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Opportunities for Energy Conservation and Improved Comfort From Wind Washing Retrofits in Two-Story Homes - Part I

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Opportunities for Energy Conservation and Improved Comfort From Wind Washing Retrofits in Two-Story Homes - Part I

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ABSTRACT

Wind washing is a general term referring to diminished thermal control caused by air movement over or through a thermal barrier. The primary focus of this paper is towards a specific type of wind washing where wind can push attic air into the floor cavity between first and second stories of the home through ineffective (or missing) air barriers separating attic space from the floor cavity. A second type of wind washing studied in this project involved insulation batts on knee walls where space between the batts and the wall board allowed air movement against the gypsum wall board.

During hot weather, the first type of wind washing pushes hot air into the floor cavity (between the first and second stories) thereby heating ceiling, floor, and interior wall surfaces (see Figures 1 and 2). Condensation may occur on cold supply duct surfaces within the floor cavity resulting in ceiling moisture damage. In cold climates, cold air from wind washing can chill surfaces within the interior floor space and result in frozen water pipes.

Through the summer of 2009, a field study tested thirty-two two-story homes and found significant wind washing potential in 40% of the homes. Part I of this paper will highlight the evaluation methods used and the extent of wind washing found in this study. Repairs and energy monitoring were completed in six of these homes to evaluate retrofit methods and cost effectiveness of retrofit solutions. These results are discussed in Part II of this paper.

PROJECT DESCRIPTION

The primary goal of the project was to characterize methods and cost-effectiveness of retrofit solutions. Secondary goals were to determine how wide-spread these envelope thermal problems are, identify the failure mechanisms that lead to wind washing, develop new-construction and retrofit solutions, recommend code modifications, and identify the energy savings potential from retrofit programs. Knee wall and wind washing problems have been recognized in recently published literature (Sidall 2009, Lstiburek 2005, DOE 2000) and provide good information on best-practice to avoid this problem. However, energy penalties and retrofit savings opportunities in hot/humid climates related to wind washing retrofits have not been published.

Figure 1 Infrared image shows that floor space behind wall is very warm. *(Image credit C. Withers)*

Figure 2 Photograph of IR image above. Floor space begins under the hung picture at top. *(Withers)*

Wind Washing Inspection and Repairs

Before wide-scale retrofit programs can begin, utilities and other parties need more knowledge of the energy and demand savings opportunities that exist from repair. The typical wind washing scenario in a two-story house consists of an interstitial floor cavity (between the first and second story) that is open to an adjacent attic space located above a first-floor portion of the building. Figure 3 illustrates wind washing caused by air movement into the soffit, then into the attic, and finally into the floor space.

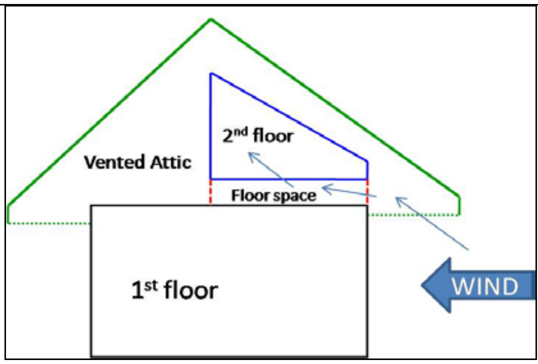

Figure 3 Wind-driven attic air is pushed into the space between floors. *(Withers)*

Repairs were implemented by application of open-cell foam over the openings between the interstitial floor cavity and the attic space, isolating the floor cavity from an adjacent attic. In some cases, foam insulation is also applied to the adjacent knee wall that separates the attic space from the indoor space. Repairs are discussed in more detail in Part II of this paper.

Before we could begin monitoring six houses, we had to find reasonable candidates. The process started with field testing two-story Florida homes to characterize wind washing failures of the house air and thermal boundary. Testing was designed to identify wind washing potential, overall house tightness, duct leakage to outdoors, and air pressure boundaries. Detailed visual inspections of attic, floor cavities, and other locations were the most effective way to identify wind washing potential. There are, however, some homes with areas that are either inaccessible or have limited accessibility for inspection. Equipment such as a bore scope or other controllable optic devices is needed in such cases. Other measurements to assess duct leakage were done as well to help identify if duct leakage could also be interacting with wind washing impacts.

FIELD TESTING RESULTS

Field testing was performed in 32 homes. This field testing consisted of the following. A blower door test characterized the airtightness of the house envelope using test protocols of ASTM E-779-03 (ASTM International 2003A). Air boundary identification was performed in the following manner. With the house at -50 pascals (Pa) (-0.20 inWC), zone pressures in various interstitial cavities of the house were measured. The cavity pressures in locations such as a floor space can be an indication of how well connected it is to outdoors. For instance when the house is at -50 Pa with reference to outside, the floor should also be at -50 with reference to out if it is 100% sealed from outdoors.

Pressure pan testing was performed. With the house at -50 Pa, a pressure pan was placed over supply and return registers/grills (air handlers off) and the pressure in the duct was measured, identifying the relative size and location of duct leakage. Pressure mapping was performed; with HVAC system operating in normal mode, pressure differentials across closed doors were measured with interior doors open and then again closed. The house infiltration rate was characterized with continuous air handler unit (AHU) fan operation using tracer gas decay method protocols of ASTM E741 (ASTM International 2006). This method involves injection of a small quantity of a tracer gas into the home. The gas is mixed well and then sampled with a gas analyzer to characterize the dilution that results from air infiltration. The infiltration rate is calculated as a natural log relationship of the ratio between initial and final concentrations. Details on the calculation can be found in ASTM E741. During the tracer gas decay test, a return leak fraction (RLF) test with the AHUs operating was also performed. Concentrations are measured at the return grill(s) and at a supply register. RLF is calculated using the equation:

$$RLF = ((A-B) / (A-C))$$

where A = return tracer gas concentration, B = supply tracer gas concentration, and C= tracer gas concentration of the air entering the return duct leak site (Cummings 1989). An AC system performance test was performed by measuring delta-enthalpy (based on supply and return temperature and relative humidity) and the AC system air flow rate measured with a flow hood or calibrated flow plate device.

Field testing also included fairly detailed inspections of attic spaces, floor cavities, and other locations to identify the potential for wind washing. Infrared scans, with a FLIR Model P40 Thermacam infrared camera, were used to identify thermal characteristics of various building cavities associated with wind washing. This camera has adjustable emissivity settings from 0.1 to 1.0, but generally the setting was left around 0.95 since most surfaces evaluated were in the range of 0.91 to 0.95. The surface temperature accuracy is +/- 2^{o}C or +/- 2% of reading. The IR camera was used primarily as a diagnostic tool to identify areas of thermal bypass. Infrared thermography works best when the temperature difference between conditioned and unconditioned spaces is large and the surfaces being evaluated have high emissivity (ASTM International 2003B).

During the cooling season, infrared scanning was typically done during early to mid afternoon after the sun had heated the attic and other materials substantially. During winter weather when heating occurred, scans were done as early as possible when the attic and external building materials were cooler. The effectiveness of using thermography is limited by cloudy mild weather or in homes with high mass construction, reflective roofing or radiant barriers which limit heat transfer to building materials. Figures 1 and 4 are examples of IR scans that show thermal patterns associated with wind washing air flows.

In Figure 1, the thermal signature shows where hot air (from an attic space located above a one-story portion of the house) has been able to migrate throughout the interstitial floor cavity, between the first and second floors of the house. This hot pocket of attic air has been pushed into the inter-floor cavity where it then delivers considerable heat, by means of conduction and convection) to the ceiling of the first floor, the floor of the second story, and a portion of the stairwell wall.

In Figure 4, the thermal signature shows where insulation batts are not held tightly against the back side of the wallboard, allowing hot air from the attic above the garage to migrate behind the batts and against the wallboard. As the hot air comes into contact with the cool wallboard, it becomes denser and falls toward the attic floor, only to be replaced by additional hot attic air. This convective loop, driven by temperature differential and air density differentials, continues throughout the day and peaks during the hottest hours of the day.

<u>Field Testing Data</u>

A spreadsheet database with 125 columns of data was created that summarizes the field testing data from 32 houses located in six Florida counties. The average age was 20 years old from 2009; oldest was 106 years old and newest was 2 years old. Construction type breaks down as follows; 2 were block only, 6 were frame, 1 was poured concrete, and the remaining 23 were combined block and frame. All were two-story except two were split level homes. Roofing type breaks down as follows; 2 were tile, 3 were metal, 1 was tile and metal, and the remaining 26 were asphalt shingle. Houses with asphalt shingle roofs tend to have very hot attics, even in cases where the shingles are somewhat lighter in color. By contrast, tile roofs and some metal roofs cause attics to be much cooler. The temperature of the attic has important bearing on the energy impacts of wind washing. Following are some key findings.

House size ranged from 1,050 ft^2 to 4,500 ft^2, with an average floor area of 2,695 ft^2. The average volume was 23,470 ft^3, indicating an average ceiling height of 8.7 ft. The second floor of the house constituted from 18% to 49% of the house floor area, averaging 34.5% of the house floor area. So, 65.5% of the house floor area was, on average, on the first floor. All homes had central forced-air cooling. Twelve homes had 1 space conditioning system serving the entire house. Nineteen of the 32 homes had 2 systems. One home had 3 systems. Heating system types break down as follows; 4 with gas heat, 4 with electric strip heat, 23 with heat pumps, and 1 house had 1 electric strip heat and 1 heat pump.

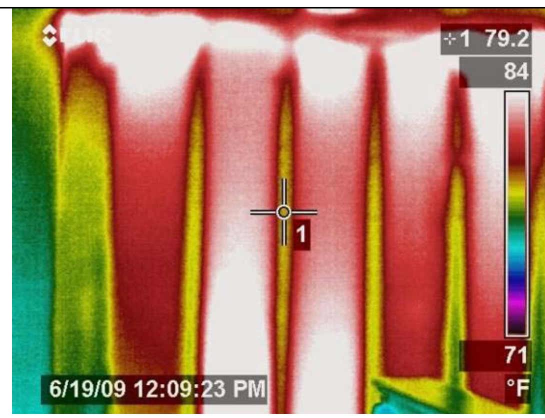

Figure 4 IR image of wood frame wall adjacent to unconditioned space. *(Image credit Withers)*


Figure 5 Photo of the stairwell wall matching the IR image of Figure 4. *(Withers)*

Most AHUs are located in the garage or indoors. The locations of AHUs serving the first floor are 11 indoors, 19 in the garage, and 2 in the attic. The locations of the second AHUs are 17 indoors, 0 in the garage, and 2 in the attic. Of the total 51 AHUs, 28 were located indoors, 19 in the garage, and 4 in the attic. Cooling capacity varies from 1.28 to 3.28 tons per 1,000 ft^2, with an average of 1.94 tons per 1,000 ft^2. Heating capacity varies from 15.38 kBtu/1,000 ft^2 to 69.9 kBtu/1,000 ft^2, with an average of 23.76 kBtu/1,000 ft^2.

Pressure mapping was performed with the AHUs off, AHUs on, and with interior doors closed (with AHUs on). The following pressures are expressed as house pressure with respect to (wrt) outdoors, unless stated otherwise. With AHUs off, house pressure averaged -0.24 Pa. With AHUs on, house pressure averaged +0.30 Pa. With AHUs on and interior doors closed, house pressure (in the central zone) averaged -0.96 Pa. From this data, we can say that turning on the AHU fans increased house pressure by 0.54 Pa, on average, indicating that return leakage (from outdoors) was, on average, greater than supply leakage (to outdoors). We can also say that closing interior doors caused a decrease in central zone pressure of 1.26 Pa, on average. Pressure was measured across closed interior doors. Maximum pressure differentials across the closed doors exceeded 20 Pa in three homes. For AC system 1 (first floor), the average pressure differential across closed doors was 2.63 Pa. For AC system 2 (typically second floor), the average pressure differential across closed doors was 5.01 Pa. The Florida Building Code, as of March 2002, has required that pressure differentials in new homes not exceed 2.5 Pa (there are also two exceptions not discussed here).

Duct leakage testing was performed in all homes by means of a pressure pan test. With the house at -50 Pa (a blower door was depressurizing the house) and the AC system off, a pan (with gasket to create a tight seal to the gypsum board) was placed over supply and return grills and a pressure in the duct (on the inside of the pan) was measured. Generally, pressure pan readings of 1.0 to 3.0 Pa indicate slight to moderate duct leakage and pressure pan readings greater than 3.0 Pa indicate substantial duct leakage.

- For AC system 1, average supply pressure pan readings ranged from 0.31 to 3.8 Pa, with an average of 0.93 Pa for the 32 homes. Average return pressure pan readings ranged from 0.1 to 24.5 Pa, with an average of 4.21 Pa for the 32 homes.
- For AC system 2, average supply pressure pan readings ranged from 0.02 to 15.0 Pa, with an average of 1.52 Pa. Average return pressure pan readings ranged from 0.5 to 21.0 Pa, with an average of 2.89 Pa for the 32 homes.

With the house depressurized by the blower door to -50 Pa wrt (with respect to) outdoors, the 2nd story floor cavity pressure was measured wrt the inside of the house. Among the 32 homes, the floor cavity pressure varied from +15.5 Pa to +48 Pa, with an average of +36.2 Pa. Generally floor spaces with significant pathways to attic or outdoors had pressures between +43 Pa to +50 Pa with reference to the house. In the case of +15.5 Pa, this indicates that the floor cavity is more “inside the air boundary of the house”. The average +36.2 Pa indicates that, on average, that the floor cavity is more “outside the air boundary of the house” and less “inside the air boundary of the house”. Those with higher floor cavity pressures were more likely to have greater wind washing potential, because the floor cavity was likely to be open to adjacent attic spaces located above first floor sections of the house. This measurement can be misleading since it is a *relative* comparison of holes that are in series from house to cavity then cavity to outdoors. The average pressure of +36.2 Pa in the floor cavity indicates that the leak pathways from indoors to the floor cavity are about half as large as the leak pathways of the floor cavities to outdoors (Fitzgerald et al. 1994). Even though this pressure measurement is not an indication of the absolute size of the cavity leakage, it provides a good indication of wind washing potential. More study is needed to develop diagnostics that can supplement visual inspections.

House envelope airtightness was measured. The average CFM50 (air leakage through the house envelope when depressurized to -50 Pa) was 3,076. The average values for C and n were 281.2 and 0.628, respectively. ACH50 ranged from 3.4 to 13.5, with the average being 8.14. Based on previous research, the average natural infiltration rate (produced by wind and temperature differential effects) in Florida homes can be estimated by dividing the blower door test result (Cummings et al. 1990) (ACH50) by 40. Using this method, the average natural infiltration rate for these 32 homes would be 0.20 ach.

A tracer gas decay test was performed with the AHUs running continuously. The air changes per hour (ach) rate varied from 0.14 ach to 0.86 ach, with an average of 0.42 ach. This suggests that the house infiltration rate increases, on average, by 110% as a result of air leakage from the air distribution system (duct leakage). The AHU “on” air change rate can be converted to an air flow rate in cubic feet per minute (cfm), by multiplying ach by volume and dividing by 60 minutes. The cfm of air exchange between indoors and outdoors (with AHUs running continuously) varied from 46 cfm to 387 cfm, with an average of 161 cfm.

Selecting Homes for Wind Washing Repair Study

Significant wind washing potential was identified (from field testing and inspection) in about 40% of the two-story homes that were tested. It should be noted that we attempted to pre-screen (typically by means of a phone call) the houses to improve the probability that the houses we inspected and tested would have wind washing potential. In this phone conversation, we would ask the homeowner if there were any attic spaces above first floor sections of the house that were adjacent to conditioned second-story sections of the house. In some cases, we would also ask if they could observe any openings from the attic space into the inter-floor cavity. Approximately 50% of potential testing candidates were then excluded from field testing prior to our making a field visit.

From the field-tested homes, six homes were selected for monitoring and repair. It should be noted that these six homes were selected from the first 16 homes that were tested. This occurred because of the project schedule for repair monitoring and repair. We wanted to make wind washing repairs in mid-summer so there would be at least a couple months of monitored air conditioning data for the pre-repair period and a couple months of monitored data for the post-repair period. By the time selection had to occur, only 16 homes had been tested. This has important implications regarding the representativeness of the monitored energy savings and peak demand savings that were found in these homes. Note also that the first five homes tested had essentially no wind washing potential. So, the six repaired homes were selected from field test houses 6 through 16. Furthermore, subsequent testing of houses 17 through 32 found that there were a greater number with high wind washing potential the latter group. As a result, we expect that the energy and demand savings from the six monitored/repaired homes under-represents potential energy and demand savings, compared to a larger sample.

Assessment of Wind Washing Air Leakage Pathways

When considering how wind-driven air enters the home through the floor space, one must imagine (typically three) "holes" or pathways in series. The size of the holes determines the resistance to air flow at each stage of the air flow pattern. Air starts outside, travels through the soffit venting, passes through another "hole" between the roof deck and top of exterior wall, finds itself in the attic, and passes into the open floor cavity of the main part of the house. The total area of open holes or pathways was evaluated for the six repaired homes. Consider this example from one of the repaired homes:

- Soffit vent free area around the garage perimeter = 6.2 ft^2
- Open area between the soffit and attic = 24.8 ft^2
- Floor cavity to attic space opening = 12.1 ft^2.

The series of leakage apertures was also evaluated for the other five repaired houses. In all cases the soffit was the smallest aperture in this series of air pathways but the ratio between the soffit vent and open floor area varied greatly. On average the soffit net free area was about 13 times smaller than the open area between floor space and attic with a range from two times smaller to as much as 50 times smaller (in house H14Y discussed later).

In addition to these identified pathways, an additional "exit" pathway plays an important role in this wind-driven air flow. This can be thought of as a complimentary pathway, providing an opportunity for air to freely flow through the house interstitial cavities. In the absence of the complimentary hole or pathway, the potential for wind washing air flow is considerably decreased. This exit pathway can be an opening in the floor cavity on the other side of the house. House number 23 provides a good example of a house with complimentary pathways. It is located within a half mile of the Atlantic Ocean, has a vented attic, and has an open floor space orientation east to west which readily allows the sea breeze to flow through the building cavities. The floor plan can be seen in Figure 6 and an example of open floor cavity on the west side is shown in Figure 7. Evidence of heated interior surface materials at this house can be seen in Figures 1 and 8.

Alternatively, the exit pathway could be into the conditioned space of the house. This was illustrated in test home number 24, which was located on the Indian River and was exposed to persistent sea breezes from the Atlantic Ocean which was about 6 miles away. Installation of hurricane shutters on the house had created penetrations/openings in the exterior walls which allowed air flow into the inter-floor cavities. Inside the house, 80 "canned" light fixtures were located in the ceiling of the first floor. These light fixtures can have leakage of at least 1.5 in^2 per unit (ELA4) (Edwards 1999). All 80 fixtures represent nearly 1 square foot of leak area. Air flowing from outdoors into the interstitial floor cavity could pass into the first floor area through the light fixtures, thus adding heat and humidity directly into the space and significantly increasing heating and cooling energy use.

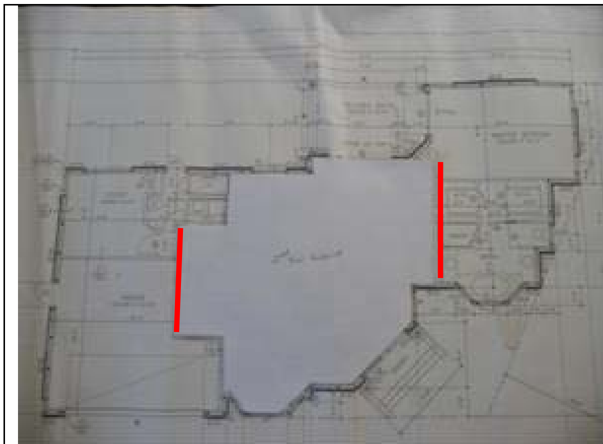

Figure 6 Floor plan of 2nd floor on top of 1st floor. Red lines show location of open floor cavity on east and west sides of House H23. Left side is to the east.

Figure 7 Open area of floor cavity below kneewall covered with house wrap on the west side of house.

Figure 8 Warm floor space area next to west attic located just to the right of image. The dark area near the time label is a cold supply grill on the first floor ceiling. *(Image credit Withers)*

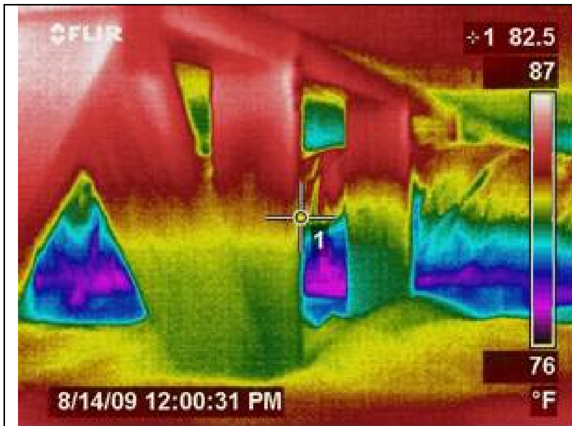

Figure 9 IR image inside a 2nd story floor cavity open to a hot attic shows thermal stratification (House 16). *(Image credit Withers)*

Figure 10 Photo of image above. The floor space is between conditioned space above and below. *(Withers)*

House number 16 was one of the houses chosen for retrofit. It had only one floor cavity open to attic space with no complimentary holes on other sides of the house. Even without complimentary pathways, air can move into floor cavities. Infrared images taken inside the floor space on a hot day show significant indications of thermal transfer between the conditioned and unconditioned space (See Figures 9 and 10). Notice the stratification of temperature inside the floor space where the hotter temperatures (seen as red) are at the top and the relatively cooler temperatures (seen as yellow-green) are in the lower half. The attic air temperature was about 90° F in front of the floor space at the time the images were taken. Normally, the inter-story floor cavity contains no insulation. However, in this case batt insulation can be seen on the bottom of the floor cavity (Figure 10). The insulation would slow heat transfer to the first floor, but do nothing to prevent aggressive heat conduction to the second floor.

CONCLUSIONS

Wind washing problems in homes were found in approximately 40% of the two-story homes examined. Wind washing was mostly related to open or partially open 2nd story floor space adjacent to attic. The extent that wind washing will occur depends upon several factors: wind speed, direction, size of floor cavity openings, area of insulation exposed to air movement, and the presence of complimentary air leakage pathways. Air will move more readily though a floor cavity that has openings to outdoors on both sides compared to having just one pathway.

Only one home in this study was identified to have a large amount of wind washing occurring around kneewall batt insulation (Figure 4). Typically, this specific type of wind washing of kneewall insulation, when it did occur, was limited to small areas of the kneewall. This would typically occur near the top or bottom of batt where it was slightly pulled away from wallboard, either due to poor installation or from being disturbed after installation during service work.

Of the first 16 homes tested, six were selected for monitoring and repair. However later in the study we found better candidates for retrofit evaluation, but did not have enough cooling season left to include them in the study. Considering the limited extent of wind washing in the six retrofitted homes, annual cooling energy savings and peak demand reductions can be considered substantial, averaging 15.3% and 12.6%, respectively. Part II of this paper discusses the extent and impacts of wind washing of each house in greater detail.

ACKNOWLEDGEMENTS

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REFERENCES

ASTM International 2003A. *Designation: E779-03 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*. ASTM International, West Conshohocken, PA.

ASTM International 2003B. *Designation: C1060-03 Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings.* ASTM International, West Conshohocken, PA.

ASTM International 2006. *Designation: E741-06 Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* ASTM International, West Conshohocken, PA.

Cummings, J.B. 1989. Tracer Gas as a Practical Field Diagnostic Tool for Assessing Duct System Leaks. *Proceedings of 6th Annual Symposium on Improving Building Systems in Hot and Humid Climates*, Dallas, TX.

Cummings, J.B., N. Moyer, and J.J. Tooley.1990. Radon Pressure Differential Project, Phase II: Infiltration. FSEC-CR-370-90, Florida Solar Energy Center, Cocoa, FL.

Edwards, C. 1999. Modeling of Ventilation and Infiltration Energy Impacts in Mid and High-Rise Apartment Buildings. Research Division, Canada Mortgage and Housing Corporation, Ottawa, Canada, p 13.

Fitzgerald, J., R. Nevitt, and M. Blasnik.1994. User-Friendly Pressure Diagnostics. Home Energy Magazine Sept./Oct.

Lstiburek, J. 2005. Builder's Guide to Hot-Humid Climates. Building Science Press.

Sidall, M. 2009. The Impact of Thermal Bypass. Green Building Magazine 19 (1), 16-23.

US DOE 2000. Technology Factsheet: Ceilings and Attics: Install Insulation and Provide Ventilation. United States Department of Energy, Office of Building Technology, State and Community Programs, DOE/GO10099-771