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.

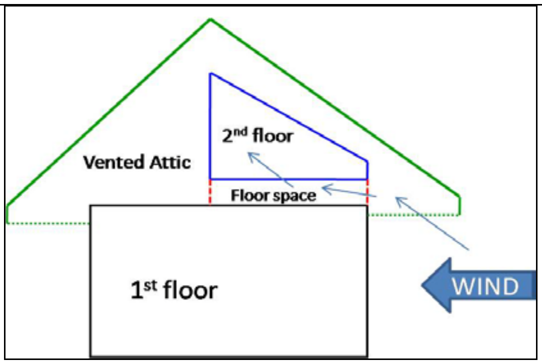

Figure 3 Wind-driven attic air is pushed into the space between floors. *(Withers)*

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.

Field Testing Data

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.

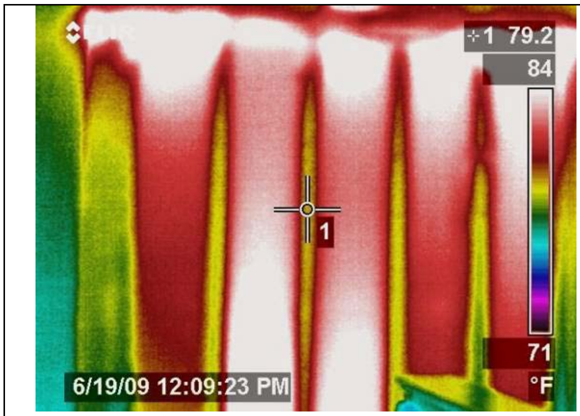

Figure 4 IR image of wood frame wall adjacent to unconditioned space. *(Image credit Withers)*

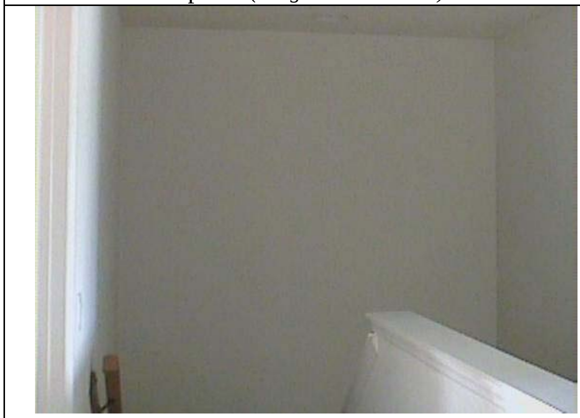

Figure 5 Photo of the stairwell wall matching the IR image of Figure 4. *(Withers)*

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.

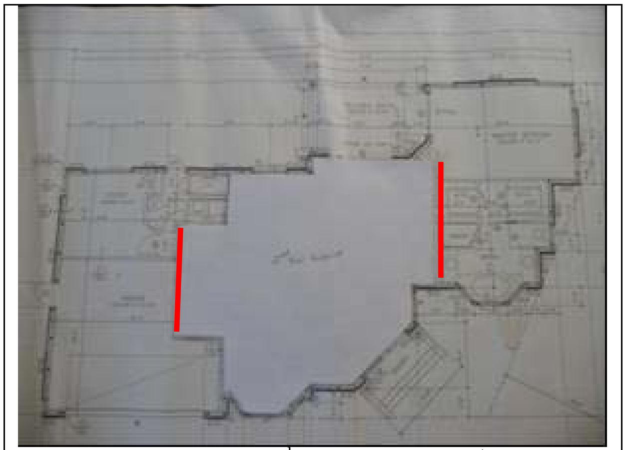

Figure 6 Floor plan of 2nd floor on top of 1st floor. Red lines show location of open floor cavity on east and west sides of House H23. Left side is to the east.

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

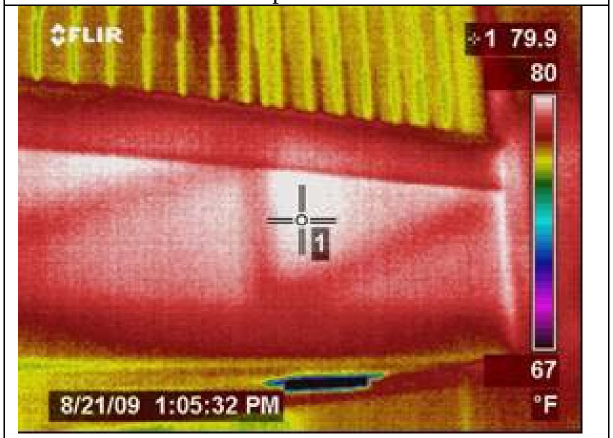

Figure 8 Warm floor space area next to west attic located just to the right of image. The dark area near the time label is a cold supply grill on the first floor ceiling. *(Image credit Withers)*

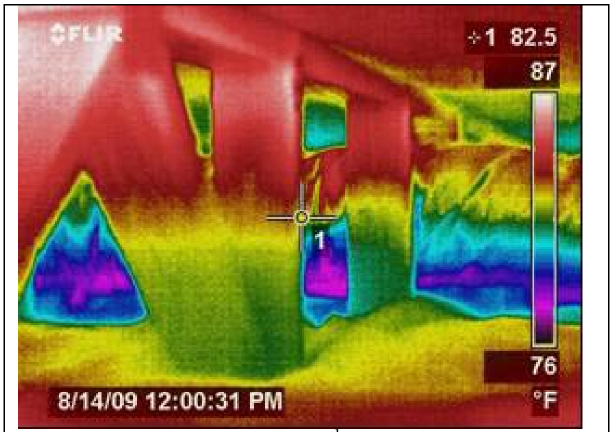

Figure 9 IR image inside a 2nd story floor cavity open to a hot attic shows thermal stratification (House 16). *(Image credit Withers)*

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.

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

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ABSTRACT

Wind washing is a general term referring to diminished thermal control caused by air movement partially or completely bypassing the thermal barrier. The primary focus of this paper relates to 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 involves insulation batts on knee walls where space between the batts and the wall board allow air movement against the gypsum wall board.

Through the summer of 2009, a field study tested thirty-two homes and found significant wind washing potential in 40% of the homes as discussed in Part I of this paper. 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 here in Part II of this paper.

This paper reports average cooling energy savings measured in six homes of 15.3%. Savings were as high as 33.1% in one home. The paper also assesses the scope of these envelope problems, discusses improvements in comfort and durability, recommends retrofit solutions, and identifies energy savings potential for retrofit programs. While energy savings were only evaluated during summer weather, wind washing repairs should save energy during cold weather and be applicable throughout the nation.

PROJECT BACKGROUND

While wind washing has been known and studied for years, most of the emphasis has been on cold climate. In a published article by Mark Sidall, he summarizes much of the work done over the years related to thermal bypass problems such as wind washing (Sidall 2009). Some of the earliest work on thermal bypass was published over 30 years ago (Bankvall, 1978). Even though previous published work has stated energy-related impacts in measures such as change in U-values or other parameters, none have quantified actual measured space cooling or heating usage impacts in real homes, particularly in hot and humid climates (Anderson 1981, Harrje 1985, Lecompte 1990, Silerbsein 1991, Uvslokk 1996, Hens 2007, Janssens 2007). The primary goal of this project was to characterize methods and cost-effectiveness of retrofit solutions for wind washing in two-story homes. This information can then be used directly by utilities and property owners to evaluate opportunities for repairs.

REPAIR RESULTS

Repairs were performed in six of the 32 tested homes discussed in Part I. Six repair homes were monitored for representative summer periods to characterize AC energy use and space conditions before and after repairs. Analysis has been performed to characterize cooling energy and peak demand savings. No energy analysis has been performed for the winter season.

Monitoring consisted of the following types of data.

- Power use of the AC system(s) (typically two) which serve(s) the house.
- Temperature measurements indoors, outdoors, in the attic, in the floor cavity between the first floor and the second floor of the house, and in the return and supply air of the AC systems.
- Relative humidity measurements indoors, outdoors, in the attic, and in the floor cavity between the first and second stories.

Data was collected in 15 minute time steps and stored in the memory of an on-site data acquisition system (DAS). Data was transferred daily from the DAS to the FSEC central computer system. The data was then retrieved for analysis through a program called WebGet 4.0.

Testing Measurement Summary for Six Repaired Homes

While there were several measurements taken at each house, it was the house airtightness and duct leakage that were impacted the greatest from wind washing repairs. Table 1 below summarizes the air changes per hour at 50 pascals (Pa) (0.20 in WC), measured infiltration in air changes per hour (ach) with the air handler unit (AHU) on, return leak fraction (RLF), and pressure pan as an indication of overall duct tightness. Testing methodologies are discussed in further detail in Part I of this paper.

Table 1 House airtightness (ACH50), infiltration (ach) with AHU “on”, RLF, and average pressure pan readings before and after repairs.

House #	ACH50 Pre Post	ach Pre Post	RLF Pre 1st fl. Post 1st fl.	RLF Pre 2nd fl. Post 2nd fl.	P-Pan Pre 1st fl. Post 1st fl.	P-Pan Pre 2nd fl. Post 2nd fl.
H10H	7.25 6.14	0.46 0.32	8.0% 2.2%	2.8% 1.1%	1.2 1.0	0.2 0.1
H8Hd	9.38 8.56	0.49 0.30	0.4% 0.4%	1.1% 1.4%	0.7 0.3	0.4 0.2
H16B	9.86 9.19	0.26 0.20	5.3% 5.3%	1.0% 1.1%	1.1 0.3	1.0 1.0
H11C	9.65 9.40	0.73 0.64	11.5% 7.9%	*No 2nd fl. A/C*	2.0 2.2	*No 2nd fl. A/C*
*H7G	12.21 9.52	0.86 0.31	NA 2.0%	9.6% 1.1%	8.7 2.4	11.6 1.6
*H14Y	11.26 11.15	0.59 0.54	4.0% 0.7%	1.2% 0.0%	12.7 1.0	1.2 1.3

*post values are after duct repair and wind washing repair

Based on the six house average pre and post values, the impacts from all repairs are as follows:

- The house envelopes became 9.5% tighter.
- Infiltration with AHU “on” decreased by 32%.
- RLF decreased by 53%.
- Pressure pan values decreased by 72%.

The wind washing repair did not directly seal return leaks. Air would still leak into the return, but the repair results in the floor cavity becoming more like indoor space. With the floor cavity more isolated from the attic, there was reduced air exchange with the attic and less thermal penalty.

We find, therefore, that repair of wind washing denies duct leaks some of their opportunity to move air across the house envelope air boundary. Wind washing repair should also be considered a way to “repair” duct leaks that are inaccessible because they are located in floor cavities, and otherwise would not be repairable. Return leakage declined by 26% in the 1st story returns of the four houses in which no duct repairs were made. Return leakage declined by 41% in the 2nd story returns of the four houses in which no duct repairs were made. The 2nd story returns experienced a larger RLF reduction since these returns either run through the floor space or have plenums in contact with the floor cavity. The overall duct leakage (as indicated by pressure pan averages) declined by 23%. It is probable, therefore, that wind washing energy savings will be greater (depending upon duct leak locations with respect to the house air envelope) in homes with large duct leaks.

Energy and Peak Demand Savings Analysis Method

As indicated earlier, all six homes were repaired in the same month (September) and in all cases, open-cell foam was applied to seal openings of the between-stories floor cavities. Specific details of the wind washing repairs and the impacts of those repairs are contained in the house by house descriptions that follow. In two homes (Houses H7G and H14Y), duct leak repairs were also separately implemented. We decided to correct these large duct leaks because they represent a large energy waste factor which could substantially impact the savings achieved by wind washing repairs. An energy monitoring period occurred before the duct repair or and another monitoring period occurred before the wind washing repair. Because of this, we were able to identify cooling energy use in these two homes for three time periods; 1) before any repairs, 2) after duct repairs, and 3) after wind washing repairs.

Energy savings analysis was performed for each home in the following manner. A linear regression best-fit analysis was used to develop the best fit lines shown in a graph for each home. Daily cooling energy use for the house was plotted versus the temperature differential between outdoors and indoors for the day (dT). The linear equations from each period were then used with 10 year composite typical meteorological year (TMY2) data representing 4 major cities in Florida. The TMY2 data has hourly outdoor dry bulb temperature for each day of the year representing a geographical weighting of Florida Power and Light’s (FPL) residential consumers. Using the TMY data, daily energy use, for the pre-repair period and the post-repair period was calculated based on the daily temperature difference between indoors and outdoors. On cold days, the calculation results in negative cooling energy values, which have been excluded from the annual cooling energy usage. Cooling energy savings for each day of the year is summed to yield annual energy savings. Because we have not considered heating season savings, the savings estimates that we have provided under-represent the total benefit of wind washing repair.

In order to perform the peak demand analysis, five to ten of the hottest monitored days were chosen with comparable pre-repair and post-repair outdoor and indoor temperatures. Only the hours from 3 PM to 8 PM were used for this regression analysis. This five-hour period was chosen in order to obtain a better range in delta-T and provide a larger database.

Hourly energy use was plotted against the hourly average delta-T (outdoor temperature minus indoor temperature). Linear regression best-fit equations were developed separately for the pre-repair and post-repair periods, and the two best-fit equations were then used with the hourly TMY data to calculate pre and post kW for the TMY day of August 15, which had the hottest outdoor temperatures of the year from 3 PM to 6 PM. The peak kW was calculated for the hours ending at 3, 4, 5 and 6 PM, and the average for this four-hour period was used to represent the peak. The peak demand reduction was obtained by subtracting the calculated peak from the pre-repair equation from the calculated peak from the post-repair equation for that hot TMY day.

RETROFIT DESCRIPTIONS AND MEASURED IMPACTS

This section provides a house by house discussion of the repairs and the measured wind washing repair impacts in each of six houses that were monitored.

House H10H and Repair Description

This 2,760 ft^2 slab-on-grade, frame construction residence was built in 1997. The first floor has 2,030 ft^2. An attached two-car garage faces east. The second floor has 730 ft^2 including a small bonus room located above the unconditioned garage space. There is approximately 82.5 ft^2 of conditioned floor area above unconditioned space. The bonus room construction is traditional gypsum board on the interior, and is insulated with R-30 kraft-faced batts with the fiberglass side facing into the garage attic. The underside (floor cavity) of the bonus room is unsealed allowing hot air to move through the floor cavity.

The kneewall (between the garage attic and the second floor of the house) on either side of the bonus room was poorly covered with kraft faced batt and allowed airflow into the interstitial floor cavity. Numerous wires, refrigerant lines, and ducts penetrate into the floor cavity and very little effort was made during construction to effectively seal the kneewall. Figure 1 illustrates the open areas in the floor space and the floor cavity of the bonus room floor, which is open to the attic on the north side. The same problem exists on the south side (not seen in photo).

Foam insulation product was applied to the floor cavity openings and the kneewall separating the garage attic and the main house. Foam insulation was also applied to the walls of the bonus room and to the floor cavity openings beneath the bonus room. The repairs required 2.25 man-hours (2 person crew for just over 1 hour) to cover 113 ft^2 of area.

Figure 1 View of kneewall and main floor space (far), and bonus room wall and floor cavity (left).

Pre and Post Wind Washing House Testing Results

Wind washing repair made the house envelope more airtight and reduced duct leakage from outdoors.

- After repair, the house was 15.3% more airtight.
- Implementation of wind washing repairs substantially reduced duct leakage to outdoors, even though no repairs were directly applied to duct leaks.
- RLF declined 69%.
- Average pressure pan values decreased indicating less duct leakage from outdoors, but the decrease was not greater than the accuracy of measurement at low pressures.
- After repair, the house infiltration rate with the AHUs operating was 32% lower.

Energy and demand savings from repairs

The linear regression of daily cooling energy versus dT was used to develop an equation. Using the TMY data weighted for FPL’s four largest regional cities, the calculated annual cooling energy use for House H10H for the pre-repair and post-repair periods were 4,629 kWh and 3,793 kWh, respectively. The resulting annual cooling energy reduction is 836 kWh or 18.1%. At a typical cost of $0.115 per kWh, this yields annual cooling energy cost savings of $96.

Also previously described in greater detail, linear regression best-fit equations were developed separately for the pre-repair and post-repair peak demand periods. The two best-fit equations were then used with the hourly TMY data to calculate pre and post kW for the hottest outdoor temperatures of the year from 3 PM to 6 PM. The average of this four-hour period was used to represent the peak. The peak demand reduction was obtained by subtracting the calculated peak from the pre-repair equation from the calculated peak from the post-repair equation. Based on this analysis, a reduction of 0.10 kW (from 2.10 to 2.00) in air conditioning electrical demand occurred at House H10H as a result of the wind washing retrofit. This is equivalent to a 4.5% reduction in peak demand.

House H8Hd and Repair Description

This 4,175 ft^2 slab on grade, block and frame house is located along an inter-coastal waterway within a mile from the ocean. Soffits provide venting to the attic space located above the attached two-car garage. Beige barrel terra cotta tile provide roof coverage and limit solar heat gain on the building. The first floor has 2,450 ft^2 and the second floor has 1,725 ft^2. There are approximately 1,653 ft^2 of first floor area located under the second floor interstitial floor space.

Figure 2 NE corner of house. *(Withers)*

The HVAC system is made up of two high efficiency heat pumps, each serving one floor of the house. The first floor system AHU is located in the garage and the second floor system AHU is located in a second floor closet. Both systems have ducted returns and well-constructed plenums.

Prior to initial inspection, the homeowner had complained of condensation, mold, and warping on two pocket doors in the 2nd level bathroom on the north side. Our inspections also identified these moisture issues. The pocket doors are located in the east and west facing interior walls running perpendicular to the north facing exterior wall. It is also important to note that the homeowners prefer lower than average thermostat set points especially during summer evening hours. Based on our inspection, it appears that outdoor air enters through soffit venting, passes into the interstitial floor cavity, and then flows into the interior wall cavities containing these pocket doors. The cold indoor temperatures enable the high moisture content air to condense on the surfaces of the pocket doors. Moisture condensation on supply registers had also caused damage to ceilings. The homeowners were aware of the wind washing issues in their home and had put effort into stopping this form of uncontrolled air flow prior to our inspection and testing. Ceiling surfaces had been repaired and some duct modifications had been made by a contractor about a year prior to our testing and monitoring.

The homeowner also brought to our attention warping and cracking of the grand staircase in the front foyer of the home. Upon inspection it became clear that the rear of this staircase could be well-connected to the interstitial floor cavities which are well-vented to the west-facing soffits. We hypothesize that prevailing winds (coming from the east from the nearby ocean) drive moist outdoor air into the interstitial floor cavities where it interfaces with the backside of the stair case promoting warping and separation of the wooden risers and treads as wood adsorbs moisture. Figure 3 illustrates cracking of the wooden risers. Wood moisture content was measured with a moisture meter before repair and was found to vary from 13.1% moisture content at the top of stairs down to 9.5% moisture content towards the bottom of the stairs. The average moisture content of wood in the staircase before retrofit was 10.9%. By comparison, wood furniture inside the home had a moisture content around 7.5% to 8%, within expectations for wood located in a humidity controlled environment. The average wood moisture declined from 10.9% to 9.0% after retrofit. Cracks in the stairs, which were quite prominent prior to repair, had nearly closed within about 6 weeks of the wind washing repairs.

Figure 3 Stair riser crack separation before repair. *(Withers)*

In addition to the staircase moisture issue, the owner also reported that supply registers on the first floor had experienced moisture condensation and dripping in areas that were directly under the interstitial floor cavity that was experiencing wind washing. The owner also noted that ceiling drywall had been damaged in the kitchen and adjacent hallway from condensation on ductwork inside the floor cavity. This is clear evidence that wind washing air flows had penetrated into the depths of the building structure.

Prior to installation of the open-cell foam product, condensation-wetted fiberglass batts in the attic were removed. These batts had been recently installed by the homeowner (prior to our involvement with the house) in an attempt to stop air flow into the interstitial floor cavities. Where the batts were in contact with supply ducts, considerable moisture condensation had occurred (Figure 4).


Figure 4 Moisture condensed on flex ducts and accumulated on insulation materials placed in contact with the supply ducts by the homeowner. *(Withers)*


Figure 5 East side floor cavity isolated from the garage attic; a protective vapor barrier/thermal barrier sleeve isolates the foam from the exterior of the supply ducts to reduce the condensation potential . *(Withers)*

Moisture condensation on ducts is an especially common problem in homes where the homeowner sets the thermostat to a low temperature continuously or even for a portion of the day, such as at this house. Colder supply air leads to a colder outer duct jacket, which in turn increases the rate of condensation. Figure 5 shows a portion of an insulated vapor barrier that was used to wrap around cold supply ducts to avoid condensation on ducts after sealing the open floor spaces. This is discussed in more detail in the MOISTURE ISSUES section.

Foam insulation product was also used to seal air pathways into the interstitial floor cavities on the north and west sides of the house. The application of foam on the north and west sides of the house was particularly difficult since it required removing the soffit face material and then building a foam barrier in the space between the top of the block wall and the roof deck, one bay at a time over a 40 foot length (Figure 6). A total of 10.0 man-hours were required to implement wind washing repair at this house, covering a total surface area of 108 ft^2. The time required to remove and re-install soffits substantially increased the amount of time required for repair.


Figure 6 Foam application into west soffit area. *(Withers)*

Pre and Post Wind Washing House Testing Results

Wind washing repair made the house envelope more airtight and reduced duct leakage from outdoors. Duct leakage was, however, small to begin with.

- After repair, the house was 8.7% more airtight.
- Implementation of wind washing repairs reduced 1st floor supply duct leakage to outdoors (as indicated by pressure pan testing), even though no repairs were directly applied to duct leaks. Average pressure pan values for the 1st floor supplies declined by an average 57%.
- RLF did not change.
- After repair, the house infiltration rate with the AHUs running continuously was 39% lower.

Energy and demand savings from repairs

Using the weighted TMY data and cooling energy versus dT linear equations, the calculated annual cooling savings for House H8Hd was 2,771 kWh (8.2%). At a typical cost of $0.115 per kWh, this yields annual cooling energy cost savings of $319. With an estimated repair cost of $770, wind washing pays for itself in less than three years excluding any incentives that might be available.

Based on the hourly regression of kW versus dT, and the TMY hourly data, the 3 PM to 6 PM kW demand reduction for the hottest day of the year was 1.80 kW in air conditioning electrical demand as a result of the wind washing retrofit. This is equivalent to a 15.0% reduction in peak demand.

House H16B and Repair Description

This 3,081 ft^2 slab-on-grade, wood frame home was built in 1990. Substantial improvements had been made to the exterior materials and windows over the past few years. It has 1,732 ft^2 on the first floor and 1,349 ft^2 on the second floor. Above the attached three-car garage is an attic with a maximum height of seven feet that follows the contours of the roof deck. There are 989 ft^2 of first floor area under the second floor and 360 ft^2 of second floor area over unconditioned space.

Additionally, the floor cavity between the first and second stories of the main part of the house was largely wide open to the garage attic space. This attic space vents to both the unfinished garage ceiling and the soffit surrounding the garage.

The infrared image in Figure 7 was taken in the attic during our field visit August 14, 2009 prior to repairs and shows cooler air displaced into the lower attic area next to the open floor space. Figures 8 and 9 show the floor cavity and knee wall prior to and after application of foam insulation. Figure 10 shows a relatively homogenous temperature plane across the foam.

Pre and Post Wind Washing House Testing Results

Wind washing repair made the house envelope more airtight.

- After repair, the house was 6.8% more airtight.
- Wind washing repair had little impact on duct leakage.
- After repair, the house infiltration rate with the AHUs operating was 23% lower.

Figure 7 IR view inside the attic shows cool temperatures in the floor space and cooled surfaces low in attic. *(Withers)*

Figure 8 Photo of IR image above. The floor cavity at the bottom of the wall is open to garage attic. *(Withers)*

Figure 9 Technician finishes up kneewall and floor cavity insulation/air tightening. *(Photo credit Ian LaHiff)*

Figure 10 IR image from inside attic after repair. *(Withers)*

Energy and demand savings from repairs

Using the four-city weighted TMY data and cooling energy versus dT best-fit equations, the calculated annual cooling savings for H16B was 682 kWh (13.4%). At a typical cost of $0.115 per kWh, this yields annual cooling energy cost savings of $78.

Based on the hourly regression of kW versus dT, and the TMY hourly data, the 3 PM to 6 PM kW demand reduction for the hottest day of the year was 0.39 kW in air conditioning electrical demand as a result of the wind washing retrofit. This is equivalent to a 17.3% reduction in peak demand.

House H11C and Repair Description

This 2,410 ft^2 split-level, block and frame home was constructed in 1967. It contains 1,610 ft^2 on the first and second levels combined and 800 ft^2 on the top level (Figures 11-12). This open floor plan home has conditioned space adjacent to very small vented attic/soffit areas on both the front and back of the house. Essentially, there is no adjacent attic space allowing air flow into the interstitial floor cavities, rather air can enter these cavities from small ventilated eave spaces. Wind washing repairs were challenging since there was very limited access to open floor areas to be sealed on the north side of house.

The only access to the small attic section on the north side of the house was through the attached garage attic. Consequently, foam had to be shot through a very narrow attic space (above the front porch) which had about 16” of vertical clearance. The problem with shooting foam through narrow areas is that the product ejection spread is approximately 6” diameter at a distance of 8 feet. This means that you can only effectively reach about 10 feet away into this space before the foam product builds up and seals off further access. Figure 13 shows wind washing repairs just underway on the opening of the floor cavity within the north side attic space.

Figure 11 Front of split level home faces north. There is a small attic space above the front porch and garage which is open to the interstitial floor cavities.

Figure 12 Back of home (facing south) with top story floor space cantilevered and vented over back patio.

Figure 13 Beginning of north side sealing. *(LaHiff)*

Sometimes the laws of unintended consequences work in your favor. In this case, the spray gun nozzle was beginning to clog for the second time that day. This produced a narrower than usual spray stream which could then be projected further into the small attic space, allowing better than expected coverage.

In spite of restricted access, foam could be applied to seal 75% to 80% of desired area on the north side of the house. If wind washing repairs become a common application in the future, it would be valuable to have various nozzle sizes and wand lengths that could allow application from a greater distance.


Figure 14 View from soffit vent looking inside towards floor space in area having no batts. *(Withers)*

Figure 14 shows the interior of the south side floor space after placing a camera into the soffit opening outside the house before sealing the floor opening. Open cell foam was sprayed inside the south vents to separate floor cavity from vented area. The south side was sealed 100%. Average foam insulation thickness was about 3 inches. We estimate that overall, the repair effort at this house resulted in sealing about 90% of openings to the interstitial floor cavities. Note that 100% sealing of wind washing leaks on one side alone can achieve much of the effectiveness of sealing both sides, because it eliminates the complimentary pathway through which wind can be pushed.

<u>Evidence of wind washing</u>

Project staff noticed that very cool dry air was felt at the south soffits prior to sealing the floor cavity. An infrared camera was used to observe surface temperatures (Figures 15-16). These images clearly indicate cool air from within the house being displaced from the leeward side of the house.

Monitored temperature and humidity data at six locations over a two-day period found dew point temperatures in both soffits that were much lower than outdoors much of the time. Figure 17 shows dew point temperatures in six locations (including indoors, outdoors, eaves, attic, and floor cavities) plus AC power over two summer days. Interesting patterns were observed. The homeowner typically raised the thermostat setting during the day, and then lowered it in the early afternoon. This causes the AC system to remain off for an approximate 7 hour period starting in the morning. While the outdoor dew point temperature was in the range of 70°F to 72°F throughout this two-day period, indoor dew point temperatures were at 48°F when the AC had been operating for a consistent period, but then rises steadily to a spike of about 60°F after the AC has been off for 7 hours.

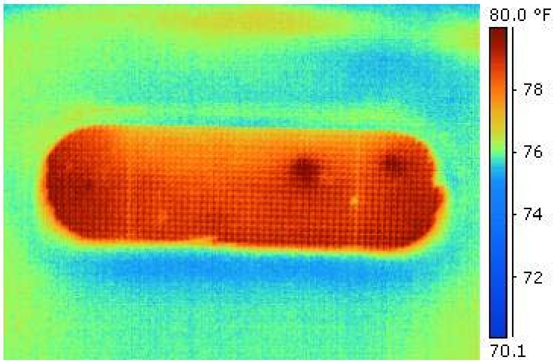

Figure 15 With 10 mph wind from the north, the north soffit vent shows interior surface temperatures about 78-80°F. Outside air temperature =80.1°F and interior air temperature=71.0°F. *(Withers)*

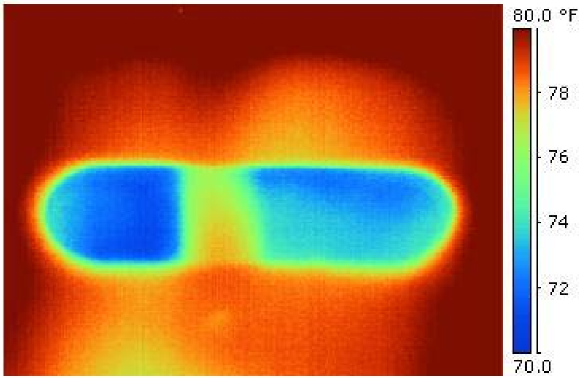

Figure 16 With 10 mph wind from the north, the south soffit vent shows average of 71.9 °F on interior surfaces in left bay and about 73.2 °F on right bay indicating cool house air being pushed through the house by means of the floor cavity and the force of the wind. *(Withers)*

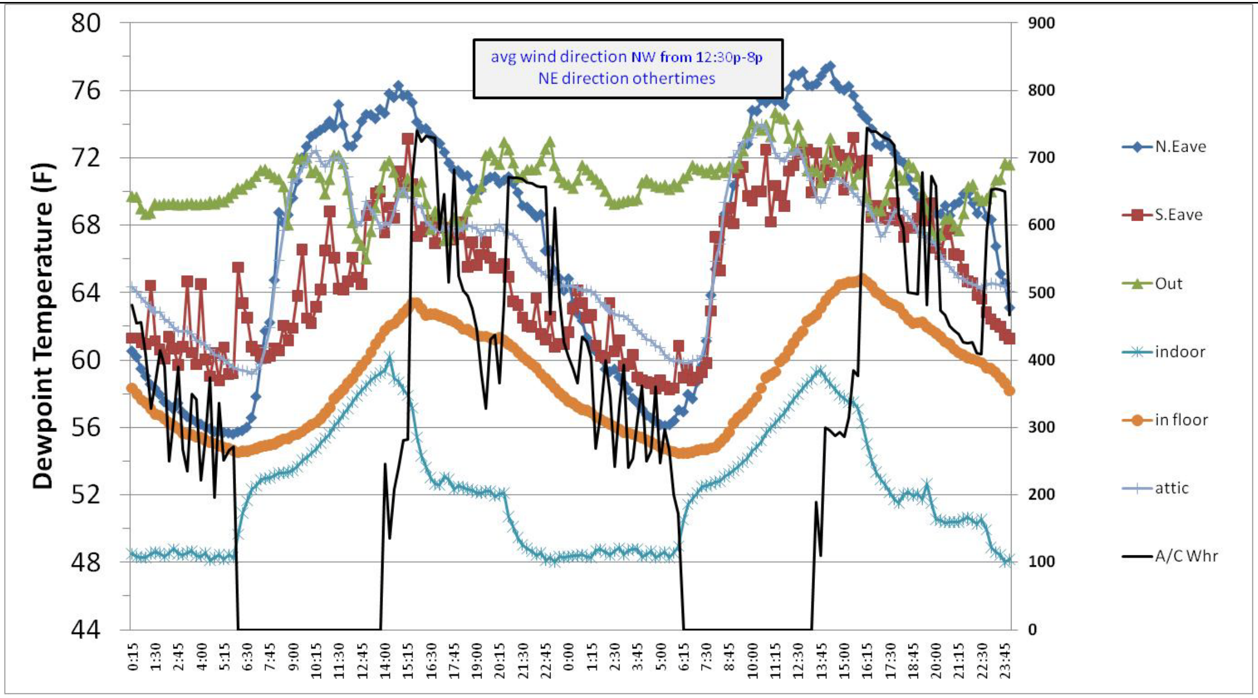

Figure 17 Graph of H11C dew point temperatures and A/C energy over two days shows patterns between A/C runtime and cool dry air from indoors making its way out to the soffit eave areas. Right Y-Axis is cooling energy in Watt-hours.

Swings in dew point temperatures can also be (unexpectedly) seen in various building cavities and buffer zones that are not normally conditioned. First, we notice that the attic dew point temperature dropped substantially during the period that the AC system runs, declining from about 72°F to about 60°F. Similar patterns can be observed for the north eave and the south eave. Additionally, the floor cavity also modulates up and down, following a pattern that is part way between the conditions at the eave vents and indoors, illustrating the fact that the floor cavities are well connected to outdoors and to unconditioned buffer zones of the house.

It appears from this, that duct leakage is creating a mechanical driving force that displaces air through the floor cavities into the eaves and attic spaces. Additionally, it is known that the wind pushes air from the floor cavities into the eaves. On three different occasions, researchers felt and measured (temperature and RH) pulses of cool dry air that were being pushed into the south eave space. These pulses coincided with significant wind from the north at times when the air handler was off.

Pre and Post Wind Washing House Testing Results

Testing indicates that wind washing repair resulted in a slightly tighter house envelope. It also found mixed results regarding duct leakage from outdoors.

- After repair, the house was 2.6% tighter.
- Implementation of wind washing repairs produced no improvement to pressure pan duct leakage values.
- RLF decreased by 31%. After repair, the house infiltration rate with the AHUs operating decreased by 12.3%.

Energy and demand savings from repairs

Using the weighted TMY data and cooling energy versus dT best-fit equations, the calculated annual cooling savings for H11C was 565 kWh (12.0%). At a typical cost of $0.115 per kWh, this yields annual cooling energy cost savings of $65.

Based on the hourly regression of kW versus dT, and the TMY hourly data the 3 PM to 6 PM kW demand reduction for the hottest day of the year was 0.43 kW resulting from the wind washing retrofit. This is equivalent to a 21.3% reduction in peak demand.

House H7G and Repair Description

This two-story home is the middle unit in a triplex. The first floor has 1,502 ft^2. A two-car garage is located at the front of the house facing west (Figure 18). The second floor has 929 ft^2, including a “bonus room” located above the garage. There is a 3-foot high space between the ceiling of the garage and the floor of the bonus room and this space was vented to outdoors by means of soffit vents on the west and south sides.

Figure 18 Front of home H7G faces west. Exterior wall surfaces reach 114°F. *(Withers)*

Insulation batts were located on top of the garage ceiling but no insulation had been applied to the floor of the bonus room. Additionally, the floor cavity between the first and second stories of the main part of the house (about 14 inches in height) was largely wide open to the 3' high cavity above the garage and beneath the bonus room, which was vented to outdoors. Finally, this 14" high floor cavity was also exposed to another attic space located to its south side, but most of the potential openings from floor cavity to the south attic space were blocked by batts with kraft paper backing so air sealing (wind washing repair) was determined to not be required except for one six-foot section.

Hot attic air could readily flow into the interstitial floor cavity located between the first and second stories. Where the heat penetrates into the house structure, it transfers heat into the ceiling of the first floor, the floor of the second story, and some stairwell walls (Figures 19-20).

Foam insulation product was applied to the floor of the bonus room and to the interface between the bonus room floor cavity and the floor cavity of the main part of the house. There was also a large opening between the large cavity below the bonus room and the south attic space; this was sealed to isolate the two spaces from each other. Figure 21 shows wind washing repair under the bonus room just before it was completed.

The wind washing repair took 4.6 man-hours to cover 510 ft^2 of area. This was the only retrofit where we received comments on the odor of the foam from the homeowner. We hypothesize that it took longer for the odor of the foam material (which is typically a light odor) to dissipate out of the space between the garage ceiling and the bonus room because there was little ventilation to carry away the active ingredients, now that all venting was sealed. We suggested that the homeowner open the garage access into the bonus room floor space, with the garage bay door open, for a couple of hours each day to see if this helped. The homeowner reported that the odors had greatly diminished within a couple days.

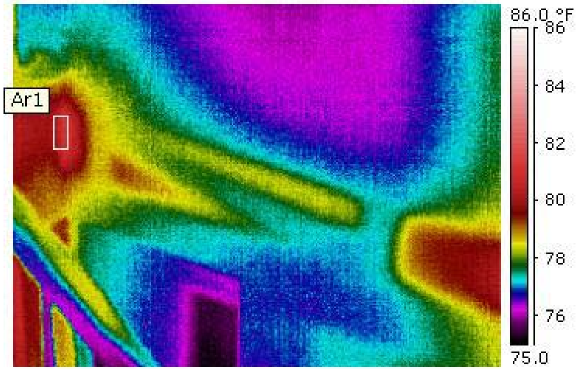

Figure 19 IR image of floor space area at stairwell shows areas of elevated surface temperature before retrofit. Area in box "Ar1" is about 81.4°F while the indoor set point was 77.3 °F on average. *(Withers)*

Figure 20 Photo of previous image. *(Withers)*

Both AC systems had large return leaks. In order to distinguish the energy savings from duct repair and wind washing repair, duct repairs were implemented in the return plenums of both AC systems. Repair of both returns involved cutting open the support platform for access and installing R6 duct board inside the platforms with the foil facing inward. It was important for the foil to face inward since it represents the air barrier of the duct board. Mastic was used to complete the air barrier from one duct section to the next and refrigerant line penetrations were sealed. Return leakage from the first floor system originated from the garage, where the AHU was located. Return leakage for the second story system originated from both the inter-story floor cavity and the attic.

Figure 21 Foam applied to wall and ceiling of the bonus room floor cavity (3' high). *(Withers)*

The second floor system was located inside a closet that had a solid door. This system had return leakage from two locations. Leakage from the floor cavity originated primarily through a large hole cut much bigger than needed for the refrigerant lines. (Note, however, that much of the air drawn from the floor cavity could originate from attic spaces above the garage and the first floor master bedroom.) The second location was from the attic above the second floor. Leakage from the attic came directly through a back wall section which was being used as part of the return plenum. The wall section did not have drywall, but was stuffed with insulation batts. Attic air could also come in to the system indirectly through the AHU closet due to leaks in the plenum and the AHU (furnace) drawing air from the closet. The closet, in turn, had air leakage at two locations. The first allowed attic air to enter the closet through the ceiling where the return duct penetrated. The second location was through a combustion/dilution vent from the closet to the attic (this vent was an intentional pathway to the attic to provide combustion/dilution air to the furnace). Air leaks in the furnace cabinet and the return plenum were sealed to address the greatest driving force for attic return leakage. The oversized duct penetration hole in the ceiling was also sealed. The combustion dilution vent was left open as required by code. Alternatively in this home, the owner would have been permitted by code to install venting from the closet to the house interior (such as installing a louvered closet door), and then seal the combustion/dilution vent.

The return leak fraction for the second story system decreased from 9.6% to 1.1% as a result of duct repair. A discussion of energy use reduction from duct repair is found in a later section of this paper. Prior to this repair, duct leakage was also measured by pressure pan. Average pressure pan supply register readings declined from 1.65 Pa to 0.92 Pa for the first floor system and from 2.18 Pa to 0.60 Pa for the second floor system, indicating substantial reduction in system duct leakage. These reductions in pressure pan readings include the effect of both duct repairs and wind washing repairs.

<u>Pre and Post Wind Washing and Duct Repair Testing Results</u>

Combined wind washing repair and return duct repair produced substantial changes in the house.

- After repairs, the house was 22% more airtight.
- RLF declined by 89% on the second floor system (from 9.6% RLF to 1.1% RLF). No pre-repair RLF was available on the 1st floor, but post RLF 1st floor was only 2.0%.
- Average <u>return</u> pressure pan values decreased by 82%.
- Average 1st floor <u>supply</u> pressure pan values decreased 44% from 1.65 Pa to 0.92 Pa. Average 2nd floor <u>supply</u> pressure pan values decreased 65% (from 2.18 Pa to 0.76 Pa).
- After repair, the house infiltration rate with the AHUs operating was 64% lower.
- We find, therefore, that combined repair of wind washing and return leakage caused a dramatic decline in duct leakage indicators.

<u>Energy and demand savings from repairs</u>

Duct repair and wind washing repairs each produced substantial energy savings. Based upon the annual energy analysis (using TMY data), duct repair produced 2,207 kWh in energy savings (24.7%; $257) per year. Implementation of wind washing repairs produced another 2,232 kWh energy savings (33.1%; $254) per year. Combined, the duct repair and the wind washing repair reduced annual space cooling energy use by 49.6% (Figure 22).

Based on the hourly regression of kW versus dT, and the TMY hourly data, the 3 PM to 6 PM kW demand reduction for the hottest day of the year was 0.24 kW in air conditioning electrical demand as a result of the wind washing retrofit. This is equivalent to a 9.9% reduction in peak demand.

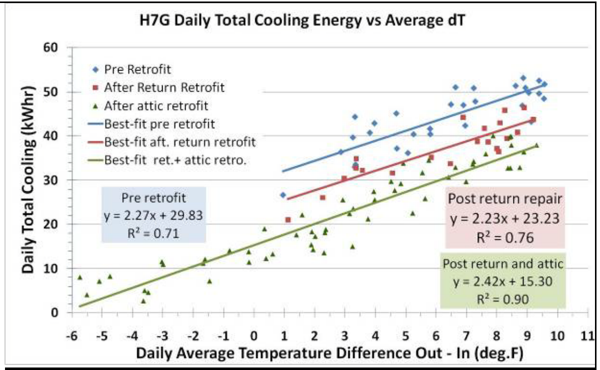

Figure 22 H7G cooling vs. temperature difference for pre-repair, for post duct repair, and for post wind washing repair.

House H14Y and Repair Description

This 1,415 ft^2 residence was constructed in 1903 making it the oldest in the study. The home was built using wood framing above a shallow crawlspace. The first floor has 821 ft^2 while the second floor has 594 ft^2. The front of house faces east and is situated near an inter-coastal waterway within 10 miles of the Atlantic Ocean. Each floor is served by one air conditioning system. There is no garage in this residence and no second floor area over unconditioned space. Figure 23 shows the house south and west sides.

Figure 23 Back of residence.

At some point after the original construction, the house was renovated to add a kitchen to the rear side (west) of the house. The roofline over this area creates the only attic adjacent to conditioned space in the house. This small attic space is very difficult to access and could only be inspected by removing a recessed florescent light fixture in the kitchen.

Figure 24 Floor cavity connected to attic space before repair. *(Withers)*

Duct Repair

This house had significant return duct leakage in the first floor system. Duct repairs were implemented in the return plenum of the first floor AC system. The purpose of the separate duct repair was to enable our analysis to distinguish savings from wind washing alone. Wind washing repair would, in our opinion, have eliminated a large portion of the duct leakage because return duct leaks were drawing air from the interstitial floor cavity between the two floors. Mastic was used to produce a continuous air barrier from the return grill through the plenum and into the air handling unit on the first floor. Refrigerant line penetrations and the mounting of the AHU to the plenum box were also sealed using rope caulk and silicone. The RLF for the first floor system was 4.0% before repair (both duct repair and wind washing repair) and 0.7% after duct and wind washing repair. The second floor system RLF was 1.2% before repair and 0.0% after both repairs.

The second floor system uses the AHU closet as a return plenum. The closet door is louvered. Because of the large net return area of the closet door, there was little depressurization in the AHU closet (-2.0 Pa wrt indoors). Therefore, even though the closet had small leakage pathways to unconditioned spaces, the operating return leakage was small. The elimination of return leakage for the second floor system can be attributed to the wind washing repair which isolated the floor cavity from the kitchen attic space.

Wind Washing Repair

The most direct way to eliminate air movement into the floor cavity would have been to apply foam sealant directly over the floor cavity openings. However, there was very poor access to the attic space and supply ducts restricted access to the floor cavity openings. It is for this reason that it was decided to modify the attic space above the kitchen from a hot and humid space to a warm and drier space to minimize the impact of hot attic air into the floor as well as attempt to seal the open floor spaces as much as practicable. Alternatively, it could be stated that we moved the air and thermal boundary so that the attic space above the kitchen was now inside the air and thermal boundary. Foam insulation product was applied to the exterior walls of the attic, to the roof deck within this attic, and to the small gable vents. Open space from the floor cavity to the unvented attic was also attempted to be sealed. Because of difficult access, we were only able to seal about 9 ft^2 or about 75% of the floor cavity opening. This repair required 4.0 man-hours to cover 209 ft^2 of surface area.

Pre and Post Wind Washing House Testing Results

Changes occurred as a result of both return duct repair and wind washing repairs.

- Prior to repair, the house airtightness was 11.26 ACH50. After repair, the house airtightness was 11.15 ACH50, indicating a tightening of 1%. This small change is not surprising given the age of the home and the fact that only small attic vents (above the kitchen) were sealed.
- RLF declined 82.5% on the 1st floor system from 4.0% RLF to 0.7% RLF. The 2nd floor system only had an initial RLF of 1.2% which was reduced to 0.0%.
- 1st floor return pressure pan values decreased dramatically from 23.0 Pa to 1.0 Pa after both repairs.
- Average 1st floor supply pressure pan values decreased 60% after all repairs (from 2.43 Pa to 0.96 Pa). Average 2nd floor supply pressure pan values remained unchanged at 1.2 Pa after all repairs.
- After both repairs, the house infiltration rate with the AHUs operating decreased by 8.5% from 0.59 ach to 0.54 ach.

We find, therefore, that the combined repair of wind washing and return leakage caused a dramatic decline in duct leakage indicators.

Energy and demand savings from repairs

Duct repair and wind washing repairs each resulted in measured savings. Based upon the annual energy analysis, duct repair provides annual savings of 296 kWh (9.5 %; $34.04) per year. Wind washing repairs produced annual savings of 201 kWh (7.2 %; $23.1) per year. Combined, the repairs save 497 kWh (16.0%; $57) per year.

Based on the hourly regression of kW versus dT, and the TMY hourly data, the 3 PM to 6 PM kW demand reduction for the hottest day of the year was 0.18 kW (from 2.27 kW to 2.09 kW) as a result of the wind washing retrofit alone. This is equivalent to a 7.8% reduction in peak demand. No demand reduction was assessed for the duct repair.

We did not expect large savings from this home. The attic vent opening area was only 1% of the gross attic-to-floor cavity opening. The fact that there were only two small gable attic vents, meant that there was very limited opportunity for wind to drive attic air into the house interstitial cavities. Our available selection of houses to monitor during the summer of 2009 had not yet found houses with better savings potential by the time we had to begin monitoring efforts. Although the savings were modest and payback is over 11 years, the repair was just one of many efficiency improvements needed in this historic house which is over 100 years old. This home would also benefit from more 2nd story ceiling insulation, higher efficiency heat pumps, better 1st floor insulation under the crawlspace, and sealing of several small electrical and plumbing penetrations.

THE COST OF WIND WASHING REPAIRS

The actual cost of wind washing repair can vary greatly. The factors most greatly affecting cost are the level of difficulty in accessing the repair locations and the total area required to be sealed. Homes with garage attic space adjacent to second-story floor cavities generally have easy access and often require less than 40 ft^2 of material to seal and insulate the floor cavity from the attic. Unlike spaces with easy access, homes with open floor construction into very small attic or soffit areas require much more time. Working within these tight spaces can also limit the options of material used. For example, a very small attic area at a great distance from attic access would make working with rigid board stock very time consuming and difficult. While the rigid board stock might be inexpensive, the labor would be very expensive and require considerable skill and agility.

The six repaired homes in this study were all sealed using a blown, expanding low-density, and open-cell foam. Other options such as sealing some with rigid board stock were considered, but not used since repairs needed to be completed in a timely manner to avoid starting post retrofit periods too late into the summer. Foam application is fast. For example, one two-person crew was able to implement less-complicated wind washing repairs in three homes in one 8-hour day, including travel time and about 2-1/2 hours down time from equipment failure.

The research project paid a flat fee of $650 per house for wind washing repairs, which may have been somewhat discounted from normal. Cost estimates from one foam manufacturer representative were, on average, $750 per house. Based on this $750 per house estimate, the average cost per square foot of applied material would be $6.93/ ft^2. A cost of considerably less than $750 would be expected for jobs having easy access and relatively small areas, such as Houses H10H and H16B. House H11C needed very little foam and took relatively little time on site, but access was much more difficult and resulted in only about 90% completion.

Clearly, wind washing repair costs will vary from one house to another. An effort has been made to estimate likely costs for each of the six houses based on time and material. The total amount of labor to complete the six retrofits was carefully monitored. The total surface area covered was also recorded for each house. Table 2 summarizes the repair material area, time, and cost/ft^2 for each house. The cost per ft^2 in Table 2 is shown using the manufacturer's estimate and separately using $50/person-hour, $2.50/ ft^2, and actual recorded time and material needed for each house.

Table 2 Calculated cost of wind washing repairs compared to manufacturer's fixed price quote.

House # →	H10H	H7G	H14Y	H8Hd	H16B	H11C	Avg.
Coverage (ft^2)	113	510	209	108	103	48	182
Time (man hrs)	2.25	4.60	4.0	10.0	3.75	3.10	4.62
Calc. cost @$50/hr & $2.50/ft^2	$395	$1505	$723	$770	$445	$275	$686
Calc. cost per ft^2	$3.50	$2.95	$3.46	$7.12	$4.32	$5.73	$4.51
Manuf. Cost $/ft^2 @$750/ house	$6.64	$1.47	$3.59	$6.94	$7.28	$15.63	$6.93

Based on time and material, we calculated that the average cost would be $686 per house, including travel time. This estimate is 8.5% less than the manufacturer's estimate.

It should be noted that there is a learning process involved in wind washing repair. At each of the repair sites, project researchers provided guidance and instruction to the foam application technicians, which added some time to the repair. In some cases, considerable time was required to examine different options about how to gain access to the repair sites and determine the best way to apply the foam product. Since we used the same contractor and technicians for all six houses, the instructional time declined as experience was gained. Once wind washing repair becomes a mature industry, the time involved would no doubt decline significantly. It seems likely, therefore, that the repair costs for the six houses repaired in this project would eventually be in the $500 to $600 per house range. Since the average cooling energy reduction from wind washing repair has been found to be $140 per house, the simple payback period would be on the order of 4 years excluding savings during the heating season and any program incentives that might exist.

MOISTURE ISSUES

Wind washing can deliver air with high dew point temperatures into contact with building materials and cause significant damages, such as those discussed in house H8Hd. These include cracks developed in the staircase, sweating supply diffusers, and wet attic insulation from sweating ducts. This house also had other symptoms that developed about a year before our research involvement such as a warped pocket door in a wall connected to the north attic wall, 2nd floor wood flooring that warped and had to be replaced, and sweating ducts inside the floor space that dripped onto the kitchen ceiling. In response to the damaged ceiling, a consultant had identified the wind washing problem and suggested duct repair and sealing the floor space from the attic. Initial efforts to seal the floor space by the homeowner and a contractor did lessen the severity of sweating problems, but did not eliminate it. The owner chose to "seal" the attic-to-floor space opening in the garage using kraft-backed insulation batts, but nothing was done to seal open floor cavities on the west and north sides. Therefore, humid air could still move into the space. This highlights a very important point, that even while partial repairs may reduce the severity of moisture problems and decrease cooling energy loads, every attempt should be made to create complete air and thermal barriers to isolate the floor space and knee walls.

Care should also be taken when sealing around cold supply ducts that penetrate from the attic space into the floor cavity. Research staff had already anticipated the problem of moisture condensing on supply ducts that would be in contact with insulation. When the research staff discovered the wet batt insulation against the supply ducts in house H8Hd, this reinforced our dedication to avoiding such condensation problems. Project staff were aware that the open cell spray foam product that we intended to use would allow vapor diffusion from the attic air to the duct surface, so we wanted to create a vapor barrier with a higher surface temperature between the duct and the foam insulation. Even if condensation was not occurring on the ducts prior to retrofit, it was likely that application of foam insulation (or other sealing materials) in contact with the duct would result in a cooler duct surface that could very likely become colder than the attic air dew point temperature. This problem was addressed by first wrapping a band of flexible but semi-rigid insulation (typically 1” thickness and R-3 thermal resistance; this product is visible in Figure 5) around the duct where the spray foam would contact. This band of insulation has a vapor barrier on both sides that helps block attic moist air from direct contact with the supply ducts. We carefully inspected the supply ducts a few weeks after the repairs for evidence of condensation on the duct surfaces (during a period of high dew point temperatures) and did not find any evidence of moisture accumulating on the duct surface. A research staff member inserted his hand into the space between the thin wrap and the flex duct and verified that the duct surface was dry since the hand came out with dry dust on it.

CONCLUSIONS

Wind washing problems were found in approximately 40% of the 32 two-story homes examined. Of the first 16 homes tested, six were selected for monitoring and repair. Annual cooling energy savings were found to be quite substantial in these six homes, averaging 15.3% or $140. Energy savings resulting from wind wash repairs at each house are summarized in Table 3. Duct leak repairs (all on the return side) in two homes produced average annual cooling savings of 17.1% or $144 (Table 4). Cooling season peak demand reduction was 12.6% or 0.52 kW on average (summarized in Table 5). Based on testing results in the second group of 16 homes, where wind washing problems were assessed to be greater, it seems likely that wind washing cooling energy savings can exceed 15.3% on average. Based on monitored cooling energy savings and likely reductions in foam insulation application costs, cooling energy savings will pay for the retrofit costs in approximately four years. Wind washing diagnosis and repair appear, therefore, to be a cost-effective energy conservation measure and therefore a potentially viable utility (or other entity) energy conservation program.

It should be understood that this project was only able to evaluate impacts of wind washing during the cooling season. Therefore, homes will also have heating energy and peak kW savings that will be in addition to the cooling savings shown for each house in Tables 3 and 4. The percentage savings of heating energy and winter peak demand (kW) reduction are likely higher than cooling season results since wind speeds and temperature differentials between indoors and outdoors are often higher during cold weather than during summer periods. Homes with electric resistance heating could see savings several times higher than those with heat pumps.

Table 3 Annual cooling energy savings from wind washing repair

	Pre-repair annual kWh	Post-repair annual kWh	Annual kWh savings	Percent savings	Annual savings (@11.5 cents/kWh)
H10H	4629	3793	836	18.1%	$96.14
H7G	6743	4511	2232	33.1%	$256.68
H14Y	2806	2605	201	7.2%	$23.11
H8Hd	33852	31081	2771	8.2%	$318.65
H16B	5103	4421	682	13.4%	$78.43
H11C	4710	4145	565	12.0%	$64.97
Average			***1214.5***	***15.3%***	***$139.66***

Table 4 Annual cooling energy savings from duct repair in two homes

	Pre-repair annual kWh	Post-repair annual kWh	Annual kWh savings	% savings	Annual savings (@11.5 cents/kWh)
H7G	8950	6743	2207	24.7%	$253.80
H14Y	3102	2806	296	9.5%	$34.04
Average			***1251.5***	***17.1%***	***$143.92***

Summer peak hour demand reduction from wind washing repairs are summarized in Table 5. Peak demand reduction resulting from wind washing repair was on average 12.6%, or 0.52 kW. If the electric utility’s cost for constructing new peaking capacity is $600 per kW, then this repair represents approximately $300 that the utility does not have to spend on new facilities to meet peak demand.

Table 5 Peak demand savings from wind washing repair in six homes

	Pre Retrofit Peak kW	Post Retrofit Peak kW	kW Reduction	% Reduction
H10H	2.10	2.00	0.10	4.5%
H7G	2.40	2.16	0.24	9.9%
H14Y	2.27	2.09	0.18	7.8%
H8Hd	11.9	10.2	1.80	15.0%
H16B	2.25	1.86	0.39	17.3%
H11C	2.02	1.59	0.43	21.3%
Average			***0.52***	***12.6%***

The results of this study also have implications for new construction. The fact that wind washing retrofits reduced annual cooling energy consumption by 15.3% indicates that failure to construct homes with proper sealing of interstitial floor cavities is creating significant failures of the house air and thermal boundaries, and creating considerable energy waste. It seems reasonable, therefore, that buildings codes for Florida as well as other states should be examined and code enforcement practices evaluated in order to eliminate this breach in residential construction efficiency.

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REFERENCES

Anderson, B.R., and T.I. Ward. 1981. Measurements of Heat Loss Through an Insulated Roof. *Building Services and Research Technology* 2(2): 65-72.

Bankvall, CG. 1978. Forced Convection: Practical Thermal Conductivity in an Insulated Structure Under the Influence of Workmanship and Wind. ASTM STP 660 pp.409-425.

Harrje, D.T., G.S. Dutt, and K.J. Gadsby. 1985. Convective Loop Heat Losses in Buildings. *ASHRAE Transactions* 91(2): 751-760.

Hens H, W. Janssens, J. Depraetere, J. Carmeliet, and J. Lecompte. 2007. Brick Cavity Walls: A Performance Analysis Based upon Measurements and Simulations. *Journal of Building Physics* 31, 95 – 123.

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

Janssens, A, and H. Hens. 2007. Effects of Wind on the Transmission Heat Loss in Duo-Pitched Insulated Roofs: A Field Study. *Energy and Buildings* 39, 1047–105.

Lecompte, J. 1990. The Influence of Natural Convection On the Thermal Quality of Insulated Cavity Construction. *Building Research and Practice* 6, 349 – 354.

Silberstein, A., E. Arquis, and D.J. McCaa. 1991. Forced Convection Effects in Fibrous Insulation. ASTM STP 1116, pp.292 – 309.

Uvsløkk, S. 1996. The Importance of Wind Barriers for Insulated Timber Frame Constructions. *Journal of Thermal Insulation and Building Envelopes* 20, 40–62.