative reduction in leakage and there was somewhat of a trend of greater reductions for the leakier buildings. In addition, the air sealing cost per CFM75 reduction increased for tighter buildings except for the *Library/Office* building where there was an isolated, significant wall/roof leak that was inexpensive to seal. The results suggest that it is possible to reduce the leakage of even tight buildings. However, the sealing potential is better for leakier buildings unless concentrated leaks can be identified that are inexpensive to seal. Since few U.S. air sealing contractors conduct air leakage tests, they must rely on smoke puffer/visual leakage investigations to identify cost effective air sealing opportunities.

Table 2: Envelope air sealing results

	Air Leakage at 75Pa				Leakage Area							Sealed Area (sf)		
	(cfm)		Reduction		EqLA (ft^2)		Reduction		Air Sealing Cost			Contractor Estimated		
Building ID	Pre	Post	(cfm)	(%)	Pre	Post	(ft^2)	(%)	Total	($/CFM75)	($/ft^2)	Roof/Wall	Total	Meas/Est
Elem School TF	27,425	22,699	4,726	17%	15.2	12.5	2.7	18%	$ 18,550	$ 3.92	$ 6,822	8.84	11.49	0.31
Middle School	32,818	28,872	3,947	12%	16.6	13.8	2.8	17%	$ 23,700	$ 6.00	$ 8,434	11.73	14.98	0.24
Small Office	9,177	8,470	708	8%	4.6	4.1	0.5	10%	$ 4,768	$ 6.73	$ 10,058			
Univ Library	23,356	21,963	1,392	6%	13.1	12.8	0.2	2%	$ 15,918	$ 11.43	$ 65,159			
Elem School PS	17,602	15,837	1,765	10%	9.6	8.9	0.7	7%	$ 26,700	$ 15.13	$ 38,132	14.45	16.94	0.05
Library/Office	12,321	11,369	953	8%	6.9	6.0	0.9	13%	$ 1,152	$ 1.21	$ 1,297			
Minimum	9,177	8,470	708	6%	4.6	4.1	0.2	2%	$ 1,152	$ 1.21	$ 1,297			
Mean	20,450	18,201	2,249	10%	11.0	9.7	1.3	11%	$ 15,131	$ 7.41	$ 21,650			
Median	20,479	18,900	1,579	9%	11.3	10.7	0.8	12%	$ 17,234	$ 6.37	$ 9,246			
Maximum	32,818	28,872	4,726	17%	16.6	13.8	2.8	18%	$ 26,700	$ 15.13	$ 65,159			

1 – at 10 Pa reference pressure for orifice with a discharge coefficient of 0.61
All leakage values are average of pressurization and depressurization tests

The contractor estimated air sealing was significantly greater than the measured values. The actual leakage sealed was estimated from the difference in the pre to post equivalent leakage area (EqLA). The ratio of measured change in the EqLA to estimated sealed area was 0.24 and 0.31 for the two leakier buildings, but only 0.05 for the second to tightest building. For that building the contractor estimated area to be sealed was greater than the total leakage. Since the post sealing inspections showed little or no leakage at the areas sealed, it appears that the reason for the high sealed area estimates was an inability to properly estimate physical leakage areas and not poor air sealing techniques. While judging the velocity of smoke movement into a gap and the size of the gap used to estimate the size of leaks, that method is only qualitative. The width of a visible gap at a joint will overestimate the equivalent width of the air leakage path when there are greater restrictions downstream in the path. For example, the visible leak area for the gaps sealed at the *Library/Office* building was 3.3 ft^2 but the measured change in the EqLA was 0.9 ft^2 when the area was sealed. Finally, while it is possible to use this method to estimate the flow rate of air moving into a leak, the pressure across the leak would need to be known to accurately quantify the equivalent leakage area. This limited sample suggests that further work is required to develop methods to more accurately determine physical leakage area.

3.3. Pressurization and Depressurization Comparison

There was a consistent and significant bias for higher leakage under pressurization than depressurization. The ratio of pressurization to depressurization tightness for the pre and post sealing measurements for the six buildings varied from 1.12 to 1.31 with a mean value of 1.22 (see top row of Figure 1). This indicates that there are portions of the building envelope that are significantly leakier under pressurization than depressurization. This could be due to membranes that are pulled tight to a surface under depressurization or other "flapper" situations. Project staff noticed that the school buildings had a number of loose door latches that allowed the doors to push open during higher pressures of the pressurization test (typically above 25Pa). Pressurization and depressurization tests were conducted on 17 doors at 3 of the buildings. Figure 2 displays the results for one of the doors with "loose latch" movement. For 65% of the doors, the pressurization CFM75 was more than 40% greater than that for depressurization and the average leakage difference was 18 CFM75. If that average difference is applied to the 26 exterior doors for *Elem School TF*, the leakage difference of 458 CFM75 would equal 17% of the 2,667 CFM75 higher leakage under pressurization for the entire building. The door movement due to loose latches provides one example of additional pressurization leakage. It is expected that there are several additional situations that are not as easy to observe or quantify. This raises an interesting issue as to whether one of the tests or an average is most representative of the building leakage under typical operation and which should be used for building tightness compliance standards.

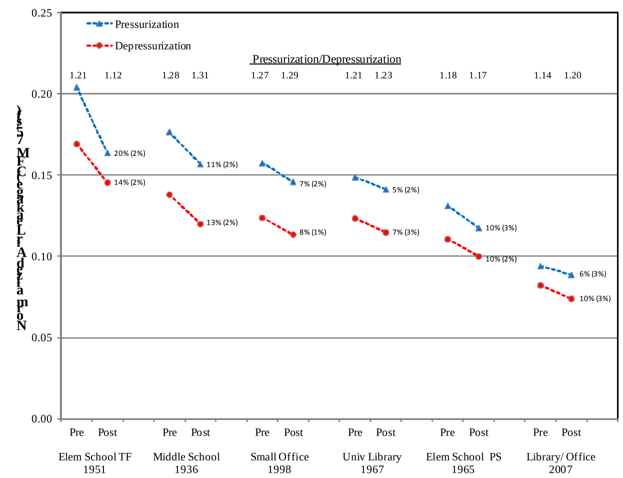

Figure 1: Building normalized envelope leakage pre and post air sealing

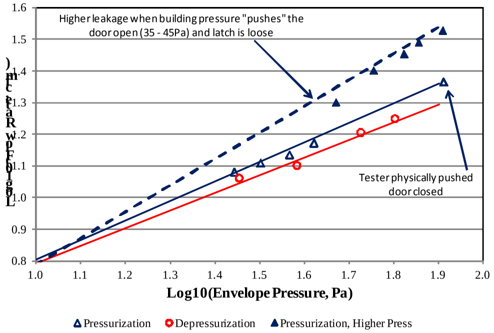

Figure 2: Pressurization and depressurization leakage tests on a door with a loose latch

The difference in the pressurization and depressurization tightness is also a concern for evaluating the effect of air sealing. Figure 1 displays the pre and post pressurization and depressurization six sides normalized leakage. The percent change is shown to the right of the post measurement and the 95th confidence interval uncertainty is included in parenthesis. For five of the six buildings the difference between percent change in tightness computed from the pressurization and depressurization tests is less than the sum of the uncertainties. This indicates that each test method provides similar relative changes in tightness and either could be used to evaluate the effect of air sealing.

There was often a significant difference in the pressurization and depressurization power law equation exponent. Figure 3 displays the exponents from the pre and post tests with the error bars representing the 95th percentile confidence intervals. The pressurization exponent was greater than that for depressurization for 10 of the 12 tests and for 7 of those the difference was greater than the sum of the uncertainties.

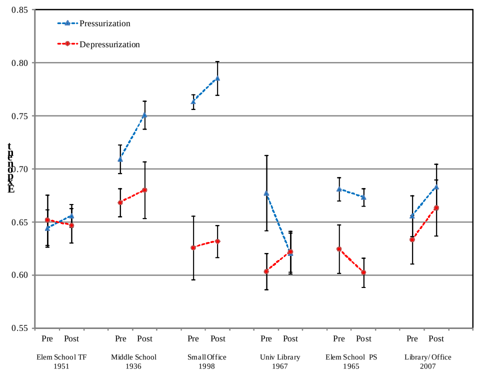

Figure 3: Power law flow equation exponent pre and post air sealing

3.4. Mechanical System Leakage

When the mechanical systems are operating and the outside/exhaust air dampers are opened to regulate air flow, the damper leakage is typically not a concern. However, when the systems are off, the dampers become part of the building's air barrier and damper leakage causes additional building air infiltration or exfiltration. Damper leakage poses a greater concern for buildings with a higher fraction of time when the mechanical systems are off.

The mechanical system leakage varied from 1,618 to 23,516 CFM75 and the six sides normalized leakage varied from 0.019 to 0.137 cfm/ft^2 with a mean of 0.047 cfm/ft^2 (see Figure 4). For three of the buildings, including the mechanical system leakage would increase leakage by over 50%. These three buildings were constructed in 1967 or earlier, while two buildings built more recently (1998 and 2007) had relatively low mechanical system leakage. This suggests that improving damper tightness offers a significant energy efficiency opportunity for existing buildings and should be a consideration for new construction. Further work is required to assess the methods, cost, and tightness improvements of damper retrofits.

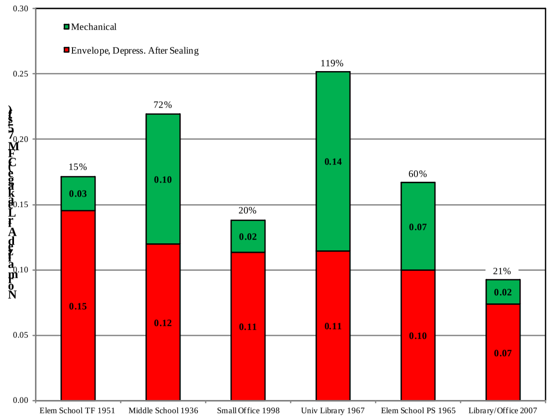

Figure 4: Building normalized envelope and mechanical system leakage

3.5. Mechanical System Building Pressure Effect

The 15 minute building pressure and weather data was sorted into occupied/unoccupied or day/night modes of operation. Figure 5 scatter and box & whisker plots display the relationship of building pressure with outside temperature for three of the buildings. The *Elem School TF* building has three air handling units, six rooftop units, and six fan coil units for the original portion of the building and the four additions. Some units have outside air and some use an economizer operation. None of the units or exhaust fans operate at night and there is no active building pressure control. The system relies on a pre-determined balance of outside and exhaust air to maintain the building design pressure. Except for one hour morning and evening transition periods, the HVAC operation produced a positive building pressure at the roof monitoring position and the majority of the building exterior was under positive pressure during the occupied mode. The second row of plots for the *Univ. Library* shows a more extreme example of building pressurization. For milder weather the pressure at the roof typically varies from +10 to +30Pa during daytime operation, but when the outside temperature is lower than 40F the building pressure is consistently above 40Pa. The four air handlers have no active building pressure control and insufficient or malfunctioning exhaust capacity that produces high positive building pressures and often causes entry doors to blow open. For both buildings ignoring the effect of HVAC operation on building pressure would produce overestimates of air infiltration loads and high predictions of energy savings due to envelope air sealing.

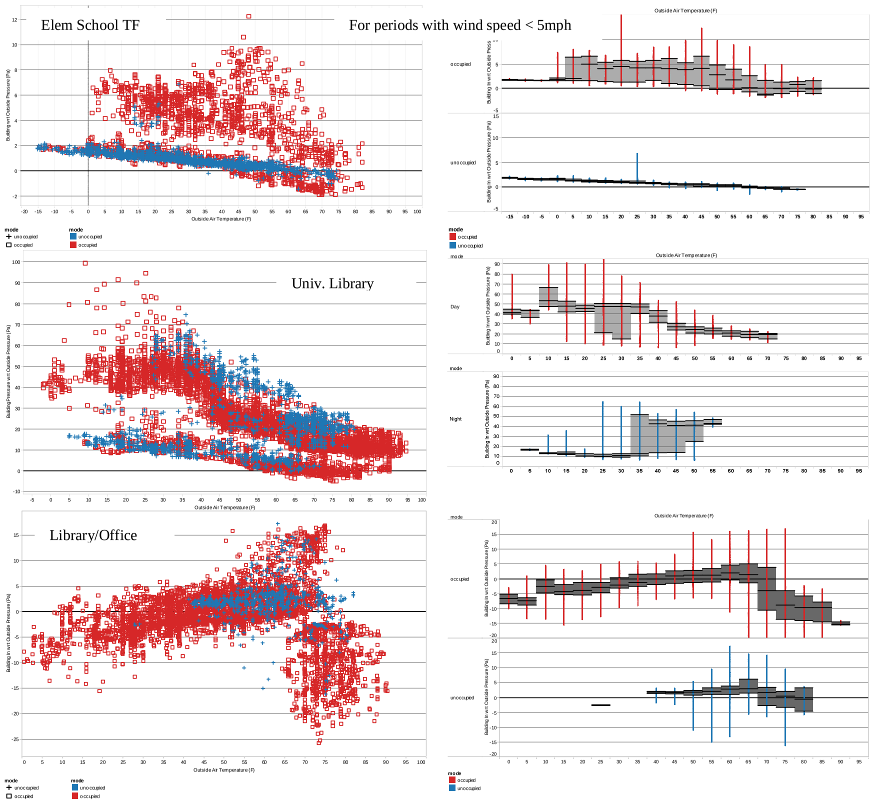

Figure 5: Occupied and unoccupied mode building pressure with outside temperature

The third building (Library/Office) has active building pressure control, but the pressure sensor for one of the five air handlers was malfunctioning. The pressure set point of +10Pa was not often achieved and a positive building pressure was typically only maintained between outside temperatures of 40F to 70F. The remainder of the time the building was depressurized with significant depressurization in warmer weather. For this situation ignoring the HVAC pressure effect results in underestimates of air infiltration and air sealing savings.

4. CONCLUSIONS

The buildings were much tighter than the U.S. average reported by previous studies, even though many of the buildings were built before 1970 and none were required to meet a tightness standard at the time of construction. Previous studies have suggested that buildings in colder climates are tighter and these buildings follow that trend. The air sealing results indicate that it is possible to reduce the leakage of even tight buildings. However, the sealing potential is better for leakier buildings unless concentrated leaks can be identified that are inexpensive to seal. The contractor estimates of physical leakage area that would be sealed were less than a third of the measured reduction in leakage area. IR scans and smoke puffer investigations confirmed that the specified leaks were successfully sealed, which suggests that improvements in methods for estimating leakage area are necessary.

The type of test and mechanical system leakage has a significant effect on building tightness results that must be considered for tightness performance standards. The leakage for pressurization tests was an average of 22% greater than that for depressurization. It is unclear which test is a more valid indicator of leakage under typical conditions. HVAC systems are often designed to positively pressurize buildings, but one of the leakage paths (i.e. loose door latches) only occurred at pressures above 25 to 35Pa. For half of the buildings including the mechanical system leakage would increase the building leakage by over 50%. Since the mechanical system is part of the envelope when it is not operating, that leakage can have a large impact on air infiltration and leakage reduction is an opportunity for energy savings.

For many of the buildings ignoring the effect of HVAC operation on building pressure would produce overestimates of air infiltration loads and high predictions of energy savings due to envelope air sealing. However, there were also times when HVAC depressurization caused increased infiltration that would result in underestimates of infiltration and air sealing savings.

5. ACKNOWLEDGEMENTS

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ACHIEVING TIGHT BUILDINGS THROUGH BUILDING ENVELOPE COMMISSIONING

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ABSTRACT

In an effort to improve building energy efficiency, functional performance, and life cycle durability, a noticeable trend in building codes, standards, and individual project specifications has been towards the 'tightening' of buildings; that is, greater control of air movement across the building envelope. Standards across the world vary with respect to airtightness requirements; in the United States, it is not uncommon to see specified performance requirements as tight as 0.10 cfm/ft^2. It is expected that these mandated improvements in air leakage resistance be achieved despite a declining pool of skilled trade labor asked to construct increasingly complex designs and details under stringent budgetary and time constraints. Notwithstanding these concerns, these stricter airtightness performance requirements are being realized, and recent data has shown Building Envelope Commissioning (BECx) to be an effective means of quality assurance that aids in the achievement of these more rigorous performance requirements.

This paper will discuss the Building Envelope Commissioning process, identifying the critical procedures of which it is comprised. Examples will be cited that demonstrate how, through the BECx plan, proactive steps are taken prior to and during the construction process to improve the completed building's air leakage performance through design concept consultation, peer review of construction documents, mock-up review and testing, and on-site inspections. Special consideration will be given to functional performance testing, and the more commonly used airtightness testing standards and procedures. Of particular interest are whole building airtightness tests and other 'end' tests that, while effective in measuring or verifying a building's air leakage rate, are often insufficient as the sole means of quality assurance in which they are often specified.

KEYWORDS

Commissioning, Building Envelope, Airtightness, Air Barrier, Testing, High-Performance

1. INTRODUCTION

The control of air movement across the building envelope is critical for three primary reasons (*Straube, 2007*): (a) The control of water vapor which, if permitted to infiltrate or exfiltrate through the building envelope and condense within the wall system, can lead to extensive damage to building components (*CMHC, 2001*); (b) Air quality and comfort, which includes reduction in air quality resulting from molds and mildews, the transmission of sound and odor from the exterior environment to the interior, and infiltration of cold air to the interior, and; (c) Energy savings, which simulation studies have shown can increase between 5% and 45% as building air leakage decreases, depending upon climate zone (*Zhivov et al., 2009*).

Energy efficiency in particular, through LEED enhanced commissioning, has been a driving force in the noticeable trend in building codes, standards, and individual project specifications towards the 'tightening' of buildings. While a whole-building air leakage characteristic of 0.40 cfm/ft^2 was once - and to some degree still is - considered 'tight', it is now common to see specified whole-building air leakage rates as low as 0.10 cfm/ft^2 under the same pressure parameters. The question becomes how these air leakage rates are achieved given a declining pool of skilled trade labor working under stringent project budgetary and time constraints with increasingly complex designs and details.

2. BUILDING ENVELOPE COMMISSIONING

Building Envelope Commissioning (BECx) is a systematic process to help ensure that the building envelope, as designed and installed, performs interactively according to the Basis-of-Design (BOD) and Owner's Project Requirements (OPR) through verification of the system's performance (*Knight et al., 2008*). ASTM E 2813 Standard Practice for Enclosure Commissioning which also references ASHRAE Guideline 0 and NIBS Guideline 3, identifies the tasks that should comprise a BECx program. While the precise tasks and frequency of those tasks may differ between individual projects, basic practice usually follows a defined series of steps that are categorized into five phases with the following goals (*de Sola et al., 2011*):

- Pre-Design Phase: Defining the OPR and developing a design concept which will satisfy the OPR given the expected external factors - including geography, climatic conditions, complexity of design, occupant usage, etc. – that may affect long-term durability and functionality of the building envelope.

- Design Phase: Reviewing design/contract documents for conformance with the OPR and BOD, and drafting the BECx specification, Functional Performance Testing (FPT) specification, and preliminary BECx Plan - including quantifiable performance metrics and quality assurance procedures – so that when the building is constructed compliant to said documents, the building envelope will function in a manner to satisfy the OPR.

- Pre-Construction Phase: Reviewing shop drawings and submittals pertinent to the building envelope, including scheduling and sequencing, material selection, quality control procedures, and assembly functionality verification. Construction of a performance mock-up will be reviewed and the mock-up tested to verify functionality of the assemblies. A Pre-Construction/Pre-Commissioning Meeting(s) will be conducted with all building envelope trades prior to the onset of construction to discuss project details, scheduling and sequencing, performance requirements, quality control and quality assurance protocols and materials compatibility.

- Construction Phase: Observing and documenting that the building is constructed in keeping with Codes, manufacturer's recommendations, construction documents, shop drawings, and good industry practice, with verification through functional performance testing.

- Operations and Maintenance Phase: Finalizing the BECx record, and compiling warranty and training documents with the intent that the building envelope remains functional over its expected life cycle.

While is it beyond the scope of this paper to discuss all of the individual tasks that comprise each phase of the BECx process, some of the tasks identified below provide results, analysis, or feedback which, when addressed, can significantly improve the air leakage characteristic of the completed building.

2.1. Design Review

During the Design Phase, project plans and specifications are reviewed by the Building Envelope Commissioning Agent (BECA) to assist in developing a fully functional building envelope. Individual details are reviewed to ensure compatibility within the confines of the system; this includes assessing the continuity of the functional layers of the building envelope through the wall plane and at all junctions between adjoining components or assemblies (including penetrations, fenestration integration, wall-to-grade beam, roof-to-wall junction, etc.), highlighting problematic details and design considerations with respect to constructability, and assessing the performance of the envelope in terms of water penetration resistance, air movement, vapor protection, thermal protection and drainage. Additionally, the overall building is evaluated to help ensure all critical or atypical conditions are details. Project specifications are reviewed to ensure the same, and that appropriate performance requirements, quality control, and quality assurance measures are in place.

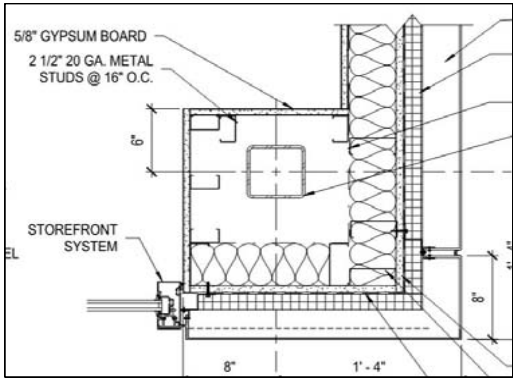

Figure 1: Wall-to-storefront system detail,
depicting a misalignment between the fenestration and opaque wall.

As they pertain specifically to airtightness, most commonly found issues relate either to discontinuity in the plane of airtightness at junctions between adjoining assemblies, non-constructability of details or unrepaired damage to the air barrier due to the sequencing of component installation, and misplacement of the air barrier relative to the other functional planes. The detail in Figure 1 depicts the junction of a wall-to-storefront. The primary sealant at the fenestration perimeter needs to be in place at the laboratory tested, warrantable location; typically, the exterior of the frame for storefront systems. Fenestrations are often misaligned with the opaque wall such that they are extended to the exterior, resulting in a disconnection between the fenestration and the opaque wall and creating a discontinuity in the air barrier.

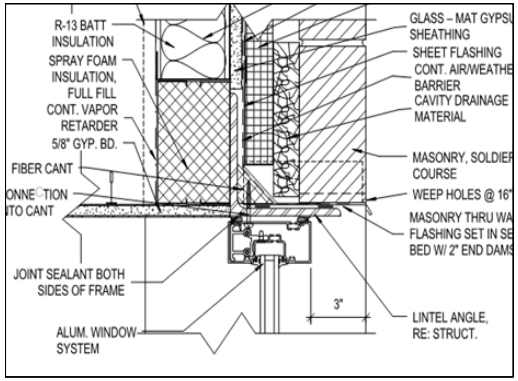

Figure 2: Sequence of work will lead
to blind penetrations being made through the air barrier membrane.

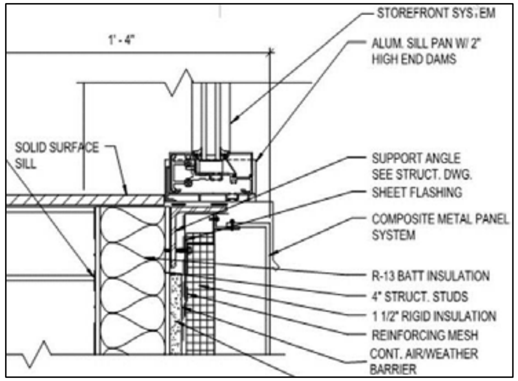

Figure 3: Flashing interrupts the air barrier.

In Figure 2, the sequence of work is such that blind penetrations through the air barrier are made, which often go unsealed. In Figure 3, the flashing interrupts the air barrier instead of the air barrier being installed continuously and flashing subsequently stripped in. If each of these details is typical on a given project, the consequence of leakage at any one of the details is amplified due to the frequency of occurrence. In some cases, only one poor detail can be enough to prevent a successful whole building airtightness test result even if the remainder of the facility is designed and built effectively airtight.

2.2. Mock-ups

Knight, Runkle and Boyle (*Knight et al., 2009*) provide a treatise on how to best utilize mock-ups within the BECx process. Mock-ups built using the exact construction techniques, materials, and technicians that will be used on a project provide the project team an opportunity to identify and resolve potential areas of conflict prior to the commencement of construction and to verify, through inspection and performance testing, that design details of assemblies/systems will function per the design intent given the skill level of the installers.

Requirements for the construction and testing of mock-ups are usually defined in Division 1 of the Project Specifications in both the BECx specification and FPT specification. The BECA typically assists the designer in developing a mock-up construction and testing protocol, identifying the specific components to be included, the number of mock-ups, performance requirements, configurations, test parameters, and inspection/documentation requirements. Other requirements peculiar to a particular component or assembly are included in the corresponding sections of the specifications.

While mock-ups can be specified for any building envelope component or assembly, functional performance testing of building envelope mock-ups primarily refers to the testing of window/curtain wall assemblies (and other fenestrations), the opaque wall system or roofing to assess or measure air leakage, water penetration resistance, vapor diffusion, and thermal performance. Common on-site test methods for airtightness testing are described below.

2.3 Visual Verification

Throughout the construction process, the BECA should perform visual examinations of the air barrier system to identify deficiencies in the installation that may affect the airtightness (or other properties) of the system. While emphasis should be on the initial stages of installation, reviews should continue throughout to ensure that the quality standard remains consistent. This includes not only the air barrier and all components that comprise the air barrier system but also, where applicable, ensuring that the substrates onto which they will be installed are acceptable (i.e. dry, clean, properly primed). Identifying deficiencies through visual examination helps prevent overusing the testing budget on samples that are obviously non-compliant. While minor discrepancies in installation can often be easily addressed if detected early, major or repeat deficiencies may be an indication that the workforce does not possess the requisite skill level or experience to install the products.

Types of 'gaps' in the system that the inspector should be aware include (Knight et al, 2004):

- 'Flutes' (long, narrow passageways that run from open membrane seams through to midfield areas of the membrane).
- Unsealed, non-airtight penetrations through the membrane. Sometimes, leaky penetrations may be obvious to the eye, but on most occasions, some form of airtightness testing will have to be conducted in order to determine whether or not the penetration has been sealed adequately.
- Unrepaired damage to the air barrier from other trades.
- De-bonded areas of membrane, especially around penetrations, window frames and other intricate or difficult to construct details.
- Discontinuities in the plane of airtightness with adjacent systems.

2.4 Airtightness Testing

Most associate building envelope airtightness testing as testing of the air barrier membrane. But many other components are installed continuous to the air barrier membrane which function as a part of the plane of airtightness. Several test methods are commonly used during the BECx process to evaluate or measure the airtightness of components, assemblies, and systems. Some of these test methods are more complex and best suited for testing mock-ups and on a limited basis during work-in-progress construction. Others are simple tests that can be performed quickly and without major disruption to the construction schedule and therefore practical for use throughout construction. Yet others are end tests that are conducted upon building completion.

The airtightness of fenestrations and/or opaque wall systems can be quantifiably measured in-situ in general accordance with ASTM E 783. To conduct this test, a test chamber – usually rigid but sometimes polyethylene sheeting – is constructed around the test sample and is pressurized and/or depressurized in order to measure the rate of air flow through the test area. Often, the test specimen consists of multiple assemblies, for example, window unit and adjacent surrounding opaque wall, where the allowable air leakage rates of the two assemblies are different. Here, a rigid chamber is often most effective, as it can be more successful in dealing with extraneous air leakage and other inherent characteristics of the polyethylene which may influence test results. This, in turn, results in a higher confidence in the numerical data obtained during the test (*Knight et al., 2011*).

ASTM test method E1186 contains numerous qualitative test procedures that can be performed relatively quickly and with minimal disruption to the construction process. Method 4.2.7 can be used to evaluate the airtightness of air barrier membrane seams, overlaps and T-joints, and penetrations through the membrane (i.e. masonry ties, through-wall piping, and fastener penetrations) through pressurization of a test chamber in conjunction with leak detection solution. Methods 4.2.2 and 4.2.6 involve the pressurization/depressurization of a zone (i.e. the room in which the test sample is housed) or a test chamber installed around the test sample in conjunction with smoke generators to provide a visual depiction of the air leakage through the test area. These 'smoke' tests are effective in pinpointing the precise location of air infiltration or exfiltration, and are often used in combination with quantitative tests methods to provide a more complete diagnosis of component or assembly airtightness.

3. WHOLE BUILDING QUANTITATIVE AIRTIGHTNESS TESTING

As its name implies, whole building airtightness testing is used to assess the air leakage characteristic of a completed building. The most common methods, ASTM E 779 and ASTM

E 1827, rely on quantitative measurement techniques utilizing fan pressurization or an orifice blower door in conjunction with computer software. As it relates to testing of new or retrofit projects for compliance to specification, typically, the pressure boundary area of the building – including the total surface area of the "six-sided" box which is the roof/ceiling, walls and ground floor – must have a total air leakage rate not to exceed a prescribed amount. For example, a single-story building with a flat roof measuring 200 feet long by 100 feet deep by 22 feet high, with an airtightness performance requirement of 0.25 cfm/ft^2 at 0.3 in. H_20, is allowed no greater than 13,300 cfm of air leakage (*Brandt, 2012*).

The benefits of whole building airtightness testing are numerous: for compliance, it provides a means of determining whether a building's air leakage characteristic meets prevailing codes and standards; as a quality tool, it assesses the effectiveness of the air barrier system; as an analysis tool, comparisons of airtightness measurements pre- and post-retrofit can be drawn; as a maintenance tool, results at different points in time post-construction can be compared to detect changes in the effectiveness of its air barrier system over time.

3.1. Quantitative Airtightness Testing is Not Commissioning

Whole building airtightness testing is not commissioning, nor should it be used as the sole means of quality assurance on a given project. While it can be an effective end test to verify the quality of the building as designed and constructed - and therefore an effective tool *as a part of the commissioning process* - it does not provide a means of quality assurance to help ensure that specified performance requirements are achieved in and of itself; that is, there is not a 'preventative' component to the test. Any deficiencies or malfunctions resulting in an air leakage characteristic greater than the allowable are only detected upon completion of the entire system. This poses several problems: (a) extensive remedial work which may be both costly and time-consuming may be required and may have been preventable had the deficiencies been discovered earlier; (b) the air barrier may be 'non-maintainable'; in other words, the air barrier may not be exposed and accessing that air barrier for the purposes of remediation may not be practical; (c) the test result provides a quantified measurement of the building's air leakage characteristic, but it does not identify where or what the breaches in the air barrier system are that are causing the elevated air leakage rates, and; (d) the measured air leakage rate for the entire building may be below the allowable, but individual components or assemblies comprising the air barrier system may have air leakage rates greater than the allowable for that given component or assembly.

Whole building airtightness testing is therefore best utilized in conjunction with other, qualitative methods when used as a tool to evaluate a building's air leakage characteristic. The other factor to consider is that airtightness testing is just that – it tests for air leakage. It does not consider other factors that may affect the performance, functionality, and durability of the building envelope system, including water penetration resistance, drainage, vapour protection, thermal performance, and acoustics.

4. CASE STUDIES

4.1 Dixie State College

The Holland Centennial Commons building at Dixie State College was a new five-story building to include a library, classrooms, office space and a data center, and requiring a low tolerance for air infiltration. A BECx protocol was established in order to help attain a whole building air leakage rate no greater than 0.15 cfm/ft^2. Several challenges were discovered and addressed during the BECx process that, left undiscovered, may have compromised the functionality of the air barrier system:

- Portions of the opaque wall consisted of masonry and metal panel cladding over insulation, air barrier, and exterior sheathing, with adjacent opaque wall sections consisting of GFRC cladding with an insulated metal back pan. Transitioning between these opaque wall assemblies and incorporating the numerous curtain wall and storefront fenestration openings presented a significant challenge for the design and construction teams. For instance, the interfaces at the GFRC panels (which were intended to work as a unitized panel with a metal back pan that functioned as the primary air, water and vapor barrier) were originally designed with a silicone sheet set in sealant at the metal back pan. Due to "true" geometry of the metal back pans, it was anticipated that achieving a continuous and robust detail using the silicone sheet would be difficult. Instead, the project team decided to use sprayed-in-place polyurethane foam (SPF) at transitions and panel-to-panel joints to ease the installation of this seal.

- Many of the subcontractors had challenges coordinating with the other trades, especially trying to show a continuous air barrier on their shop drawings. To address these concerns, weekly coordination meetings with trades and manufacturers were conducted, and air barrier coordination drawings were developed which were believed to be critical in achieving sufficient system airtightness. Building Information Modelling (BIM) was also used extensively to identify key transitions and details for air barrier continuity.

- Testing of a stand-alone mock-up of the wall assembly prior to the onset of construction identified numerous breaches that were contributing to an excessive rate of air infiltration – critical points that would require greater diligence during installation and subsequent field inspection and testing. The contractor's proactive response to these items, and other field inspection punch list items such as discontinuities in the air barrier, sealants or SPF, led to the continual improvement in airtightness as verified through functional performance testing throughout the remainder of the construction process.

Upon completion of the project, the building air leakage rate was measured at 0.07 cfm/ft^2.

4.2 Weber State University, Residential Life Phase II – Building 2

Weber State University Residential Life Phase II – Building 2 was an 81,000 square foot new construction project with a specified whole building air leakage rate of 0.10 cfm/ft^2. Several issues were identified during the design review process: (1) The storefront windows were not interfaced with the air barrier; (2) The roof vapor barrier and roof membrane were not interfaced with the air barrier at the exterior wall, and; (3) The air barrier was not continuous at soffit locations.

A stand-alone mock-up of the air barrier system was constructed, an enclosure consisting of a four-sided 'box' with roofing and five punched openings each representing a type to be installed on the building. The mock-up achieved an air leakage rate of 0.02 cfm/ft^2, well below specification, which verified that the building, all things being equal, should be able to achieve the specified airtightness characteristic. Additionally, the mock-up set the benchmark for future installations on the project; as an example, all air barrier membrane overlaps on the mock-up were sealed. On-site reviews of the work-in-progress revealed that the vapor permeable air barrier was not adhering sufficiently at overlaps due to a low amount of adhesive, and were peeling back. To keep consistent with the mock-up, all membrane overlaps throughout the building were sealed.

Upon completion of the project, the building air leakage rate was measured at 0.099 cfm/ft^2.

5. CONCLUSIONS

Energy and environmental codes continue to evolve, the prevalence of "green" building continues to intensify, and building performance requirements are becoming increasingly stringent, especially as they pertain to building airtightness. Given the resources that can be saved by achieving a functional building envelope and a reduction in energy consumption, effective quality assurance mechanisms must be in place during new and retrofit building construction projects to help minimize uncontrolled air leakage through the building envelope, a critical factor that also affects not only energy consumption, but also building durability and occupant comfort.

Building envelope commissioning has proven to be an effective process in reducing building envelope leakage and achieving a high-performance building envelope. The progressively stringent specified airtightness requirements, which are verified via whole-building airtightness testing, are often significantly exceeded by well-commissioned building. Through involvement during all phases of the project, building envelope commissioning can detect or identify design errors, material incompatibilities, and installation deficiencies sufficiently early so to prevent costly remediations and delays to project completion. And while the BECx program can be tailored to suit the parameters of any particular project, and it may tempting to limit the program to isolated activities, it is imperative to include all key tasks in the process to best reap the quality assurance benefits that it provides.

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Commissioning of Exterior Building Envelopes of Large Buildings for Air Leakage and Resultant Moisture Accumulation using Infrared Thermography and Other Diagnostic Tools

Mario D. Gonçalves, Patenaude-Trempe [1]

Abstract

Infrared thermography is used extensively in the building construction industry as a quality control and forensic tool to assess air leakage performance and the presence of moisture in exterior wall assemblies. Infrared thermography applied to large buildings however requires a good building science background and understanding of the dynamic forces which act on the building envelope. This paper focuses on diagnosing building envelope anomalies in large buildings using infrared thermography and other diagnostic tools.

The application of infrared thermography to assess building envelope anomalies in large buildings is presented in this paper through several practical case study examples. All the case study examples are from buildings located in the north-eastern Canada region. Given the harsh winter conditions and significant temperature variations throughout the year, air leakage and moisture ingress within exterior wall assemblies is a common source of building envelope failures in large buildings. Canadian building codes and construction methods have consequently evolved considerably over the past several years in order to address these issues.

Building science principles are discussed in this paper in order to highlight the basic fundamental principals pertinent to using infrared thermography as a diagnostic tool to assess building envelope anomalies in large buildings. The use of other diagnostic tools, in conjunction with infrared thermography, such as high power blower doors specifically designed for large buildings and portable high output smoke generators, are also discussed.

The primary objective of this paper is to provide an increased level of knowledge to the building community for an improved awareness of the benefits and limitations of using infrared thermography and other diagnostic tools applied to large buildings.

Keywords: building envelope, infrared thermography, air leakage, large buildings.

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Commissioning of Exterior Building Envelopes of Large Buildings for Air Leakage and Resultant Moisture Accumulation using Infrared Thermography and Other Diagnostic Tools

Mario D. Gonçalves, Patenaude-Trempe

Introduction

Infrared thermography applied to large buildings is an excellent tool to help identify and locate air leakage and the presence of moisture in exterior wall assemblies. Infrared thermography alone however will **not identify the cause or source** of any given anomaly. In fact, what appears to be an anomaly based on thermographic imaging alone may not necessarily be a problem at all (as illustrated in Figures 1, 2 and 3 – anomaly noted on exterior is actually an interior heat source). Proper interpretation based on a thorough assessment of the building being evaluated as well as a solid understanding of building science principles and the dynamic forces which act on the building envelope are of utmost importance.

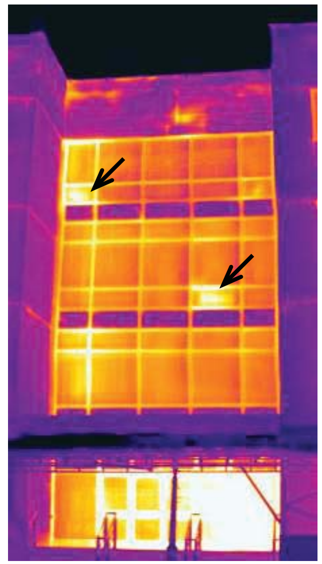

Figure 1: What may appear to be a thermal anomaly in the curtain wall assembly is visible in this exterior thermogram (building under positive pressure).

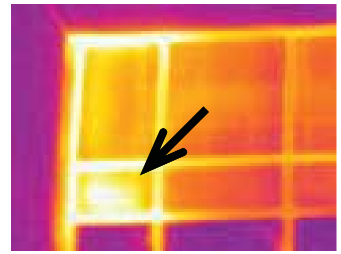

Figure 2: Close-up view of figure 1.

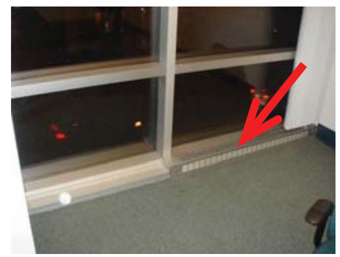

Figure 3: An interior heat source located directly against the interior side of the CW assembly yields misleading results.

The primary objective of this paper is to provide an increased level of knowledge (and not a detailed guide) to the building community for an improved awareness of the benefits and limitations of using infrared thermography and other diagnostic tools applied to large buildings.

Principals

Infrared thermography is a technology that allows infrared or heat radiation to be transformed into a visible image. Combined with other diagnostic tools, infrared thermography can be used to assess the overall air leakage and thermal performance of a building envelope. Heat loss by conduction (Figure 4), convection (Figure 5) and air leakage (Figure 6) as well as the presence of moisture in an exterior wall assembly (Figure 7) can be detected by use of infrared thermography. Each of these different heat and moisture transfers produces different thermal expressions and need to be interpreted accordingly. Strict adherence to the necessary environmental conditions for each type of building inspection is required to ensure suitable results from the thermographic inspection. An inspection carried out under unsuitable environmental conditions will provide no results at best and erroneous results at worst.

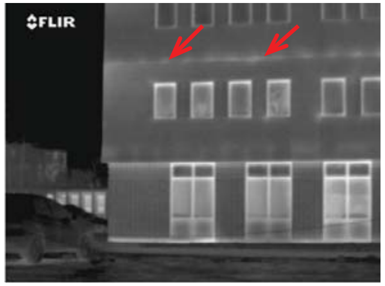

Figure 4: Conductive heat loss at masonry structural shelf angle support (building under positive pressure).

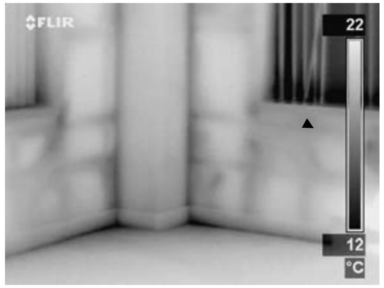

Figure 5: Convective heat loss pattern noted below windows (building under negative pressure).

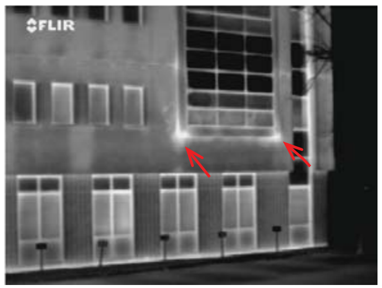

Figure 6: Air leakage noted at the bottom corners of the curtain wall assembly (building under positive pressure).

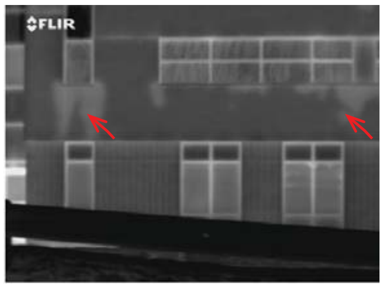

Figure 7: Moisture noted below the windows in the exterior masonry wall assembly (building under positive pressure).

Infrared cameras for building applications are available in a wide variety of models and price ranges. Apart from using the proper camera and lens for a given application, the qualifications of the person operating the camera and performing the inspection is the most determining factor in obtaining an accurate assessment of the performance of the building envelope. An excellent camera used with the wrong settings and under inappropriate environmental conditions will ultimately yield misleading and inaccurate results. Reporting results based on an inaccurate assessment will have an important impact on the subsequent decision making process. In certain instances, what appears to be an anomaly may in fact not be a problem at all and an inaccurate assessment may result in needlessly recommending extensive remedial measures. In other instances, an inaccurate assessment may result in important anomalies being overlooked. When dealing with large buildings, the inaccurate assessment of a given deficiency can be repeated several times throughout the building and may as a result imply serious implications.

A prerequisite for any thermographer dealing with buildings, particularly large buildings, is a thorough understanding of building science and construction. A thermographer's level of expertise will vary considerably depending on his fields of application. An experienced roofing thermographer, for example, does not necessarily have the necessary experience to undertake a building envelope thermograhic assessment, just like a building thermographer is not necessary qualified to undertake electrical inspections. Another distinction is the difference between home inspections and large building assessments which require different qualifications and often different equipment and diagnostic tools.

The following consists of a non-exhaustive list of some primary basics which apply to the assessment of the building envelope of large buildings:

1. Camera and settings
The infrared camera shall have the appropriate wave length, thermal and spatial resolution, level of temperature accuracy and temperature operation range. The camera shall also be mounted with the appropriate lens depending on the viewing distance (typically, a minimum of two lenses are required; a telephoto lens for exterior applications and a wide angle lens for interior and exterior applications). The ability to view images in either color or monochrome is an added feature which may facilitate interpretation in certain conditions.

The thermographer must have an in-depth knowledge of the use, operation and limitations of the specific camera he is using. The camera's emissivity, viewing distance, temperature and range as well as relative humidity settings must be calibrated and set accordingly before each inspection. The thermographer must also ensure that he is positioned at a proper viewing angle (often access to neighboring roofs or motorized lift equipment is required when looking at the exterior of tall buildings). Given the complexity and scale of assessing large buildings, in addition to recording infrared still images, the entire infrared inspection should be videotaped and reviewed in detail after the inspection as part of the reporting process. Actual photographs of the areas inspected should also be recorded and referenced to the corresponding thermograms (Figures 8 and 9).

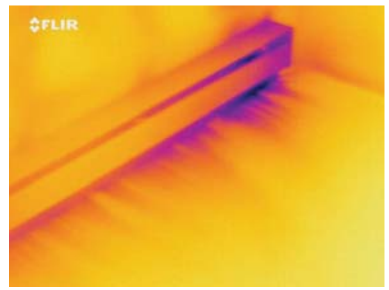

Figure 8: Air leakage noted below electric base board (building under negative pressure).

Figure 9: Actual photograph of corresponding area.

2. Exterior environmental conditions
The exterior environmental conditions play an important role on the quality and accuracy of the infrared inspection assessment. Precipitation in the form of rain or snow will create an obstacle between the infrared camera and the exterior surfaces being inspected (exterior thermographic inspections shall not be undertaken under these conditions). Depending on the type of building envelope enclosure (masonry cladding, solid masonry or curtain wall for example), the exterior ambient temperature and temperature differential across the wall assembly, time lag after sunset, time lag after last rainfall as well as wind intensity and direction will all have an important impact on the infrared results. In the case of a solid masonry wall for example, when assessing air leakage, the temperature differential between the interior and exterior of the building must be much greater than in the case of a metal and glass curtain wall. However, wind conditions are much more critical when assessing air leakage of a metal and glass curtain wall (due to its limited capacity for heat retention) compared to a solid masonry wall assembly.

3. Interior environmental conditions
Much like the exterior environmental conditions, the interior environmental conditions also play an important role on the quality and accuracy of the infrared inspection assessment. In occupied buildings, the interior environmental conditions such as temperature and relative humidity are typically maintained at the building's normal operating conditions. Building pressurization is however by far the most important and critical factor which must be monitored and controlled when undertaking a building envelope thermographic assessment. Depending on the type of inspection (exterior or interior), the type of assessment (air leakage assessment, moisture detection or thermal evaluation) as well as the wall composition, different building pressurization conditions will be required (positive or negative pressure at different intensities and duration).

Ideally, building pressurization is controlled by the building mechanical systems. This is accomplished by controlling the supply air intake and exhaust (supply open and exhaust closed for positive interior pressure, supply closed and exhaust open for negative interior pressure). This is however not always possible depending on the building's mechanical system and their limitations. With the exception of the common corridors, residential condominium buildings for example are typically not equipped with a centralized mechanical system. In other instances, buildings with older mechanical systems are often limited in terms of control as well as operating temperatures (fully opening the supply air intake is often not possible during extreme cold conditions). Under these circumstances, the use of portable high-power pressurization equipment is required to create the necessary pressure conditions (Figures 10 and 11).


Figure 10: High power three-fan portable building pressurization system installation.


Figure 11: Monitoring panel equipped with remote weather station receiver and digital micro manometers.

Depending on the size and level of air-tightness of the building, it is typically possible to pressurize either the entire building, several floors at a time or individual units using a portable three to six high-power fan system. The resulting pressure differential is measured and controlled by using calibrated digital micro manometers. It is also important to monitor the exterior and interior temperature as well as the wind intensity and direction (this can be done by using a calibrated portable remote weather station).

4. Inspection process
A thorough inspection process must be well established and rigorously followed to ensure consistent and reliable results. The inspection process should proceed in accordance with industry recognized standards. The principal references are listed below:

- CAN/CGSB 149-GP-2MP: Manual for Thermographic Analysis of Building Enclosures;
- ASTM C1060: Standard Practice for Thermographic Inspection of Insulation Installations in Enveloppe Cavities of Frame Buildings;
- ANSI-ASHRAE 101: Application of Infrared Sensing Devices to the Assessment of Building Heat Loss Characteristics;
- ASTM E1186: Standard Practice for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems;
- ASTM E779: Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.

In addition to the references listed above, a generic specifications format developed in Canada by the National Master Specification (NMS) will be introducing four new sections relating to specifying inspection services for building envelopes, roof assemblies, electrical and mechanical systems. These generic specifications are intended to be used for bid projects for large buildings in both the private and public sector. The NMS sections will define thermographic and other equipment requirements, thermographic equipment operators and report authors qualifications, general and specific inspection procedures as well as specific submittal and report requirements for the different type of assessments and inspection. Specifiers will be able to use the generic format as a template to add or delete items required for their specific project.

5. Validation
An important and often neglected step in the assessment process consists in identifying and validating the causes of the observations noted with the infrared camera. The cause of certain anomalies may be obvious to an experienced thermographer and should be backed at the very least by referencing detail drawings (Figure 12). When further investigation is required, exterior or interior dismantling (Figure 13) and/or smoke testing should be undertaken (Figures 14 and 15). In order to adequately assess the performance of the building envelope of large buildings and provide conclusions and recommendations forming part of the thermographic analysis process, technical or professional training in building envelope design and hygrothermal performance coupled with pertinent field experience dealing with large buildings is essential.

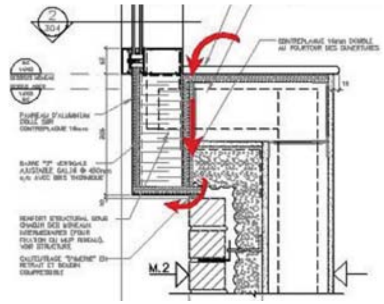
Figure 12: Detail drawing illustrating air leakage path.


Figure 13: Dismantlement of interior finishes at window head reveals direct air leakage path.


Figure 14: Excessive smoke exfiltration below wall assembly.


Figure 15: Excessive smoke exfiltration at curtain wall weep hole locations.

Summary and Conclusion

Infrared thermography is a technology that allows infrared or heat radiation to be transformed into a visible image. Combined with other diagnostic tools and when undertaken in strict adherence to the necessary environmental conditions, infrared thermography applied to large buildings is an excellent tool to help identify and locate air leakage and the presence of moisture in exterior wall assemblies. Given the complexity and scale of assessing large buildings, in addition to recording infrared still images, the entire infrared inspection should be videotaped and reviewed in detail after the inspection as part of the reporting process. Infrared thermography alone will **not identify the cause or source** of any given anomaly. Proper interpretation based on a thorough assessment of the building being evaluated as well as a solid understanding of building science principles and the dynamic forces which act on the building envelope are of utmost importance.

The thermographer must have an in-depth knowledge of the use, operation and limitations of the specific camera he is using. Apart from using the proper infrared camera and lens for a given application, the qualifications of the person operating the camera and performing the inspection is the most determining factor in obtaining an accurate assessment of the performance of the building envelope. A thorough inspection process in accordance with industry recognized standards must be well established and rigorously followed to ensure consistent and reliable results. Identifying and validating the causes of the observations noted with the infrared camera is an important and often neglected step in the assessment process. Observations and recommendations should be backed by referencing detail drawings and conducting further investigations consisting of exterior or interior dismantling combined with smoke testing on an as required basis. In order to adequately assess the performance of the building envelope of large buildings and provide conclusions and recommendations forming part of the thermographic analysis process, technical or professional training in building envelope design and hygrothermal performance coupled with pertinent field experience dealing with large buildings is essential.

References and Additional Reading

1. National Research Council Canada, ''CBD-229. Thermographic Identification of Building Enclosure Effects and Deficiencies'', December 1983.
2. Colantionio, T. and McIntosh G.B., ''Pressurization Effects on Thermal Images of Building Envelopes'', Thermalsense XI 1989.
3. Colantonio, T, ''Infrared Thermographic Investigation Procedures for Four Different Types of Generic Exterior Wall Assemblies'', Thermalsense XXI 1999.
4. Snell J. and Spring R., ''Nondestructive Testing of Building Envelope Systems using Infrared Thermography'' InfraMation 2002.

Case Study Examples

Three case study examples are presented below in order to illustrate the type of anomalies commonly encountered during a thermographic assessment of the building envelope of large buildings.

Case study example no. 1
In this example, complaints of flies entering the building at the beginning of the first year heating season were reported by the building owner. A thermographic analysis of the building envelope was undertaken during the heating season. The building was pressurized by means of the building's mechanical systems and excessive air-leakage was noted at the top of several of the curtain wall assemblies (Figures 16 to 20).

Figure 16: Actual photograph of one of the curtain wall sections inspected for air leakage.

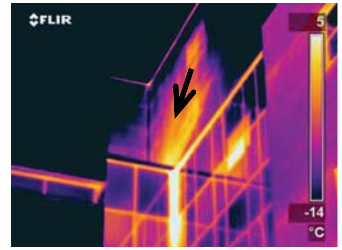

Figure 17: Thermogram of the top portion of the CW assembly in figure 16.

Figure 18: Subsequent smoke testing undertaken to determine and validate air leakage sources.

Figure 19: Excessive smoke exfiltration was clearly visible at the top portion of the CW assembly.

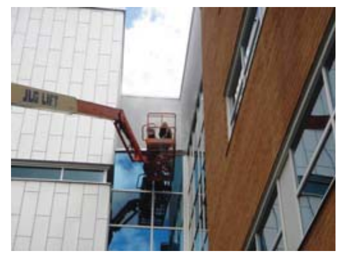

Figure 20: Dismantlement of the top portion of the CW assembly was undertaken to establish appropriate corrective measures.

Case study example no. 2

In this example, a thermographic analysis of the vertical building envelope was undertaken as part of the commissioning process of this new building construction. Several anomalies were identified, including excessive air leakage via the metal paneling below one of the curtain wall assemblies (Figures 21 to 24) and excessive moisture accumulation in the exterior masonry of part of the building (Figures 25 and 26).

Figure 21: Actual photograph of one of the curtain wall sections inspected.

Figure 22: Thermogram of the overall CW assembly in figure 21.

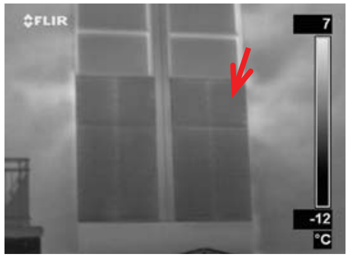

Figure 23: Thermogram of bottom CW section with building under negative pressure.

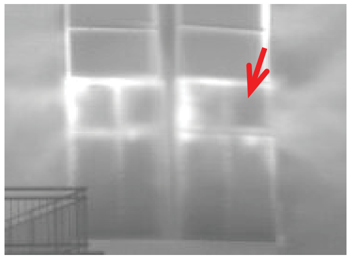

Figure 24: Thermogram of bottom CW section with building under positive pressure.

Figure 25: Actual photograph of one of the masonry wall sections inspected.

Figure 26: A large portion of the masonry wall assembly in figure 25 noted to contain moisture.

Case study example no. 3

The interface detail between two different wall assemblies is a common source of air leakage and water infiltration problems. In these two examples, a thermographic analysis revealed excessive air leakage at the curtain wall interface with the adjacent masonry, requiring extensive remedial measures to correct.

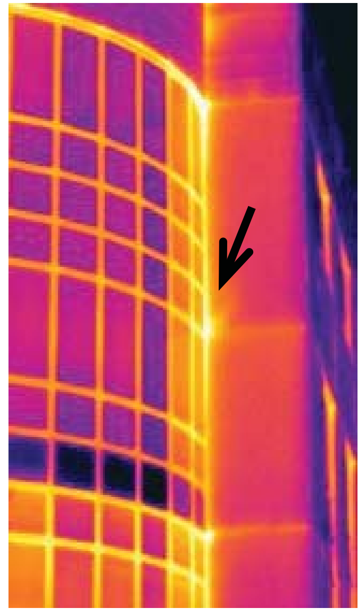

Figure 27: First example thermogram of interface of curtain wall and masonry wall assembly.

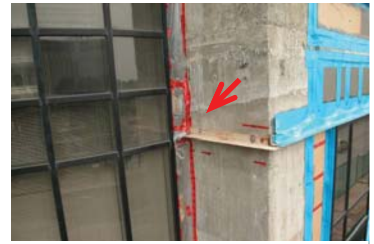

Figure 28: Overall view of the interface detail in figure 27 after removing the adjacent masonry.

Figure 29: Close-up view of figure 28 - no air seal at the interface detail (the polyethylene sheet was installed as a temporary measure after removing the masonry).

Figure 30: Second example actual photograph of inspected curtain wall and masonry assembly.

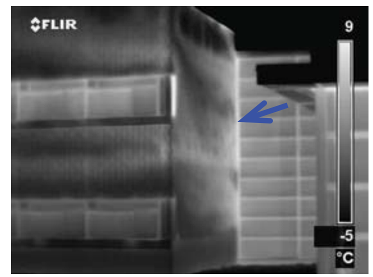

Figure 31: Thermogram reveals excessive air leakage at interface of curtain wall and masonry assembly shown in figure 30. Further investigation confirmed no air seal at the interface detail.

PAPER TITLE
An Airtight Shell for Effective Ducts

MAIN AUTHOR
Tom Schneider

OTHER AUTHORS
Ron Tatley

ABSTRACT

Certainly ductwork can be made airtight and these airtight ducts would be more efficient than leaking ductwork. The expected gaskets, sealants and tape, correct dimensions, proper materials and installation procedures are all mentioned in literature, instructions, bid packages and specifications. The difference between what is expected and the realities of a job-site are the gaps that leak air and energy.

HVAC systems are made not by robots in a factory or laboratory environment, but are often pieced together in the wind and rain late Friday afternoon with little or no supervision or inspection. It would be safe to assume the ducts will leak.

Tracing leaks is expensive and time consuming even with the latest in smoke, light and sound detecting methods and remedying these leaks is even more expensive in spite of remote controlled spray cans of sealant equipped with IR cameras.

At some point in the future it may be worth measuring, tracing and repairing these leaks in ductwork to maximize an efficient HVAC system.

In the meantime the elephant in the room is the airtightness of the building envelope, the most important aspect of the HVAC system, and until the building envelope is airtight for the duration of the life of the building, duct leaks are no more than a distraction.

A leaking building envelope is like a camera body that leaks light, nothing that goes on inside will be as important as fixing the leak. What causes these leaks will be addressed in this paper as well as some ideas on how to minimise them.

Leaks take place at points of differential pressure, where air flows from high pressure to low pressure. Weather or atmospheric conditions create pressures and blower motors in HVAC systems create pressures. These two forces must be separated by an airtight building envelope for the accurate measurements the HVAC system relies on to remain efficient and high performing.

More on how a leaking building envelope affects the performance of the HVAC system will be addressed in this paper.

“We have not because we ask not”. We will look at new ideas on what constitutes an air-barrier, what it should be tested to and how it affects the ductwork in an energy efficient future.

PAPER TITLE
Thought Experiments for Evaluating Building Air Leakage Test Procedures

MAIN AUTHOR
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OTHER AUTHORS
none

ABSTRACT

Field tests of building air leakage by fan pressurization can be difficult to analyse because of factors such as wind, stack effect, complex building configuration, etc. These factors make It difficult to run controlled experiments to evaluate the influence of variations in test procedures under all the possible test conditions. One alternative is to conduct ‘thought experiments’ where all of the variables can be controlled in a few simple situations.

This paper attempts to construct thought experiments defining simplified models of the physics of building pressurization air leakage tests in the presence of wind and stack effect. Calculations from these thought experiments may be useful in understanding the consequences of various testing options, and may help guide the development of more accurate testing standards. These calculations may also be useful in suggesting experimental tests of alternative test procedures, and in suggesting alternative statistical analysis. Of course this document only constitutes a first step in this thought experiment development, but it may show the utility of this approach.

Some of the aspects of building air leakage testing that can be explored with simple models of test physics include:

1. location of the outside pressure tap and compensation for outside pressure bias
2. comparison of pressurization only tests, depressurization only tests, and averaging both pressurization and depressurization tests,
3. evaluation of wind errors and flow reversal as a function of wind speed
4. evaluation of stack effect errors and flow reversal as a function of temperature

PAPER TITLE

Optimizing Outside Pressure Taps To Reduce Wind Induced Pressure Errors

MAIN AUTHOR

David Saum, Infiltec

OTHER AUTHORS

none

ABSTRACT

Airtightness tests require an outside pressure tap to determine the differential pressure across the building envelope. Unfortunately the technology of this pressure tap has changed little since the first airtightness tests were done. This paper looks at the pressure averaging techniques that have been developed for infrasound monitoring of nuclear test ban treaty verification, and attempts to apply them to building airtightness testing. A test procedure is developed and a wide variety of outside pressure taps are evaluated. Recommendations for improved outside pressure taps are made.

Friday 19 April 2013

08:00-09:30 Session 6: Large and multi-family buildings

1. How Leaky is your Building? Case Studies of Two Whole-Building Air Leakage Tests, Jason S. Der Ananian, Simpson Gumpertz & Heger, USA
2. Measuring the Air Tightness of Mid and High Rise Non-Residential Buildings. Wagdy Anis, WJE, USA.
3. Large Building Air Leakage Measurement – What Has Been Done and What Is Possible, Denali Jones, Retrotec, USA
4. Estimates of Uncertainty in multi-zone air leakage measurements, Erin Hult, LBNL, USA
5. Air tightness of buildings in Poland, Michal Szymanski, Poznan University of Technology, Poland

Short Presentation

6. *Large public buildings air tightness in Poland, Radoslaw Gorzenski, Poznan University of Technology, Poland*

HOW LEAKY IS YOUR BUILDING? CASE STUDIES OF TWO WHOLE-BUILDING AIR LEAKAGE TESTS

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ABSTRACT

Air leakage testing is used to qualitatively identify or quantitatively measure air leakage through the building enclosure. The testing process involves pressurizing a space (e.g., a room in an apartment complex, building floor, whole building, etc.) with blower door fans to create a pressure differential across the building enclosure. For qualitative tests, tracer smoke or an IR camera are some of the available diagnostic tools used to detect air leakage paths through the envelope. Quantitative tests require experimental measurement of air leakage through the envelope; the results are used to refine energy models for retrofit projects, improve mechanical system operation or reduce system size, or demonstrate compliance with energy codes or project specifications for new construction.

The need for quantitative testing continues to increase as energy code requirements for airtightness become stricter and designers include airtightness targets for specialty high humidity buildings such as pools and museums. The 2012 International Energy Conservation Code (IECC) is the first ICC code to require a dedicated air barrier for the building enclosure; the 2012 IECC allows whole building air leakage testing to demonstrate air barrier compliance. Although only four states have currently adopted the 2012 IECC, states including New York and Washington State amended their state energy codes to specify maximum whole building air leakage rates and allow or require whole building air leakage testing to demonstrate energy code compliance.

This paper will briefly summarize building code requirements and industry standards and provide quantitative air testing case studies of a new art museum and an existing high-rise residential tower to illustrate air testing execution and results. This paper will also demonstrate how air leakage testing can be used as a diagnostic and forensic tool.

KEYWORDS

Quantitative air testing, whole-building air testing, commercial air testing, 2012 IECC

1. INTRODUCTION

Code officials and industry agencies in the United States are realizing the need for tighter building air barriers, and building codes are becoming stricter with respect to air barrier requirements in buildings. Continuous air barriers limit uncontrolled air leakage through building enclosures, thereby reducing building energy consumption, allowing more-precise control of building interior conditions, and preventing premature failure of building enclosure cladding systems in humidified buildings.

The 2012 International Code Council (ICC) codes, some state building codes, and several government agencies are beginning to require quantitative field testing to measure the air leakage rate in whole-buildings to demonstrate compliance with predefined target air leakage rates. Building codes recognize that it is not possible to determine the whole-building air leakage rate analytically or through computer simulation due to building complexity, the wide range of air barrier materials, vast differences in air barrier installation workmanship and quality, and a general lack of data for commercial building airtightness. Quantitative air test results are not only used to demonstrate compliance with energy codes or project specifications for new construction but also to refine energy models for retrofit projects, improve mechanical system operation, and reduce system size. Due to the high cost and disruption associated with repairing air barrier breaches postconstruction, air leakage testing is a useful and efficient diagnostic tool to identify and repair locations of air barrier breaches during construction.

2. PROBLEMS WITH DISCONTINUOUS AIR BARRIERS

In general, the air barrier system consists of a combination of materials joined in an airtight manner to restrict air infiltration or exfiltration through the building enclosure. An air barrier must be able to resist pressure differentials without tearing or displacement. Because air barriers are often membranes or, in some instances, sheet goods, they must be well attached to a solid substrate to be able to resist the pressure drop across them. To be effective, these systems must be continuous at walls, roofs, penetrations, and transitions between systems to prevent the uncontrolled passage of air. The term "uncontrolled air" is used because the air barrier materials, assemblies, and system allow a small amount of air to pass through each component as defined by the industry standards or building codes. Most problems arise when breaches, voids, and other defects allow large quantities of air to bypass the air barrier. These defects often occur at penetrations (e.g., structural steel or conduit penetrations through the air barrier material) or at cladding intersections and transitions.

Air barriers that contain voids can have several consequences depending on climate and building pressurization. Primarily, heat/cooling loss through air barrier breaches results in poor mechanical system performance requiring additional energy to condition a building. As a result, building owners incur additional operating costs and potentially require systems to be replaced.

Uncontrolled air infiltration through the building enclosure can also allow environmental allergens/pollutants and other airborne particulates to contaminate interior air. In heating climates for all building types, uncontrolled air exfiltration can exacerbate icicle formation or ice dams at roof eaves (Photo 1) and increase the risk of condensation in wall assemblies and associated deterioration of cladding assemblies. This risk is greatest in specialty high-humidity buildings such as natatoriums or museums because of the high interior air dew point temperatures.

Photo 1: Severe icicle and ice dam formation at metal roof eave (arrow).

In cooling climates, exterior warm/moist air infiltration can cause condensation on interior surfaces and biological/mold growth within the building enclosure.

3. AIRTIGHTNESS INDUSTRY STANDARDS

Various standards or organizations provide guidelines for air barrier design and performance. Several building codes, including the 2012 IECC, incorporate air barrier installation and performance standards. The 2012 IECC is the first code published by the ICC that requires a continuous air barrier in commercial buildings, except for buildings in Climate Zones 1 through 3. The 2012 IECC allows designers several options to demonstrate air barrier compliance, one of which is to measure the air leakage rate through the building enclosure postconstruction (maximum whole-building air leakage rate of 0.40 cubic feet per minute (CFM) per square foot (sq ft) at 75 Pa (0.30 in. water) when tested per ASTM E779 – Standard Test Method for Determining Air Leakage Rate by Fan Pressurization). As a point of reference, 75 Pa (0.30 in. water) is the air leakage test pressure for a fenestration unit rated Commercial (CW) per the American Architectural Manufacturers Association (AAMA) Standard 101 – North American Fenestration Standard – Voluntary Performance Specification for Windows, Skylights, and Doors.

Many states are adopting air barrier provisions either explicitly or via the IECC. Washington is the first state to require whole-building air leakage testing prior to building occupancy. The target air leakage rate through the enclosure is 0.40 cfm/sq ft at 75 Pa (0.30 in. water). However, Washington State only requires that the air leakage rate be reported for information purposes, and passing the test is not required to obtain a certificate of occupancy.

The following industry organizations publish standards for building airtightness performance levels, summarized below:

- U.S. Army Corps of Engineers (USACE) requires that all buildings be field tested and demonstrate a maximum air leakage rate of 0.25 CFM/sq ft at 75 Pa (0.30 in. water) pressure differential, which is stricter than the 2012 IECC. Recent USACE studies show that both small and large buildings are meeting or exceeding the 0.25 cfm/sq ft airtightness requirement.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 90.1-2010) requires continuous air barriers for most commercial buildings but does not require field testing to demonstrate compliance.
- The U.S. General Services Administration (GSA 2010 P100 standard) allows a field test to demonstrate a maximum whole building air leakage rate of 0.40 cfm/sq ft at 75 Pa (0.30 in. water) pressure differential.
- Air Barrier Association of American (ABAA) established a guideline of 0.40 cfm/sq ft at 75 Pa (0.30 in. water) for new commercial buildings with continuous air barriers but does not require field testing to demonstrate compliance.

4. TEST METHODS

Performing whole-building air infiltration testing can help verify the performance of air barrier installations as well as locating defects in the system. For new construction, it is prudent to perform testing before the air barrier system is concealed by cladding materials or interior finishes so that defects can be identified and repaired more easily. Removing cladding postconstruction to locate and repair air barrier discontinuities is often costly and disruptive to the building occupants.

Field testing requires that the building be positively or negatively pressurized using blower door fans or manipulating the HVAC system to force air to leak through any air barrier discontinuities in the building enclosure. Various quantitative and qualitative techniques are available to identify air leakage paths, including infrared (IR) thermography and tracer smoke. These tests should be discussed with the project team early in the design process and required by the project specifications so that they are scheduled at the appropriate time during construction.

Qualitative Air Infiltration Testing. ASTM E1186 – Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems – describes various qualitative methods to locate air barrier discontinuities. One such practice is to pressurize or depressurize the building or individual spaces by using fans (Photo 2) or by manipulating the HVAC system, and then using a tracer smoke source over the interior or exterior surfaces of the building enclosure. Qualitative testing is generally performed prior to the quantitative testing to identify and repair air barrier breaches prior to measuring the air leakage rate.

Photo 2: Test setup for blower door test with calibrated fans.

Placing the tracer smoke source at the building interior and pressurizing the building or space to locate air exfiltration sites reduces the influence of wind or stack effect. In this case, tracer smoke will be drawn from the building interior through any breaches in the air barrier and be identifiable at the building exterior (Photo 3).

Photo 3: Tracer smoke exfiltration at roof eave (arrow).

Although it is possible for some projects to depressurize the building and locate the source of tracer smoke on the building exterior, this method may be difficult because of the influence of wind and the risk that the tracer smoke will rapidly dissipate before it is drawn into the building interior through the air leakage site.

IR Thermography. IR thermography (per ASTM E1186) is another useful and efficient qualitative method to locate discontinuities in the air barrier. The purpose of the IR scans is to identify locations of elevated heat loss through the building enclosure. Air infiltration or exfiltration through the building enclosure modifies temperatures of wall components in the region of air leakage pathways, given an interior and exterior temperature difference; IR scanning equipment can be used to detect local surface temperature differences (Photo 4).

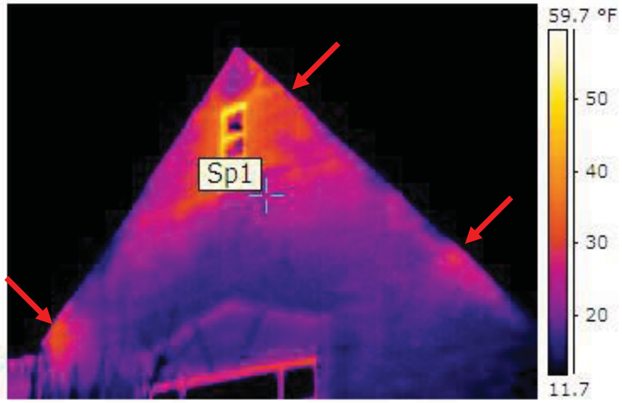

Photo 4: Infrared image of exterior wall taken during the winter in a heating climate. Orange/yellow regions indicate locations of elevated heat loss (arrows).

The conditions most conducive to accurate IR scans are low winds with a large temperature difference (at least 20°F) between the interior and exterior air temperatures. Additionally, IR scans should be performed before sunrise or after sunset to maximize the temperature difference between the interior and exterior as well as to avoid false readings due to solar exposure. Depending on the building pressurization, the IR scans can be conducted from the building interior or exterior. Using fans or the HVAC system to pressurize or depressurize the building during the IR scan can exacerbate air leakage through discontinuities in the air barrier, making it easier to identify air barrier breaches on an IR image.

Quantitative Air Infiltration Testing. Blower door testing per ASTM E779 is intended to characterize the airtightness of the building enclosure. The test results can be used to compare the airtightness of the subject building to similar buildings or against criteria set by industry standards or governing building codes. The tests are conducted using calibrated fans (Photo 2) to pressurize and depressurize the building under controlled conditions.

The ASTM E779 test procedure typically requires a range of induced pressure differences (pressurization and depressurization) from 10 Pa to 60 Pa. The measured air leakage flow rates (cubic feet per minute) are typically normalized by the building surface area (walls, roof, and floor) and calculated as the average of the pressurization and depressurization at 75 Pa (0.30 in. water) pressure difference using the air flow equations provided in ASTM E779.

Should the initial results of the ASTM E779 test exceed the air leakage rates required by the project specifications, various qualitative testing methods such as tracer smoke and IR testing are available to help identify breaches in the air barrier system.

5. AIR LEAKAGE TEST PLANNING

Quantitative whole-building air leakage testing is a labor and equipment-intensive process. In the authors' experience, the most successful tests are planned at least one month in advance to allow sufficient time to develop and fully vet the project specific testing procedure and coordinate with facilities personnel. The following highlights some, but not all, considerations for air leakage test preparation and execution:

- **Initial Planning** – Review the construction documents, if available, to assist with estimating the air leakage rate and required field equipment (i.e., blower door fans); the estimated air leakage rate depends on the presence and continuity of an air barrier. Performing a field visit to verify as-built conditions will reduce unanticipated conditions identified during the test.
- **Coordinate with Owner** – Test results are most accurate when interior and exterior temperatures are similar (to reduce the influence of stack pressure). Scheduling air leakage testing while the building is unoccupied will reduce interruptions during the test. Deactivation of the mechanical and combustion systems, smoke/fire alarms, and security systems is necessary during the test, particularly when using tracer smoke to identify locations of air leakage.
- **Test Execution** – Use automated software to control blower door fans to pressurize and depressurize the building, record real-time pressure and air flow data, improve the test accuracy, and reduce the test duration. Interior and exterior temperature, relative humidity and barometric pressure affect air density and leakage results. These air density corrections must be performed prior to analyzing the results.

6. CASE STUDIES

The authors' firm has performed many air leakage tests on commercial and residential buildings, including a new art museum and an existing high-rise residential building.

6.1 New Art Museum in Northeast U.S.

Air barrier breaches can result in severe consequences (e.g., condensation and concealed deterioration) in high-humidity specialty buildings such as museums in cold climates. The authors' firm performed air leakage testing of a new two-story art museum located in the northeast U.S. to measure the air leakage rate and identify deficiencies in the air barrier system. The exterior wall systems consist of glass curtain wall, terra-cotta, and precast concrete panels over exterior gypsum sheathing and steel stud framing. The exterior wall and roof assemblies include a self-adhering sheet membrane to function as a combined vapor retarder and air barrier. Although the project specifications required an air leakage test to measure the building airtightness, they did not specify a maximum allowable air leakage rate. For comparison purposes, the governing building code allowed a maximum air leakage rate of 0.40 cfm/sq ft at 75 Pa (0.30 in. water) pressure difference.

Test Preparation and Execution

The contractor installed a majority of the air barrier and exterior cladding systems prior to the authors' arrival on site. However, several curtain wall openings and HVAC construction openings were incomplete due to fabrication delays. The accelerated construction schedule did not allow postponement of the field test until the contractor installed the remaining HVAC and curtain wall components. Therefore, the construction team in-filled these construction openings with 2x4 stud walls covered with polyethylene sheets (Photo 5) to create a temporary air seal for the test.

Photo 5: Construction opening with a temporary stud wall wrapped with polyethylene sheet to create an air seal during the test.

Photo 6: Tracer smoke exfiltration (arrow) at a transition between cladding systems (precast concrete to terra-cotta) and waterproofing membranes (below-grade waterproofing to wall AVB membrane).

Test Results

Using two blower door fans, the authors measured air leakage rates for the positive and negative air tests of 0.10 cfm/sq ft and 0.12 cfm/sq ft, respectively, at 75 Pa pressure difference. These test results indicate that the enclosure airtightness exceeds typical expectations for new construction and the governing building code requirements.

Despite the low air leakage rates, smoke testing also identified several air barrier breaches at complex cladding intersections or transition details. Tracer smoke testing identified air leakage at gaps in the above-grade to below-grade waterproofing transition (Photo 6) and the spandrel beam penetration through the air barrier (Photo 7). The contractor immediately repaired these air barrier deficiencies before completing cladding installation.

Photo 7: Unsealed beam penetration through air barrier at masonry wall (arrow).

6.1. 1960s Residential Tower in Northeast U.S.

The authors' firm performed air leakage testing of an existing brick, limestone, and concrete-clad building constructed in the early 1960s. The residential tower, located in northeast U.S., exceeds fifteen stories and consists of a concrete-framed structure with reinforced concrete-masonry-unit (CMU) backup and cast-in-place concrete at exterior walls. The exterior walls contain a minimal amount of rigid insulation. Steel-framed (nonthermally broken) windows with fixed and operable sash and monolithic glazing are set into masonry openings; the operable sash lack contemporary weatherstripping to reduce air infiltration. Occupants report excessive air leakage through the existing operable sash during the winter; the building consumes approximately 20% of the total heating plant capacity during winter. As such, the building owner is considering replacing the existing windows with more airtight and thermally efficient insulating glass units combined with other building enclosure or mechanical system upgrades to reduce energy use. The air leakage testing is part of a study to evaluate the potential impact upgrading the building enclosure or mechanical systems will have on reducing energy consumption.

Test Preparation and Coordination

The high-rise tower required substantial more preparation time for test set-up and execution than the previous case study. This is primarily due to the building height and the need to install blower door frames in existing window openings at intermediate floors to provide a uniform pressure differential on the building enclosure for the full building height. This test required custom-built frames to retain the blower door fans in the existing window openings (Photo 8).

Photo 8: Custom-built blower door frame installed in a window opening.

Test preparation included propping over 500 interior doors to equalize pressure distribution throughout the building, filling drain p-traps to minimize the risk of sewer gas migration during testing, and air sealing areaways at grade, louvers, chimney and other roof penetrations, and hallways connected to adjacent buildings (Photo 9). It took six personnel working in parallel two days to prepare the building for the quantitative testing.

Photo 9: Various envelope penetrations sealed with tape and polyethylene sheet.

Test Results

Using eight blower door fans, the authors' measured air leakage rates for the positive and negative pressurization tests are 0.78 and 0.68 cfm/sq ft, respectively, at 75 Pa pressure differential. The existing building envelope is significantly leakier than contemporary industry standards; these results will be used as inputs in a whole-building energy model to better predict building energy use with various enclosure/mechanical system modifications. The tracer smoke testing effectively identified the operable window sash as a major contributor to overall building air leakage (Photo 10).

Photo 10: Tracer smoke exfiltration (arrow) at the operable window sash.

7. CONCLUSIONS

Continuous air barriers will help reduce building operating costs and minimize carbon footprint in the face of rising energy costs and an increased demand for high-performance buildings. Design professionals should be aware that code requirements for air leakage rates are becoming stricter, and this trend is likely to increase significantly as more states adopt the 2012 IECC. Quality-control methods built into the design and construction schedule including whole-building blower door tests can be implemented to identify issues early during construction when correction is more-easily achieved than after building occupancy.

PAPER TITLE

Measuring the Air Tightness of Mid and High Rise Non-Residential Buildings

MAIN AUTHOR

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ABSTRACT

There is currently little information on the air tightness of recently constructed midrise buildings. To fill this gap in our knowledge, the ASHRAE 1478 RP Project involves blower door testing 16 non-residential buildings, constructed after the year 2000 in climate zones two through seven of the IECC Climate Zone map. The ASTM E779 protocol is used for testing with modifications to address the complexities of larger buildings, as the buildings in this study are four stories or greater with complex mechanical systems. An advanced protocol was developed during this process, that resulted in a test protocol for commercial buildings, further developed by the Air Barrier Association of America and adopted by the US Army Corps of Engineers. During testing, a single zone is created by opening interior doors and the careful placement of test fans. Pressure measurements in the interior, at each orientation of the building, on the roof, and at one other elevation are tracked in real time. To ensure uniform pressure, zonal pressure differences must be no greater than 10% of the shell pressure. In preparation for the test, all operable intake, relief, and exhaust dampers are closed. In addition, exhaust or relief outlets that have no dampers are sealed manually using plastic. This step allows the researchers, after measurement of the enclosure airtightness, to unmask the HVAC equipment at the end of testing to understand its contribution to air leakage. Besides pressurization and depressurization tests accomplished at every site, other tests conducted intermittently include changing the location and method of pressure measurement, air leakage of different aspects of a building, and test repetition to understand accuracy. All of the data is analysed and reported according to ASTM E779. An existing standard published by the US Army Corps of Engineers states that buildings should only allow 0.25 cubic feet per minute of air to flow at 0.3” w.g. (75 Pascals) (1.25 $L/s/m^2$ @ 75 Pa) of pressure for every square foot of enclosure area, which includes all six sides of the building. Of the 13 buildings with currently calculated results, the range in air leakage is between 0.057 to 0.59 CFM75 / ft^2. Not only is this range large, it displays no airtightness trend concerning the structures that were built to environmental standards, such as LEED certification. Another finding of this project is the lack of tightness of HVAC equipment, determined using the louver or damper unmasking test. Both of these results expose a great need for more careful design and implementation of air tight barriers. Primary fenestration seals, soffit conditions, and damper airtightness and control or lack of dampers are just a few examples of building leakage locations seen during this study that could be improved to increase the air tightness, and therefore energy efficiency, of our built environment.

PAPER TITLE

Large Building Air Leakage Measurement – What Has Been Done and What Is Possible

MAIN AUTHOR
Denali Jones

OTHER AUTHORS
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ABSTRACT

Retrotec has been involved with measuring air leakage in large buildings since 1985 when we developed a fire suppression containment standard for the National Fire Protection Association. This taught us how large buildings worked and how to manage testing in an environment where stack and HVAC pressures made testing difficult since our induced test pressure were often less than pre-existing pressures. This led Retrotec to develop a series of testing methods that were impervious to existing fluctuations and culminated in the writing of the first draft of the USACE protocol which is effectively the only large building air leakage initiative in the USA. This resulted in our working with clients who performed over 400 tests on a variety of large buildings. Along the way methodology evolved and this is the first track of our presentation.

Slowly, other States began looking at putting large building testing into Code. This is our second track.

Meanwhile, our European colleagues have taken large building testing by storm and have outdone the USA in imaginative tests. They have tested a wider variety of buildings and much larger buildings as well showing us that there is no effective limit on what we can test and how large a building that can be tested. This same group has worked in the Middle East as well and encouraged changes in building regulations there. Our final track will give some insights into our experiences there.

ESTIMATES OF UNCERTAINTY IN MULTI-ZONE AIR LEAKAGE MEASUREMENTS

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ABSTRACT

Although standards for single-zone air leakage tests are well established and widely used, there is no existing standard for testing air leakage between adjacent zones. While a range of test procedures have been used to determine inter-zone leakage using fan-pressurization, the accuracy of the methods can vary significantly. Using field measurements and simulations, we have compared the uncertainty in the leakage between two adjacent zones for different measurement and calculation methods. We present the most accurate methods for determining inter-zone leakage between two adjacent zones, based on field and simulation results.

In multi-family housing buildings, air leakage from a single zone to the outside is often measured by pressurizing adjacent units to the same test pressure. We have investigated how sources of uncertainty affect zone-to-outside leakage test results using the guarded zone test method. We considered two sources of uncertainty that are common in the guarded test: 1) pressure fluctuations in the different units, and 2) interconnected zones that are not pressurized during the test. Adjacent units are pressurized in the guarded test to isolate leakage to the outside, but it is difficult in practice to ensure a zero-pressure drop across boundaries, and wind-driven pressure fluctuations can lead to increasing uncertainty in the test results. We also consider interconnected zones that are not pressurized directly in the guarded test method, because leakage to these zones is not always equivalent to leakage to the outdoors. We modelled a building with three adjacent units with an analytical model using the statistical computing program R. Fluctuations in the pressure and variability in leakage parameters are based on field observations and in the analysis, the collection of data is simulated using Monte Carlo techniques. While the uncertainty in leakage to outside due to pressure fluctuations and calibration error in guarded test results is relatively small (4-14%), leakage to interstitial zones may have a much more substantial impact (on the order of 30-100% of the leakage directly to the outdoors). The implications of the test results and uncertainty with respect to air-sealing efforts are discussed.

KEYWORDS

Air tightness, multi-zone, uncertainty

1. INTRODUCTION

Both performing and interpreting results from air leakage tests are significantly more complicated in multi-zone buildings than in single zone spaces. Often, the objective is to quantify either the leakage from a single unit to the outdoors, or the leakage from one zone to another, both of which require isolating the leakage flow through one interface from the overall network of airflows between conditioned zones, interstitial spaces and the outdoors. In this paper, we explore several factors that impact the accuracy and interpretation of multi-zone leakage measurement results in two scenarios: (i) house with an attached garage, and (ii) a three-unit row house as an example of multi-family buildings.

Section 2 in this paper summarizes results of a detailed study to analyse the accuracy of different methods used to determine leakage between two adjacent zones. The section refers to a house and attached garage zone, but any two adjacent zones could be considered. While a number of strategies have been used to determine interzonal leakage, currently no standard exists for this measurement. Because the interzonal leakage is often small relative to the overall leakage of either zone, this quantity can be difficult to resolve using fan pressurization tests. We compare the uncertainty associated with different techniques.

Section 3 considers uncertainty in determining the leakage to the outdoors from a single unit in a multi-zone building. To determine the air leakage to outside from a single unit in a multi-zone building, one common method is the 'guarded' test. The zone of interest as well as any adjacent conditioned zones (beside, above and/or below) are pressurized to the same test pressure to minimize leakage to adjacent zones in the measured leakage (Modera et al., 1986; Furbringer et al., 1988; Feustel, 1989). In multi-zone buildings, however, an individual unit might also have connections to unguarded zones such as interstitial spaces and hallways that may be unconditioned or partially conditioned. In Section 3, we examine how measurement uncertainty as well as leakage to unguarded zones can impact leakage estimates from guarded tests of individual units in multi-zone buildings.

In this study, air leakage flow through an interface from Zone A to Zone B, q_{AB}, is assumed to behave:

$$q_{AB} = C_{AB} P_{AB}^{n_{AB}} \quad (1)$$

where P_{AB} is the pressure in zone A relative to that in Zone B, C_{AB} is a flow coefficient proportional to the leakage area in that interface, and n_{AB} is the pressure exponent for that interface. If a blower door is placed in the AB interface, flow *through the blower door* is indicated by Q_{AB} (lower case q refers to flow through leaks). We modelled these interzonal flows with control volume based models using the statistical computing package, R.

2. LEAKAGE BETWEEN TWO ADJACENT ZONES

There are many possible approaches to determining the air leakage between two adjacent zones. The objective of this study was to determine the simplest fan-pressurization (blower door) test that will reliably deliver accurate results. Various data collection and analysis methods were compared using both simulated data sets as well as field data. Results of the field data and simulations were used to identify the most robust methods and to quantify the uncertainty of the different methods. Additional details of the methodology can be found in Hult et al. (2012).

In the field, single-zone blower door tests are often performed by taking flow rate measurements at a single pressure (typically 50 Pa), rather than fitting a curve to measurements over a range of pressure differences. The ASTM and ISO standards to determine air leakage using fan pressurization require measurements over a range of pressure differences to improve the accuracy of extrapolation to calculate the air leakage at low, operational pressure differences (ASTM, 2010; ISO, 2006). This study used simulations and field data to compare tests where measurements are taken at a single pressure difference vs. at multiple pressure differences, as well as different test methods using one or two blower doors. First, the methods used to generate and analyze the synthesized data are presented. A discussion of the results of the synthesized data analysis follows.

Diagnostic methods

A number of methods have been developed to determine leakage between adjacent zones (some focusing specifically on the house and attached garage scenario), but there is no existing standard for how to make this measurement. Parallels exist between interzonal leakage methods and ASTM test methods for measuring duct leakage (E1554-07) which also include methods to distinguish leakage to the outside from total leakage and employ more than one pressurization device. A number of strategies have been explored to use a single blower door to test interzonal leakage in buildings with two or more zones. Blasnik and Fitzgerald (1992) provide an accessible overview to the benefits of interzonal leakage testing to facilitate air sealing and describe several strategies to determine the leakage between adjacent zones using different single blower door tests. Several of the most common methods using different sets of single blower door tests are outlined in the following subsection. Additional test methods as well as two blower door tests are not described in detail here but are included in Hult et al. (2012).

The blower door is used to measure the flow rate Q through a door in the interface segment denoted by the subscript (HO for house-outside, HG for house-garage, and GO for garage-outside interface). P is the pressure difference across the interface indicated by the subscript.

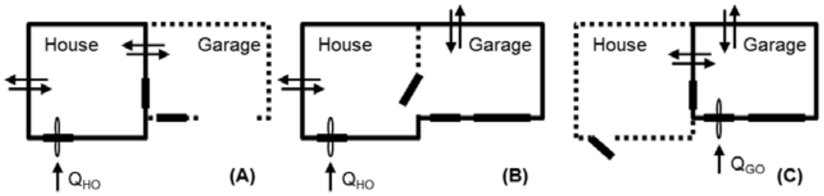


Figure 1 Three single zone methods using test configurations A, B & C. The three zones refer to the house (A), the garage (C), and then the combined house/garage zone (B).

Three Single Zone Method. Emmerich et al. (2003) used results from the 3 configurations illustrated in Figure 3 to calculate the leakage between the two zones. This is equivalent to performing three single zone tests, where the single zone contains the HO+HG interface, the GO+HG interface, and then the HO+GO interface:

$$Q_{HO,A} = C_{HO}P_{HO,A}^{n_{HO}} + C_{HG}P_{HG,A}^{n_{HG}} \quad (2)$$

$$Q_{GO,B} = C_{GO}P_{GO,B}^{n_{GO}} + C_{HG}P_{GO,B}^{n_{HG}} \quad (3)$$

$$Q_{HO,C} = C_{HO}P_{HO,C}^{n_{HO}} + C_{GO}P_{GO,C}^{n_{GO}}. \quad (4)$$

where C_{HO}, C_{GO} and C_{HG} are the flow coefficients and n_{HO}, n_{GO} and n_{HG} are the pressure exponents associated with the leakage through each envelope segment.

Similarly to determining the leakage of a single zone, this system can be solved for the coefficients using measurements at a single pressure difference if the pressure exponent assumed; a value of n=0.65 is common (Chan et al., 2012). Alternately, the parameters C_{ij} and n_{ij} can be determined explicitly if measurements are taken at multiple pressure differences. Emmerich et al. (2003) took measurements at 4 to 7 pressure differences for 4 houses with attached garages. Using a slightly different formulation of the equations above, they determined a value of n and C for each single zone control volume using linear regression, from which the leakage flow through each interface could be determined. If n is not assumed, the system has 3 equations and 6 unknowns. The calculation methods used in this section are described in the *Methods* subsection below.

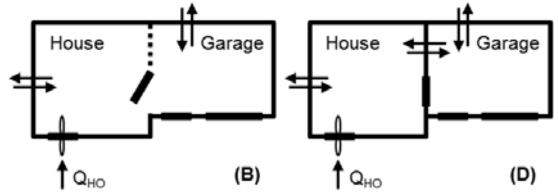


Figure 2 Standard Method, using configurations B & D.

Standard two test method. For determining house-garage leakage, Blasnik and Fitzgerald (1992) recommend completing a pair of tests with the blower door in the house-outside interface and the garage door closed. In the first test, the door between the house and garage is closed (D), and then in the second test the door between the house and garage is opened (B), as shown in Figure 2. Blasnik and Fitzgerald outlined the test at a single pressure (P=50 Pa), but the house zone pressure can also be increased over a range of pressure differences (Offermann 2009). This test method is convenient to use because although it requires two tests, the blower door only needs to be installed once.

The following equations govern the air leakage in the D configuration:

$$Q_{HO,D} = C_{HO}P_{HO,D}^{n_{HO}} + C_{HG}P_{HG,D}^{n_{HG}} \quad (5)$$

$$C_{GO}P_{GO,D}^{n_{GO}} = C_{HG}P_{HG,D}^{n_{HG}} \quad (6)$$

Configuration B is the same as shown in Figure 1 for the three single-zone method, which is described by Equation (3). As in the three single zone case, this system of equations can be solved either using measurements at a single test pressure, P_{HO}, or using measurements at a range of pressure differences. As for the three Single Zone method, for single pressure difference testing, we need to assume a pressure exponent, n, and we can solve for the flow coefficient, C_{HG}.

Garage 0/1 method. Alternately, the interzonal leakage can also theoretically be determined using two tests without moving the blower door using configurations A and D: the home is pressurized with the garage closed and then open. In practice, however, these configurations do not provide significantly different conditions to determine the interzonal leakage.

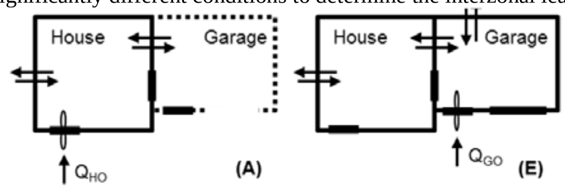


Figure 3 LBNL IzLT, using configurations A & E.

LBNL IzLT. While the Standard B/D method is convenient because it does not require moving the blower door, other test configuration pairs are also possible. Given that the blower door can be installed in doorways in each of the three interfaces (HO, HG, and GO), and the remaining interface doors can each be either open or closed, 12 unique configuration pairs can be used to determine the interzonal leakage. Hult et al. (2012) explored the 12 pairs and identified the LBNL IzLT method as the most robust pair of single blower door tests to determine interzonal leakage. Figure 3 illustrates configurations A and E used in the LBNL IzLT method. By applying control volume analysis to the house zone in A and the house and garage zones in E, the problem can be described by the three equations resulting from applying control volume analysis to the house zone in A and the house and garage zones in E.

For some configurations (e.g., A and C), the blower door could be placed in either doorway to the pressurized zone.

Simulations

Two approaches were used to assess interzonal leakage measurement strategies: Monte Carlo simulations and field tests. Simulation results are discussed below and field results from 6 houses are discussed in more detail in Hult et al. (2012, 2013). The simulations allow for a more thorough exploration of the parameter space, but require some assumptions about the nature of actual leakage and measurement noise. The field tests were helpful to bound conditions such as the magnitude of leakage quantities and wind-induced fluctuations, but were limited in terms of how many tests could be performed.

To determine the uncertainty in the total leakage from a single zone, it is possible to use uncertainty propagation techniques (Sherman and Palmiter, 1995). However, the non-linear system of equations makes it difficult to estimate the uncertainty in the interzonal leakage case. Instead, we used Monte Carlo simulations to mimic the collection of blower door measurements. In each simulation, a set of exact leakage parameters was selected, then the exact flow rates were calculated at a set of pressure differences for a given testing configuration. For multiple pressure difference tests, the 6 pressure differences used were 12.5, 25, 37.5, 50, 62.5, and 75 Pa. Then, to simulate the effects of measurement noise, randomly chosen fluctuations from a normal distribution with zero mean and a varied standard deviation were added to generate each ‘measured’ flow rate and pressure. The air leakage parameters C_{ij} and n_{ij} were then fit to these simulated ‘measured’ data. The leakage flows calculated from these fitted parameters C_{ij} and n_{ij} were then compared with the ‘exact’ leakage rates specified initially, allowing us to assess the error resulting from the added noise and the assumptions of each calculation method. In the results shown in this paper, the standard deviation of the fluctuations in the pressure was 0.5 Pa and 10 cfm for flow rate, and the interzonal leakage area as a fraction of the house to outside leakage area was $C_{HG}/C_{HO}=0.05$ (sensitivity to these parameters was found to be low, as discussed in Hult et al. (2012)).

Because the fluctuations were chosen randomly from a specified distribution, results vary to some extent between subsequent simulations, in the same way field test results at the same site may vary between repeated tests. Therefore, for convergence 500-1000 simulations were run for each set of conditions to determine the typical (median) uncertainty as well as the range (one standard deviation above and below the median). Other factors taken into account in the selection of parameters and simulation of measurements include:

- Difference between pressurization & depressurization leakage parameters due to valving effects (mean difference between pressurization and depressurization and then variation about that mean),
- Distribution of actual pressure exponents vs. assumed value (n=0.65)
- Uncertainty in the mean pressure exponent in distribution
- Calibration error in pressure and flow rate measurements

Additional details of the Monte Carlo simulation methods can be found in Hult et al. (2012).

Other issues that were explored in detail in Hult et al. (2012) include additional possible testing configurations, sensitivity to fluctuations in pressure and flow rate measurements, and sensitivity to the magnitude of the interzonal leakage relative to the house leakage (C_{HG}/C_{HO}) and the relative leakage in the two zones (C_{GO}/C_{HO}). The report also compared various calculation methods including: fitting coefficients C_{ij} and pressure exponents n_{ij} values to pressurization and depressurization data separately or jointly; fitting or specifying n_{HG} for the interzonal leakage explicitly; and fitting C_{ij} but assuming a fixed n for all leakage interfaces.

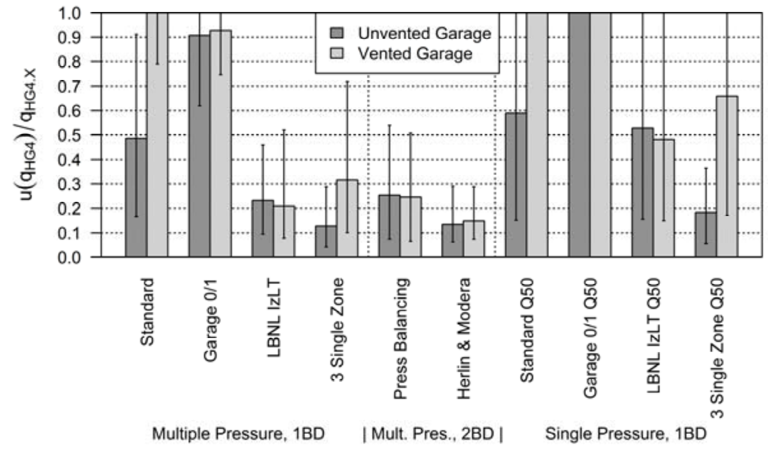


Figure 4 Comparison of the uncertainty resulting from different measurement methods to estimate interzonal leakage using simulated data. Bars show the median uncertainty $u(q_{HG4})$ in the interzonal leakage, scaled by the exact interzonal leakage and error bars show one standard deviation above and below the median. Single Blower Door tests (left) and Two Blower Door tests (center) using multiple pressure differences. For single pressure difference methods (right), measurements were taken at 50 Pa. Bars are truncated at 100% uncertainty but several extend above.

House-garage results

Simulations were used to compare the uncertainty resulting from different test configurations and calculation methods under the same conditions. Figure 4 compares the uncertainty in the interzonal leakage using different test methods, for the case when both zones are relatively tight (unvented garage, $C_{GO}/C_{HO}=0.7$), and the case when the garage zone has a much larger leakage area than the house zone (vented garage, $C_{GO}/C_{HO}=8$).

Figure 4 summarizes the results from the synthesized data analysis. The pair of single door configurations with the lowest uncertainty was the LBNL IzLT Method using multiple pressure differences. While other pairs of single blower door configurations had similar results when the leakage area of the two zones was comparable, the LBNL IzLT Method was more accurate when the second zone was much leakier than the house (vented garage case). The Three Single Zone method requires three blower door tests instead of two, but the results were excellent when the leakage area of the two zones was comparable: for the unvented garage case, the median uncertainty in q_{HG4} was 13% of itself when multiple pressure differences were used. When the garage zone was vented, the uncertainty increased but only to 32% of q_{HG4}. The Standard Method used by Blasnik and Fitzgerald (1992) and Offermann (2009) provided relatively consistent results if the two zones had comparable leakage area (uncertainty is about 50% of q_{HG4} at $C_{GO}/C_{HO}=0.7$), but when $C_{GO}/C_{HO}=8$, the uncertainty is near 100% of q_{HG4}. Although this uncertainty may seem small relative to the total house leakage, we found that the calculated values were often not meaningful because a good fit to the measured data could not be found (Hult et al. 2012). Results for Garage 0/1 Method are also included to show that the performance was also poor and the test should be avoided.

Analysis of the simulation results suggests that the Two Blower Door methods can be used to determine the interzonal leakage to within 20%. The method developed by Herrlin and Modera (1988) was used to determine q_{HG4} to within 16%, regardless of C_{GO}/C_{HO} or C_{HG}/C_{HO}. This measurement routine was also largely insensitive to fluctuations in the measured quantities, making it a very robust choice if two blower doors are available for use. The Pressure Balancing Method led to an uncertainty of approximately 25% of q_{HG4}.
Overall, the simulations suggest that using a single pressure difference (e.g., 50 Pa) lead to unreliable estimates of the interzonal leakage. If C_{GO}/C_{HO} is not large (i.e., less than 3), simulation results indicate the uncertainty using the Three Single Zone Method is relatively low. However, the field test results indicated that the Three Single Zone Method was not reliable using a single pressure difference. Overall, the configuration sets that performed well in the simulations discussed above also had the most consistent results in the field tests (Hult et al., 2012; Hult et al., 2013).

3. GUARDED METHOD IN MULTIZONE BUILDINGS

We examine the sources of uncertainty in the guarded test method to determine leakage to outdoors from a single unit in a multi-zone building. In this method, adjacent zones are raised to the same test pressure to minimize leakage to other conditioned spaces.

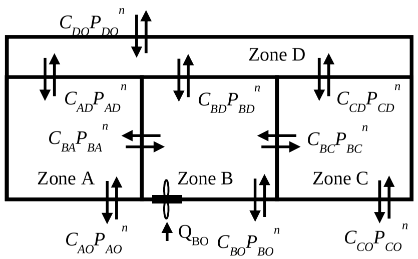


Figure 5: Schematic of guarded test on Zone B, with adjacent Zones A and C also pressurized, and all three zones are connected to the outside and to a common Zone D.

3.1. Uncertainty in the guarded method

In this subsection, we use a similar approach to the simulations in the previous section to explore how sensitive the guarded test method is to calibration error and fluctuations in the pressure measurements. To explore this question, we simulate the testing of Zone B in Figure 5, assuming in this case that there was no leakage to the interstitial Zone D from A B or C. Following the approach as described in Section 2, test measurements are simulated at pressures between 12.5 and 75 Pa and we assume the measured pressure can fluctuate from the effective pressure in each zone by a random perturbation with standard devation u(P) = 0.5 Pa, the measured flow fluctuation has standard devation u(Q)=10cfm, and the calibration errors for pressure and flow are 1 and 3% respectively.

Several studies have used tracer gas methods to estimate the air leakage between units to typically 15-30% of a unit's total infiltration (e.g., Francisco and Palmiter, 1994; Bohac et al. 2007). However, limited information is available on where the actual leakage area is located, and how units interact with interstitial spaces to lead to this air exchange in multi-zone buildings. Therefore, we will explore the impact of leakage to non-guarded spaces over a feasible parameter space. If the interzonal leakage area is small relative to the leakage area to the outside ($C_{BA}/C_{BO}=C_{BC}/C_{BO}=0.1$), then uncertainty in the leakage to the outside is 4%. If the interzonal leakage area is increased relative to the leakage area to the outside ($C_{BA}/C_{BO}=C_{BC}/C_{BO}=0.5$), the uncertainty in the measured leakage is 14%. Thus, unless the interzonal leakage and/or pressure fluctuations are unusually high, the impact of measurement noise and calibration error is not expected to lead to significant uncertainty in guarded tests.

3.2. Flow to interstitial spaces

In multifamily buildings, there may be pathways from an individual room or apartment unit through wall cavity, hallway, attic, basement or other conditioned or semi-conditioned spaces that are unlikely to be pressurized during a guarded test. A guarded test prevents air exchange only between the zone of interest (Zone B), and the adjacent, pressurized zones (Zone A & C). In a guarded test, the flow quantity measured in the test will include leakage from the zone of interest to the outside, as well as leakage from the zone of interest to any other zones that have not been pressurized, i.e., $Q_{meas}=q_{BO}+q_{BD}$ (Figure 5). The impact of the number of zones leaking to the interstitial zone was also explored by also simulating cases where Zone C or Zones A & C were sealed off from the other zones.

It is important to distinguish between leakage directly to the outdoors and leakage to interstitial spaces. Interstitial zones may be partially conditioned, in which case there is a smaller energy loss associated with air exchange between interstitial spaces and the conditioned zone, relative to air exchange with the outdoors. These zones are also more protected from weather than exterior walls, and so there are likely to be lower driving pressure differences across leaks at the interface between the zone of interest and the interstitial zone, compared with leaks in exterior walls. For these reasons, it is important to acknowledge that leakage area to non-guarded spaces is not equivalent to leakage area to the outside, even if leakage through the interstitial space eventually flows to the outdoors.

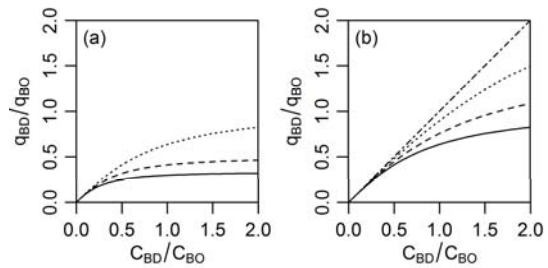
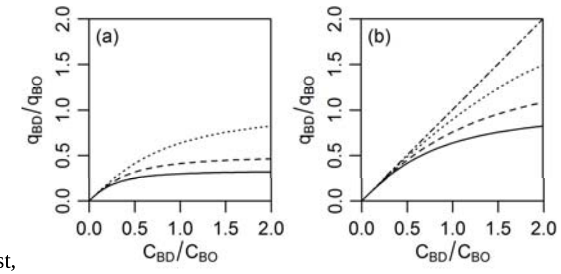
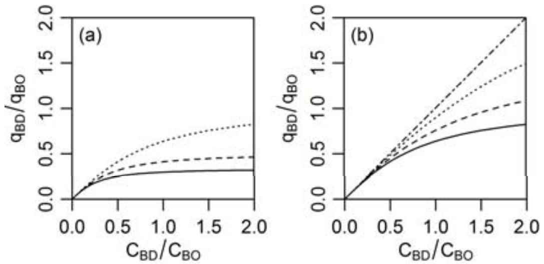


Figure 6: Ratio of leakage flow from B to D relative to the leakage from B to outside (q_{BD}/q_{BO}) as a function of the leakage area ratio. In (a), Zone D has the same leakage area to the outside as Zone B, in (b), Zone D has three times the leakage area to the outside as Zone B. The dotted curve (…) assumes only one room zone (Zone B), the dashed (- - -) has two room zones (Zone A & B), and the solid curve (—) has three room zones (A,B & C). The dashdot curve (._.) shows the limit as C_{DO} becomes very large relative to C_{BO}.

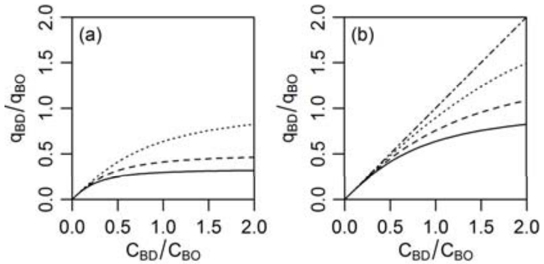
In this section, we explore what fraction of the measured leakage in a guarded test might actually be leakage to interstitial zones. We use the model of three adjacent units all connected to a common forth zone, shown in Figure 5. Here, the leakage area between each of Zones A, B & C and the outside are equal and held constant. The leakage area between Zone D and the outside is varied to simulate a range in the degree of connectedness to the outside. The guarded test method was simulated, so zero direct leakage flow was assumed between conditioned zones.



For a guarded test,
Figure 6 shows how much leakage flow there is to the interstitial zone compared with the leakage flow to the outdoors (q_{BD}/q_{BO}), as the leakage area ratio is varied for those interfaces. The leakage flow rate q_{BO} is constant across all cases and we examine the magnitude of the flow from Zone B to the interstitial space relative to this quantity. As the leakage area to the interstitial zone is increased, the total leakage flow 'measured' in the simulated guarded test of Zone B increases because of the additional leakage to Zone D. Overall, the actual leakage area in the interface directly between the zone of interest in the outdoors may only be one half to two thirds of the leakage flow resulting from the guarded test.



In
Figure 6(a), the interstitial space has the same leakage area to the outside as each of the conditioned zones (i.e., $C_{DO} = C_{AO}=C_{BO}=C_{CO}$). Here, the leakage flow ratio to the interstitial zone increases with the leakage area ratio but once the leakage area to the interstitial zone is as large as the leakage area to the outside, the increase in the leakage flow to the interstitial zone diminishes. For example, if the leakage area to non-guarded zones in Zone B is evenly divided between leakage area to the outside and leakage area to the interstitial space, then the total 'measured' leakage flow from the guarded test will be about 30% higher than the 'actual' leakage flow directly to the outdoors. In this case, sealing one square inch of leakage area in the BD interface will have less effect on the measured leakage than sealing one square inch in the interface between B and the outside, both because Zone D is slightly pressurized and because it may be partially conditioned. The number of guarding zones connected to the interstitial zone also has a substantial impact on how much leakage there is to the interstitial zone: the more guarding zones that are also connected to the interstitial space, the lower the leakage flow from the zone of interest to the interstitial space.



In
Figure 6 (b), the leakage between the interstitial zone and the outdoors is increased so that $C_{DO} = 3C_{BO}$. This represents a case where the interstitial zone is more connected to the outdoors or simply a larger interstitial space. As the leakage area between the interstitial space and the outdoors increases, all curves approach the limiting curve shown in Figure 5(b), where leakage to the interstitial space behaves like leakage directly to the outdoors. In the case shown in (b), the leakage flow to the interstitial zone continues to rise with increasing leakage area to this zone. Thus if there is significant leakage area to an interstitial zone not very well sealed from the outdoors, leakage to this interstitial zone may constitute a significant fraction of the measured leakage in a guarded test.

4. CONCLUSIONS

Uncertainty can be significant when using fan pressurization methods to determine the leakage between two adjacent zones and care should be taken to use recommended testing configurations and to use measurements at multiple pressure differences. When using the guarded method in a multi-zone building to determine the leakage to the outdoors, uncertainty due to measurement noise and calibration error is estimated to be relatively small, but leakage to unguarded interstitial zones may have a large impact on results. If all flow measured in the guarded test is assumed to be between the zone of interest and the outdoors, and if the neglected interstitial zones are significant, then air leakage measurements may give misleading estimates of building airtightness. This is because the actual leakage area in the interface directly between the zone of interest in the outdoors may only be one half to two thirds of the leakage flow resulting from the guarded test. Thus, care should be taken when interpreting the results of guarded leakage tests in multi-zone buildings so that the possible energy savings due to leakage directly to the outdoors are not overestimated.

5. ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, and by the California Energy Commission (Energy Commission), Public Interest Energy Research (PIER) Program, under Work for Others Contract No. 500-08-061. The authors also thank Darryl Dickerhoff and Phillip Price for their contributions.

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PAPER TITLE
Air tightness of buildings in Poland

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ABSTRACT

This paper presents a general overview of the building envelope airtightness requirements in Poland. The Energy Performance of Buildings Directive (EPBD) established the first regulations in Polish law, regarding airtightness of buildings (Building Codes 2008). Unfortunately, these provisions are currently not precise enough and not sufficiently developed to implement effectively appropriate testing procedures and ensure high airtightness. Other requirements such as passive house guidelines are applied in Poland very seldom and only by very conscious investors.

A step in a good direction was performed recently by National Fund for Environmental Protection and Water Management (NFEPWM). The Fund set up requirements for new low energy buildings and among them also obligatory testing of building airtightness. Fulfillment of all these demands in case of residential houses results in getting subsidy which is a good stimulus to care about the building quality.

Unfortunately at the moment we have no requirements imposed for measurement companies - their competencies, experience, references, equipment and certification.

Generally, the situation in the field of airtightness on the Polish construction market looks like at the very beginning of the whole long quality-improvement process. In the paper, there is presented brief characteristics of the market like e.g. problems in investor's and contractor's budget planning, lack of awareness, knowledge and experience. Public procurement law also doesn't help in this issue – the most popular tender criteria is the lowest price. This obviously results in deficiencies in the bids and finally in poor quality of workmanship.

The European norm PN-EN 13829 is actually the only guideline and source of knowledge relating to air leakage tests. Performing measurements strictly according to this norm in large buildings causes some doubts and difficulties in practice like for example possibility of ventilation system use, its accuracy, building preparation procedures.

There are several representative for polish residential and non-residential buildings measurements, obtained results and comments presented in this paper. These airtightness measurements of realized buildings show what can be achieved in practice of our country. With NFEPWM grants program it is going to be a strong progress in the field of airtightness techniques and measurements next years.

PAPER TITLE
Large public buildings air tightness in Poland

MAIN AUTHOR
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OTHER AUTHORS
Michal Szymanski, Tomasz Mroz

ABSTRACT

Large public building airtightness specification, implementation and verification, as a part of investment process is described in the paper. Poznan University of Technology new building called Mechatronics, Biomechanics and Nanoengineering Centre, with internal volume of almost 50.000 m^3 (1.800.000 cu ft), was used as a case study. Erected in 2010-2011 turned out to be the first large public building to be airtightness measured in Poland.
Centre was financed with respect to public procurement law, which influenced the design and construction process. Airtightness measurement requirements were formulated in tender conditions, what is very rare in Poland, yet. Lack of consciousness, knowledge and experience among designers and contractors was perceived during design and construction process. Thanks to strong investor awareness in the field of energy efficiency, a very good airtightness (n_{50} = 0.3 ACH) was achieved, much better than required by law (n_{50} = 1.5 ACH). During construction process a lot of positive effects like workmanship quality improvement and contractor awareness rise were observed. Airtightness ensuring techniques and solutions were precisely described together with the measuring procedure. As a typical heavy construction building, mechanically ventilated and raised with use of common materials it could be a good case study for airtightness concerned investors in Poland.
Two other large building case studies were generally described in this paper.

Friday 19 April 2013

10:00-11:30 Session 7: Large and multi-family buildings

1. Repeatability of Whole-Building Airtightness Measurements: Midrise Residential Case Study. Collin Olson, The Energy Conservatory, USA
2. Stack Effect and Mechanical Exhaust System Impacts on Building Pressures and Envelope Air Leakage, Sean M. O'Brien, Simpson Gumpertz & Heger, USA
3. Field Experience with Sealing Large-Building Duct Leakage with an Aerosol-Based Sealing Process, Mark Modera, UC Davis, USA
4. Analysis of the NIST Commercial and Institutional Building Envelope Leakage Database. Steven Emmerich, NIST, USA
5. Practical experience with training and performing airtightness tests in large buildings. Karl Grimnes, Termografi og Maaleteknikk as, Norway

REPEATABILITY OF WHOLE-BUILDING AIRTIGHTNESS MEASUREMENTS: MIDRISE RESIDENTIAL CASE STUDY

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ABSTRACT

This case study describes repeated whole-building airtightness measurements of an unoccupied ten story residential building in Madison, Wisconsin (USA). Tests were performed in two phases of testing – summer (June) and late fall (November) – over a wide range of temperatures and wind speeds in each test phase. Both multi-point regression tests (similar to ASTM-E779 and EN-13829) and repeated single point tests (similar to ASTM E-1827) were performed. Tests were performed in both pressurization and depressurization mode using portable blower door equipment. Eight separate enclosure pressures were measured – 4 at grade and 4 along the parapet wall. Throughout the tests all pressure and flow measurements were continuously recorded at one second intervals.

The short term (within-phase) results had measured standard deviations of order 1% for both single point and multi-point tests. However, between the two test phases there was a measured difference in airtightness of about 10% (with the building measuring tighter in June than in November). This difference could not be explained by any of the identified error sources. The question remains whether it may be the result of physical changes in the building.

A detailed comparison of the two test methods is given. Single point testing was more effective at precisely determining the leakage (within a given test phase) than was mutlti-point regression testing. Precision was not markedly improved by the use of both pressurization and depressurization compared with using either separately.

KEYWORDS

Airtightness, blower door, uncertainties, repeatability, pressurization, testing, large building, multiple fans, automated

1. INTRODUCTION

The airtightness of building enclosures has long been understood to have an impact on building durability, energy consumption, indoor air quality and occupant comfort. Increasingly, new buildings and buildings undergoing remedial air sealing are being tested and a significant dataset of leakage values is being developed. Even so, there is a relative lack of information on the accuracy and precision of these tests on larger buildings due, at least in part, to the difficulty and expense of conducting the appropriate experiments. This information is needed for standards development.

Buildings undergoing remedial air sealing and newly constructed buildings require measurements that are of high data quality yet are as streamlined as possible. When trying to determine compliance with a specific target airtightness, the uncertainties must be estimated and accounted for in a pass-fail determination.

This case study looks at two primary issues: The merits of single point versus multi-point testing and the benefits of conducting tests in both pressurization and depressurization modes. Many secondary issues are considered.

2. BUILDING CHARACTERISTICS AND TEST EQUIPMENT CONFIGURATION

2.1. Building Characteristics

The building is a dormitory built in 1962 with approximately 84,000 ft^2 (7800 m^2) of total enclosure area including exterior walls, roof and below grade surfaces. The interior volume is approximately 1,000,000 ft^3 (28,000 m^3). The building is situated on an isthmus, allowing direct exposure to winds coming across the lakes to the north and south. As shown in Figure 1, the building is tall and narrow. The west side of the building contains 87 windows and the east side contain 125 windows. The short ends (north and south) do not contain windows. Most floors consist of a central hallway with dorm rooms on each side. A single elevator shaft serves all residences and a ventilation air shaft also provides connections vertically. There are stairwells in the north and south running the full height of the building.

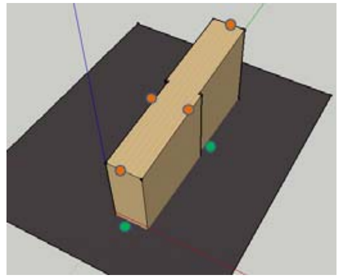

Figure 1: Building geometry and location of the 8 outside pressure taps

2.2 Preparation for testing

There are a total of 13 exterior mechanical openings which were masked for the testing, some at grade and others on the walls and roof. A detailed list was maintained so that the test setup in June could be reproduced in November. During each week of testing, the building was set up once and left in the test configuration during the overnight periods.

2.3 Equipment layout

A total of 4 blower door fans were installed, all at grade. Fans 1 and 2 were set up in a two-fan frame in the south entrance and fans 3 and 4 similarly in the west. Digital manometers with 0.1 Pa resolution were used for measuring all pressures and fan flows. All manometers were connected back to a central computer on the ground floor using cat5 cable and pressure sampling tube lengths were minimized as much as possible.

3. TEST PROTOCOL

The testing consisted of a multi-point sequence and a single point sequence. The goal for each day of testing was to alternate between the two and to complete as many repetitions as possible. Each week of testing started with setting up the building and thereafter as many tests as possible were completed. Each day started with multi-point as this was thought to be a more commonly used procedure and thus of greater interest.

3.2 Multi-point Sequence

Depressurization:

5 minute pre baseline

-30 to -75 induced pressure in 5 Pa increments, each for one minute

5 minute post baseline

Pressurization: Repeat under positive pressure.

3.3 Single point Sequence

Depressurization (repeat x 10):

1 minute baseline

1 minute induced -75

Pressurization: Repeat under positive pressure.

4. RESULTS

Table 1 contains the data for all multi-point tests and Table 2 contains all single point tests. The first character in the Test name represents the Test Phase where a=June, b=November.

Table 1: Multi-point Tests

Test	T in (F)	T out (F)	Wind mi/hr.	CFM75(d)	+/- 95%	CFM75 (p)	+/- 95%
amp1	78	77	15	14913	236	16255	229
amp2	78	85	23	14479	458	16097	512
amp3	78	57	14	14552	203	16008	192
amp4	78	54	16	14402	140	15868	310
amp5	78	56	9	14567	85	16040	224
amp6	78	53	7	14767	51	16102	229
bmp1	66	35	23	16153	915	18177	483
bmp2	73	32	7	16049	68	17266	70
bmp3	67	45	9	15851	131	17327	207
bmp4	65	41	11	16035	184	17617	160
bmp5	75	38	3	15977	122	17542	210
bmp6	70	41	7	16186	112	17272	190
bmp7	68	40	19	16362	262	17248	549
bmp8	77	27	2	16309	146	17852	266

Table 2: Single Point Tests

Test	T in (F)	T out (F)	Wind mi/hr.	CFM75(d)	+/- 95%	CFM75 (p)	+/- 95%
asp1	78	82	18	14757	400	15883	448
asp2	78	55	11	14548	75	16353	157
asp3	78	56	12	14515	82	16408	161
asp4	78	55	4	14498	56	16189	97
bsp1	69	37	4	15856	24	17673	56
bsp2	67	45	9	15929	156	17905	164
bsp3	69	41	4	15849	85	17576	143
bsp4	68	42	7	15892	77	17985	196
bsp5	69	37	6	15994	71	17913	95

The CFM75 values for Multi-point and Single-point tests are shown below in Figures 1 and 2, respectively. Note that the reference lines for each test phase are the weighted mean of the given test mode (pressurization or depressurization) within the given test phase (June or November). The weights are the inverse of the calculated variance of the test.

Pressurization produced consistently higher leakage than depressurization, and there was a clear shift between June and November which was about equal for pressurization and depressurization. No cause for this shift has been identified.

The noticeable positive deviation of the pressurization value for test index 7 in Table 1 is the result of a loose panel on an air handler cabinet being blown open. This was discovered not by looking at the data but by a pre-planned inspection of all seals, underscoring the importance of such inspections. The errant value does not significantly change the conclusions of this work and is therefore being included in the analysis.

The error bars in Figure 2 are the predicted 95% confidence intervals directly from the regression statistics. Visual inspection shows that they are not adequate to explain the deviations from the weighted mean, even within test phase. By calculating the standardized errors (from the weighted means within test phase) it can be shown that the error bars are roughly 3 times too small.

The error bars in Figure 3 are based on standard statistics applied to the 10 repeats which represent each data point. These errors are approximately the right size to explain the deviations from the weighted means, and it appears that the standard statistical techniques are adequately explaining the precision errors. This is not the same procedure as in ASTM E-1827 but is applied here as it is thought to be a simpler and more appropriate statistical technique for this experiment.

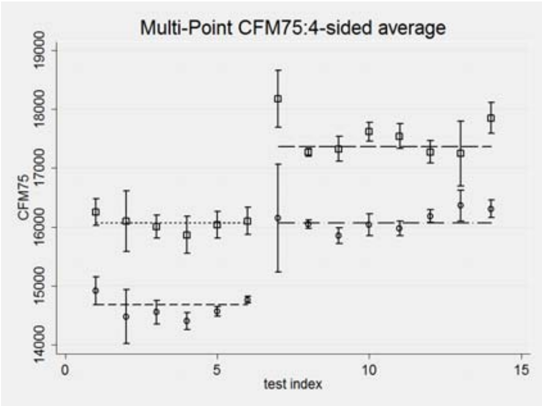

Figure 2: Multipoint CFM75 versus test index using 4 outside pressure taps

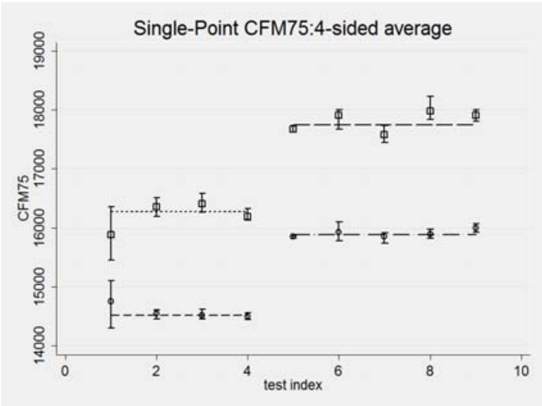

Figure 3: Single point CFM75 versus test index using 4 outside pressure taps

Figures 4 and 5 show the estimated precision errors versus average wind speed of each test. The wind speeds used in this analysis come from a nearby weather station on top of a tall building approximately 1 mile from the site. It is expected that wind speeds experienced by the test building are somewhat lower than those of the weather station.

Note that the estimated errors seem to be roughly the same (at a given wind speed) for single point tests and multi-point tests. However, recall that the multi-point errors were being underestimated by a factor of about 3. Therefore single point tests provide a more precise result at a given wind speed for this building under the conditions in which these tests were performed.

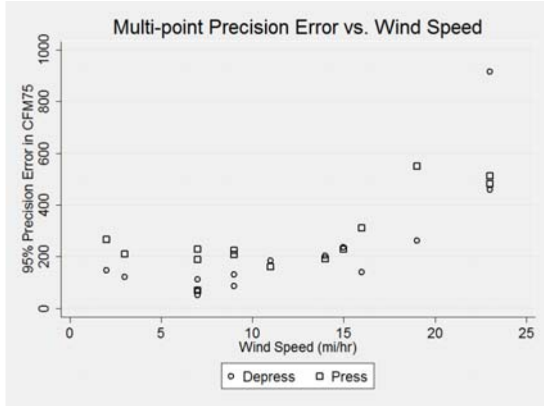

Figure 4: Multi-point precision errors versus wind speed

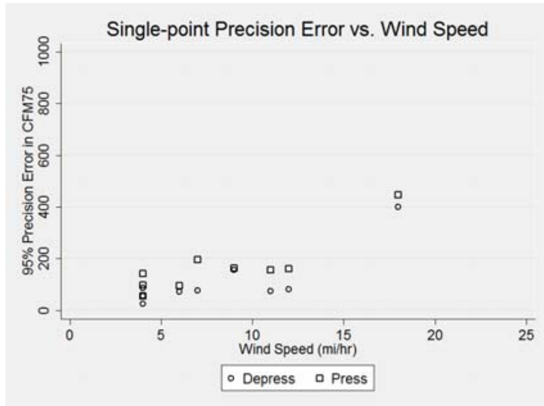

Figure 5: Single point precision errors versus wind speed

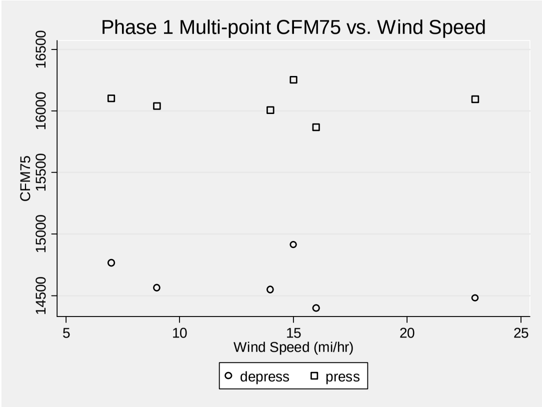

Figure 6: Phase 1 Multi-point CFM75 versus wind speed

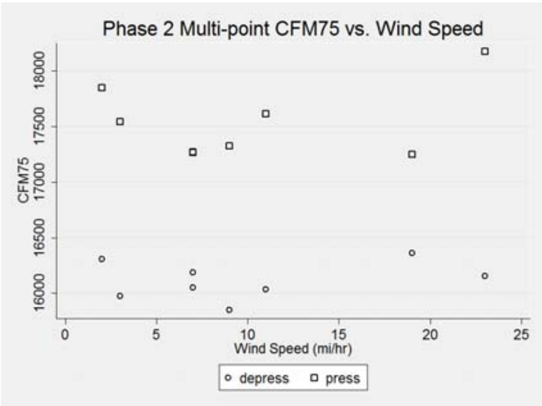

Figure 7: Phase 2 Multi-point CFM75 versus wind speed

Below are some representative graphs of individual tests. Figure 8 shows the combined pressurization and depressurization results of the first multi-point sequence (MP1). Figure 9 shows the first depressurization run in single point test (SP1).

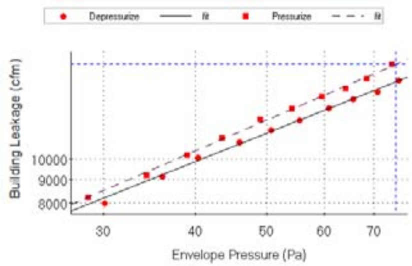

Figure 8: Multi-point sequence MP1, pressurization and depressurization

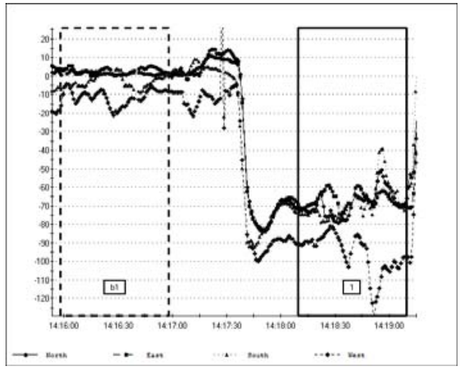

Figure 9: First of 10 repeats for SP1 (depressurization), pressure versus time

4. ANALYSIS

The multi-point confidence intervals are clearly too small. This most likely means that some underlying statistical assumption is not being met. One important contributor may be the baseline fluctuations, which are not being accounted for properly. Baseline readings clearly contain an error component, yet when these readings are simply subtracted from the fan-on pressure readings there is not proper accounting for their uncertainty. These errors may cause nonlinearity in the log-log data, resulting in a slight increase in estimated uncertainty, but the effect is too small.

If we perform the simple calculation of how much difference it makes to use the post baseline (alone) versus the pre-baseline (alone) it should give an idea how large the effects can be. Table 3 shows the change in CFM75 caused by using the post-test baseline versus the pre-test baseline for both depressurization and pressurization. It is noteworthy that there appears to be a systematic shift towards tighter results using the post-baseline in depressurization mode. There is not such as obvious trend with the pressurization data. These changes are also expressed as a fraction of the 95% confidence interval. It is seen that in some cases the change in measured leakage can be several times the estimated 95% precision error. This suggests that the baseline errors can be important contributors to the overall precision errors and need to be accounted for in the analysis. It is beyond the scope of this paper to develop such a model but this will be an area of on-going work.

Table 3: Impact of using just post-test baseline versus just pre-test baseline

Change in CFM75(D)	Fraction of 95% error	Change in CFM75(P)	Fraction of 95% error
-106	-0.45	56	0.25
-46	-0.10	-128	-0.25
24	0.12	36	0.19
67	0.49	59	0.19
-9	-0.11	65	0.29
-103	-1.94	111	0.49
-585	-0.62	-68	-0.14

-338	-5.45	118	1.66
-213	-1.59	60	0.29
-124	-0.66	20	0.13
-247	-2.09	-43	-0.21
-391	-3.62	61	0.33
-725	-2.51	-20	-0.04
-244	-1.69	87	0.33

5. CONCLUSIONS

Short term (within-phase) repeatability was excellent for both multi-point and single point tests over a range of wind speeds and temperatures. Single point repeated tests had better precision than multipoint tests and, importantly, the precision errors could be adequately estimated using standard statistical techniques. The multi-point precision errors seemed to be underestimated by about a factor of 3 when using standard regression statistics. Averaging all four sides of the building improved the precision as compared with randomly selecting a single outside pressure tap. For any given test, a carefully selected pressure tap on the leeward side of the building often had better precision than the average of the four.

One reason often cited for specifying both pressurization and depressurization tests is that there are cancellations of errors due to wind, stack and other sources such that there is an improvement in precision and accuracy. That does not seem to be the case with these results. There was no obvious precision benefit from testing in both pressurization and depressurization modes. If the goal were to make a measurement as precise as possible, in the least amount of time, these data suggest it would be better to test one mode twice than to test both modes. The time spent reversing the fans was not rewarded in an improvement. There was, however, about a 10% leakage difference between the two test modes and in some cases that would be important to consider. But if, for example, you want to measure a change in building tightness from remedial air-sealing it may be more efficient to specify just one test mode.

For the range of wind speeds encountered, there was no clear bias due to wind. There was an increase in the *estimated* precision errors but not enough data to observe an actual increase in errors due to wind. Studies of short term repeatability should be conducted for various building geometries in even higher wind speeds in order to bracket the conditions under which testing can occur.

There was an inexplicable shift in airtightness of about 10% (tighter in June than in November). Despite careful effort, it could be that there was a failure to replicate the test conditions between phases, or some other cause of a large concentrated leak which was different between test phases. It could also be that many leaks changed - effectively an overall change in permeability. Additional Studies should be conducted on other buildings of various construction types to look for seasonal changes in airtightness.

5. ACKNOWLEDGEMENTS

This authors wish to thank Mark Faultersack of Madison Gas and Electric, not only for getting us permission and access but also for helping significantly with the testing. Secondly, thanks to Peter Burns and Paul Morin of The Energy Conservatory for their assistance and the building owners and staff for their efforts.

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Stack Effect and Mechanical Exhaust System Impacts on Building Pressures and Envelope Air Leakage

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ABSTRACT

Air leakage through building enclosures is driven by air pressure differentials between the interior and exterior of a building. In a typical low-rise building, pressure differentials are primarily driven by transient wind effects – air is "pushed" in at the windward side and "pulled" out on the leeward side. On a calm day, even a relatively leaky building enclosure will experience only minimal air leakage due to low pressure differential. Conversely, many of the features of mid- and high-rise buildings, including height, can impact pressure differentials and thus air leakage. Stack pressure in tall buildings can lead to significant and relatively constant pressure differentials throughout the height of the building during cold weather, exacerbating air infiltration on the lower floors and exfiltration on the upper floors. Often more significant, however, is the impact of mechanical ventilation and exhaust systems, such as unit-by-unit ventilation, constant bathroom exhaust fans, and intermittent clothes dryer and kitchen exhausts. These systems can generate sustained pressure differentials with much greater impact than wind or stack pressure alone; they create internal airflows between units/spaces and floors, and constant (year-round) driving force for air leakage through the building enclosure. This paper discusses the physical phenomena that drive pressure differentials and air leakage in mid- and high-rise buildings, uses case studies and investigative examples to illustrate both the magnitude and impact of these phenomena, and provides guidelines for designing mechanical systems to control air pressure and minimize air leakage in these types of buildings.

KEYWORDS

Infiltration, Ventilation, Stack Effect, Exhaust, Air Leakage

1. INTRODUCTION

Air leakage in buildings can have many undesirable effects, including condensation, increased heating and cooling costs, noise, transfer of air-borne contaminants, and reduced occupant comfort. It follows that reducing air leakage has many benefits, hence the development of continuous air barrier industry guidelines, such as specifications from the Air Barrier Association of America, and local and national energy code requirements, including ASHRAE 90.1-2010: Energy Standard for Buildings Except Low-rise Residential Buildings and state-wide energy codes in Massachusetts, New York, Maryland, Washington, and others. While airtightness is important in all buildings, it is especially important in mid- and high-rise buildings due to the potential impact of leakage through the large enclosure areas, and the presence of mechanical ventilation and exhaust systems which can significantly impact building pressures – the driving force behind air leakage through building enclosures. Air leakage rates through building enclosures in low-rise buildings are relatively well understood, and these buildings are typically the most common subject of studies on the topic. In taller buildings, however, the magnitude of air leakage in "tight" buildings may still be much greater than that of a "leaky" low-rise building due to the effects of mechanically-induced pressure differentials. This paper reviews the driving forces behind air leakage in tall buildings, compares leakage in low-rise buildings to leakage in mid- and high-rise buildings, and discusses strategies for minimizing mechanically-induced pressure differentials as a means of controlling air leakage.

2. SUMMARY OF DRIVING FORCES

The driving force behind air leakage is a difference in air pressure between the interior and exterior of a building. Air will naturally flow from regions of high pressure to regions of low pressure. Just as a building with no roof covering will never leak if it never rains, a "leaky" building enclosure will only experience air leakage if a pressure differential exists.

Pressure differentials in buildings can be caused by three different phenomena. The most common, and the primary driver for air leakage in low-rise buildings, is wind. Wind creates a positive pressure on the windward side of a building, negative pressure on the leeward side, and varying pressures over surfaces parallel to the direction of flow, such as roofs and side walls. The effects of wind are intermittent and highly variable, as buildings rarely see constant, sustained winds for extended periods of time.

The second driver is a phenomenon known as "stack effect". Warmer air is naturally less dense than cooler air, so in a heated building in a cold climate, the air within will tend to rise. This effect is a function of interior/exterior temperature differentials and building height, so low-rise buildings rarely experience noticeable stack pressure effects. In a mid or high-rise building, especially in colder climates, stack pressure can be significant, often creating higher pressure differentials than wind, and for greater lengths of time. Rising air within the building "column" will create a negative pressure at the base of the building, where air is drawn in, and a positive pressure at the top, where air is forced out. The reverse is also true during warm weather, as cooler interior air tends to sink and create a negative building pressure at the top and positive pressure at the bottom. This effect is usually less pronounced due to the lower temperature differentials present during the cooling season (usually about 5 to 10ºC, as opposed to 25 to 35ºC during the heating season). For all buildings, there exists a point where the interior and exterior pressures are balanced. This point is known as the "neutral pressure level" or "NPL". For a single-zone building of any height, with no internal flow resistance, the NPL would be located at mid-height, halfway up the building. Real buildings contain interior components such as walls and floor partitions, as well as full-height shafts for utilities, elevators, and stairwells, which can significantly affect the location of the NPL. Data on the location of the NPL in tall buildings is sparse, but the available data suggest that the NPL is typically between 0.3 and 0.7 of the total building height (Tamura and Wilson 1966, 1967b).

The last, and potentially most significant driver of building pressure, is mechanical pressurization/depressurization. There are a wide variety of mechanical systems in modern (as well as many older) buildings that can influence building pressure by forcing air in or drawing air out of the space. These include ventilation systems (either dedicated outside air systems or smaller air handlers with outside air capacity), kitchen and bathroom exhausts, dryer and other equipment exhausts, and economizer systems on air handling equipment. Unlike wind, and to a lesser extent, stack effect, which are both transient phenomena, mechanical systems often run 24 hours per day and 365 days per year, creating a constant pressure differential between the interior and exterior and greatly exacerbating air leakage as a result. Mechanical systems are also the only one of the three phenomena that a designer can modify substantially to control air flow and leakage, and are the focus of this paper.

For reference, the three phenomena that impact building pressure and air leakage are shown graphically in Figure 1.

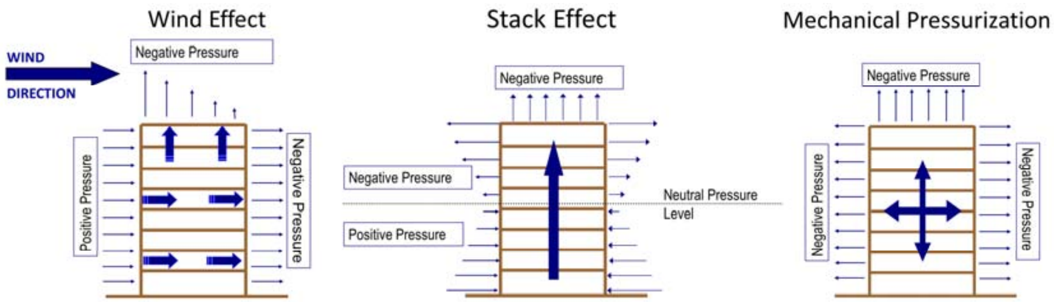

Figure 1 – Primary drivers of air leakage in buildings

3. STACK EFFECT

Stack effect in tall buildings is typically only a problem where mechanical systems (discussed in more detail below) fail to provide sufficient control over building pressures. In these cases, or in isolated cases within otherwise well-controlled buildings, stack effect can lead to significant air leakage into and out of buildings. Take the worst-case scenario of a 30m tall mid-rise building in Washington, DC, where the winter design temperature is approximately -10ºC. In a completely open building without floor or area separations, heating the building space to 21ºC during the winter results in a total potential stack pressure of nearly 40 Pa. That potential represents the greatest possible pressure differential that could occur due to stack effect within the building. If the pressure at the ground floor is neutral with respect to the exterior, this would mean a positive pressure of 40 Pa would be possible at the roof level. For an NPL at the mid-height of the building, the result would be a pressure of -20 Pa at the ground floor and +20 Pa at the roof (infiltration on the lower half of the building followed by exfiltration at the top).

It is important to note that for simple openings (“leaks”) in building enclosures, air leakage is relatively unaffected by the direction of airflow. This means that a hole in the building’s air barrier will generally allow the same amount of air leakage regardless of whether air is flowing into or out of the building. However, components such as windows and doors often rely on gasket compression for air and water sealing, and may experience different amounts of air leakage depending on the direction of flow. For example, under positive interior pressure the sash of an outswing casement window will be pushed away from the perimeter gaskets, reducing their air sealing effectiveness. Conversely, negative pressure will pull the sash in and provide greater compression of the gaskets, which may actually improve airtightness. The net result is that for tall buildings, stack effect may exacerbate air leakage in some areas while reducing it in others, depending on the specific enclosure systems being used on the building as well as their specific location.

4. MECHANICAL SYSTEMS IN TALLER BUILDINGS

Mid and high rise buildings often contain significantly more mechanical equipment than smaller, low-rise buildings. This is due to the sheer size of the buildings and the need for common equipment to handle bathroom exhaust, kitchen exhaust, and other air systems. Moving air over large vertical distances requires carefully designed ductwork, fans, and controls capable of providing balanced airflows to the spaces that the equipment serves. Unfortunately, these systems are often subject to generic design approaches that may be inadequate or inappropriate for specific building configurations and layouts. Well thought out designs are often considered excessive or unnecessary and end up being “value engineered” down to much less effective systems. Poor design and installation seem to be more common in residential-use buildings (including mid and high rise construction), which typically produce a greater number of problems related to air flow and air leakage. This paper will focus on multi-family residential buildings which have a large number of bathrooms, kitchens, and other features that result in much greater mechanical system airflows than similarly sized office and general commercial buildings.

4.1 Code Provisions

The 2009 International Mechanical Code (the “Code”), which forms the basis for many state and local codes, contains provisions for outside air supply and exhaust air systems. The Code requires all occupied spaces to be ventilated, but it allows ventilation to be provided by either natural or mechanical means. Mechanical ventilation requires specific flow rates for specific applications, and will generally result in more even and consistent ventilation of spaces as the systems can all be adjusted and balanced to provide the desired flows.   Natural ventilation simply requires providing a certain percentage of the occupied floor space as “openable area to the outdoors” (currently 4%), and provides highly variable and inconsistent airflow. In many cases, areas such as interior (windowless) bathrooms must be mechanically exhausted, but are allowed under the Code to draw makeup air from the adjacent spaces – which may be naturally ventilated using operable windows. This “hybrid” ventilation scheme, which is very common in tall residential buildings, can lead to a wide range of problems as discussed further in the following sections.

4.2 Outside Air Systems

A distinguishing feature of tall residential occupancy buildings is the typical reliance on operable windows to provide ventilation air to the spaces, as opposed to office and commercial spaces which are almost exclusively mechanically ventilated. The driver behind this difference is simple economics – adding mechanical ventilation to a commercial building with 5 to 10 air handlers is relatively simple, requiring localized components in the air handlers to control the flow of outside air into the recirculating airstream within the ducts. In contrast, a large residential tower may contain 50 to 100 units, each of which has its own air handling system (or other space conditioning equipment). The cost and logistics of providing dedicated outside air to each of those air handlers are often prohibitive, and almost always ends up being less than the cost of using operable windows, which may be in the design already, to meet code requirements for ventilation air. An additional contributing factor is the difficulty of accommodating large numbers of outside air intakes within the architecture of the building, especially for buildings with large glazed areas or monolithic facades.

4.3 Exhaust Systems

"Ventilation" for areas such as bathrooms is typically provided by exhausting air from the bathrooms and allowing makeup air to enter from the surrounding spaces. The Code allows either constant or intermittent exhaust to be used, with the intermittent requirements being 2-1/2 times higher than the constant requirements. However, as with the outside air systems, residential buildings rarely include dedicated (intermittent) exhaust for bathrooms as that option requires an independent, controllable fan in each unit as opposed to constant exhaust where a single fan at the roof level will accomplish the same end.

Other major exhaust systems include kitchen clothes dryer exhaust. The amount of exhaust for these systems is not specifically noted in the code, although for single installations, no make-up air is required for dryers exhausting less than 95 L/s or kitchen devices exhausting less than 190 L/s (less of a problem for kitchen systems that operate intermittently, but dryer systems with longer run times may be a bigger issue). Dedicated makeup air supply is required above those levels to prevent pressure imbalances, but typical residences will not have exhaust flows exceeding those limits. The Code does require makeup air for common dryer exhaust risers in multi-story structures, but individual dryers attached to the riser will still be drawing air out of the occupied spaces in their respective units even if the main riser has an opening to the exterior.

5. TYPICAL PROBLEMS

5.1 Design

The design of exhaust systems in tall buildings is fairly complex, as designers must account for moving air over large vertical distances, maintaining consistent flow through multiple inlets at different elevations, and accounting for stack pressures that vary from month to month and can upset airflow balances between floors. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) provides guidance for designing vertical duct runs to achieve balanced flow, but unfortunately these guidelines seem to be ignored more than they are implemented. In many of the buildings that the authors have investigated, exhaust risers consist of a straight, constant cross-section ductwork extending from the roof-mounted fan all the way to the ground level. In cases where balancing dampers are not installed at the inlets, the result is a disproportionate amount of airflow through the upper inlets, nearest to the fan, and little to no flow near the bottom of the shaft. This effect is magnified where the exhaust fan is oversized and produces greater-than-code-minimum exhaust flows, also a common occurrence. This produces strong negative pressures near the top of the stack, the opposite of what one would expect in a tall building where stack effect typically produces positive pressure in that location. Variable cross section duct and/or the use of balancing dampers are necessary to prevent these flow imbalances and generate a consistent exhaust flow at all levels.

In order to prevent excessive stack pressures from developing, buildings need to have relatively continuous horizontal partitions (at floor levels) to "compartmentalize" the interior space. In most cases, this happens by default rather than design, since floors often require fire and smoke seals at penetrations, etc. which also function as air barriers. Vertical shafts such as elevators, stairs, and duct/utility chases must be effectively isolated from the occupied spaces of the building using seals, gaskets, and fire doors to minimize their impact on building pressures. It is more common for unbalanced mechanical systems (supply or exhaust) to contribute to poor control over stack pressure more than the physical design of the building. Stack pressure is typically more of a localized effect, for example leading to moderate air leakage at the top of elevator shafts, which are often (by code) vented directly to the exterior. These shafts basically function as chimneys, drawing in warm building air from all areas and exhausting it to the exterior above the roof level.

We recently investigated a large, 20+ story condominium building in the mid-Atlantic region that exhibited strong negative pressures on the upper floors. The occupants on the upper floors complained of drafts, loud "whistling" noises near doors, and difficulty opening doors. We measured negative pressures, relative to both the corridors and the exterior, of 60 to 80 Pa on the upper floors, with pressures approaching neutral near the ground floor. The bathroom exhaust risers were constant cross section ducts for the full height of the building, with no balancing dampers or other provisions for adjusting airflows from the units. The corridors were supplied with dedicated outside air but did not have return or relief ducts, increasing the pressure differential to the units. The high negative pressures we observed were creating forces of over 100N on doors, making both interior (to the corridor) and exterior (to balcony) doors difficult to operate. Whistling was being caused by high speed airflows around the entry doors, which were fairly well-sealed due to the need for fire/smoke resistance but not completely airtight. Due to the high negative pressures, air leakage was significant in some areas of the enclosure despite the wall systems being relatively airtight.

This building was a classic case of imbalanced airflows leading to building-wide problems. In the case of the corridors, this was apparently intentional since there was no exhaust or return air to compensate for the supply. Although larger residential buildings often use the strategy of supplying ventilation air to the corridors which then supplies the individual units via door undercuts (which is oddly enough prohibited by most building and fire codes), this was not the design intent here as the units had sealed entry doors and specifically included operable windows to provide ventilation directly to the units. In the case of the bathroom exhaust risers, it was simply poor design which resulted in unacceptable pressure differentials. Remediation of these problems involved a combination of new balancing dampers at the bathroom inlets and removing sweeps from the unit entry doors (with building department approval) to allow the excess fresh air from the hallway into the units, helping to minimize pressure differentials by balancing out the bathroom exhaust flows.

5.2 Construction

The best-designed building will still fail to perform if that design is not properly implemented by the builders. In the same building discussed above, we observed a variety of construction errors that contributed to the pressure issues and in some cases made them more difficult to diagnose. The typical exhaust risers were enclosed in gypsum wallboard shafts, with branch ducts running to bathrooms on each floor. In the majority of these cases, the ductwork was stopped short of the surface-mounted intake grilles, resulting in large gaps between the duct and the inlet (Figure 2).

Figure 2 – Gaps between exhaust ductwork and surface mounted grilles (removed in this photograph)

In these cases, air was drawn through and around the gypsum wallboard shafts in addition to through the actual duct. When bathroom doors were closed, these gaps often presented the path of least resistance for air, as the bathroom doors were fairly tight and did not allow for makeup air to enter those areas (as is required by the Code). The net effect of these gaps was that exhaust shafts in one vertical "stack" of the building were affecting pressures in adjacent stacks of units as well. In one case, the only way we were able to reduce pressure differentials in a test unit (for diagnostic purposes) was to shut down exhaust fans in that stack as well as in the stacks of units on either side. Shutting down the stack in question produced a slight difference in pressure, but because adjacent, poorly sealed exhaust risers were still drawing air from the adjacent areas, moderate to significant negative pressure persisted.

Although not specifically a construction issue, mechanical contractors are often required to retain independent testing, adjusting, and balancing (TAB) firms to determine if the installed systems are functioning as intended. The design team needs to pay very close attention to this work and carefully review the resulting reports, as the TAB report will contain valuable information on the operation of the building. It also represents the "last chance" for designers to identify problems and make changes before the building is occupied. On most of the buildings that the authors have investigated, at least some of the problems that we were asked to solve were clearly identifiable in the TAB report but were never addressed by the design team.

5.3 Operation

Despite being allowed by the mechanical code, reliance on operable windows for ventilation is generally a poor strategy in terms of airflow control, pressure balancing, and air leakage. The primary reason for this is that there is no way to regulate the amount of ventilation air entering a space (i.e., the makeup air required to balance out exhaust flows) since the occupants of the unit have complete control over opening and closing windows.

With windows open and relatively mild exterior temperatures, the concept works well as the windows allow makeup air to enter the space and supply the various exhaust flows from the occupied space, all without increasing space conditioning loads or affecting occupant comfort.

In reality, conditions in most areas of the United States, especially the Northeast, are only conducive to natural ventilation for a limited amount of time – it is typically either too cold or too humid for naturally-ventilated spaces to meet the often-discerning preferences of occupants, especially in residential buildings. Even if comfort were not an issue, opening a window in January in a building in New York or Boston to provide makeup air for exhaust systems will introduce significant quantities of unconditioned outside air to the occupied spaces – increasing heating loads and reducing energy performance. In this one-sided approach, where air is exhausted but not specifically replaced using mechanical systems, there is no practical way to incorporate heat exchangers or heat recovery systems which are commonly used in fully mechanically ventilated buildings to reduce the inefficiencies associated with providing simultaneous fresh air and exhaust.

6. MAGNITUDE OF AIR LEAKAGE

As discussed previously, even at low pressure differentials, the constant nature of mechanically-induced pressure differentials creates significantly higher potential for air leakage as compared to transient or seasonal effects such as wind and stack pressure. To demonstrate this, we calculated potential air leakage rates for a building on which we recently performed whole-building air leakage testing. The building in question was a 16 story residential tower with approximately 60 individual units, built around 1960. We calculated a pressure-flow curve for the building, which allows us to determine the whole-building leakage rate at any pressure differential within the test results based on the overall area of the building enclosure (in this case, approximately 5,900 m^2). The tested air leakage rate for the building was 3.45 $L/s/m^2$ @ 75 Pa. For reference, current industry guidelines and some state building codes set the target for whole building leakage rate at 2.0 $L/s/m^2$ @ 75 Pa.

We used historical hourly weather data for a mixed Mid-Atlantic climate to calculate hourly wind pressures on the facade, and then used the pressure-flow curve from our testing and the overall area of the building enclosure to convert those into leakage rates. It is important to note that this approach will overestimate wind effects as the reported hourly values for wind speed will rarely be constant for the whole hour and pressure distribution over the façade area will not be uniform; the intent of this exercise was to provide a general comparison, not an exact calculation of air leakage. We used pressure differentials of 10, 20, and 30 Pa (a typical range of pressures for many of the buildings that we have investigated) to calculate leakage rates for the enclosure. The results of this comparison, shown in Figure 3, demonstrate the potentially significant effects of constant mechanically-induced air leakage when compared to intermittent wind pressures. It is important to keep in mind that the relative differences shown on this graph will exist regardless of the airtightness of the building enclosure; although the relative magnitude of leakage will be reduced in a tighter building, leakage due to mechanically induced pressure differential will still be much greater than that induced by wind alone. Similarly, the magnitude of leakage will change based on the exterior climate, but the relative differences between wind- and mechanically-induced air leakage will remain about the same.

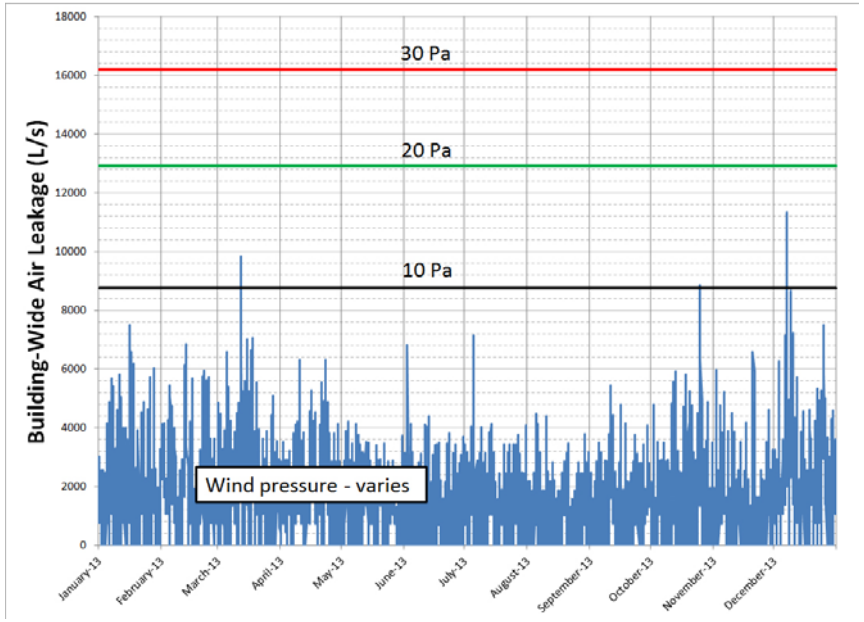

Figure 3 – Comparison of wind vs. mechanically induced air leakage

To further highlight the impact of mechanically induced air leakage, we next calculated the additional heating load on the building resulting from the quantities of air leakage shown in Figure 3, for both the wind-induced and mechanically-induced cases. For comparative purposes, we calculated the conductive heat losses for the building enclosure, using both the existing conditions (minimally insulated walls, single-glazed steel windows) and for an enclosure meeting the basic prescriptive requirements of the 2009 International Energy Conservation Code (IECC), using the maximum allowed value of 40% glazing for the exterior walls. Using the same hourly weather data for Washington, D.C., we calculated the conductive heat loss through the walls, windows, and roofs of the example building on an hourly basis. For an interior temperature of 21ºC, we summed the air leakage-related and conductive heat losses through the enclosure for the month of January. A comparison of these values is shown in Figure 4.

Figure 4 – Comparison of air leakage and conductive heat losses for the example building

This comparison demonstrates that mechanically induced air leakage can form a disproportionately high fraction of the overall heating load for a building, and greatly overshadow the increased heating loads associated with wind-driven air leakage only (as is more typical for low-rise buildings).

7. STRATEGIES TO ADDRESS AIR LEAKAGE AND REDUCE HEAT LOSSES

While improving building airtightness is always one of the first steps in reducing air leakage rates, as the above discussions demonstrate, controlling mechanically-induced pressure differentials is equally important, as it is unreasonable to expect any building to be perfectly airtight. , Some leakage will always occur as long as a pressure differential exists. Understanding the causes of pressure differentials in taller buildings is critical to controlling and reducing the resulting air leakage. Many of the strategies discussed below may be costly in comparison with typical residential building construction standards, but they are sound design guidelines which can significantly improve building performance:

- Provide continuous sealing of vertical shafts (“chimneys”) through the building to prevent stack pressure induced airflows and minimize stack effect over the height of the building. Although this is required by most codes, it is often poorly executed in the field.
- Do not rely on operable windows to provide makeup air for constant-run exhaust systems.
- Consider intermittent bathroom exhaust systems to reduce constant pressure differentials. Some minimal constant exhaust may be necessary to provide sufficient clearing of the exhaust stack, and additional equipment (independent fans in each bathroom) will represent an added project cost.

- For dryer exhausts, consider variable speed fans in the main exhaust riser to prevent the system from operating at full capacity when only a fraction (if any) of the dryers on the stack are active.
- If possible, provide dedicated makeup air, introduced mechanically, to individual units. The specific delivery method (ductwork, door undercuts, etc.) will depend on the details of the project, location of fire separations and rated partitions, and local building and fire code regulations.
- Design constant exhaust risers to provide balanced flow, whether by using variable cross-section ductwork or individual balancing dampers.
- Confirm, through review of field conditions and TAB reports, that the design is properly implemented and that airflows and pressure differentials are within expected limits.

8. SUMMARY

Based on the discussions and calculations discussed above, we conclude as follows:

- The operation of mechanical systems in tall buildings can lead to significantly higher pressure differentials than wind or stack pressure alone.
- Even properly functioning systems will lead to pressure differentials and air leakage; improperly functioning or imbalanced systems will create more significant problems and greater pressure differentials.
- Constant pressure differentials will induce air leakage that can be many times that produced by wind or stack pressure. The increased heat loss associated with this air leakage may far exceed the typical conductive heat losses from a building during cold weather.
- Eliminating excessive constant pressure differentials and using dedicated mechanical ventilation (as opposed to operable windows) are keys to reducing air pressure differentials that result in air leakage in tall buildings.
- Steps to reduce pressure differentials are often more expensive than more common, but less effective, systems and must be included early in the design process.

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FIELD EXPERIENCE WITH SEALING LARGE-BUILDING DUCT LEAKAGE WITH AN AEROSOL-BASED SEALING PROCESS

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ABSTRACT

This paper describes a limited set of large-building applications of a process that uses aerosolized sealant particles to seal leaks in duct systems, focusing in particular on sealing duct leakage in exhaust systems. The process was first commercialized for sealing residential ducts in the late 1990's, but has been applied increasingly to larger-building duct systems. The technology has been applied in a variety of large-building exhaust duct sealing applications, ranging from sealing leakage in large exhaust systems in laboratory buildings, to sealing leaks in exhaust systems in hospitals, to sealing toilet exhausts in large commercial office buildings, to sealing leaks in toilet/kitchen exhaust shafts in low- and high-rise apartment buildings and hotels. Observed initial leakage rates, sealing accomplished, and some of the issues encountered in these applications are presented. The rationales for having this leakage sealed are presented, as are some of the techniques applied when conducting this type of sealing. Overall, the average duct leakage encountered in these buildings was 28% of fan flow, and aerosol process sealed over 90% of that leakage.

KEYWORDS

Aerosol, duct, exhaust, sealing, shafts

1. INTRODUCTION

Over the past 15 years, the subject of duct leakage in buildings other than single family residences has received considerable attention by various researchers (Cummings et al 1996, Delp et al 1998, Delp et al. 1998b, Franconi et al. 1998). This work has included characterizing the stock of duct systems in large commercial buildings (Modera et al. 1999), characterizing duct leakage levels and efficiency metrics for commercial-building thermal distribution systems (Diamond et al. 2003), field testing the impact of supply duct sealing in an office building (Diamond et al. 2003) and a light commercial building (Sherman et al. 2002), as well as the development and application of an aerosol based sealing technology applicable to large commercial buildings (Diamond et al. 2003).

Duct-system research at Lawrence Berkeley Laboratory (LBNL) also resulted in the development of a technology for sealing duct leaks from the inside by Carrie and Modera (Carrie and Modera 1998, Modera et al. 1996). This technology seals leaks in ductwork from the inside by pressurizing the duct system with a fog of atomized sealant particles. By temporarily blocking all the normal exits from the duct system (as well as any coils or fans) the fog is forced to the leaks. The acceleration of the air through the leaks causes the sealant particles to leave the air stream and deposit on the leak edges. By the right choice of particle size, duct flow rate and duct pressure, the particles remain suspended as they travel through the duct system, and thus only a very small fraction of the particles deposit on the duct walls.

The aerosol sealing technology was initially applied to single-family residences, becoming commercially available for that market in 1999. The first commercial applications of the technology in large buildings started in 2003 with the introduction of a new atomization technology that significantly increased sealing rates, and allowed the sealant to be atomized inside the ductwork instead of externally.

This paper presents some field experiences and results related to sealing exhaust systems in large buildings. The issues touched upon include: 1) impetus for sealing, including duct leakage identification, 2) measured duct leakage levels, 3) duct sealing results, and 4) some techniques applied to accomplish this sealing.

2. IDENTIFYING LEAKAGE IN LARGE BUILDINGS

The impetus for duct sealing in large buildings can come from several different driving forces: 1) test and balance reports that indicate duct leakage and/or inadequate zone flows, 2) code driven requirements for flows or pressures for new construction or renovation, 3) comfort and/or pressure control complaints, and sometimes 4) a desire to save energy. These sources are more or less listed by frequency of occurrence. In general, knowing whether the ducts in an existing large building are leaking is considerably more difficult and expensive than uncovering duct leakage in single family residences. Test and balance reports provide a reasonably certain indication of leakage, however such measurements are generally too expensive to be performed solely to look for duct leakage. Some simplified techniques for quantifying duct leakage in specific applications have been developed, in particular for measuring leakage downstream of VAV boxes (Modera, 2007), and for estimating leakage in modest-length bathroom exhaust shafts.

2.1. Observed Impetus for Sealing Duct Leakage

For the buildings listed in Table 1, which represent a modest subset of the large-building exhaust systems that have been sealed over the past several years, there were several different reasons why the building owner decided to have sealing performed. In the case of the hotels, the reason for sealing varied. For Building 1, which was new construction, the driving force was a need to pass exhaust-duct leakage criteria that turned out to be tighter than the initial construction could pass. For the other two hotels, the driving force was to assure that the pressure-independent bathroom grilles being installed would have enough pressure to work properly.

The rationale for sealing leakage in exhaust shafts in apartment buildings (Buildings 4-7) included a desire to save energy, a desire to provide more uniform (temporal and spatial) ventilation, and in the case of Building 7, a desire to produce the desired ventilation when switching the shafts from naturally driven to fan-driven flow. In other instances, the rationale has been to reduce overall ventilation rates (e.g. as allowed by code changes in New York City), without risking unreasonably low ventilation rates in some apartments, or under some weather conditions.

In the case of the toilet exhaust in the office building, the driving force for sealing was to address tenant complaints about odors in the men's and women's restrooms. For the hospital denoted as Building 9, the driving force was to meet the exhaust flow requirements needed for occupancy, which were not being met based upon flow measurements at the grilles. For the laboratory building (Building 11), the driving force was a desire to save energy. In such a building, as in a hospital, the HVAC systems are typically single-pass (i.e. 100% outdoor air), which means that any unnecessary exhaust needs to be made up with additional outdoor air that needs to be heated or cooled. In addition, significant fan power savings are made available in such a building by the fact that fan power scales with the cube of the volume flow rate in an exhaust system.

Table 1: Examples of Buildings Seeking Exhaust Duct Sealing

Building Type	Bldg.	Bldg. Age	Bldg. Size [m^2]	Bldg. Stories	Location	Exhaust System
Hotel	1	2007	~150,000	57	Las Vegas, NV	Bathroom
	2	2005	>200,000	45	Las Vegas, NV	Bathroom
	3	2008	>100,000	63	Las Vegas, NV	Bathroom
Condominium/Apartment/Dormitory						
Condominium	4	1971	~70,000	40	Boston, MA	Bath/Kitchen
Dormitory	5	2003	4,600	6	Columbus, OH	Bathroom
Apartments	6	1979	~25,000	23	Camden, NJ	Bath/Kitchen
Apartments	7	1960s	N/A	5	Bordeaux France	Bathroom
Large Office Bldg.	8	1958	300,000	59	New York City	Toilet (one section)
Hospital	9	N/A	N/A	6	San Francisco, CA	General
	10	2012	29,000	3	Abu Dhabi, UAE	General
Laboratory	11	~1965	~4,000	2	Berkeley, CA	General

3. SEALING LEAKAGE IN LARGE BUILDINGS

Some of the sealing data from the buildings identified in Table 1 is summarized in Table 2. In general sealing ducts in large buildings (exhaust systems or otherwise) with aerosol injection is considerably more complicated than sealing ducts in single family homes. For example, sealing exhaust shaft/duct leaks in a multi-family apartment building requires simultaneous access to all of the apartments being served by a specific shaft, which means that occupants must be informed in advance. In addition, in such an application, it is essentially impossible to completely vacate the building during injection, which means that extra care needs to be taken. This problem is easier to handle in a hotel, where the management can select the rooms to be left vacant.

Another issue in tall buildings is the stack effect created by the temperature differential between indoors and outdoors. The stack effect both creates measurement issues (not being sure exactly where to measure the pressure difference between the ducts and their surroundings), and minimal or even negative pressure differentials across the duct walls (which can make the sealing process slow or even impossible). Both of these problems are reduced or eliminated by performing the sealing process at a larger pressure differential, thereby reducing the relative magnitudes of the stack effect.

It should also be noted that there is a distinct advantage associated with sealing vertical ducts/shafts with an aerosol, namely that because the ducts are vertical, the issue of aerosol particles settling onto the bottom of the duct due to gravity essentially goes away. As long as the injection is performed from the top of the ductwork, gravity essentially helps transport the particles to furthest leaks, as opposed to robbing some particles along the way as in a horizontal duct system.

The standard of care is also elevated in a hospital situation, where vacancy is generally not an option, and neither is dispersion of aerosol particles. In the case of Building 9, the sealing process was initiated, and was found not to provide any reduction in leakage. As there appeared to be no good reason for why it did not seal, a camera was dropped down the shaft to look for a gross leak in the system. As it turned out, the problem was an open access door to the duct, one that the long-term building operators claimed did not exist until it was found with the camera and shown to them. In this case, the size of the opening for the access was determined to be roughly large enough to account for the measured leakage flow (~4000 cm^2), and remobilizing to seal the remaining leakage was deemed not to be cost effective.

The laboratory system that was sealed presented some additional complications. These complications included the fact that, like many laboratory buildings, it contained ongoing experiments, some of which are sensitive in nature, and included expensive non-standard equipment. This sensitivity sometimes included access issues, such as to rooms with biological or radiation hazards, or potentially with lasers in operation. This necessitates good communication with the individual investigators in the building, preferably through a trusted building manager. Another challenge encountered in this particular building was the fact that the entire duct system had to be sealed all at once, which entailed blocking all 80 grilles, spread over 4,000 m^2, simultaneously. This necessitates a large crew, and a well-organized system to assure that no grilles were missed. This issue is particularly problematic in a large system with many grilles, as a missing block typically changes the total leakage sensed by the sealing system by only a few percent.

Table 2: Exhaust-System Sealing Results

Building	Nominal Fan Flow [l/s]	Estimated Average Leak Pressure [Pa]	Effective Leakage Area [cm^2]	Estimated Fractional Leakage [%]	Fraction Sealed [%]
1	35,000 (est.)	100	3900	16%	97%
2	128,000 (est.)	50	47,800	36%	93%
3	48,000 (est.)	50	13,700	28%	92%
4	30,000 (est.)	25	11,000	24%	96%
5	7,300	500	512	27%	95%
6	14,500 (est.)	25	8190	36%	81%
7	N/A	80	58	N/A	89%
8	20,400 (treated section)	250	1630	20% (treated section)	96%
9	N/A	N/A	N/A	N/A	0%
10	17,900	250	2340	34%	85% (est.)
11	10,400	150	1670	31%	85%

3.1. Example Sealing Results – Large Office-Building Toilet Exhaust

One sealing application was chosen to be presented in a bit more detail, as this application involved some previously un-encountered issues. The application involved sealing the exhaust ductwork for a large Class-A office building in Manhattan (New York City). The results presented are only for one section of that sealing application, as the remaining data was not immediately accessible. The section reported on is a horizontal run in a mechanical story of the building, combined with a 15-story “express” duct run used to ventilate toilets at least 15 stories below the mechanical story. The nice part of this application was that most of the ductwork was vertical; however because of the size of the building, there was still a long horizontal section on the mechanical story.

The two key issues associated with sealing a large duct system are: a) assuring that an adequate pressure differential can be produced across all the leaks in the system, and b) assuring that the velocity in the horizontal sections is high enough to keep the particles from settling out by gravity. In general, the minimum pressure differential across the leaks for sealing is 10 Pa, however minimum pressures of 25-50 Pa are desired, particularly in a tall building, where the stack effect can change that pressure differential significantly between the top and bottom of the vertical run. The pressure produced by the sealing equipment is a function of the maximum flow that it can provide, as well as by the leakage of the duct system. As the standard fan on the aerosol system can produce a maximum flow of roughly 300 l/s, the most leakage that it could address while maintaining 25 Pa would be roughly 300 l/s@25Pa, which translates to roughly 450 cm^2 of effective leakage area. As the leakage of the treated section of Building 8 has more than three times this leakage (Table 2), it is clear that four separate aerosol system fans would be required.

Turning to the second constraint, the need to maintain adequate velocity to avoid gravitational settling, for the purposes of this paper we will use a target of 1 m/s for that velocity, at least at the beginning of the sealing process. Thus the minimum aerosol fan capacity could also be determined by the cross-sectional area of the ductwork, combined with this 1 m/s target velocity. In this building the horizontal ductwork had a cross-sectional area of roughly 2 m^2, which means that we would need roughly 2000 l/s to produce 1 m/s, or in other words seven aerosol system fans. As this is not a practical or efficient solution, we chose to instead to employ a calibrated “blower-door” fan that can produce up to almost 4,000 l/s under free-air conditions. As these “blower-door” fans are not generally calibrated to operate against the large back pressures associated with the aerosol sealing process (e.g. up to 500 Pa), we had to ask the manufacturer for a special calibration of the fan. In the end, a combination of one aerosol system fan and one blower-door fan (Figure 2) is what was employed in this application, resulting in the sealing plot illustrated in Figure 1. Note that the breaks in the curve correspond to changing the injection point for different portions of the section being sealed.

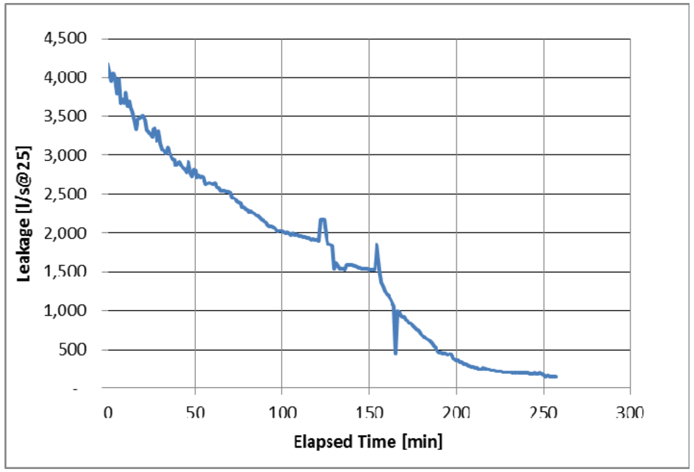

Figure 1: Leakage versus elapsed aerosol injection time for upper section of office-building toilet exhaust that moves 20,400 l/s (Building 8 in Tables 1 and 2)

Figure 2: Blower-door fan being applied in combination with the aerosol sealing system (Building 8 in Tables 1 and 2)

4. CONCLUSIONS

This paper provides a quick look at some of the large-building exhaust duct sealing that has been performed recently with an aerosol-based remote sealing technique. It describes some of the reasons why this sealing was performed, as well as some of the issues encountered in these applications. Based upon what is presented, it is clear that duct leakage was significant in all these applications (averaging 28% of fan flow), and that the aerosol-based sealing process was able to seal roughly 90% of the leakage encountered in small to very-large exhaust systems.

5. ACKNOWLEDGEMENTS

The author would like to thank Aeroseal LLC, and in particular Neal Walsh for assembling the data from the office-building sealing application, as well as Rick Papetti for compiling data on various buildings.

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ANALYSIS OF THE NIST COMMERCIAL AND INSTITUTIONAL BUILDING ENVELOPE LEAKAGE DATABASE

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ABSTRACT

In 1998, NIST published a review of commercial and institutional building airtightness data that found significant levels of air leakage and debunked the "myth" of the airtight commercial building (Persily 1998). Since then, NIST has expanded and maintained a database of whole building envelope leakage measurements of U.S. commercial and institutional buildings. In addition to building leakage values collected from research publications, low-energy building programs and private pressurization testing firms, the database includes basic building characteristics such as year built, building type, floor area, number of stories, location, and wall construction type for many of the buildings. The purpose of the database is to establish default values for building simulation, to estimate the energy savings potential of airtightness requirements in standards and codes, and to identify opportunities for additional improvements in building airtightness performance. This paper presents an update of the currently available airtightness data from the NIST commercial building air leakage database.

The U.S. commercial building envelope leakage database now contains data for almost 350 buildings including more than 50 constructed in the past decade. The data were analysed to determine the impact on airtightness of factors such as building type and height. Significantly, recent additions to the database include numerous buildings constructed to meet the specifications of sustainable or high performance building programs such as the U.S. Green Building Council's LEED rating system as well as buildings designed and constructed with air barriers, both of which tend to correlate with lower building envelope air leakage.

KEYWORDS
Airtightness, air barrier, fan pressurization test, infiltration, sustainable buildings

INTRODUCTION

As described by Chan et al. (2012), the U.S. National Institute of Standards and Technology (NIST), along with other research institutes in the Czech Replubic, France, Germany, the United Kingdom and the USA, maintains a database building air leakage measurements. The NIST database focusses on whole building tests of commercial and institutional buildings and is maintained for the purposes of establishing default values for modeling (Ng et al. 2013), estimating the energy savings potential of improvements via standards and codes (Emmerich et al. 2005), and identifying progress needed in improving building airtightness. It includes basic building characteristics such as year built, floor area, number of stories, location, and wall construction type for many of the buildings, though this information is not always available from the original data sources. This paper presents the currently available airtightness data from the NIST database.

Past NIST efforts have demonstrated that, despite assumptions to the contrary, typical modern U.S. commercial building envelopes are not particularly airtight (Persily 1998, Emmerich and Persily 2011), building envelope leakiness results in a significant energy cost (Emmerich and Persily 2005), and substantial energy savings would result through the requirement of an effective air barrier for new commercial buildings (Emmerich et al. 2007). This work has led to the consideration and adoption of prescriptive air barrier requirements in a number of building standards, codes, and programs (e.g., ASHRAE Standard 90.1, the USACE, and several states in the U.S).

The airtightness of building envelopes is measured using a fan pressurization test in which a fan is used to create a series of pressure differences across the building envelope between the building interior and the outdoors. ASTM Standard E779 (ASTM 2010) is a test method that describes the fan pressurization test procedure in detail, including the specifications of the test equipment and the analysis of the test data. In conducting a fan pressurization test in a large building, the building's own air-handling equipment sometimes can be employed to induce the test pressures. A Canadian General Standards Board test method, CGSB 149.15, describes the use of the air-handling equipment in a building to conduct such a test (CGSB 2010). Typically, the test results are reported in terms of the airflow rate at some reference pressure difference divided by the building volume, floor area or envelope surface area. While traditionally most of the data available to NIST was normalized by above-grade surface area (i.e., 5-sided box), many U.S. codes and standards now prescribe requirements normalized by total enclosure surface area (i.e., 6-sided box).

The airtightness values in the database are collected from a number of different sources that use a variety of units and reference pressure differences. The results are presented here as airflow rates at an indoor-outdoor pressure difference of 75 Pa normalized by either the above-grade or total surface area of the building envelope. For some buildings in the database, complete dimensions were not available for the conversion between above-grade and total (e.g., due to the lack of specific details on the below-grade wall area). For these buildings, an assumption was made that there were no below-grade walls and the conversion was based merely on adding the footprint of the floor slab to the building envelope surface area. When these data were lacking, a conversion factor of 1.5 was used for the ratio of the 6-sided to 5-sided envelope surface area based on the average value for other buildings in the database. Also, when necessary, conversion of air leakage at a pressure other than 75 Pa is based on an assumed pressure exponent value of 0.65. The values of envelope airtightness are given in units of $m^3/h{\cdot}m^2$, which can be converted to cfm/ft^2 by multiplying by 0.055. In cases where existing buildings were tested in both before and after airtightness retrofit, only the before (or as-found) value is included in the database. A future paper will address the impact of such retrofits on airightness.

DATABASE AND ANALYSIS

Table 1 contains a summary of the air leakage data for the 345 U.S. commercial and institutional buildings included in the NIST database. Significant sources of new data since Persily and Emmerich (2011) include 41 buildings built or renovated under the Efficiency

Vermont program which provides technical assistance and financial incentives to help Vermont households and businesses reduce their energy costs, 16 recently built mid- and high-rise buildings tested under ASHRAE research project 1478, 38 additional buildings located primarily in Vermont and New Hampshire which were tested by several building envelope consultants, 18 buildings in Washington state that were tested due to a local code requirement that includes a non-mandatory target airtightness level, and three other buildings (12, 16). The buildings in the database were tested for a variety of purposes and were not randomly selected to constitute a representative sample of U.S. commercial buildings.

In the past, the NIST commercial building air leakage database did not include many buildings known to be designed or constructed with the intent to achieve a tight building envelope. This update however includes many such buildings. However, the database does not include several hundred buildings designed, built and tested to meet the USACE maximum whole building airtighness specification of 4.5 $m^3/h\ m^2$ at 75 Pa based on the entire building enclosure area including the slab and any below grade walls (USACE 2009). The USACE buildings are tested and improvements to airtightness are made if they fail to meet the standard.

Table 1. Summary of Building Airtightness Data

		5-sided Air Leakage at 75 Pa ($m^3/h·m^2$)				6-sided Air Leakage at 75 Pa ($m^3/h·m^2$)			
Dataset	Qty	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
Efficiency Vermont	36	9.6	10.3	0.7	48.4	6.4	6.9	0.5	32.3
ASHRAE RP 1478	16	7.0	5.0	1.4	20.4	5.3	3.7	1.0	13.6
Washington	18	10.5	4.1	3.0	17.5	7.2	2.8	2.0	11.6
Other VT/NH	38	11.3	9.5	1.4	45.9	7.2	5.7	0.9	26.0
Other	9	8.8	6.6	2.6	22.7	9.0	5.7	4.3	1.6
All new data	**117**	**9.9**	**8.5**	**0.7**	**48.4**	**6.6**	**5.4**	**0.5**	**32.3**
All buildings	**344**	**19.8**	**19.2**	**0.7**	**124**	**13.3**	**11.8**	**0.5**	**77.9**

Note : Convert to cfm/ft^2 by multiplying by 0.055

Table 1 presents a summary of the airtightness values for the buildings in the database, with seaprate summaries using 5-sided and 6-sided surface area normalizations. As seen in the table for 5-sided normalization, the average air leakage at 75 Pa for the 344 buildings is 19.8 $m^3/h·m^2$, which is 20 % tighter than the average of 24.8 $m^3/h·m^2$ for the U.S. buildings included in the earlier analysis by Emmerich and Persily (2011). Calculated flow exponents were available for 149 of the buildings with an average of 0.62 and a standard deviation of 0.086. Figure 1 shows a frequency distribution of the normalized building air leakage (based on 6-sided enclosure).

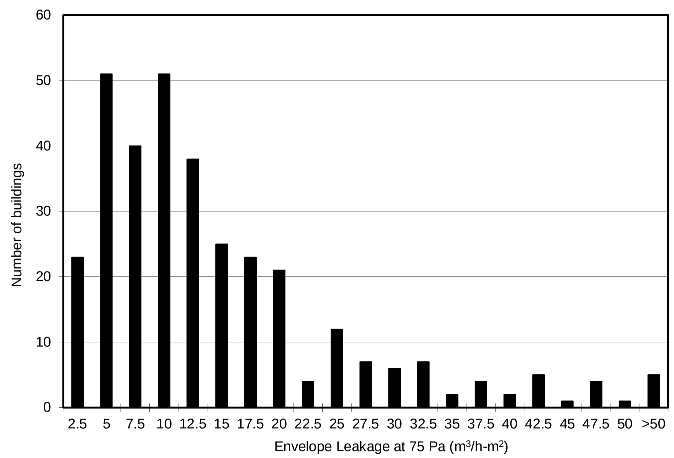

Figure 1 Frequency distribution of normalized building air leakage (6-sided enclosure)

Impact of air barrier

The most significant feature of the additional buildings in the database is that a majority are buildings in which there is reason to believe some care was taken to achieve a tight building envelope, including both many new buildings and several retrofit cases. This is in sharp contrast to the buildings included in past publications in which very few of the buildings were identified as such. A wide variation exists among the measures taken to limit or reduce air leakage among these buildings and detailed descriptions of the air barrier or measures are rarely available. Some of the new buildings would not fully meet the air barrier requirements of standards such as ASHRAE Standards 90.1 or 189.1 while others would exceed those requirements by having a high degree of attention to airtightness during design, construction and commissioning. However, very few of the buildings had a specific mandatory airtightness limit such as that required by the USACE. Buildings counted as having an air barrier for the purposes of this analysis included those with an air barrier identified as part of the design by the building tester, buildings participating in the Efficiency Vermont program, those known to have used a building envelope consultant, and those in Washington state with a code requirement for an air leakage test but with a non-mandatory target value.

Figure 2 show the measured leakage at 75 Pa (normalized to 6-sided enclosure area) of the buildings with and without an air barrier designation as described above. Existing buildings tested after air sealing are excluded from Figure 2 and will be addressed in a future publication. As shown in Figure 2, the average of 5.4 ± 4.0 $m^3/h·m^2$ for the 68 buildings with an air barrier is 66 % less than the average of 16.1 ± 12.6 $m^3/h·m^2$ for the buildings without one. Despite the wide range of attention to airtightness among these buildings, the standard deviation of the leakage for the buildings with air barriers is also much smaller than the non-air barrier buildings, thus, making the air leakage of such buildings more predictable. However, it is still difficult to predict an expected level of airtightness from a specific air barrier approach due to the lack of detail on the air barriers for most of these buildings.

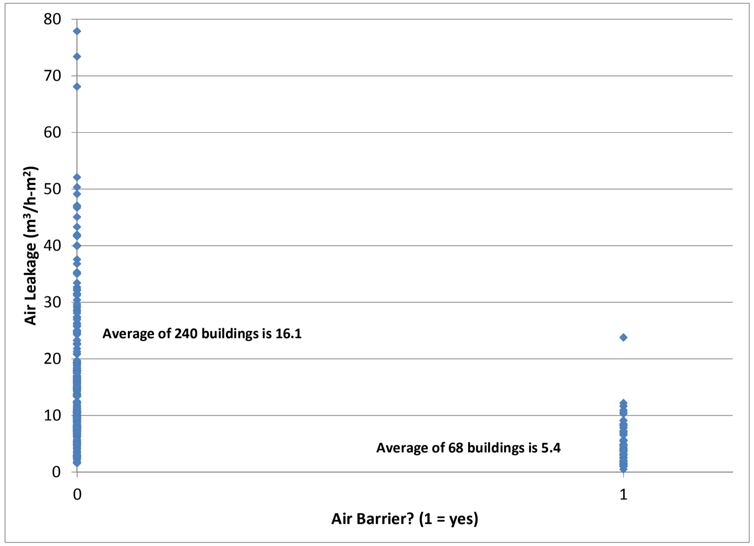

Figure 2 Normalized building air leakage (6-sided enclosure) of buildings with and without air barrier

Other Factors

The airtightness data were also analyzed to assess the impact of a number of factors on envelope airtightness including number of stories and building type. It is important to note that the lack of random sampling and the small sample size limits the strength of any conclusions concerning the impacts of these factors. As mentioned previously, not all of these parameters were available for all buildings in the database.

Past analsysis has shown that the air leakage at 75 Pa shows a tendency toward more consistent tightness for taller buildings (Emerich and Persily 2005 and 2011). However, data was available for relatively few buildings of 4 stories or more which limited the robustness of this evaluation. ASHRAE Research Project RP 1478 was initiatied to help address this lack of data, and, largely due to the results of that project, the number of mid- and high-rise buildings in the data base has more than doubled. Figure 3 is a plot of the air leakage at 75 Pa (normalized by 6-sided enclosure surface area) vs. the reported number of stories of the building. These data still shows a tendency toward more consistent tightness for taller buildings (one building over 16 stories is not shown). The average leakage for the 29 buildings of 4 or more stories is 7.7 ± 5.1 $m^3/h{\cdot}m^2$, while the average for the 268 buildings of 3 or fewer stories is 15.1 ± 12.4 $m^3/h{\cdot}m^2$. As before, the shorter buildings display a wider range of building leakage. The number of stories is not reported for the remaining buildings.

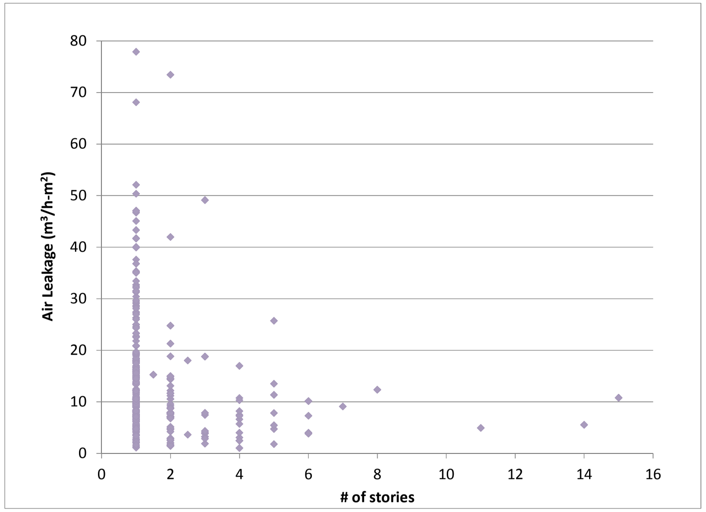

Figure 1: Normalized building air leakage vs. height of building (in stories)

Figure 4 is a plot of the air leakage at 75 Pa (normalized by 6-sided enclosure area) vs. building type for 303 of the buildings from the database (only categories with at least 10 buildings are shown). The average air leakage ranges from a low of 11.9 ± 9.2 $m^3/h{\cdot}m^2$ for education buildings to a high of 20.0 ± 11.6 $m^3/h{\cdot}m^2$ for restaurants. While the data suggests that restaurants and industrial buildings are leakier than the other types (office, education, retail, public assembly, and long-term healthcare which are all very similar), the large standard deviations for the individual categories do not support any firm conclusions.

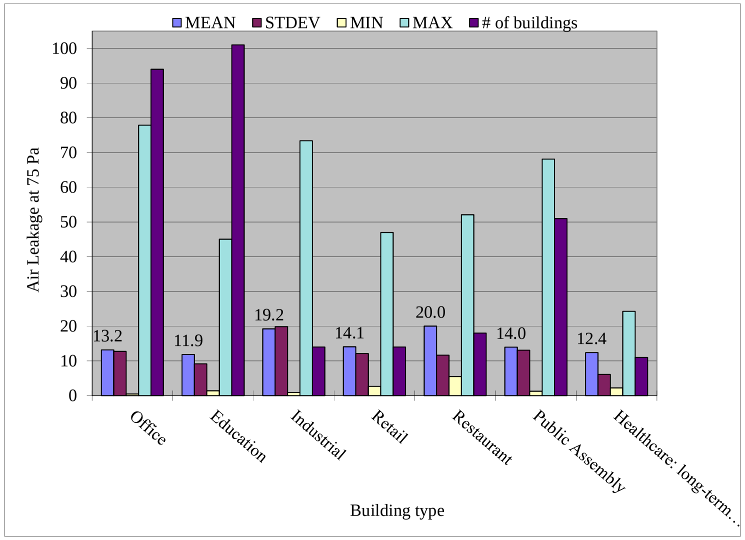

Figure 4: Normalized building air leakage vs. Building type

The recent additions to the database also include numerous buildings constructed to meet the specifications of sustainable or high performance building programs such as the U.S. Green Building Council's LEED rating system (USGBC 2009). The average leakage at 75 Pa (normalized by 6-sided enclosure area) was 5.2 ± 3.6 $m^3/h{\cdot}m^2$ for the 17 buildings reported with various green labels compared to the average of 13.7 ± 11.9 $m^3/h{\cdot}m^2$ for the 327 buildings not identified as « green buildings ». However, one should not draw the conclusion that these buildings are tighter *because* they have green building labels since the 17 green buildings overlap substantially with other factors shown above to correspond to reduced air leakage. Specifically, 11 of them have air barriers and 11 of them are 4 stories or taller; also, until recently, most green building programs paid little attention to building airtightness.

CONCLUSION

Past NIST efforts have demonstrated that, despite assumptions to the contrary, typical modern U.S. commercial building envelopes are not particularly airtight, building envelope leakiness results in a significant energy cost, and substantial energy savings would result through the requirement of an effective air barrier for new commercial buildings. The average airtightness of the 345 buildings currently available in the NIST database is about 20 % tighter than the average based on 228 buildings reported by Emmerich and Persily in 2011. The data show only weak trends related to height or building type, but do demonstrate that buildings designed and constructed with attention to airtightness are much tighter than typical commercial buildings. The wide variation among the measures taken to limit or reduce air leakage among these buildings and the lack of detailed descriptions of the air barrier make it difficult to predict a specific level of airtightness that will result from a specific air barrier approach.

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PAPER TITLE
Practical experience with airtightness testing of large buildings in Norway

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More than 35 years of theoretical and practical test of buildings with BlowerDoor and Thermography.

ABSTRACT

Combined airtightness measurements and IR thermography inspection have become increasingly popular in Norway because of problems related to the airtightness of the wind stopper and/or the vapor barrier. This presentation will focus on large buildings that have specific challenges for airtightness design and testing.

According to measurement standard EN 13829 “Thermal performance of buildings. Determination of air permeability of building. Fan pressurization method” which is widely used in Europe, a large building is a building whose volume is greater than 4000 m^3. In practice however, buildings are considered as large for airtightness pressurization tests when you need more than one common commercially-available fan to test them.

We will discuss recurring problems in large buildings in Norway based on practical experience. We will also explain airtightness testing procedures in pre-fabrication processes where we test:

- the airtightness of the element itself at the factory;
- the element when delivered to the building site to check if anything has happened through transportation;
- the first elements when they are assembled to see that the connections work.

We normally combine airtightness measurements with thermography inspection. Combining these two methods gives the airtightness metric and at the same time the location of leakage paths, if any. This has become more and more popular in Norway.

Friday 19 April 2013

11:45-12:45 (13:00) Session 8: Data collection, perspectives

1. Improving Building envelope and duct airtightness of US dwellings – the current status of energy retrofits, Wanyu R. Chang, LBNL, USA
2. Achieving and Certifying Building Envelope Air Tightness with an Aerosol-Based Automated Sealing Process, Mark Modera, UC Davis, USA
3. The effect of air tightness on the energy consumption - Analyses of field measurements. Wouter Borsboom, TNO, Netherlands
4. Workshop summary, Andy Persily, NIST, USA

IMPROVING BUILDING ENVELOPE AND DUCT AIRTIGHTNESS OF US DWELLINGS – THE CURRENT STATE OF ENERGY RETROFITS

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ABSTRACT

We analyzed the building envelope and duct system airtightness of US single-family detached homes, manufactured homes, and multi-family homes, before and after energy retrofits. These data are part of the Lawrence Berkeley National Laboratory Residential Diagnostics Database (ResDB). Weatherization assistance programs (WAPs) contributed 21,140 paired blower door measurements of building envelope air leakage, and residential energy efficiency programs contributed another 10,000 paired measurements. Eighteen states are represented. There are fewer duct blaster measurements to characterize the duct systems air leakage. Pre- and post-retrofit measurements are available from only 460 homes located in California and Nevada for this analysis. The overall improvement in building envelope airtightness from energy retrofits is 20 to 35% (median). The levels of improvement varied slightly from states to states, and also between program types. Larger improvements were observed among WAPs homes, and in particular those that were very leaky before the energy retrofit. In contrast, the duct leakage data show improvements that varied substantially by programs. Based on total duct leakage data from California only, non-WAPs homes that were retrofitted by energy efficiency programs showed a median reduction in duct leakage of 75%. On the other hand, WAPs only showed improvements in the 25% range. This is evident of some of the programmatic differences that influenced the retrofit outcomes. For example, WAPs are required to demonstrate savings-to-investment ratio, which may put duct airtightness improvement work a on less favorable term. In contrast, residential energy efficiency programs have more flexibility in work scope and budget to replace inefficient heating and cooling equipment, which is more likely to lead to an overhaul of the duct systems. Estimates of airtightness improvements are useful for calculating the energy savings and cost-benefit of air sealing as a way to improve the energy efficiency in US homes. In addition, this analysis shows that there is a small fraction of retrofitted homes by energy efficiency programs that have post-retrofit airtightness exceeding 15 ACH50 for building envelope, and 12 CFM25 (per 100 ft^2 of conditioned floor area) for duct leakage. Among the WAPs retrofitted homes, about one-fifth of the homes exceeded 15 ACH50 post-retrofit, and three-quarter exceeded 12 CFM25. These leakage values are far higher than levels that are considered as acceptable airtightness even for existing homes. This shows that there are opportunities to increase the energy saving potentials of energy retrofit programs if these inadequacies can be identified and improved.

KEYWORDS

Blower door; duct blaster; fan pressurization test; weatherization; energy efficiency

1. INTRODUCTION

Airtightness testing of building envelope and duct system are frequently performed to show the improvements from energy efficiency retrofits. The Weatherization Assistance Programs (WAPs) under the American Reinvestment and Recovery Act (ARRA) of 2009 had led to a large number of building envelope and duct system airtightness testing before and after retrofits. Between 2002 and 2007, the average number of income-qualified homes weatherized per year was about 100,000 (DOE 2010a). Under ARRA, over 600,000 homes were weatherized in less than two years (DOE 2010b), as of November 2011. In addition, many states have utility sponsored energy efficiency programs that give their customers incentives to preform home energy upgrades. In many cases, such programs follow the Home Performance with ENERGY STAR (HPwES) guidelines. HPwES is implemented in over thirty states in US. Since its launch in 2001, 200,000 homes had performed energy upgrades under HPwES (EPA 2012).

There are significant differences between WAPs and HPwES type of energy efficiency programs in terms of funding sources, eligibility criteria, target households, etc. But common to all energy retrofits are some measures that aim to reduce air leakage, including air sealing joints, seams, and penetrations, attic openings, rim joints, and weatherstripping (Baechler and Love, 2010). Polly et al. (2011) evaluated the variety of energy efficiency options and predicted their energy saving potentials for the US housing stock in the different climate zones. Their evaluations are based on the modeling assumptions that energy efficiency measures can reduce the whole-building envelope air leakage by half, from 19 ACH50 to 10 ACH50. Polly et al. (2011) referenced the HPwES website (EPA, 2013) that states: "EPA assumed that a knowledgeable homeowner or contractor could cost-effectively", and where a 55% reduction post-retrofit is estimated from the following statement (EPA, 2013): "An average documented baseline value of 0.91 ACHNAT (natural air changes per hour) was used for Northern homes and 0.94 ACHNAT was used for Southern homes. Both Northern and Southern homes were estimated to be improved to a leakage level of 0.50 ACHNAT."

Furthermore, Polly et al. (2011) assumed that duct sealing can also reduce duct leakage to-outside by half, from 15% of the total fan flow to 8%. The 50% reduction in duct leakage to-outside is based on a study by Francisco et al. (1998). Citing other field studies where the reduction in duct leakage is less, Polly et al. (2011) described the 50% modeled as "possible but could be toward the upper range of what is commonly achieved in the field".

There are many factors that can impact the level of airtightness improvements achieved from retrofits, such as the existing condition of the homes, available time and budget to do the work, workmanship, and so on. Therefore, to evaluate the airtightness improvements from retrofits commonly achieved in the US would require a large dataset that include the before and after retrofit measurements from various types of programs. The Residential Diagnostics Database (ResDB) by Lawrence Berkeley National Laboratory contains air leakage and other diagnostic measurements of US homes that are contributed voluntarily by various energy auditors, building contractors, energy efficiency program managers, and researchers (Chan et al. 2012). In this paper, we compared the whole-building envelope and duct system air leakage before and after retrofits using the data available from ResDB.

2. RESDB AIR LEAKAGE MEASUREMENTS

In 2011, a large number of whole-building envelope air leakage data from more than 100,000 homes were added to ResDB. Chan et al. (2012) described the air leakage data of single-family homes, and presented a regression model that relates normalized leakage (NL) to house characteristics, such as climate zone, year built, floor area, and so on. Over the years, air leakage data have been gathered and analyzed to support calculations of air infiltration and implications to residential energy use (e.g., McWilliams and Jung 2006, Chan et al. 2005, Sherman and Matson 2001, Sherman and Dickerhoff 1998).

This analysis only considers a subset of the data in ResDB where air leakage measurements were made before and after retrofit. Two types of programs contributed these data: (i) WAPs and (ii) energy efficiency programs that follow HPwES guidelines, often sponsored by utilities. There is one exception to the data considered as part of (ii), where the homes being tightened participated in a noise reduction program. This particular program is also included in this analysis because the types of improvements performed, e.g., air sealing and insulation, were largely the same as those undertook in energy retrofits. Overall, (i) include 13 WAPs, and (ii) include ten energy efficiency programs and also data from the noise reduction program. All together, air leakage data of US homes from 18 states are considered here.

Most of the analyses focus on single-family detached homes, which is the dominant type of housing in the US. A subset of single-family homes is the manufactured homes, sometimes referred as mobile homes. Manufactured homes are considered as a separate group because their constructions are substantially different from conventional homes. In the US, manufactured homes are built to the Manufacture Home Construction and Safety Standards set by the Housing and Urban Development (HUD 2013). This is unlike the other housing types that are built to state building codes. In addition, the WAPs data also include a small number of multi-family units. Because only few data on multi-family units are available, the various types (e.g., townhouse, apartments, etc.) are considered in this analysis as a group, despite their structural differences mean that air leakage pathways may differ sustainably among them. All data on manufactured and multi-family homes are contributed by WAPs.

2.1. Blower door measurements

E779-10 (ASTM 2010) is the measurement standard used in the US to measure building envelope air leakage. Air leakage is measured by the airflow rate, Q (m^3/s) through the building envelope at a function of the pressure difference, ΔP (Pa), across the building envelope. The most common pressure difference used is 50 Pa, which is low enough for standard blower doors to achieve in most houses, and at the same time high enough to be reasonably independent of weather influences. Many metrics are used to describe whole-building envelope air leakage that normalized to building volume or some definitions of surface area, such as ACH50 (air changes at 50 Pa pressure difference), NL (normalized leakage), ELA (effective leakage area), SLA (specific leakage area), and so on. There is no consensus from retrofit guidelines or buildings codes on which one metric is preferable to the others. In this analysis, ACH50 is used as the metric of airtightness improvement comparing pre- and post-retrofit, as follows:

$$\% \text{ Reduction} = \left(1 - \frac{ACH50_{post}}{ACH50_{pre}}\right) \times 100\% \quad (1)$$

2.2. Duct blaster measurements

Duct leakage is commonly measured following E-1554 (ASTM 2007) using a duct blaster. A calibrated fan delivers air to pressurize the duct system with all registers closed. For measuring duct leakage, 25 Pa is commonly used to represent a pressure difference that closer resembles typical conditions during system operation. Among the many different metrics used to describe duct system air leakage, one that is commonly used in the US is CFM25 (cubic foot of air flow per minute at 25 Pa) normalized to per 100 ft^2 of conditioned floor area. This is the metric used here to compare the airtightness improvement before and after duct sealing.

Most of the data in ResDB are total duct leakage, $Q_{duct, total}$, that includes air leakage to outside as well as to other parts of the building. In addition, there are a small number of homes where duct leakage to-outside was measured by pressurizing the house simultaneously with a blower door to the same pressure as the duct system during the test. The duct leakage to-outside, $Q_{duct, to-outside}$, is the flow required to equalize the house and duct pressures.

3. WHOLE-BUILDING ENVELOPE AIRTIGHTNESS IMPROVEMENTS

3.1. Data Analysis

The pre- and post-retrofit whole-building envelope airtightness measurements are shown in Figure 1. There are clear improvements across all programs and housing types. Comparing the non-WAPs energy retrofit and WAPs single-family detached homes, the improvements made by WAPs tend to be slightly larger, as shown in Table 1. This may be because it is easier to achieve a large improvement in airtightness if the homes were more leaky to begin with. Among these WAPs single-family detached homes, there is a positive correlation between $ACH50_{pre}$ and the percentage reduction: Pearson correlation coefficient $r = 0.399$ (95% confidence interval: 0.385–0.413). The correlation is also positive among non-WAPs energy retrofit homes ($r = 0.132$, 95% C.I.: 0.113–0.151), but the relationship is weaker. This is likely because there were fewer non-WAPs energy retrofit homes with very high initial ACH50 where the opportunities for substantial improvements were possible.

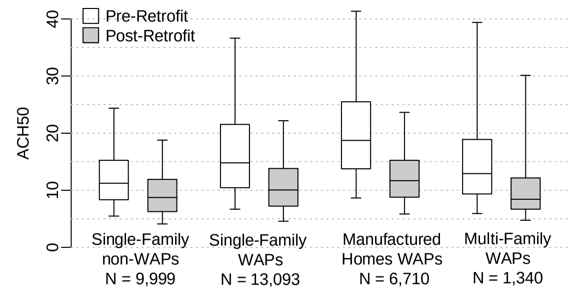

Figure 1: Whole-building envelope airtightness, in units of ACH50, of US homes measured before and after energy retrofit. Each boxplot shows the median and interquartile range, and the whiskers show 5th and 95th percentiles. N = number of homes.

Table 1: Percentage reduction in whole-building envelope air leakage (ACH50) following retrofit.

	non-WAPs	Weatherization Assistance Programs (WAPs)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
Median	20%	30%	35%	28%
5th to 95th Percentiles	5% to 47%	5% to 61%	9% to 64%	3% to 59%

Among the WAPs homes, manufactured homes have higher ACH50 than the single-family detached homes, but the multi-family homes have lower ACH50. This is true both in the pre- and post-retrofit data. These three housing types are very different in characteristics that may contribute to this apparent variance in airtightness. For example, the median floor area of manufactured homes in ResDB is 93 m^2, which is smaller than both the single-family detached homes (median = 132 m^2) and the multi-family homes (median = 129 m^2). Since floor area is one of the housing characteristics found to be negatively associated with air leakage (Chan et al. 2012), the manufactured homes being smaller in floor area may explain the higher in ACH50 overall. In addition, climate zone and year built are two factors that the regression analysis identified as the most influential on normalized leakage (Chan et al. 2012). Unfortunately, the differences among climate zones cannot be properly accounted for because only a small number of states are represented (see Figure 2). There are also too many missing data to compare the year built of homes among the three housing types.

The ACH50 measurements of multi-family homes included both the air leakages to outside and to adjacent units. The majority of WAP contractors used this whole-unit approach because it is the least time consuming. On the other hand, if the purpose is to determine the to-outside air leakage only, multiple blower doors will be needed to simultaneously pressurize the adjacent units. This is not only more labor intensive to do, but it is also logistically demanding because it requires access to multiple housing units for testing. Therefore, the improvement in airtightness shown in Table 1 cannot be used directly to estimate energy savings. Rather, it reflects an improvement in compartmentalization, where the reduction in inter-unit air flows also benefits occupant health and comfort, besides energy savings.

3.2. Implications

The modeling assumption by Polly et al. (2011), i.e., 50% reduction from 19 ACH50 to 10 ACH50, is overly optimistic for a vast number of US homes based on data from ResDB. WAPs and energy efficiency programs typically improved airtightness by 20% to 35% (Table 1) across all housing types. This analysis shows that there are opportunities for further improvements. The first is the large scattering in the percentage reduction across many of these retrofit programs, where some homes received marginal improvements in airtightness. Approximately 16% of the non-WAPs energy retrofitted single-family detached homes had marginal improvements (<10% reduction in ACH50). Because WAPs require contractors to repeat the blower door measurements multiple times during retrofit to check if a reduction has been made, there are fewer cases of marginal improvements: 6% in manufactured homes, 12% in single-family detached homes, and 16% in multi-family homes.

The second issue is the large fraction of homes that continue to have poor airtightness even after the energy retrofit. Most retrofit programs in the US do not set a target for improvement in airtightness, but rather suggest best-practice approaches for contractors to follow, such as HPwES (EPA, 2012). Table 2 shows a significant portion the homes, ranging from 36 to 64% depending on the housing types, exceed 10 ACH50 after energy retrofits.

Table 2: Percentage of homes with post-retrofit envelope air leakage exceeding two levels: 10 and 15 ACH50.

	non-WAPs	Weatherization Assistance Programs (WAPs)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
$ACH50_{post}$ >10	39%	50%	64%	36%
$ACH50_{post}$ >15	12%	20%	26%	18%

WAPs and energy efficiency programs differ by states so that they can tailor the requirements to better suit homes in their climates and that are appropriate for the structural types. Figure 2 shows that the between-state difference in the median % reduction is about 10%. While this between-state difference is not negligible, it is far less than the within-state difference between homes. Overall, there are more similarities between states from the WAPs data than the non-WAPs data. This is because there is more common ground among the WAPs where all participating homes were qualified by household income. This comparison also shows how incentives can drive outcomes in energy retrofits. For example, in California, where many homes are located in more moderate climates and the energy penalty of air leakage is less severe, the improvement in airtightness is also the least.

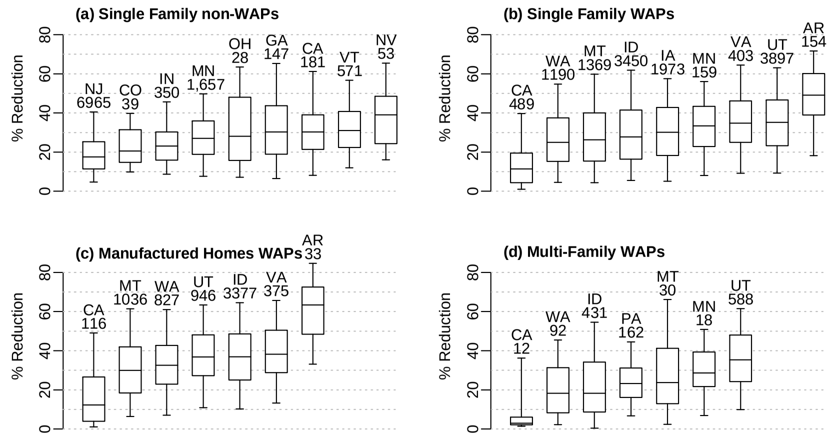

Figure 2: Percentage reduction in whole-building envelope air leakage (ACH50) following energy retrofit. Each boxplot shows the median and interquartile range, and the whiskers show 5th and 95th percentiles. Boxplots are labeled by the state abbreviation and the number of homes plotted.

4. DUCT SYSTEM AIRTIGHTNESS IMPROVEMENTS

4.1. Data Analysis

ResDB only contains a small number of data from California and Nevada that show improvements in duct leakage from retrofit. This lack of data is because initially, the ResDB data collection effort focused more heavily on whole-building envelope airtightness data than on duct leakage. Figure 3 compares the before and after duct leakage data from the 460 homes. Before retrofit, the median $Q_{duct, total}$ is 27 CFM25 for the non-WAPs single-family detached homes in California. The pre-retrofit duct leakage is roughly the same among the WAPs single-family detached and manufacture homes in California, where the median $Q_{duct, total}$ are 22 and 29 CFM25, respectively. However, there are stark differences in the improvements made by the retrofit. The median reduction by non-WAPs after retrofit is 75% (Table 4). Whereas in the case of WAPs, the median reduction is 23% among the single-family detached homes, and 28% in the manufactured homes. This vast difference between the two program types is likely because weatherization contractors tend to use relatively simple measures to reduce obvious leakage in the duct systems. On the other hand, energy efficiency programs with more flexibility in work scope and budget are more likely to recommend heating and cooling equipment upgrades, and thus trigger a throughout inspection and overhaul of the duct systems. Moreover, identifying duct leakage is also a relatively time-consuming and labor-intensive process, which makes duct sealing less favorable when evaluated on a savings-to-investment ratio for WAPs.

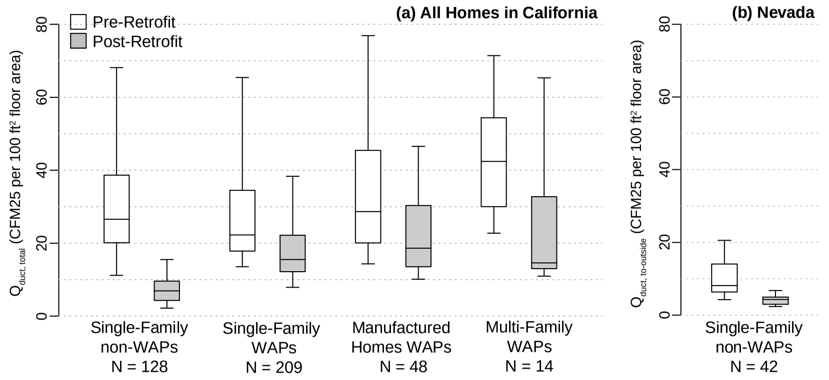

Figure 3: Duct leakage of US homes measured before and after energy retrofit. The California data (a) are total duct leakage, whereas the Nevada data (b) are duct leakage to-outside. Each boxplot shows the median and interquartile range, and the whiskers show 5th and 95th percentiles. N = number of homes.

The multi-family measurements shown in Figure 3 were likely performed on the duct systems that are present within each unit. Typically, this is a prerequisite for compliance testing in multi-family homes; e.g., RESNET draft standards on air leakage testing (2013). From this small dataset of 14 homes only, it appears that duct leakage is a problem in multi-family homes at a level that is comparable to the WAPs single-family homes. Proctor et al. (2011) compared the duct leakage of newly constructed single-family and multi-family homes in California also found relatively higher duct leakage among the multi-family homes. However, the same value of $Q_{duct, total}$ can have vastly different energy implications depending on the location of the ducts (e.g., inside versus outside of the conditioned space), sizing of the heating and cooling equipment, and so on. Unfortunately, there is insufficient data on duct leakage from ResDB to support a more detailed analysis of energy implications at this point.

Table 4: Percentage reduction in total duct system air leakage (CFM25 per 100 ft^2 floor area) following retrofit.

	non-WAPs	Weatherization Assistance Programs (WAPs)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
Median	75%	23%	28%	46%
5th to 95th Percentiles	43% to 93%	4% to 72%	6% to 66%	2% to 72%

Measurements from an energy efficiency program in Nevada provide data on the change in duct leakage to-outside before and after retrofit. The change in $Q_{duct, to-outside}$ has a median value of 49% (5th to 95th percentiles = 11% to 80%), which is the same as the level of reduction (50%) assumed by Polly et al. (2011) in their modeling work.

4.2. Implications

The duct system airtightness of non-WAPs homes following energy retrofits is sufficient to meet levels that are expected of new homes. For example, the IECC (2009) requirement was ≤12 CFM25 (per 100 ft^2 of conditioned floor area) for total duct leakage, and ≤8 CFM25 if the duct leakage to-outside is measured instead. Figure 3 shows that majority of the non-WAPs homes retrofitted in California (85%) and in Nevada (98%) met those airtightness levels. On the other hand, relatively few WAPs homes would meet IECC (2009): 23% of single-family detached homes, 13% of the manufactured homes, and 15% of the multi-family homes (Table 5). Recall that WAPs homes also had higher pre-retrofit building envelope air leakage than the non-WAPs homes (Figure 1); this is the same as the case for duct leakage. However, opposite to the case of building envelope leakage, WAPs improved the duct leakage of homes by a lesser extent overall than the energy efficiency programs. Contrasting these two cases, it is evident how incentives can drive the level of airtightness improvements in energy retrofits.

Table 5: Percentage of homes with post-retrofit total duct leakage exceeding two levels: 8 and 12 CFM25 per 100 ft^2 floor area.

	non-WAPs	Weatherization Assistance Programs (WAPs)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
$CFM25_{post}$ >8	39%	95%	96%	100%
$CFM25_{post}$ >12	15%	77%	87%	85%

In their evaluation of energy efficiency measures, Polly et al. (2011) assumed that duct system air leakage to-outside would be reduced by half from 15% of the total fan flow to 8%. The energy efficiency programs in California reduced total duct leakage by 75%, and in Nevada by 50% on the duct leakage to-outside. These airtightness improvements are on par with the modeling assumptions by Polly et al. (2011). On the other hand, WAPs, at least among those in California where the data is available from ResDB, achieved much less improvement in duct system airtightness than the 50% modeled by Polly et al. (2011). The conversion from CFM25 (per 100 ft^2 of conditioned floor area) to duct leakage as a percentage of fan flow depends on many factors. If applying common assumptions of 400 CFM per ton of air conditioning and 400 ft^2 per ton, then roughly speaking, 8 CFM25 per 100 ft^2 of conditioned floor area is simply 8% of fan flow. Using this rough conversion, almost all of the single-family detached homes in Nevada have duct leakage to-outside <8% of fan flow post-retrofit.

5. CONCLUSIONS

We analyzed the building envelope and duct system airtightness of US single-family detached homes, manufactured homes, and multi-family homes, where the data was part of the Residential Diagnostics Database (ResDB). The data in ResDB were mostly contributed by weatherization assistance programs (WAPs) and residential energy efficiency programs. The analysis here shows that these programs typically reduced building envelope air leakage by 20 to 35% (median reduction in ACH50, N = 31,140). The reduction in building envelope air leakage post-retrofit was slightly higher among WAPs, for reasons that may be associated with how weatherization contractors are required to check for improvements for each increment of work. Greater improvements are also correlated with the higher initial ACH50 found among the income-qualified homes that participated in WAPs.

It is more difficult to draw conclusion from the duct leakage retrofit comparison because far fewer data (N = 460) are available from ResDB to compare duct system leakage before and after retrofit. From the limited data available in California, single-family detached homes retrofitted by energy efficiency programs showed a reduction in total duct leakage (CFM25 per 100 ft^2 of conditioned floor area) of 75%. Such improvements are significantly greater than the WAPs homes, where CFM25 reduced by 25% roughly. In Nevada, the median reduction in duct leakage to-outside is 50% estimated from a small set of single-family detached homes retrofitted by an energy efficiency program. The larger reductions observed from these two energy efficiency programs mentioned suggest that given the resources to overhaul the duct systems, which may be cost prohibitive to WAPs, duct leakage can be effectively minimized in existing homes.

The air leakage reductions presented here are useful for calculating the energy savings and cost-benefit of air sealing as a way to improve energy efficiency in US homes. This analysis also identified opportunities for retrofit programs to enhance their energy saving potentials. Homes with minimal improvements (e.g., less than 10% reduction in ACH50), and those that ended with relatively high post-retrofit air leakage (e.g., >15 ACH50), should prompt further investigation. Once an acceptable set of thresholds is established as target, retrofit programs should implement procedures that will provide incentives for a follow-up visit. They should also ensure that the recommendations from best practice guides on air sealing (e.g., Baechler and Love (2010)) are fully utilized by contractors in energy retrofits.

6. ACKNOWLEDGEMENTS

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Achieving and Certifying Building Envelope Air Tightness with an Aerosol-Based Automated Sealing Process

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ABSTRACT

This paper describes a process developed at UC Davis that uses aerosolized sealant particles to seal leaks in building envelopes. The process is similar to that used for sealing leaks in ducts; however it does not depend on a carrier flow to transport the sealant to the leaks, and therefore has to address the likelihood of particles settling to the ground, as well as the possibility of particles depositing on vertical surfaces. One unique aspect of this process is that it utilizes a blower door to both facilitate and track the sealing process, providing immediate certification of the sealing performed. Testing of the process in the laboratory and in several homes is described. The laboratory tests investigated the impacts of pressure and particle size on the sealing process. The field tests showed how well the process performed in new-construction applications (sheetrock installed, but not yet painted), and an empty existing home application (horizontal surfaces covered with paper and plastic). The results presented include a sub-set of the laboratory tests, as well as selected field test results. These tests suggest that the process should be able achieve better levels of air tightness as compared to manual sealing methods, at lower cost, and with automated air-tightness verification.

KEYWORDS

Envelope, air-tightness, sealing, aerosol

1. INTRODUCTION

Residential building shells are often leaky, causing unintended flows between conditioned and unconditioned spaces that result in additional loads for the heating and air conditioning equipment to address. Sherman indicates that houses built in the 1990's can have as much as 180 in^2 of leakage area for a 1500 ft^2 home [Sherman and Dickerhoff 1994]. A significant effort has been made to reduce the leaks in building shells through current construction practices, but the problem remains one of excess labor costs, constant vigilance and quality control issues. The objective of this research is to develop and demonstrate a remote sealing process that uses aerosolized sealant particles to simultaneously measure, find, and seal leaks in a building envelope shell in a cost effective manner. The tested process involved pressurizing a space with a fog of sealant particles that travel to, and as they escape, seal the leaks.

A similar process, developed by Lawrence Berkeley National Laboratory (LBNL) and commercialized under the name Aeroseal, has been used to seal leaks in ducts with great success. The process injects a solution of Poly Vinyl Acetate (PVA) sealant and water into a high-pressure air stream to produce tiny droplets. A calibrated fan and heater produce the carrier flow that transports the sealant through the duct system and evaporates the water surrounding the sealant particle. Tests at LBNL of the particle size produced by a compressed-air nozzle similar to the one used in the commercial Aeroseal machine (used for our testing) generated particles with a mean diameter around 7 µm. With all catastrophic leaks repaired, such as disconnected ducts, the aerosol sealants have been shown to typically seal approximately 80% of the leaks encountered in residential homes [Modera et al 1996]. In general, the sealing rate in duct applications was shown to vary with the width (or smallest dimension) of the leak squared [Carrie and Modera 1998, 2002]. Thus, although there is no well-established maximum leak size, this efficiency creates practical limitations on the size leak that can be sealed. For example, a 1/8th inch (3 mm) gap should seal sixty-four times faster than a 1 inch (25 mm) gap, although 1 inch (25 mm) gaps have been sealed. For reference purposes, the company that sells the equipment for aerosol duct sealing quotes maximum practical leak sizes between 3/8 inch and 5/8 inch (10 mm to 16 mm) across. The work presented in this paper looks at a similar process applied instead in a nominally quiescent environment without the use of a carrier flow to deliver the aerosol sealant to the location of the leaks.

2. LABORATORY TESTING

2.1 Test Apparatus

The Western Cooling Efficiency Center (WCEC) constructed an 8 ft x 8 ft x 4 ft (2.4m by 2.4m by 1.2 m) enclosure with leak panels distributed at various locations around the shell of the enclosure (Figure 1). Figure 2 presents an illustration of the location of the leak panels installed. The approximate size of each leak is 0.1 to 0.12 inch X 10 inch X 0.125 inch (2.5 to 3 mm by 25 cm by 3 mm) (H X W X D) and there are six leaks on each leak panel. The height of each leak was meant to be representative of a typical leak in a building shell, but the depth is much shorter than what is expected to be found in buildings. The total measured leakage was approximately 41 square inches (260 cm^2) of open leakage area. A 14-inch (36 cm) diameter hole was used as the injection site to introduce the sealant fog near the top of the enclosure (see Figure 1).

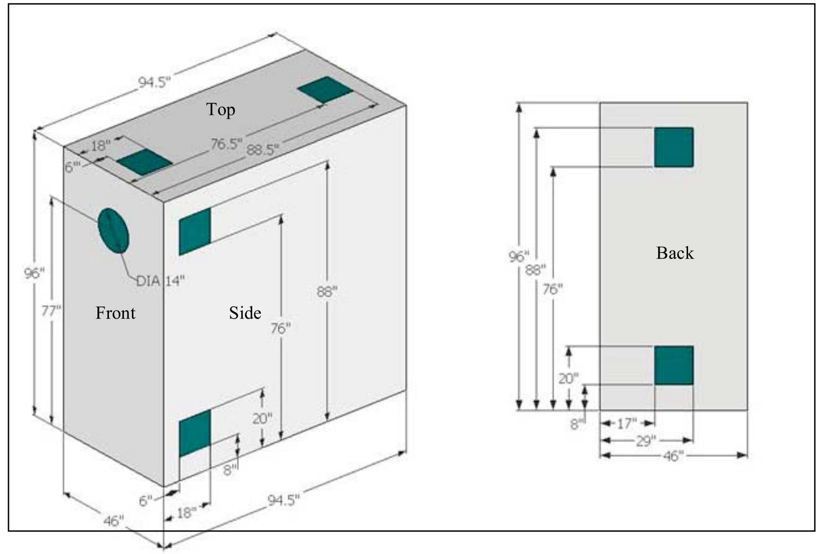

Figure 1: Dimensioned views of the enclosure showing the various leak locations. Each leak panel, illustrated by the green squares, contained six slot leaks, and the sealant was introduced through the injection hole illustrated by the green circle on the front.

2.2 Analysis Method

The performance of the remote sealing technology was evaluated using three primary metrics: 1) the time needed to seal the enclosure, 2) particle deposition inside the enclosure, and 3) the uniformity of sealant deposition at the leaks. These performance metrics were used to evaluate several independent parameters to understand their effects. The parameters evaluated included the pressure inside the enclosure, the flow rate of sealant injected, and the size of the particles injected.

The commercial Aeroseal machine, although probably not appropriate for building applications, was used for our initial tests of sealing building shells. It includes instrumentation for measuring differential pressure between the enclosure and ambient, as well as for measuring the air flow, thereby facilitating continuous monitoring of leakage area during the sealing process. The leakage area was computed using Equation 1 [4] and Equation 2 [5].

$$Q = ELA_{ref} \cdot \sqrt{\frac{2 \cdot \Delta P_{ref}}{\rho}} \cdot \left(\frac{\Delta P}{\Delta P_{ref}}\right)^n$$ Equation 1

$$LA = \frac{ELA}{0.6}$$ Equation 2

Where Q is the measured airflow rate, ELA_{ref} is the effective leakage area, ΔP is the pressure measured across the leak, ΔP_{ref} is a reference pressure (chosen to be 25 Pascals), ρ is the air density, n is the flow exponent (typically 0.5 for an orifice), and LA is the leakage area. The ELA_{ref} of a leak is the area of a sharp-edged orifice that at some reference pressure that will produce the same flow as the leak at that pressure. It has been shown experimentally and theoretically that the ELA is related to the actual area of an orifice by a factor of 0.6 [Batchelor 1967].

A mass balance was used to determine where the sealant was ultimately deposited. Using a scale with a 0.001 gram resolution, the weight of various components before and after sealing allowed us to track the fraction of sealant that was lost due to settling or turbulent deposition onto surfaces. These components included: a sheet of plastic placed on the bottom of the test enclosure, the plastic tubing used to transport the sealant from the generation point to the enclosure, and plastic sheets placed on the walls and ceiling. In addition, the sealant deposited in each panel leak was determined by removing the sealant in and around the leak and then weighing the removed sealant. The results for different panels were to get a feel for the particle distribution inside the enclosure. Errors may have been introduced by the following: not completely removing all sealant from the panels, the sample sections of plastic used for measuring wall and ceiling deposition not being representative of the entire surface, and the fact that we used the manufacturer calibration for the sealant flow rates. Assuming the pump calibration is reasonably accurate, the overall error in the measurements was expected to be with ±5%.

The approach for the first stage of development employed the existing Aeroseal equipment to seal the test enclosure. Initially, it was expected that the particle size produced by the existing Aeroseal equipment would be too large to allow for sufficient particle suspension. This was not the case, as the leaks were more than sufficiently sealed in the initial tests. Observations in the small-scale tests led to further research on the impact of reducing particle size. In addition to reducing particle size, oscillating fans could be used to assist in keeping the particles suspended and to make the indoor-air particle distribution more uniform in an actual application.

The performance of each test was evaluated using leakage versus time profiles, as well as analyses of sealant use efficiency quantified by the mass balance of sealant materials (i.e. fraction on floor, in leaks, on walls, and lost through leaks).

The independent variables investigated included:

- Average particle size (controlled by sealant dilution)
- Enclosure pressure control
- Sealant injection rate

The dependent variables that were used to quantify performance included:

- Sealing rate
- Sealing uniformity (comparison of the amount of sealant deposited on panels in different locations)
- Sealant use efficiency (fraction that settles on the floor and other surfaces, versus deposited in leaks)

2.3 Results

Several tests of the envelope sealing process were performed, all of which showed promising results, sealing the enclosure in as little as six minutes. Tests were performed to study the impacts of the independent variables on the sealing parameters (Table 1).

Table 1: Test protocol for each of the nine tests

Test number	Box Pressure (Pa)	Sealant Injection Rate (ccm)	Sealant Dilution
1	No pressure/flow control	100	No Dilution
2	100	25	No Dilution
3	No pressure/flow control	25	No Dilution
4	50	25	No Dilution
5	100	25	No Dilution
6	50	25	No Dilution
7	100	25	No Dilution
8	50	25	No Dilution
9	100	25	1 part sealant/1 part water

Figure 2 shows the leakage profiles for each of the nine tests in the enclosure. All tests successfully sealed the enclosure to nearly zero leakage in less than 30 minutes. Note that, at the beginning of each test, the sealant lines were first purged of water before sealant reached the injection nozzle, causing a slight delay at the beginning of each test, which for 25 ccm tests was about 5 minutes and for 100 ccm test was about 2 minutes.

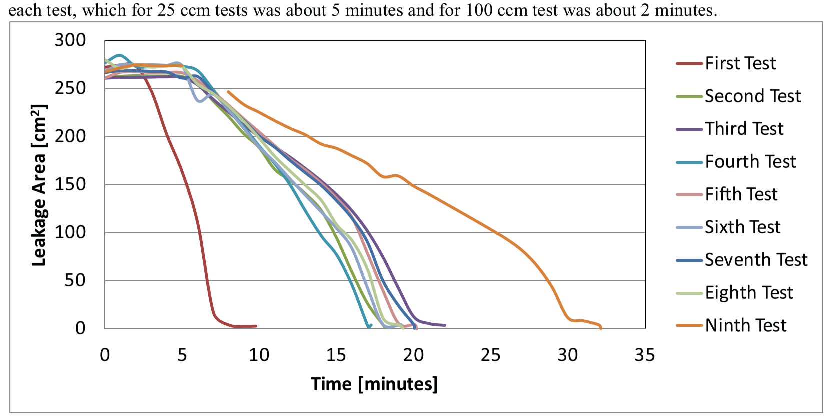

Figure 2: Leakage profiles for each of the nine tests

The leakage profiles show that the sealant injection rate has a significant impact on sealing time, whereas controlling the pressure inside the enclosure had a less significant impact. Tests performed at a 25 ccm injection rate at various pressures all sealed the enclosure in 13-15 minutes, whereas injecting sealant at 100 ccm sealed the enclosure in six minutes. Reducing sealant particle size by diluting the sealant with water also significantly extended the sealing time. This is due to the reduced solid sealant injection rate associated with diluting without adjusting the pump rate. In the test with diluted sealant, the enclosure sealed in approximately 28 minutes (Figure 2).

Deposition at high pressure and 100 ccm injection rate

Deposition at high pressure and 25 ccm injection rate

Deposition at 50 Pa and 25 ccm injection rate

Figure 3: Sealant deposit pattern on back low panel for tests 1, 3 and 4

The sealant deposition pattern could be a quick indication of the sealant deposition efficiency. Figure 3 shows the sealant deposition pattern observed during three different tests, a) a high-pressure test with 100 ccm sealant injection rate, b) a high-pressure test with 25 ccm sealant injection rate, and c) a test at 25 ccm sealant injection rate, but with the pressure differential controlled to maintain 50 Pa. The largest spread of sealant around the leak is for the high-pressure test at 100 ccm, and this spread is decreased when the sealant injection rate is reduced, and when the pressure differential is maintained at 50 Pa. These results suggest that excess deposition is reduced, producing cleaner seals, when the sealant flow rate is reduced, and when the building pressure is reduced. We believe the former may be due to the size particles created by the nozzle used for these experiments, and that the latter is due to the lower velocities around the leaks at lower pressures. In terms of spatial uniformity in the lab tests, there was only a 1-2% variation in the mass of sealant deposited between any of the leak panels distributed around the enclosure at any given sealant flow, suggesting very good particle distribution and sealing uniformity for all the lab tests performed.

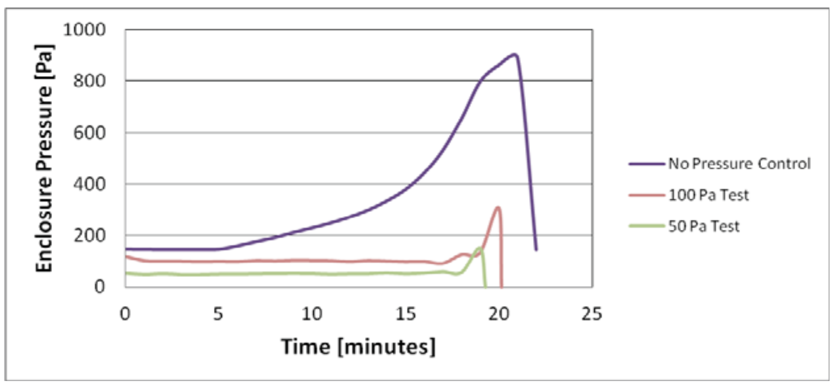

Figure 4: Typical Pressure profiles inside the enclosure during tests with no pressure control, and tests controlled at 100 Pa and 50 Pa

The pressure was regulated by a calibrated fan that controlled the airflow delivered to the test enclosure. Three operating pressures were studied in the small-scale tests: 1) no pressure control (which effectively allows the fan curve to control the injection flow), 2) manual flow control to maintain 100 Pascal pressure differential, and 3) manual flow control to maintain 50 Pascal pressure differential. Due to the very low absolute leakage level achieved by injecting aerosol sealant, the pressure inside the enclosure became difficult to control as the flow approached the minimum achievable by the equipment (Figure 4). This could mean that better control of the pressure inside building shells for the duration of the installation of aerosol sealant will be needed to prevent over-pressurizing the space, although there is no need to bring building leakage levels to the values obtained in the laboratory.

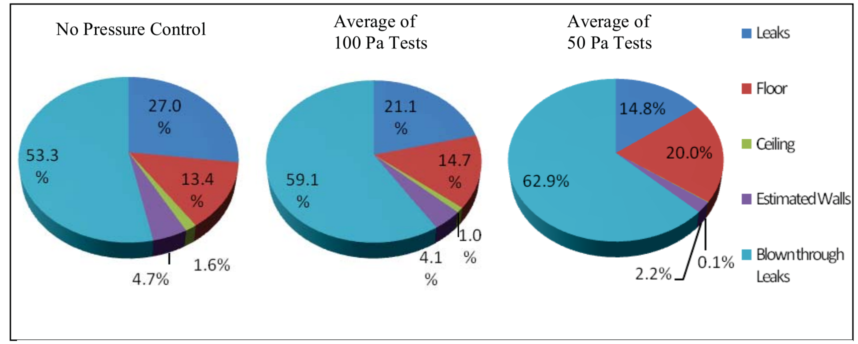

Figure 5: Average sealant distribution for tests at various pressures and 25 ccm sealant injection rates

The mass balance analysis allows for accurate tracking of where the sealant is ultimately deposited. The sealant distributions in Figure 5 show how pressure control affected the sealing process. There is a clear trend showing that lower enclosure pressure leads to less sealant deposited in and around the leaks, more sealant depositing on the floor, less sealant depositing on the walls and ceiling, and more sealant getting blown through the leaks. Although the majority of sealant injected was blown through the leaks, it is expected that the geometry of leaks in typical buildings will be different than the test enclosure. The longer flow path of typical leaks in buildings is expected to reduce the amount of sealant blown through and, therefore, improve the efficiency of sealant use. We expect that the typical building leaks sealed during this process would be at the joints and seams between building materials that are much deeper then the leaks tested in the lab enclosure.

3. FIELD TESTING

Several full-scale tests of the aerosol-based sealing technology have been completed in the dry-wall phase of construction, plus one test on an empty existing home. The initial tests were performed using the existing aerosol duct sealing technology that was tested in the laboratory experiments while the latest application tested a new aerosol injection technology developed by UC Davis. The first full-scale tests demonstrated a lack of sealant transport to adjoining rooms which required that the atomization nozzle be moved from room to room. The new aerosol injection system is capable of multiple injection points allowing nozzles to be distributed throughout the building both expediting the sealing process and eliminating the need to enter the building while applying the aerosol (Figure 6 and Figure 7).

Figure 6: Photo of sealant atomization

Figure 7: System developed by UC Davis, capable of multiple aerosol injection points

Figure 8 shows a snapshot view of the time history of the sealing process, illustrating the slope of the sealing profile for two field tests, one using the new injection system with five injection points and the other the existing injection system with one injection point.

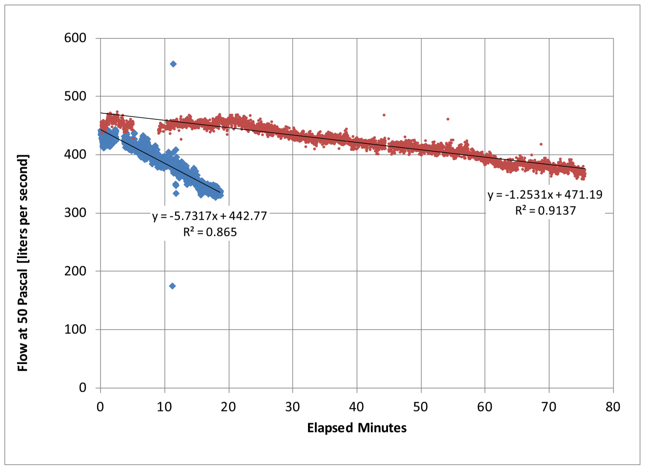

Figure 8: Snapshot of sealing profile for new injection system vs. existing duct sealing system

The slope of the sealing profiles indicates a more than four-fold increase in the sealing rate for the multi-point injection system. However, when the results were normalized by the solid sealant injection rate, the sealing performance was slightly lower for the newer injection system. The slight decrease in performance is likely due to the over-saturation of air during the sealing process, preventing the sealant particles from drying out sufficiently for effective deposition. Future testing will slow the sealant injection rate to test this hypothesis.
The field tests of the sealing process showed that it could seal at least 50% of the initial leakage observed prior to injection, as well as that the floors did not need to be prepped in new-construction applications. The tests also showed that particular care needs to be taken in existing homes, even if they are empty of contents at the time of sealing (e.g. protecting carpeted stairways from more than just particle settling). Figure 9 shows examples of leaks sealed during the field testing, including leaks at sill plates and electrical boxes.

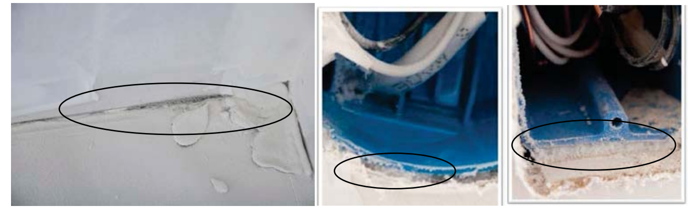

Figure 9: Envelope leaks sealed during the field tests (sill plate and electrical boxes).

4. CONCLUSIONS

Based upon the laboratory and field test results presented in this paper, it appears that aerosol particles can be employed to seal leaks in building envelopes. In the lab, our tests suggest that lower sealant injection rates result in cleaner seals, we believe due to smaller particles created by the lab-test nozzle at lower sealant injection rates. Our lab tests also suggest that a smaller pressure differential across the leaks creates an even cleaner seal, most likely due to lower approach velocities to the leaks. This needs further investigation.
In the field, in both the new construction and existing home applications, the process was able to seal at least 50% of the observed leakage within a reasonable amount of time. For field applications, what remains to be done is to understand and optimize the preparation process required for sealing, to get more experience in field applications of the sealant injection and preparation process, and to turn the multi-point injection system into a viable commercial product.

5. ACKNOWLEDGEMENTS

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THE EFFECT OF AIR TIGHTNESS ON THE ENERGY CONSUMPTION ANALYSES OF FIELD MEASUREMENTS

Wouter Borsboom TNO, Ivo Opstelten, Willem de Gids

The energy consumption of buildings is effected by the air tightness level. Everyone can understand this statement but what are the effects of deviations from air tightness in the design on the total energy consumption of dwellings, and how can we control the quality. In the Netherlands, the Innovation-implementation program "Energiesprong" (Energyleap in dutch) focuses on the development of marketable propositions for energy neutral (on the meter) buildings which are affordable, profitable for the building industry, provide good living conditions and realize the promised performance characteristics. Integral monitoring of demonstration projects is an important part of this program. Lessons learned will be presented in this paper.

With multi-zone models, the relation between energy consumption and air tightness is estimated for a standardized dwelling. The effect of different air tightness levels is calculated for the heating load. But the effect is also highly dependent on what happens in the dwelling, what kind of ventilation system is installed and how all ventilation provisions are used. Analyses of field measurement findings in about 15 dwellings, where air tightness and energy consumption were measured, show that a simple relation is not so evident. Other parameters in practice dominate the actual energy consumption more than the air tightness levels. To better estimate and understand this effect of the user, different studies are performed in the Netherlands.

To control the quality of renovated and new dwellings where air tightness is an important aspect, the tool "Bouwtransparant" (Building Transparently) will be used in the Energiesprong program. This tool consist of calculations, inspections and awareness raising amongst the professionals in the field. First results of this approach are presented.