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Investigating Solutions To Wind Washing Issues In 2-Story Florida Homes; Phase 1

Florida Solar Energy Center

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FLORIDA SOLAR ENERGY CENTER®

Final Report

Investigating Solutions to Wind Washing Issues in 2-Story Florida Homes; Phase 1

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Executive Summary

Wind washing has been identified as a potentially significant issue regarding energy, demand, comfort, and humidity in some two-story Florida homes. In its most common configuration, wind washing occurs when attic spaces over first-floor portions of the home abut the second story, and the floor cavity of the second story is open to that attic space. Wind blowing into attic vents can push hot attic air into the inter-story floor cavity, bypassing the typical thermal boundaries of the building and introducing considerable heat into the house. Even in the absence of wind, thermal buoyancy can create air transfer between a hot attic and the interstitial floor cavity. Wind washing can also occur when little or no attic is involved, where outdoor air can infiltrate directly into the floor cavities. Phase 1 of a study to identify these air flow failures and possible insulation system failures in adjacent knee walls has been completed. Field testing has been completed in 32 homes and monitoring and repair has been implemented in six homes. Significant wind washing potential has been found in about 40% of the tested homes. Relatively few knee wall insulation problems have been identified, though it is common for knee walls facing into attic spaces to have effective R-values of less than 10. Monitoring of temperature, humidity, and AC energy consumption in six homes was implemented for about six to eight weeks before and after wind washing repairs were implemented. Duct leaks were separately repaired in two of the six homes. Energy and peak demand analysis was implemented. As a result of wind washing repair in these six homes, annual cooling energy savings averaged 15.3% and peak demand savings averaged 12.6%. Duct repairs produced an average 17.1% cooling energy savings in two homes. Because the wind washing potential identified in the six repaired homes was less than other homes tested later, the research team believes that these cooling energy and demand savings may be lower than average.

Scope of Work

Field testing was performed in 32 two-story Florida homes to characterize wind washing failures of the house air and thermal boundary, including a blower door test, air boundary location, pressure mapping, air leakage assessment, infrared scans of house surfaces, and visual inspections. Cooling energy reduction, peak demand reduction, and indoor environment impacts due to wind washing repairs were monitored in 6 homes. Additionally, the extent and magnitude of moisture impacts of wind washing has been examined. No winter weather monitoring occurred in this Phase 1 effort. Field testing consisted of the following; a blower door test to characterize the airtightness of the house envelope, air boundary identification; during the blower door test with the house at -50 pascals, zone pressures in various interstitial cavities of the house were measured, pressure pan testing to identify the relative size and location of duct leakage, pressure mapping with various HVAC operating modes, infiltration and return leak fraction (RLF) tests with the air handler units (AHUs) operating, and an AC system performance test. Field testing also included fairly detailed inspections of attic spaces, floor cavities, and other locations which would help to identify the potential for wind washing to occur.

Wind Washing Inspection and Repairs

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. Figures E-1 through E-6 illustrate wind washing failures by photo and infrared images.

Repairs were implemented by application of open-cell foam over the openings to the interstitial floor cavity, typically to isolate 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. Figures E-7 through E-13 illustrate wind washing repairs in several homes.

Figure E-1 Home (H7G) faces west.

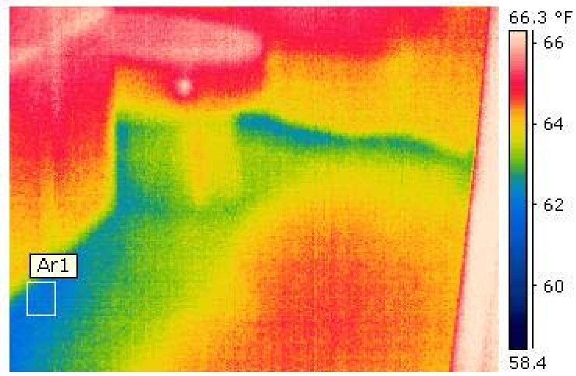

Figure E-2 Infrared image of 2nd story bathroom floor before repair. Area in box (Ar1) is 62.7°F on a cold day.

Figure E-3 IR scan inside (H7G) bonus room floor cavity facing west. Coldest area is plywood.

Figure E-4 Photo of image at left. Small hipped, vented attic area is on the other side of this cold area.

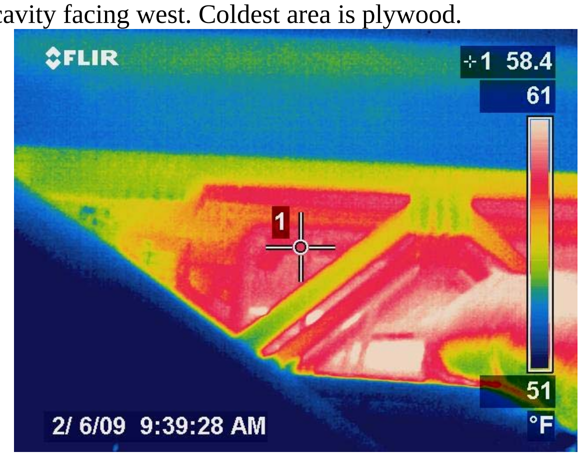

Figure E-5 IR image inside bonus room floor space facing east (H7G). The truss marks the boundary between 2nd story floor space (which is much warmer) and bonus room floor space (which is much colder).

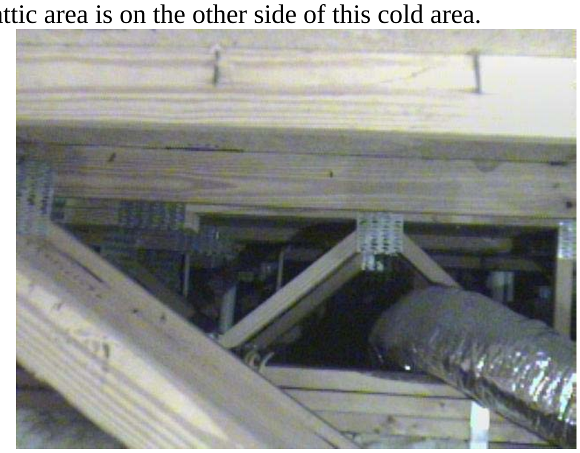

Figure E-6 Photo of image at left. View is facing east into 14" high 2nd story floor space in the main part of the house.

Figure E-7 Technician applying foam to opening between the 2nd story floor cavity and the bonus room floor cavity (H7G).

Figure E-8 Foam applied to wall and ceiling of the bonus room (3' high) floor cavity.

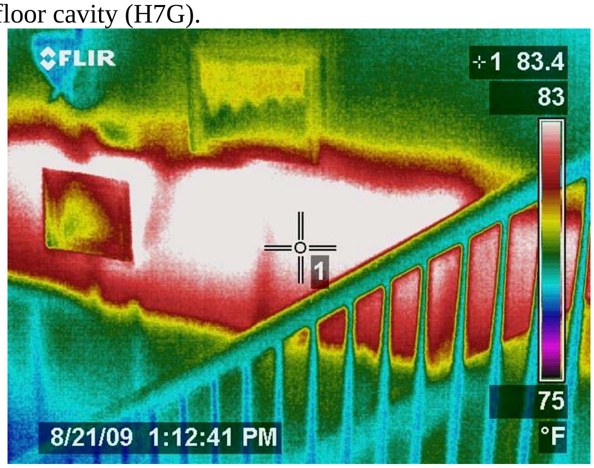

Figure E-9 Infrared image of floor space behind wall in house H23**.** Wall surface is about 83.4F at floor space due to open floor space to attic on east and west sides of house.

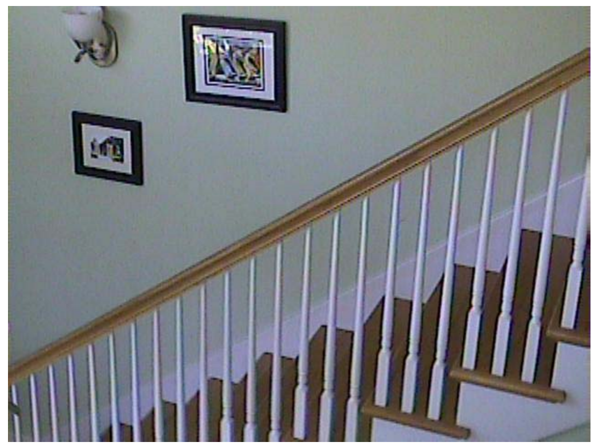

Figure E-10 There are conditioned rooms on the other side of this wall above and below the floor space that runs along the lower picture hung on wall.

Figure E-11 Attic over garage faces south in house H16B.

Figure E-12 Insulation tech just finishing up kneewall and floor insulation/ air tightening (H16B).

Figure E-13 IR view inside the hot attic shows cooled surfaces low in attic in H16B before repair.

Figure E-14 Photo of IR image to the left. The floor cavity at the bottom of the wall is open to attic space.

Executive Summary -- Conclusions

Wind washing problems in homes were found in approximately 40% of the two-story homes examined. Of the first 16 homes tested, six were selected for monitoring and repair. Annual cooling energy savings was found to be quite substantial in these six homes, averaging 15.3%. Peak demand reduction was 12.6%. 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 on average exceed 15.3%. Based on monitored cooling energy savings and likely reductions in foam insulation application costs, energy savings will pay for the retrofit costs in approximately four years. Wind washing diagnosis and repair appears, therefore, to be a cost-effective energy conservation measure and therefore a potentially viable utility energy conservation program.

It should be understood that this project was conducted to evaluate only cooling season impacts of wind washing. Therefore, homes will also have heating energy and peak kW savings in addition to cooling savings shown for each house in Tables E-1 and E-2. The percentage savings of heating energy and winter peak demand (kW) reduction are likely higher than cooling season results since windspeeds and temperature differentials between indoors and outdoors are much higher during cold weather than summer periods. Homes with electric resistance heating could see savings several times higher.

Cooling energy savings and summer peak hour demand reduction from wind washing repairs are summarized in Table E-1, with an average reduction in cooling energy use of 15.3% or $140 per year. Peak demand reduction resulting from wind washing repair was 12.6%, or 0.52 kW.

Table E-1 Annual cooling energy and peak demand savings from wind washing repair

	Annual Cooling Energy					Summer Peak Hour Demand			
	Pre-repair kWh	Post-repair kWh	kWh savings	% savings	$ Savings (@ $0.115/ kWh)	Pre-repair Peak kW	Post-repair Peak kW	kW Reduction	% Reduction
H10H	4629	3793	836	18.1%	$96	2.10	2.00	0.10	4.5%
H7G	6743	4511	2232	33.1%	$257	2.40	2.16	0.24	9.9%
H14Y	2806	2605	201	7.2%	$23	2.27	2.09	0.18	7.8%
H8Hd	33852	31081	2771	8.2%	$319	11.9	10.2	1.80	15.0%
H16B	5103	4421	682	13.4%	$78	2.25	1.86	0.39	17.3%
H11C	4710	4145	565	12.0%	$65	2.02	1.59	0.43	21.3%
Average			*1214.5*	*15.3%*	*$140*	***Average***		*0.52*	*12.6%*

In two of the six homes, large duct leaks were repaired (all on the return side). Average cooling energy savings from duct repair was 17.1% or $144 per year.

Table E-2 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 cent/kwh)
H7G	8950	6743	2207	24.7%	$253.80
H14Y	3102	2806	296	9.5%	$34.04
Average			*1251.5*	*17.1%*	*$143.92*

An initial effort has begun to create a wind washing potential (WWP) evaluation matrix. The evaluation criteria include such things as the size of holes from attic to interstitial floor cavity, complimentary holes, attic temperature, exposure to wind, and size of soffit venting. Further refinement of this WWP evaluation matrix will be helpful in the implementation of a utility retrofit incentive program, by helping to identify homes with the greatest savings potential.

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.

Abstract: Wind washing has been identified as a potentially significant issue regarding energy, demand, comfort, and humidity in some two-story Florida homes. In its most common configuration, wind washing occurs when attic spaces over first-floor portions of the home abut the second story, and the floor cavity of the second story is open to that attic space. Wind blowing into attic vents can push hot attic air into the inter-story floor cavity, bypassing the typical thermal boundaries of the building and introducing considerable heat into the house. Wind washing can also occur when there is little or no attic involved, where outdoor air can infiltrate directly into the floor cavities. Phase 1 of a study to identify these air flow failures and possible insulation system failures in adjacent knee walls has been completed. Field testing has been completed in 32 homes and monitoring and repair has been implemented in six homes. Significant wind washing potential has been found in about 40% of the tested homes. Relatively few knee wall insulation problems have been identified, though it is common for knee walls facing into attic spaces to have effective R-values of less than 10. Monitoring of temperature, humidity, and AC energy consumption in six homes was implemented for about two months, repairs were implemented, monitoring continued for about 6 to 8 weeks after repair. Energy and peak demand analysis was implemented. Annual cooling energy savings averaged 15.3% and peak demand savings averaged 12.6% for these six homes. Because the wind washing potential identified in the six repaired homes was less than other homes tested later, the research team believes that these cooling energy and demand savings are less than might otherwise be found.

1.0 Project Objectives

In some two-story homes, attic spaces over first-floor portions of the home that abut the second story may have two potential breaches of the thermal boundary. 1) Attic air above the first-floor space can be driven into the cavity between the first and second floors by wind (Figures 1 and 2). 2) Insulation batts installed on knee walls may have gaps (between the batt and the gypsum board) that allow circulation of hot air against the wall gypsum board. The primary goal is to characterize methods and cost-effectiveness of retrofit solutions. Secondary goals are to determine how wide-spread these envelope thermal problems are, identify the failure mechanisms, develop new-construction and retrofit solutions, recommend code modifications, and identify the energy savings potential from retrofit programs.

2.0 Background / Prior Work

Residential construction is moving from simple one-story to architecturally complex two-story homes. Consequently, more attic spaces are horizontally adjacent to conditioned spaces and air and thermal boundary failures are now more widespread. As a result, second story cooling loads often exceed AC capacity. Knee wall and wind-washing problems have been recognized in the literature, especially in response to freezing pipes in cold climates. For example, a US DOE Technology Factsheet titled *Ceilings and Attics: Install Insulation and Provide Ventilation* (February 2000 DOE/GO10099-771) and the US DOE sponsored *Builder's Guide (Hot-Humid Climates)*[1] provide information related to floor truss closure and insulation. However, energy penalties and retrofit savings opportunities in hot/humid climates have not been documented.

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[1] J. Lstiburek, *Builder's Guide to Hot-Humid Climates*, EEBA, 2005.

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.

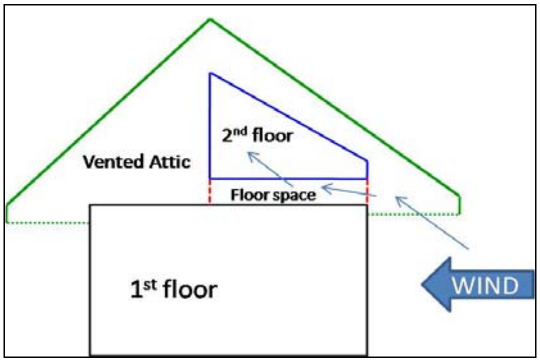

Figure 1 Wind-driven attic air is pushed into the space between floors.

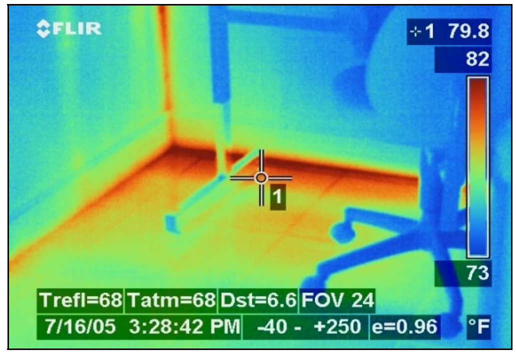

Figure 2 Elevated floor temperature results from hot attic air flowing through the floor cavity.

3.0 Project Scope

The two primary objectives of this project have been to perform a field assessment of a sample of houses and measure the effectiveness of repairing wind washing in a smaller group. 1) Field assessments have been completed in 32 homes to characterize wind washing failures of the house air and thermal boundary, including a blower door test, air boundary location, pressure mapping, air leakage assessment, infrared scans of house surfaces, and visual inspections. 2) The energy reduction and indoor environment impacts due to wind washing repairs has been completed in 6 homes and cost of repairs will also be reported. In addition to energy and demand analysis, we will examine the extent and magnitude of moisture impacts of these thermal and air barrier failures during hot and humid weather. The findings of this study will apply most directly to homes that experience hot summer weather. However, the repair techniques will be applicable for colder weather as well. A phase 2 Wind Washing research effort has also been proposed (in a separate document) which will focus in significant part on winter wind washing impacts.

4.0 Field Testing

Field testing has been completed in 32 homes, which is the full complement of homes for this Phase 1 project. For purposes of identification, we refer to specific homes as H1, H2, H3, etc in sequence of testing. For the six homes for which we monitored and performed repairs, we use the designation H7G, H8Hd, H10H, etc. with the last letter(s) indicating additional occupant identification, and that this is a monitored/repaired house.

Field testing consisted of the following:

- A blower door test to characterize the airtightness of the house envelope
- Air boundary identification; during the blower door test with the house at -50 pascals, zone pressures in various interstitial cavities of the house were measured.
- Pressure pan testing; during the blower door test with the house at -50 pascals, a pan with gasket was placed over supply and return registers/grills (AHUs off) and the

pressure in the duct was measured. This identified the relative size and location of duct leakage.

- Pressure mapping; with HVAC system operating in normal mode, pressure differentials were measured with interior doors open and then again closed.
- Infiltration and return leak fraction (RLF) tests with the AHUs operating.
- AC system performance test. This was performed by measuring the AC system air flow rate, the return air temperature and relative humidity, and the supply air temperature and relative humidity.

Field testing also included fairly detailed inspections of attic spaces, floor cavities, and other locations which would help to identify the potential for wind washing to occur. Following is a sequence of photos (Figures 3 -16) which illustrate inspection and testing activities.

Figure 3 House H13. Visual inspection in the attic space is necessary to identify the presence and magnitude of wind washing.

Figure 4 Photo from inside attic at House H13. A 1” gap exists between plywood that covers the kneewall and the 1st floor ceiling below. This gap allows air to flow from the attic space to the 2nd story floor cavity.

Figure 5 In House H2, a loose fitting flex duct creates part of a large return leak.

Figure 6 Specific gas analyzer measures the house air change rate and return leak fraction with the AHUs operating.

Figure 7 Air temperature and relative humidity measurements were taken using a Vaisala HM34 probe.

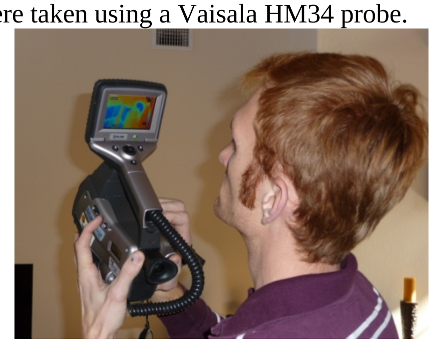

Figure 8 Infrared images taken using a FLIR Model P40 Thermacam.

Figure 9 In House H5, a pressure pan measures return leakage in a wall cavity indicating substantial return leakage.

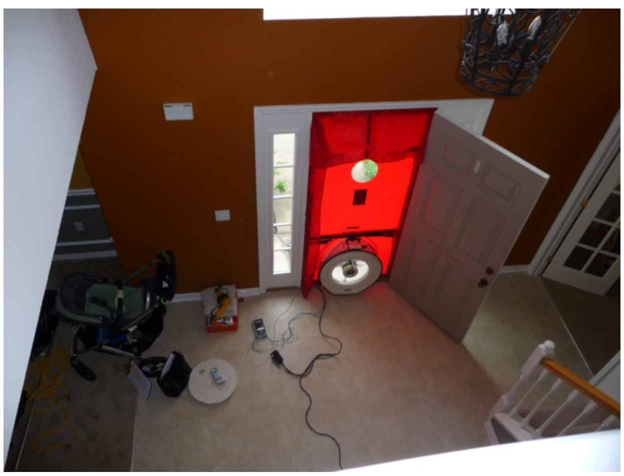

Figure 10 House H17 airtightness test using a blower door.

Figure 11 Airflow measurement at House H7.

Figure 12 No wind washing potential was found in House H18 because the kneewall insulation and floor cavity are covered by plywood.

Figure 13 Good quality insulation batt installation blocks opening to floor cavity in House H22. No insulation on top of ceiling since garage is below.

Figure 14 In House H22, batts and blown insulation cover the opening to floor cavity.

Figure 15 In House H22, an area of fallen batt on kneewall allows hot attic air to transfer heat through wallboard into conditioned space.

Figure 16 A view inside the floor cavity of House H22 shows that batt insulation is lying on top of 1st floor ceiling, providing a thermal barrier to heat flow through the ceiling, but not through the floor of the 2nd story. These batts were used only where garage portions were below 2nd story conditioned space.

IR scans were used to identify thermal characteristics of various building cavities associated with wind washing. Figures 17 through 20 illustrate some wind washing locations and infrared signatures.

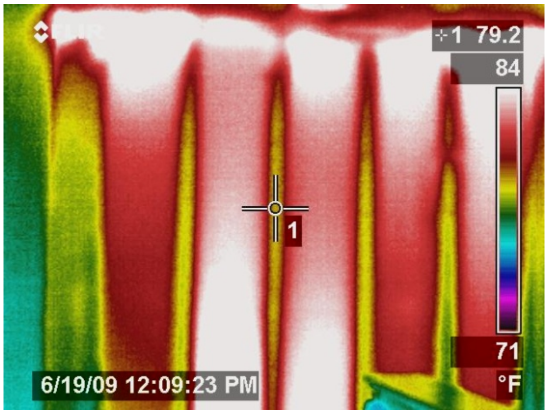

Figure 17 IR image of Wall adjacent to unconditioned space.

Figure 18 Photo of image at left.

Figure 19 Infrared image of floor space behind wall**.**

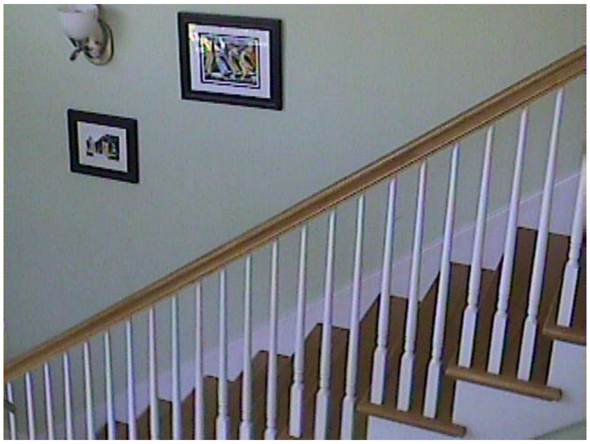

Figure 20 There are conditioned rooms on the other side of this wall.

5.0 Field Testing Data

A spreadsheet database has been developed that summarizes the field testing data. The spreadsheet has 125 columns of data. Following is a summary of this field testing database.

The 32 tested homes were found in six counties; 26 were located in Brevard County, 2 in Orange County, 1 in Volusia County, 1 in St. Lucie County, 1 in Martin County, and 1 in Broward County. All were two-story homes except two were split level homes. 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. 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.

House size ranged from 1050 ft^2 to 4500 ft^2, with an average floor area of 2695 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; on average this was 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.

Most air handler units (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 1000 ft^2, with an average of 1.94 tons per 1000 ft^2. Heating capacity varies from 15.38 kBtu/1000 $ft^2$to 69.9 kBtu/1000 ft^2, with an average of 23.76 kBtu/1000 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. With AHUs off, house pressure averaged -0.24 pascals. With AHUs on, house pressure averaged +0.30 pascals. With AHUs on and interior doors closed, house pressure (in the central zone) averaged -0.96 pascals. From this data, we can say that turning on the AHU fans increased house pressure by 0.54 pascals, 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 pascals, on average. Pressure was measured across closed interior doors. Maximum pressure differentials across the closed doors exceeded 20 pascals in three homes. For AC system 1 (first floor), the average pressure differential across closed doors was 2.63 pascals. For AC system 2 (typically second floor), the average pressure differential across closed doors was 5.01 pascals. The Florida Building Code, as of March 2002, has required that pressure differentials in new homes not exceed 2.5 pascals (there are also two exceptions).

Duct leakage testing was performed in all homes by means of a pressure pan test. With the house at -50 pascals, a pan (with gasket to create a tight seal to the gypsum board) was placed over supply and return grills (AHU off) and a pressure in the duct (on the inside of the pan) was measured.

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

Generally, pressure pan readings of 1.0 or greater indicate slight to moderate duct leakage and pressure pan readings of 3.0 or greater indicate substantial duct leakage.

With the house depressurized by the blower door to -50 pascals, the 2nd story floor cavity pressure was measured wrt (with respect to) the inside of the house. In all cases, the floor cavity will be positive (greater than zero). Among the 32 homes, the floor cavity pressure varied from +15.5 pascals to +48 pascals, with an average of +36.2 pascals. In the case of +15.5 pascals, this indicates that the floor cavity is more "inside the air boundary of the house" while +48 pascals indicates that the floor cavity is almost completely "outside the air boundary of the house". The average +36.2 pascals 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".

House envelope airtightness was measured. The average CFM50 (air leakage through the house envelope when depressurized to -50 pascals) was 3076. 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 (ACH50) by 40[2]. 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. From this, we can see that the house infiltration rate increases, on average, by 110% as a result of air leakage from the air distribution system (duct leakage). 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.

6.0 Selecting Homes for Monitoring and Wind Washing Repair

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. It was necessary to select the repair candidates from just the first half of the total field testing sample because of the schedule requirements for monitoring and repair. We wanted to make wind washing repairs in mid-summer so there would be at least a couple months of monitored 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 of high wind washing potential homes in 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.

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

7.0 Monitoring of Six Repair Homes

The six repair houses 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 channels of data.

- Power use of the AC system(s) (typically two) which serve(s) the house
- Temperature measurements indoors, 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 streams of the AC systems.
- Relative humidity measurements indoors, in the attic, and in the floor cavity between the first floor and the second floor of the house.
- Monitoring varied slightly from one house to another. A typical channel map is shown in Table 1.

Data was collected in 15 minute time steps and stored in the memory of the on-site Campbell Scientific CR10 datalogger. Data was transferred on a daily basis from the datalogger to the FSEC central computer system. The data was then retrieved for analysis through a program called WebGet 4.0.

Table 1 Typical channel map for monitoring

Channel acronym	Description	Units
BATVOL	CR10 battery voltage average	V
TFLOR1	Temperature first floor	F
TFLOR2	Temperature second floor	F
TATTIC	Temperature in an attic space adjacent to a floor cavity average	F
TRFDEC	Roof deck temperature in attic average ***	F
TFLSPC	Temperature inside the second story floor space average	F
TOUTDR	Temperature outdoors average	F
RHOUTD	RH outdoors average	%
RHATIC	RH in attic average	%
RHFLR2	RH on second floor average	%
RHFLSP	RH inside second-story floor space average	%
ACWHR1	Energy 1st floor AC total	Wh
ACWHR2	Energy 2nd floor AC total	Wh
TRETF1	Temperature return air 1st floor AC avg. (only during AHU on)	F
TSUPF1	Temperature supply air 1st floor AC avg. (only during AHU on)	F
TRETF2	Temperature return air 2nd floor AC avg. (only during AHU on)	F
TSUPF2	Temperature supply air 2nd floor AC avg. (only during AHU on)	F

Figures 21 through 24 below highlight some of the tasks involved in monitoring installations.

Figure 21 H8 Installing datalogger program and connecting sensor wires to datalogger.

Figure 22 H8 2nd story temperature and RH measured in hallway near return.

Figure 23 Datalogger seen inside enclosure with door open and located below electric service panel.

Figure 24 H10 outdoor temperature and relative humidity measured about 6 feet above ground within gill plate radiation shield.

8.0 Developing Wind Washing Repair Plans

Repair plans were developed for each of the six homes in which repairs were to be performed. Part of the process of developing the repair plans was to interview spray foam application contractors to find out about their products, application procedures, and costs. An important part of the repair planning was to determine the most suitable method of minimizing condensation on cold supply ducts (that might come into contact with the spray foam) after repair. This concern relates to duct surfaces becoming colder when in contact with any insulating material and when there is no vapor barrier to prevent airborne water vapor from migrating to the duct surface. After meeting with representatives from two local firms, we decided to contract with a foam application contractor which uses both open cell and closed cell products with the trade name Demilec and that also had a material in mind for wrapping ducts to avoid condensation issues where the foam would contact the ducts. Our wind washing repairs used only open-cell Demilec.

Retrofit plans were developed for each of these repaired homes. Generally, these plans included installing air/thermal barriers at the perimeter of the between-floors cavity. In all cases this was achieved by applying an open-cell expansive foam to the interface between the open floor cavity and adjacent attic spaces. In some cases, the insulation level of knee walls was identified as being substandard (R11 batts tucked into a dense framework of framing members, with an effective R-value on the order of R7 to R9), so foam insulation was applied to the knee wall as well. The additional cost in time and product for applying foam to the knee wall was generally very small, so it is likely that this supplemental application of insulation is cost-effective.

9.0 Discussion of Our Approach to Wind Washing Repairs

FSEC research staff member, Chuck Withers, was present during each repair from start to finish, providing repair instruction (to the foam application technicians), inspection, and documentation of every site. Research engineer Ian LaHiff was present at four of the six repairs, assisting with inspection and repairs.

Repairs were made by the same two-person crew of a professional insulation company, Foam Insulation Specialists. The primary material used in repair was an open-cell foam, Demilec, which is identified as a manufactured “SEALECTION® 500” polyurethane foam. Following is information provided by the manufacturer:

> “SEALECTION® 500 is a two-component, open celled, spray–applied, semi-rigid polyurethane foam system.” The product is water-blown, meets off gassing requirements of CGSB 51.23-92, has been approved by the EcoLogo Program of Canada, and is listed as a Certified Green Product.

- Being open-cell it is low density (0.45-0.5 lb/ft^3).
- The thermal resistance is 3.81 ft^2 hr ^{o}F/BTU at 76^{o}F per inch of product.
- Air leakage of 3.5“-thick product @75 Pa is 0.001 L/s m^2.
- Water vapor permeability of 3.5”thick product is 6.6 perms.

Three homes were repaired on September 1, one home was repaired on September 9, and the final two homes were repaired on September 17, 2009. The repairs consisted of application of a 3” to 5” thickness of open-cell foam across the opening of the floor cavity, where the floor cavity met attic spaces above first-floor portions of the house. In some cases, the knee wall above the open floor cavity was determined to have substandard insulation. In one house, for example, the triangle-shaped knee wall had R11 batts placed into a frame-work of wood studs, where the studs represented 15-20% of the surface area of the knee wall. The effective R-value of the knee wall prior to repair was about R8. With a 3.5” coating of Demilec, the knee wall insulation value would increase from about R8 to R21. R21 is a more appropriate level of insulation between an attic space (with potential peak temperatures of 130oF) and conditioned space on the other side of the wall assembly. Considering that this knee wall is separating conditioned air on one side at about 75^{o}F from attic air that can reach 125^{o}F on the other side, it is clear that a better thermal barrier would be beneficial. Illustrations (photos) of typical repair can be found in Section 11 of this report.

The typical repair time – after the contractor staff had traveled to the house, set up the equipment, and positioned themselves in the attic – was on the order of 30 to 60 minutes (one-two person-hours). Since the largest part of the cost of applying foam in these attic environments is the time to travel to the house, set up the equipment, and get situated in the attic, the additional cost of applying foam insulation to the kneewall or the roof deck is minimal. A more detailed discussion of time and cost of repairs is found in the following section.

10.0 The Cost of Wind Washing Repairs

The actual cost of repairing wind washing can vary greatly. The greatest factors affecting cost are the level of difficulty to access repair areas and the total area required to be sealed. Homes with garage attic space next to second-story floor space 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 take 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, 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 three 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.

Cost estimates from one foam manufacturer representative were obtained. This industry estimate was \$750 per house. While the estimate seems high to the authors, there are substantial overhead costs for the equipment, travel to and from site, and for a two-person crew. Based on this \$750 per house estimate, the average cost per square foot would be \$6.93/ft^2. Clearly, a cost of \$750 is not reasonable for jobs having easy access and relatively small areas to cover such as H10H, 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. In terms of the price we actually paid for repairs in these six homes, we were charged a flat rate of \$650 per house for the six house repairs.

Since we are not satisfied with these estimates, because they do not differentiate by size and complexity of the wind washing repair, we have made an effort 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.

House # →	H10H	H7G	H14Y	H8Hd	H16B	H11C	**Average**
Coverage (ft^2)	113	510	209	108	103	48	**182**
Time (man hours)	2.25	4.60	4.0	10.0	3.75	3.10	**4.62**
Calculated cost @\$50/hr & \$2.50/ft^2	\$395	\$1505	\$723	\$770	\$445	\$275	**\$686**
Calculated 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, which 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, Chuck Withers provided guidance to the foam application technicians, so some time was involved in training or education. In some cases, considerable time was required to examine different options for how to gain access to the repair sites and determine the best way to apply the foam product; this time would decline with experience. 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 (more energy and demand savings in Sections 11 of this report), the simple payback period would be on the order of 4 years.

11.0 Description and Impacts of Wind Washing Repairs

As indicated earlier, all six homes were repaired in 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; a period of time was allowed between duct repair and wind washing repair to characterize the savings resulting from each. 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 either duct repair or wind washing repair were implemented. 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. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida. The TMY data has hourly outdoor dry bulb temperature for each day of the year representing a geographical weighting of Florida Power and Light's 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. Cold days result in negative cooling energy values, which we have excluded from the annual cooling energy consumption. 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.

Following is a discussion of wind washing characteristics, duct repair and wind washing repair, energy savings, and peak demand reduction in each of the monitored houses in the study.

11.1 House H10H

11.1.1 Description

This 2760 ft^2 slab-on-grade, frame construction residence was built in 1997. The first floor has 2030 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 for cross ventilation via the adjacent soffit vents. Figures 25 and 26 illustrate the construction within the garage attic.

Figure 25 Bonus room with steep pitched wall/ceiling assembly

Figure 26 One side of bonus room wall as seen from attic space.

The house was not originally designed with the bonus room in mind; it was added later to serve as conditioned storage, but is now used as a computer room. Interestingly, the bonus room is conditioned by both HVAC systems. Two supply grills are located on the low south wall of the room, each ducted with flex duct to a different air handling unit. Except for the bonus room, each air handling unit serves the entirety of the floor on which is it located.

The kneewall (between the garage attic and the second floor of the house) on either side of the bonus room is poorly blocked with kraft faced batt and allows for uncontrolled airflow into the interstitial floor space. Numerous wires, refrigerant lines and ducts penetrate into the floor cavity and very little effort was made during construction to effectively seal the kneewall. Figures 27 - 30 illustrate the open areas in the kneewall and the floor cavity of the bonus room floor, which is open to the attic air.

Figure 27 Garage attic open to interstitial floor space**.**

Figure 28 Kneewall partially blocked adjacent to floor space

Figure 29 View of kneewall, floor space (far), and bonus room wall. Unsealed floor cavity is to the left.

Figure 30 Bottom of bonus room wall and open floor space as seen from garage attic. Wall assembly (as described above) is also evident in this picture.

Figures 31 – 36 contain infrared images taken on a mild day in March when the attic was about 90^{o}F and indoor AC setpoint was 68^{o}F.

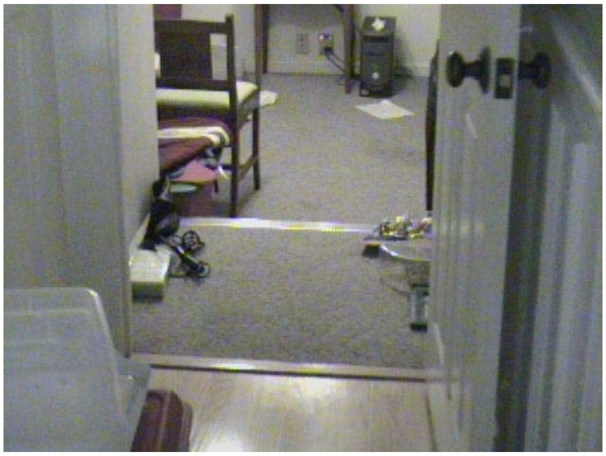


Figure 31 Floor of the bonus room

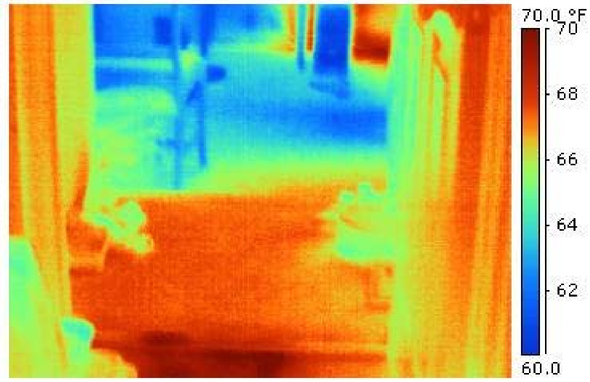


Figure 32 Warm (red) heat signature due to unconditioned air beneath the bonus room floor. The blue emanating from the right is due to the low supply grills.

Figure 33 Ceiling of bonus room with leaky recessed light.

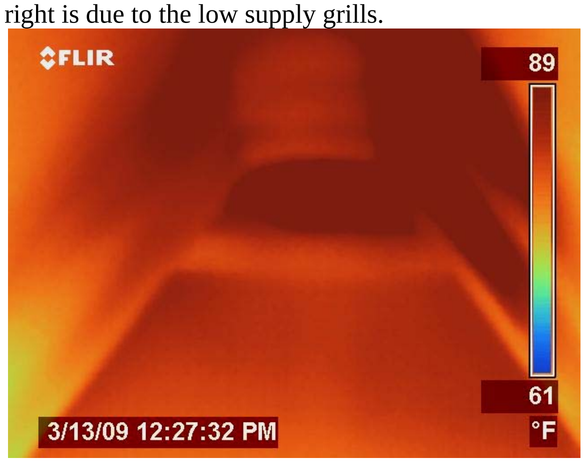


Figure 34 IR image showing very hot areas of ceiling and air infiltrating from the garage attic.

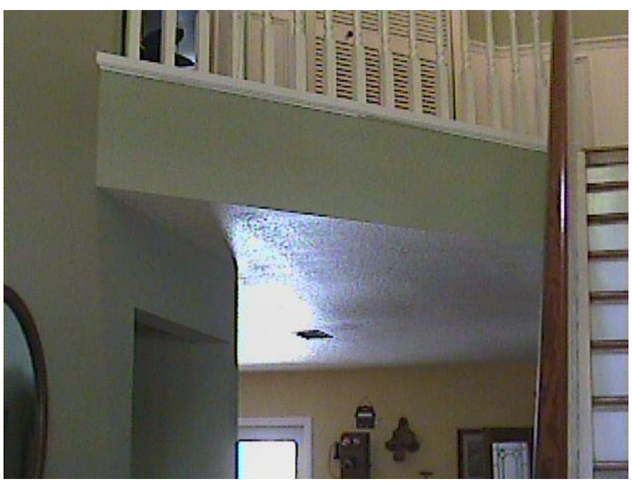


Figure 35 Second story floor space

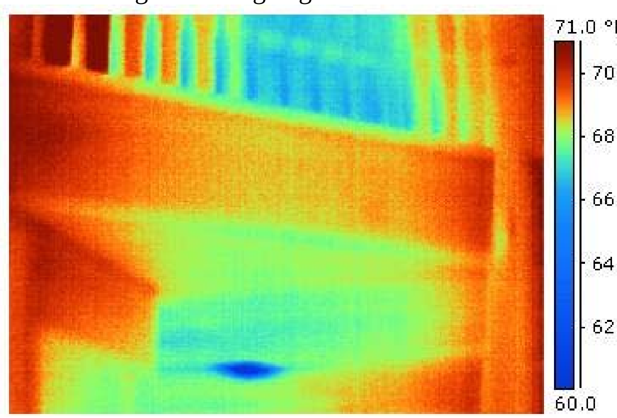


Figure 36 Infrared image of 2nd story floor cavity which is partially open to the attic. Slightly warmer temperatures in proximity to the attic.

11.1.2 Assessment of the Wind Washing Air Leakage Pathway

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 finally passes into the open floor cavity of the main part of the house. The total area of open hole was evaluated for this series at this house and is summarized as follows:

- 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 large 2nd story floor space opening to the bonus room is not included since the bonus room wall is what separates the floor space from the attic space.)*

The soffit is the smallest aperture in this series of air pathways and is 51% of the opening from the attic to floor cavity The open area between the soffit and the attic is about 4 times that of the soffit vent net free area. Lastly, the floor cavity has an opening of about 12 ft^2 to the garage attic, with about a 50/50 split on either side of the bonus room.

We also examined the wind washing pathways associated with the floor cavity of the bonus room. The open cavity under the bonus room is oriented in a north-south direction. The opening between the attic space and the floor cavity is about 5.4 ft^2, with about 2.7 ft^2 on each side. In total, we estimate total openings between floor cavities and attic space to be 17.4 ft^2.

Estimates of the air pathway from soffit vents into the attic were also developed. The gross vent area of north soffit is about 5.6 ft^2. The gross vent area of south soffit is about 5.6 ft^2. The eastern side soffit has a gross area of about 5.1 ft^2 of opening. In total, the combined space between the attic to soffit eave opening is an estimated 16.3 ft^2.

The soffit vent net free area on north and south sides are about 1.1 ft^2 each, and another 1.0 ft^2 on the east side. Therefore, the total soffit vent open area is estimated to be 3.2 ft^2. The soffit is the smallest aperture in this series of air pathways and is only 18% of the open floor area to attic. The amount of air flowing through any one of these holes or pathways depends upon the size of the opening and the driving force (wind) that is pushing air into the space. The soffit vent net free area on north and south is estimated to be 0.8 ft^2.

11.1.3. Description of the Wind Washing Repair

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. Figures 37 – 46 illustrate the wind washing repair at this house and thermal affects on a hot September afternoon more than one week after the repairs had been implemented.

Figure 37 Kneewall effectively sealed with foam product. Duct penetrations were wrapped with a foil faced insulation product to prevent moisture condensation.

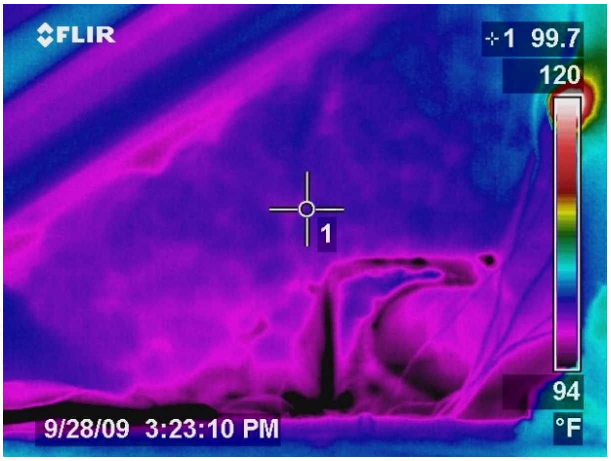


Figure 38 A continuous shield of foam was applied to the kneewall, sealing off attic air from house interstitial cavities.

Figure 39 Kneewall on opposite side sealed with foam.

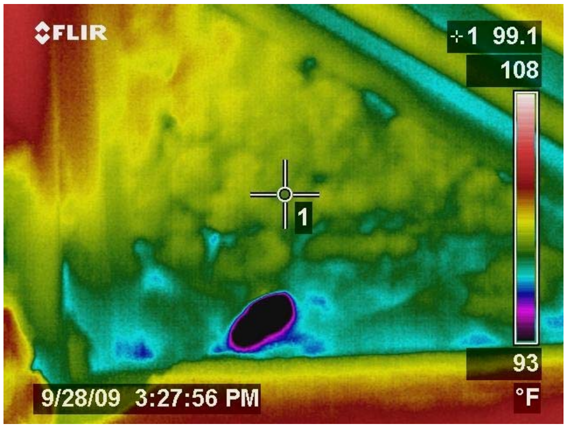


Figure 40 A relative cool spot is a bathroom exhaust duct that vents to the attic.

Figure 41 Ceiling and east wall of bonus room.

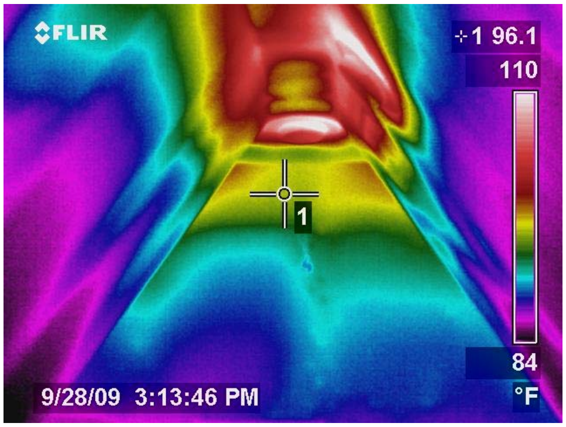


Figure 42 heat transfer through the bonus room walls is high in upper sections which are close to attic roof deck.

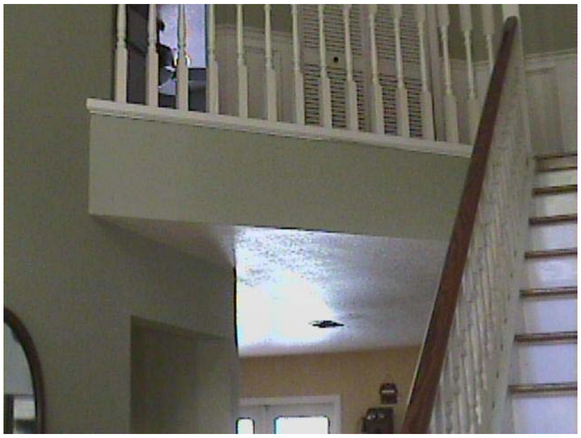


Figure 43 Photo of second story floor space.

Figure 44 After repair, evidence of wind washing heat penetration into house interstitial cavities is now gone.

Figure 45 Garage with standing seam metal roof.

Figure 46 Roof in excess of 100°F. The bonus room is located in the center of the garage attic space.

11.1.4 Pre and Post Wind Washing Repair House Testing Results

Wind washing repair made the house envelope more airtight. Prior to repair, the house airtightness was 7.25 ACH50. After repair, the house airtightness was 6.14 ACH50, indicating a tightening of 15.3%.

Implementation of wind washing repairs substantially reduced duct leakage to outdoors, even though no repairs were directly applied to duct leaks.

- Prior to wind washing repair, the return leak fraction (RLF) for the first floor system was 8.0% and for the second story system was 2.8%. After wind washing repairs were implemented, the RLFs declined to 2.2% and 1.1%, respectively, indicating a 69% reduction in return leakage from outdoors. Since our wind washing repair did not directly seal return leaks, this reduction in return leakage should be interpreted to mean that nearly 70% of the outdoor air (or attic air) that was being drawn into return leaks is now originating from within the air boundary of the building, because the wind washing repair moves the floor cavity from which duct leak air is being drawn more completely to within the house air boundary.
- Prior to wind washing repair, pressure pan measurements averaged 0.63 pascals for the first floor system supplies and 0.44 pascals for the second floor system supplies. After

wind washing repair, pressure pan measurements averaged 0.31 pascals for the first floor system supplies and 0.24 pascals for the second floor system supplies.

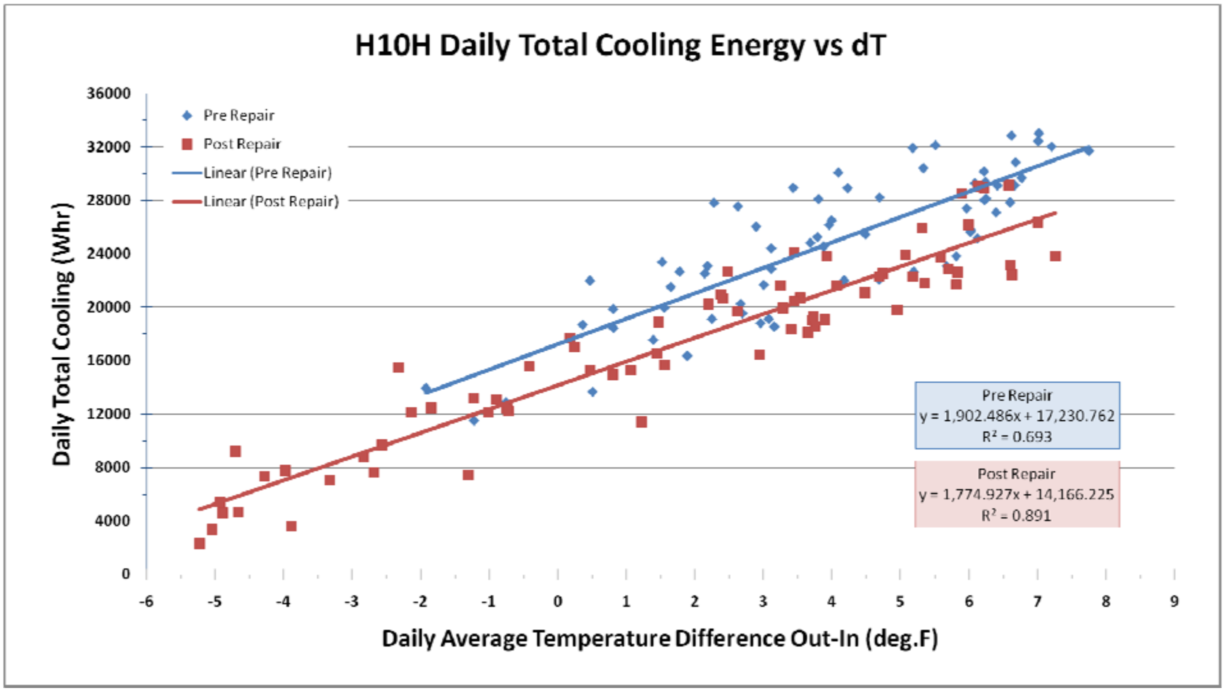
- We find, therefore, that repair of wind washing air flows into building cavities denies duct leaks some of their opportunity to move air across the house envelope air boundary. Wind washing repair should also be considered a way to "repair" duct leaks that are inaccessible because they are in floor cavities, and otherwise would not be repairable. Overall, return leakage declined by 69% and the overall duct leakage (as indicated by pressure pan readings) declined by 49%. 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.

The house infiltration rate with the AHUs running continuously declined sharply as a result of wind washing repair. Prior to repair, the house infiltration rate was 0.46 ach. After repair, the house infiltration rate was 0.32 ach. This indicates a 32% reduction in the house infiltration rate with the AHUs operating.

As a result of wind washing repairs house pressures between rooms changed by a small amount. The average pressure differential across closed interior doors increased from 4.1 pascals to 4.7 pascals for the first floor system and from 4.4 pascals to 4.7 pascals for the second floor system. With all interior doors closed and both AHUs operating, the central zone pressure went from -4.2 to -3.8 pascals wrt outdoors.

11.1.5 Energy savings from repairs

The graph below shows daily total cooling energy for this home versus the daily average temperature difference between indoors and outdoors (dT).



Graph 1 H10 cooling energy versus temperature difference.

A linear regression analysis was used to develop the best fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida. Using the TMY data, the calculated annual cooling energy use for House H10H for the pre-repair and post-repair periods were 4629 kWh and 3793 kWh, respectively. The resulting annual 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.

11.1.6 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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 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.

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.

11.2 House H7G

11.2.1 Description

This home is the middle unit in a triplex. The first floor has 1502 ft^2. A two-car garage is located at the front of the house facing west. 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. 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 beneath the bonus room. 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 located near the bonus room floor space.

Figures 47 – 53 illustrate various aspects of the floor cavity openings, lack of air sealing, and thermal signatures on a cold Florida morning on February 6, 2009.

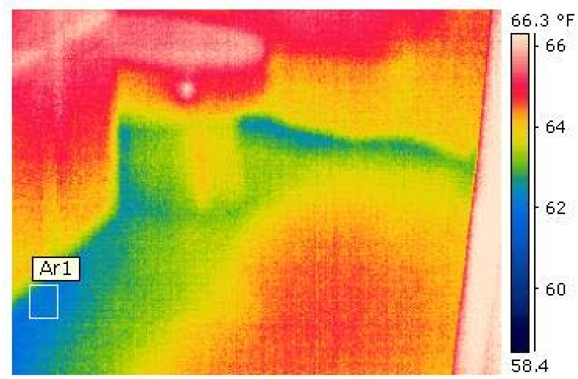


Figure 47 2nd story bathroom floor before repair. Area in box is 62.7°F on a cold day.

Figure 48 H7 inside bonus room floor space facing south. Batts separate floor space from a small vented attic area.

Figure 49 H7 inside bonus room floor space. View is facing east into 14" high 2nd story floor space in the main part of the house.

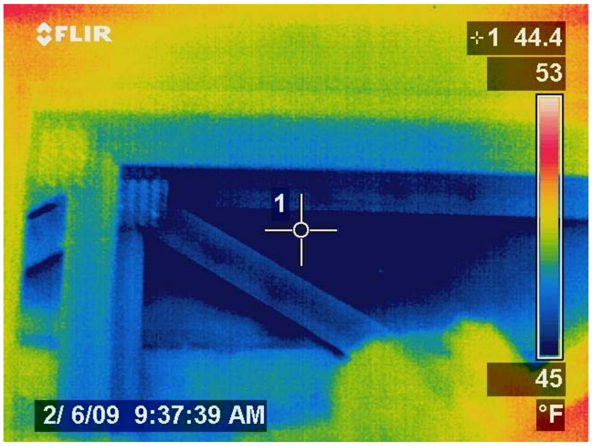


Figure 50 IR scan inside bonus room floor cavity facing west. Coldest area is plywood. Small hipped, vented attic area is on the other side of this cold area.

Figure 51 Photo of image at left**.**

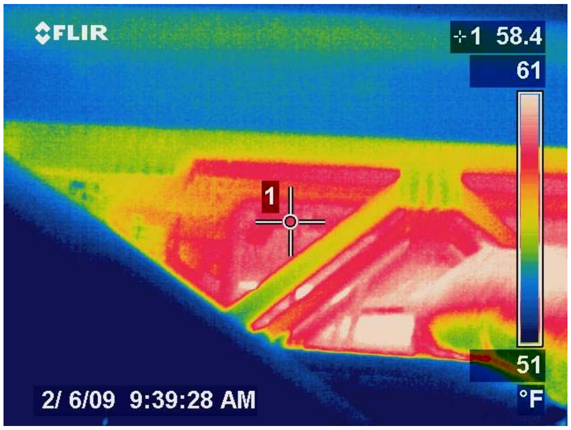


Figure 52 IR image inside bonus room floor space facing east. The truss marks the boundary between 2nd story floor space (which is much warmer) and bonus room floor space (which is much colder).

Figure 53 Photo of image at left.

Figures 54 – 63 illustrate various aspects of the floor cavity openings, lack of air sealing, and thermal signatures on a hot August afternoon.

11.2.2 Assessment of the Air Leakage Pathway (Series Leakage)

When considering how wind driven air enters the home through the floor space, one must imagine a series of three "holes" or pathways. 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 finally passes into the open floor space. The total area of open hole was evaluated for this series at this house and is summarized as follows:

- Soffit vent free area around garage perimeter = 6.2 ft^2
- Open area between soffit and attic = 24.8 ft^2
- Open floor space to attic pathway = 12.1 ft^2
  (*the large 2nd story floor cavity opening to bonus room is not included since the bonus room wall is what separated floor space from attic space.)*

Accordingly, the soffit is the smallest aperture in this series of air pathways and is 51% of the open floor area to attic. The amount of air flowing through any one of these holes or pathways depends upon the size of the opening and the driving force (wind) that is pushing air into the space.

Figure 54 H7 Front of home faces west.

Figure 55 H7 Infrared image of west facing front taken August 19 about 4 PM.

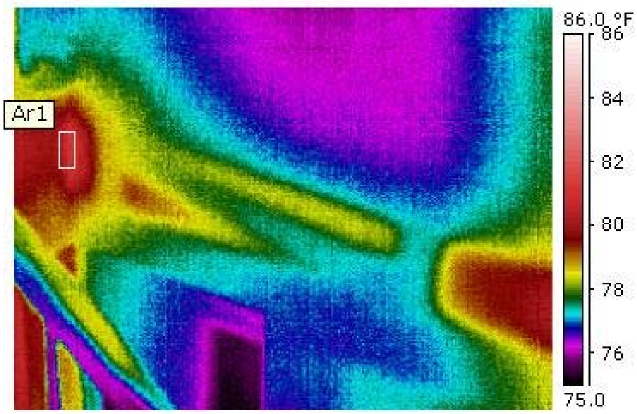


Figure 56 IR image of floor space area at stairwell shows areas of elevated surface temperature before retrofit. Area in box is about 81.4F.

Figure 57 Photo of image to left. Indoor set point is about 77.3 F on average.

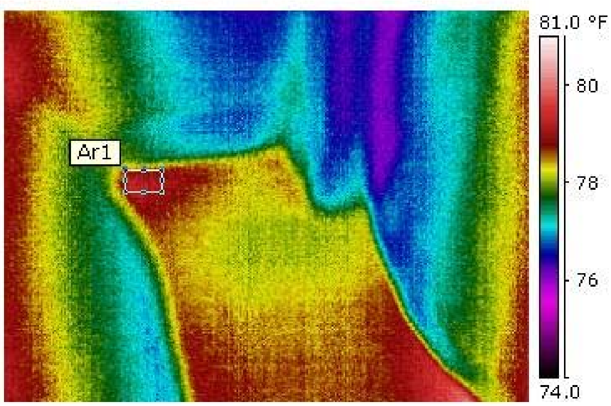


Figure 58 Tile floor surface temperature before repair in the area box is in a location shielded from the supply vent and is about 79.5F when indoor air temperature is about 77F.

Figure 59 Photo of IR image at left.

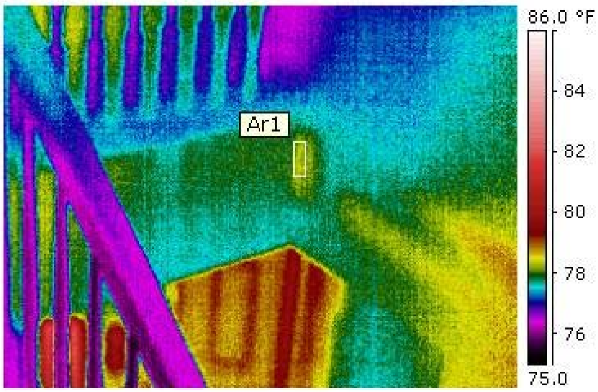


Figure 60 Post Retrofit IR image of stairwell floor space area on a hot day in October. Area in box is 78.5°F, approximately 2.9 deg °F cooler than pre retrofit.

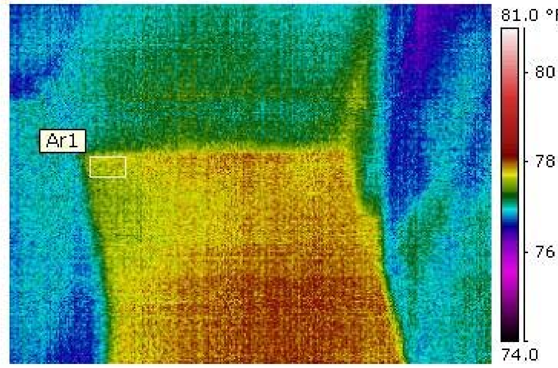


Figure 61 Post retrofit IR image of bathroom floor. Area in box is 78.0°F, approximately1.5 deg °F cooler than pre-retrofit.

Figure 62 IR image of 2nd story bathroom floor after repair. Floor surface is about 1.2°F cooler than pre-repair.

Figure 63 A relative cool spot is a bathroom exhaust duct that vents to the attic**.**

11.2.3. Description of the Wind Washing Repair

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. In addition, foam was also applied to stop air flow from the south attic space from flowing to the bonus room floor cavity (which is now sealed off from the soffits) and to the main floor cavity (in a six foot section). Figures 64 – 65 show wind washing repair. The wind washing repair took 4.6 man-hours to cover 510 ft^2 of area. This was the only retrofit where we had comments on the odor of the foam from the homeowner. It took longer for the odor of the foam material to dissipate out of the bonus room floor space since the repair isolated it more from the vented attic. We suggested the homeowner open the garage access into the floor space while the garage bay door is open for a couple of hours each day to see if this helped. This was reported by the homeowner to help within a couple days after which he did not feel the need to ventilate further.

Figure 64 Technician applying foam to opening between the 2nd story floor cavity and the bonus room floor cavity.

Figure 65 Foam applied to wall and ceiling of the bonus room (3' high) floor cavity.

11.2.4 Duct Repair

Both AC systems had large return leakage. In order to distinguish the energy savings from duct repair from wind washing repair, duct repairs were implemented in the return plenums of both AC systems. Figures 66 – 67 show duct repairs being implemented. Repair of both returns involved cutting open the support platform for access and installing R6 duct board inside the platforms with the foil facing side inward. Mastic was used to complete the air barrier from one duct section to the next and refrigerant line penetrations were sealed. Return leakage for the second story system was drawing from the inter-story floor cavity and from the attic. Return leakage from the first floor system originated from the garage.

Figure 66 Inside of return plenum after repair.

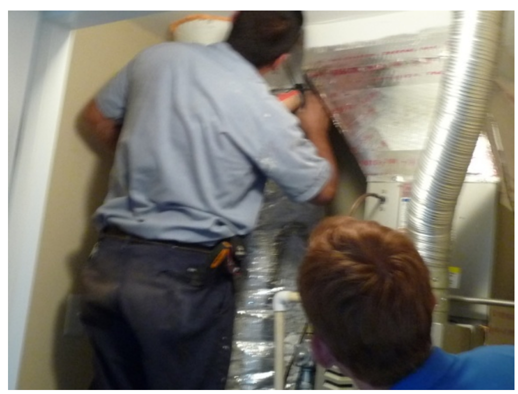


Figure 67 Technician sealing duct penetration on second floor system.

The second floor system was located inside a closet that had a solid door. This system had return leakage from two locations. The first location was from the floor space 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 master bedroom.) The second location was from the attic. 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 due to plenum and furnace leakage sucking air from the closet. Much of this air was replaced by attic air coming through ceiling leakage at two locations. The first ceiling location was through an opening cut too large where the return duct penetrated. The second location was through a combustion dilution vent from the closet to the attic (this vent was provided because a gas furnace was located in the closet). The furnace and plenum leakage 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.

The return leak fraction for the second story system decreased from 9.6% before repair and 1.1% after repair. A discussion of energy use reduction from duct repair is found in a later section of this report. Prior to repair, duct leakage was 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 include the effect of both duct and wind washing repairs.

11.2.5 Pre and Post Wind Washing Repair House Testing Results

Wind washing repair made the house envelope more airtight. Prior to repair, the house airtightness was 12.21 ACH50. After repair, the house airtightness was 9.52 ACH50, indicating a tightening of 22%.

Implementation of return duct repairs (on both AC systems) and wind washing repairs substantially reduced duct leakage indicators.

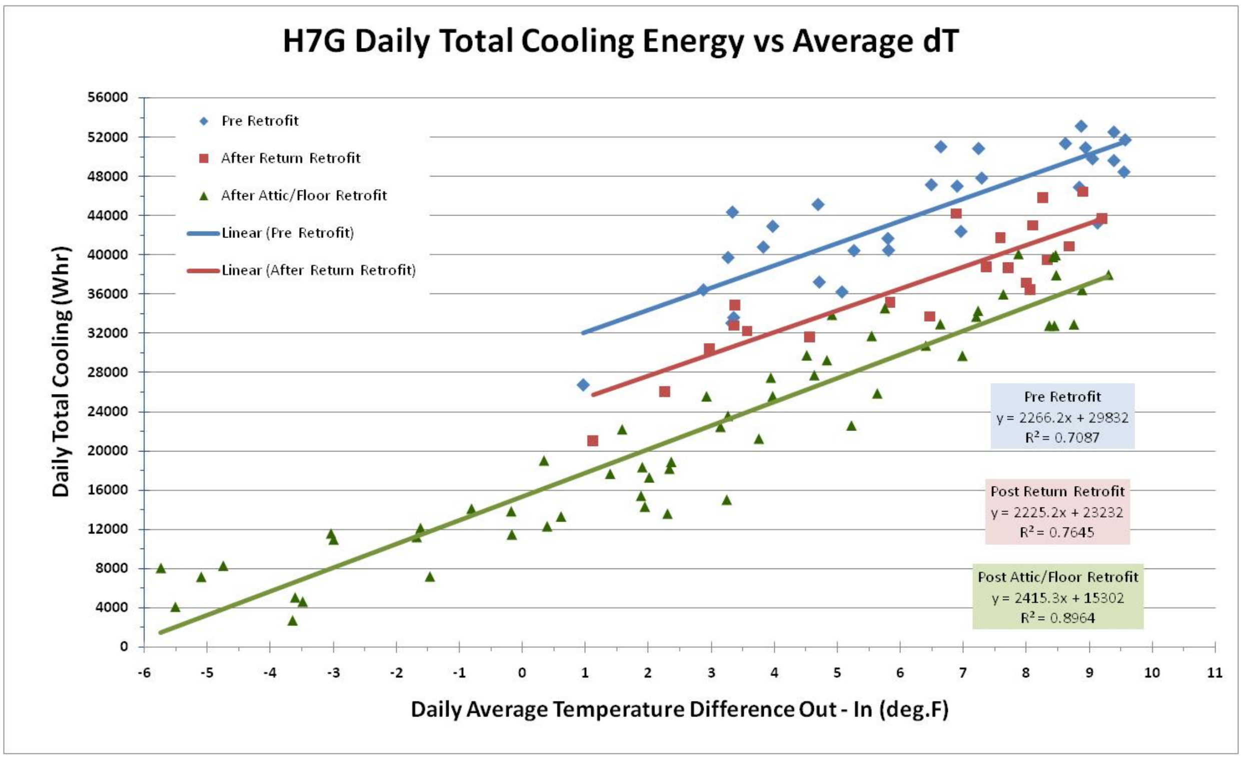
- Prior to these repairs, the return leak fraction (RLF) for the second floor system was 9.6%. After repair, the RLF declined to 1.1%, indicating an 89% reduction in return leakage from outdoors. No RLF test was performed for the first floor system before duct repair. Pressure pan readings found significant return leakage in the first floor system, however. A post repair RLF test was performed; RLF was found to be 2.0%.
- Prior to these repairs, pressure pan measurements for the returns were 15.8 pascals and 21.0 pascals for the first and second floors respectively. After repairs, these pressure pan readings had declined by an average 82% to 3.9 pascals and 2.4 pascals, respectively.
- Prior to repairs, pressure pan measurements averaged 1.65 pascals for the first floor system supplies and 2.18 pascals for the second floor system supplies. After repairs, pressure pan measurements averaged 0.92 pascals for the first floor system supplies and 0.76 pascals for the second floor system supplies.
- We find, therefore, that combined repair of wind washing and return leakage caused a dramatic decline in duct leakage indicators.

The house infiltration rate with the AHUs running continuously declined sharply as a result of the combined wind washing and duct leakage repair. Prior to repair, the house infiltration rate was 0.86 ach. After repair, the house infiltration rate was 0.31 ach. This indicates a 64% reduction in the house infiltration rate with the AHUs operating.

11.2.6 Energy savings from repairs

Since return leaks were severe, they were repaired before the wind washing retrofits. Monitoring was carried out for several weeks before the return retrofit (blue points) to be able to isolate the impact of the duct repairs (red points are the post-duct repair period). Several weeks later the wind washing retrofit was implemented and monitoring resumed for an extended period (green points).

The graph below shows the daily cooling energy versus the daily average temperature difference between indoors and outdoors (dT). Indoor temperature was the average of both floors.



Graph 2 H7 cooling energy versus temperature difference.

A linear regression best-fit analysis was used to develop the best fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida.

Duct repair and wind washing repairs each produced substantial energy savings. Based upon the annual energy analysis (using TMY data), duct repair is indicated to save 2,207 kWh (24.7%; $257) per year. Implementation of wind washing repairs produces 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%.

11.2.7 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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). A linear regression best-fit was 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 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.

Based on this analysis, a reduction of 0.24 kW (from 2.40 to 2.16 kW) in air conditioning electrical demand occurred at House H7G as a result of the wind washing retrofit. This is equivalent to a 9.9% reduction in peak demand.

11.3 H14Y

11.3.1 Description

This 1415 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 façade faces east and is situated near a coastal waterway.

Two air conditioning systems serve each of the floors independently. There is no garage in this residence and no second floor area over unconditioned space. Figures 68 – 70 show the house exterior.

At some point after the 1903 original construction, the house was renovated to add a galley kitchen off the rear (west) side of the house. The cantilevered roofline over this kitchen area creates the only attic adjacent to conditioned space in the house. This area is very difficult to access and could only be inspected by removing a recessed florescent light fixture in the kitchen.

Figure 68 IR view of well-shaded front of H14Y.

Figure 69 Front façade (front door facing East).

Figure 70 Back of residence.

11.3.2 Assessment of the Air Leakage Pathway (Series Leakage)

The outside air leakage pathway from outdoors to the interstitial floor cavity starts with two small opposing gable vents in the attic above the kitchen. They provide (limited) cross ventilation to the attic space above the kitchen. Each vent is a 6" diameter round opening with a grill covering with estimated 0.65 open fraction (each with 0.13 ft^2 net free area). In addition to leakage to the outside, the first floor AC system had a leaky return plenum which was able to draw considerable air from the interstitial floor cavity (between the two floors) and indirectly from the kitchen attic space. In all, the opening between the floor cavity and the adjacent attic space over the kitchen is estimated to be 18 ft^2 gross and about 12.0 ft^2 net free area. (Note that the attic vent opening area was only 1% of the gross open floor cavity opening.) Because of difficult access, we were only able to seal about 9 ft^2 or about 75% of the floor cavity opening.

Figures 71 – 74 show the attic space, attic access through the light fixture, openings to the floor cavity, and very small gable vents.

Figure 71 Gable vent view from outdoors.

Figure 72 Access to attic space through light fixture opening in kitchen ceiling.

Figure 73 Photo of attic space with gable vent (left circle).

Figure 74 Floor cavity directly connected to attic area.

Two photos below are of return leakage of first floor system.

Figure 75 Leaky return plenum.

Figure 76 A view from inside the return plenum shows a lack of sealant or air barrier in return plenum.

11.3.3. Description of the Wind Washing Repair

Foam insulation product was applied to the open floor cavity and exterior walls of the attic. Open cell foam was also used to seal any open space that connected the floor cavity to the unvented attic. The gable vents were sealed to create a semi conditioned attic space and further reducing the potential for wind washing. This repair required 4.0 man-hours to cover 209 ft^2 of surface area.

11.3.4 Duct Repair

Duct repairs were implemented in the return plenum 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 duct leak air flows were interacting 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. Figures 77 through 80 illustrate this duct leakage repair.

Figure 77 1st floor system return plenum with effective air barrier at all joints and penetrations.

Figure 78 Mastic properly applied reduced return leaks from unconditioned space.

Figure 79 AHU leaks sealed with expanding foam and caulk on first floor system.

Figure 80 Conduit and refrigerant line penetrations were sealed on the second floor system.

The return leak fraction 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 the repair. The second floor system uses the AHU closet as a return plenum. The closet door is louvered. Because of the large net return air of the closet door, the closet pressure was small. Therefore, even though the closet had leakage pathways, 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 isolate the floor cavity from the kitchen attic space. A discussion of energy use reduction from duct repair is found in a later section of this report.

Prior to repair, duct leakage was measured by pressure pan. Average pressure pan supply register measurements declined from 2.43 Pa to 0.96 Pa for the first floor system and but increased slightly from 1.17 Pa to 1.30 Pa for the second floor system. This indicates considerable reduction in system duct leakage for the first floor system. The slight increase of supply pressure pan in the second floor system is not related to the duct being leakier, and is within the error band of reading this type of measurement.

11.3.5 House Testing Results

Changes occurred as a result of both 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%.

Implementation of return duct repairs to the first floor AC system and wind washing repairs substantially reduced duct leakage indicators.

- Prior to these repairs, the return leak fraction (RLF) for the second floor system was 1.2%. After repair, the RLF declined to 0.0%. The RLF for the first floor system declined from 4.0% to 0.7%.

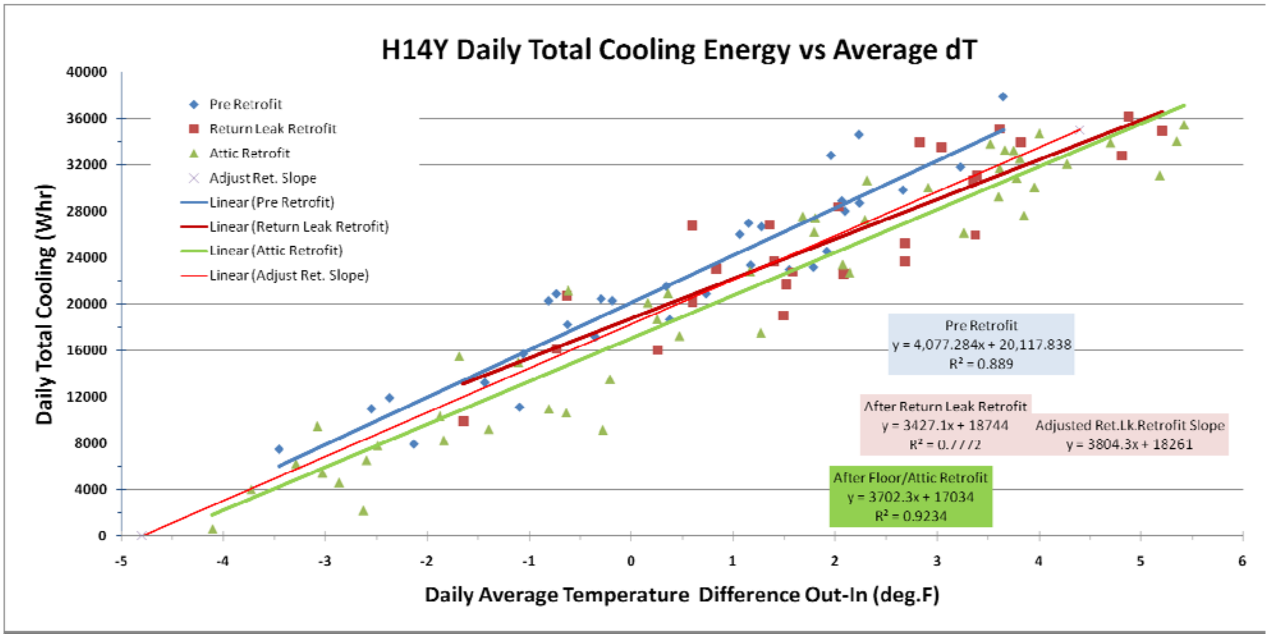
- Prior to these repairs, the pressure pan measurement for the first floor return was 23.0 pascals. After both duct repair and wind washing repair, the pressure pan readings had declined sharply to 1.0 pascals.
- Prior to repairs, pressure pan measurements averaged 2.43 pascals for the first floor system supplies. After repairs, pressure pan measurements averaged 0.96 pascals for the first floor system supplies. Pressure pan reading for the second floor system actually increased from 1.17 Pa to 1.30 Pa as a result of the combined duct leak and wind washing repairs.

The house infiltration rate with the AHUs running continuously increased after the repairs. Prior to repair, the house infiltration rate was 0.43 ach. After repair, the house infiltration rate was 0.58 ach. This indicates a 35% increase in the house infiltration rate when the AHUs are operating. Since the house is quite leaky (ACH50 = 11.2), the infiltration rate would logically be sensitive to environmental factors of wind speed and temperature differential. The initial test day had wind speeds that ranged from 10 mph at the start to 4 to 8 mph at the end of the test and there was approximately a 10 degree delta T between inside and out conditions. The Post testing day was not very windy 0-1mph at the start and 2-4 at the end of the test and the difference between indoor and outdoor temperatures was less than one degree. No explanation is available to provide understanding for this unexpected increase in infiltration.

11.3.6 Energy Savings from Duct Repair and Wind Washing Repair

It was determined that return leaks on the first floor system plenum and AHU should be repaired prior to the wind washing retrofit. Monitoring was carried out several weeks before the return retrofit (blue points) to be able to measure the impact after return retrofit (red points). Several weeks later the wind washing retrofit was completed and monitoring resumed for an additional time period (green points). In an effort to analyze the effects of each phase of repair, an accurate estimation was made to predict the impacts at a wide range of outdoor temperatures.
The return leak retrofit regression line required adjusting due to the smaller timeframe of monitored data for that period. The adjusted retrofit slope is shown in the graph as a thin bright red line. Due to limited data, particularly at lower dT (cooler outside temperatures) the slope of the best-fit line for this data (thick red line) did not fit as one expects between the pre and post wind wash best-fit lines. This line predicts a doubtable outcome that there will be less cooling energy saved from wind wash repair as outdoor temperatures become hotter, and ever increasing cooling savings as outdoor temperatures decrease. The adjusted return repair line was developed by creating a line through two points. The first point was chosen at about a dT of 1.5 (approximately half-way between the range of dT measured) where the original best-fit line crosses. The second point was subjectively chosen as slightly more than half-way between pre and post wind wash line with some convergence towards the later at low dT.

The graph below shows the total cooling energy each day for this home versus the daily total average temperature difference between indoors and outdoors (dT).



Graph 3 H14 cooling energy versus temperature difference.

A linear regression best-fit analysis was used to develop the best fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida. 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.

11.3.7 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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). A linear regression best-fit was 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 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.

Based on this analysis, a reduction of 0.18 kW (from 2.27 kW to 2.09 kW) in air conditioning electrical demand occurred at House H14Y as a result of the wind washing retrofit. This is equivalent to a 7.8% reduction in peak demand.

11.4 H8Hd

11.4.1 Description

This 4500 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 2450 ft^2 and the second floor has 1725 ft^2. There is approximately 1653 ft^2 of first floor area located under the second floor interstitial floor space.

Figure 81 Front view of H8Hd. Front door faces east.

Figure 82 West back side of house

The HVAC system is made up of two high efficiency heat pumps, each serving one floor of the house. The first floor system is located in the garage and the second floor system is 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 (Figure 84 shows a warped door). 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 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 (AC setpoint) enable the high moisture content air to condense on the surfaces of the pocket doors. As shown in Figure 83, the homeowner had put effort into stopping this form of uncontrolled air flow prior to our inspection and testing.

Figure 83 Attempt by homeowner to seal perceived air pathway in bathroom.

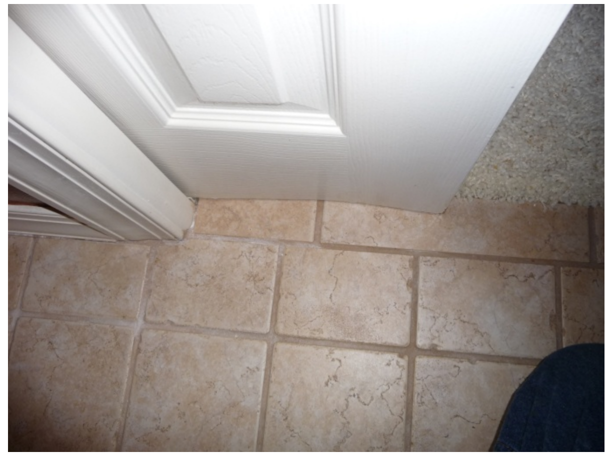


Figure 84 Warped pocket door from air infiltration from north attic area.

11.4.2 Assessment of the Air Leakage Pathway (Series Leakage)

Initial inspections identified that the interstitial floor cavity is well connected to both the garage attic at the front of the house (east) and the soffit venting at the rear of the house (facing west). This can be considered complimentary air pathways. Soffits on the north side are also connected to the floor cavities. Therefore, there are openings from the interstitial floor cavity to outdoors from three sides of the house. The first floor north wall of the house is offset three feet further out than the second floor. This creates a small attic space into which uncontrolled air enters the open second story floor cavity. The interstitial floor cavity opening in the garage attic was about 17 ft^2. Soffit vent gross area was 150 ft^2. Because the soffit net free area fraction is only 0.042 (4.2%) of the gross soffit area, the free area of soffit venting around garage perimeter was only about 6.3 ft2. Clearly the controlling aperture (hole with most limitation) is at the soffit vents.

The open area of floor space adjacent to the North attic section is about 35 ft^2 (41ft x 0.85 ft). The next hole in the series to outdoors is through the space between the roof deck and the top of exterior wall. This hole has an effective size of 11.0 ft^2 (31.5% of open floor area). The last hole in the series is through the soffit vents which have a net free area of 2.3 ft^2. Again, the controlling aperture is at the soffit vent.

On the West side, the open pathway went from the floor space through the external vents had open area of about 7.6 ft^2. The total open area of soffit is only 1.9 ft^2, so the soffit venting is the limiting hole also on the west side. Figures 85 – 90 show the soffits on three sides of the house and the interstitial floor cavity.

Figure 85 North attic is next to open floor space

Figure 86 NE corner of house.

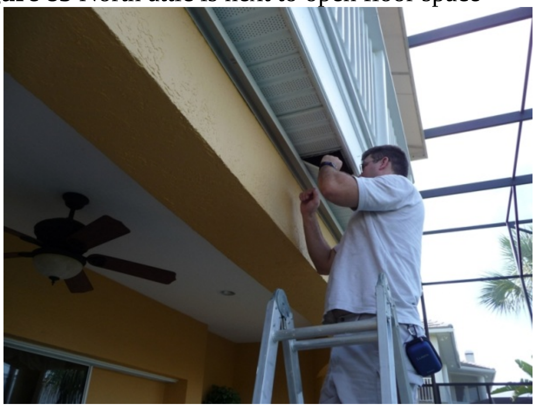


Figure 87 Rear (west) soffit access

Figure 88 View from inside west soffit, evidence of complimentary air pathway at back of photo.

Figure 89 North vented soffit.

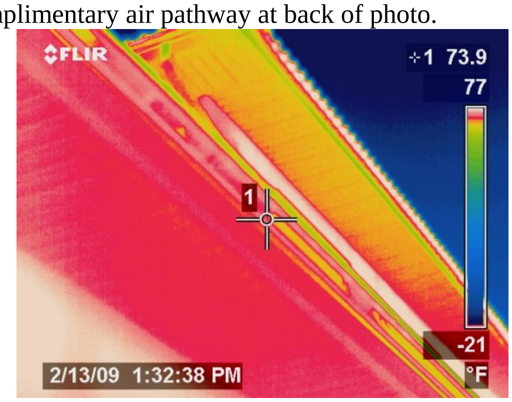


Figure 90 IR North soffit.

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 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 absorbs moisture. Figures 91 – 96 illustrate moisture issues, including cracking of the wooden risers. (Note that these moisture-induced cracks had been largely eliminated within two months of the wind washing repairs.) Moisture data was collected with a Delmhorst 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 staircase before retrofit was

10.9% . By comparison, wood furniture inside the home had a moisture content around 7.5%-8% , within expectations for wood located in a humidity controlled environment. The average wood moisture dropped down to about 9.0% after retrofit.

In addition to the staircase 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 (Figure 96). 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 of wind washing penetration into the depths of the building structure. These ceiling surfaces had been repaired and some duct modifications made by a contractor about a year prior to our testing and monitoring.

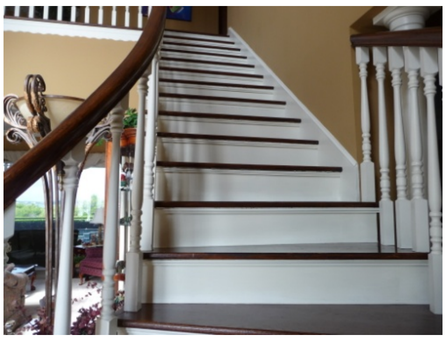


Figure 91 Right staircase

Figure 92 Riser separation before repair.

Figure 93 Moisture content readings were about 13% at top of stairs with trend that fell to about 9.5% at bottom of stairs.

Figure 94 Cracking and separation before repair.

Figure 95 Foyer grand staircase had more cracking on the right side stairs which is closer to most of wind washing areas.

Figure 96 Evidence of condensation damage, mold and recent repairs by homeowner.

11.4.3. Description of the Wind Washing Repair

Prior to installation of the open-cell foam product, condensation-damaged fiberglass batts in the attic were removed. These batts had been recently installed by the homeowner 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 97). Moisture condensation on ducts is an especially common problem in homes where the homeowner sets the thermostat to a low temperature or in cases where the system is set to a lower temperature 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 97 Moisture damaged batt**.**

Figure 98 Supply duct running into an open floor cavity in garage attic kneewall.

Foam insulation product was applied to the kneewall in the garage attic. Where the existing ducts penetrate from the garage attic into the interstitial floor cavity, the foam insulation was isolated from outer jacket of the ducts by an insulating vapor barrier/thermal barrier product to prevent these moisture condensation problems from reappearing.

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 north and west side instillations were particularly difficult since it required removing the soffit face material and then building a foam barrier into the space between the top of the block wall and the roof deck, one bay at a time over a 40 foot length. 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 take down and re-install soffits substantially increased the amount of time required for repair.

Figure 99 Garage attic adjacent to floor cavity.

Figure 100 Preparation before foam installation to protect wall and glass from overspray.

Figure 101 Foam application into west soffit area.

Figure 102 North soffit area after foam installation.

Figure 103 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.

11.4.4 House Testing Results

Wind washing repairs produced a changes in house test numbers. Prior to repair, the house airtightness was 9.38 ACH50. After repair, the house airtightness was 8.56 ACH50, indicating a tightening of the house envelope of 8.7%.

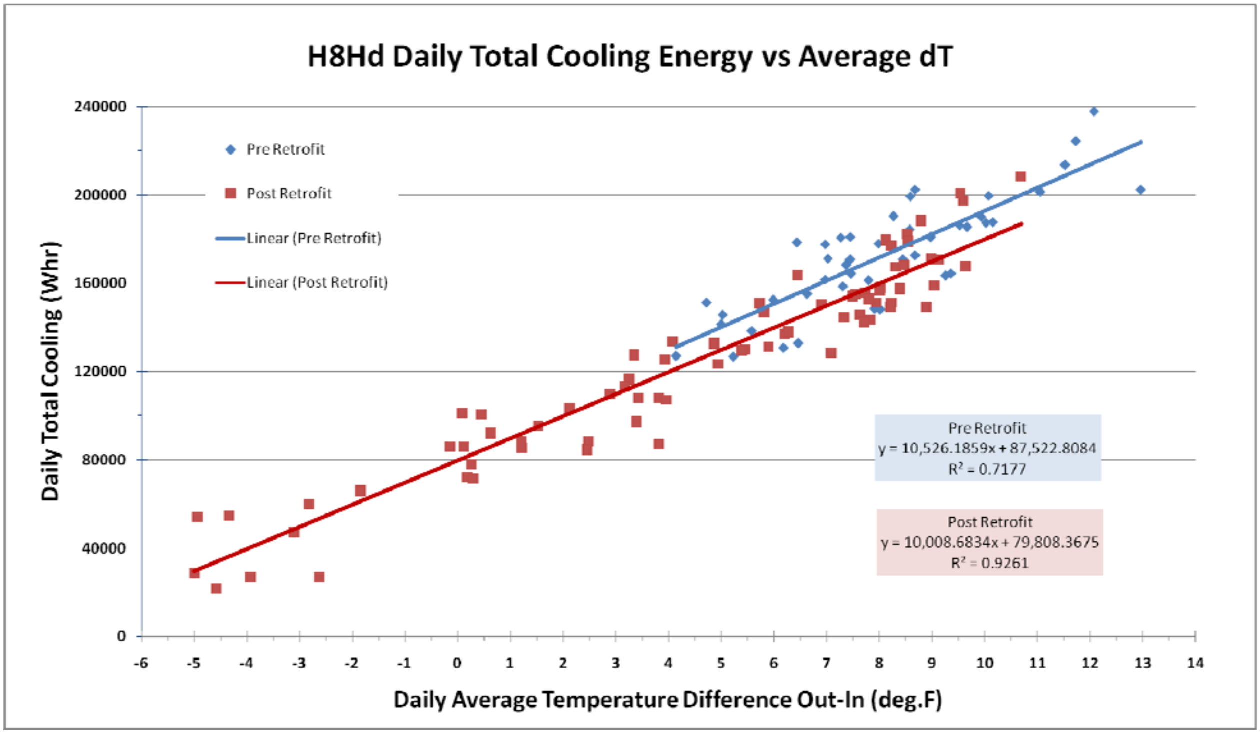
Wind washing repairs impacted duct leakage.

- Prior to these repairs, the return leak fraction (RLF) for the second floor system was 1.1%. After repair, the RLF declined to 0.4%. The RLF for the first floor system declined from 1.4% to 0.4%.
- Prior to these repairs, supply pressure pan measurements for the first floor averaged 0.73 pascals. After repairs, the average supply pressure pan readings had declined to 0.40 pascals.
- Prior to repairs, pressure pan measurements averaged 2.55 pascals for the first floor system supplies. After repairs, pressure pan measurements averaged 2.1 pascals for the first floor system supplies.

The house infiltration rate with the AHUs running continuously decreased sharply after the wind washing repairs. Prior to repair, the house infiltration rate was 0.49 ach. After repair, the house infiltration rate was 0.30 ach. These results indicate a 39% decrease in the house infiltration rate when the AHUs are operating.

11.4.5 Energy savings from repairs

The graph below shows the total cooling energy each day for this home versus the daily total average temperature difference between indoors and outdoors (dT).



Graph 4 H8 cooling energy versus temperature difference.

A linear regression best-fit analysis was used to develop the best fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida. Wind washing repair resulted in projected annual cooling energy savings of 2771 kWh (8.2 %; $318.65).

11.4.6 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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). A linear regression best-fit was 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 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.

Based on this analysis, a reduction of 1.80 kW in air conditioning electrical demand occurred at House H8Hd as a result of the wind washing retrofit. This is equivalent to a 15.0% reduction in peak demand.

11.5 H16B

11.5.1 House Description

This 3100 ft^2 slab-on-grade, wood frame home was built in 1990 and had substantial improvements made to the exterior materials and windows over the past few years. It has 1732 ft^2 on the first floor and 1349 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.

Infrared images below were taken during our field visit August 14, 2009 prior to repairs (Figures 104-107).

Figure 104 Attic over garage faces south.

Figure 105 IR image of attic over garage. East-facing roof is about 151deg. F just before noon.

Figure 106 IR view inside the attic shows cool temperatures in the floor space and cooled surfaces low in attic.

Figure 107 Photographic view of IR image to the left. The interstitial floor cavity at the bottom of the wall is open to garage attic space.

11.5.2 Assessment of the Air Leakage Pathway (Series Leakage)

The opening between the second story floor cavity and the garage attic is about 25 ft^2. This opening is facing south into the garage attic. The open area of space from the soffits into the attic is very small since batts are located on top of the garage attic floor close to the roof deck. We estimate that the total soffit-to-attic opening is only about 1 ft^2.The soffit vent net free area is estimated to be about 1.6 ft^2. Therefore, the opportunity for wind driven air entry into the interstitial floor cavity is small. There are no complimentary holes or pathways on the other side of the house to allow air to flow freely through the interstitial floor cavity. Note, however, that passive, stack-effect air flow between the attic and the floor cavity may be occurring, as is suggested in the IR image of Figure 108, where there is considerable stratification of temperatures from top to bottom of the floor cavity.

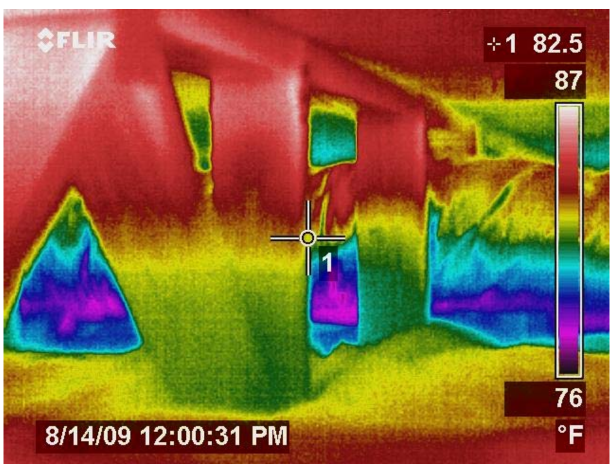


Figure 108 IR inside floor space shows stratification before foam retrofit.

Figure 109 View inside floor space.

11.5.3. Description of the Wind Washing Repair

Foam insulation product was applied to the open area around the floor of the garage attic, providing an effective air barrier sealing the interstitial floor space. Also, the knee wall that ran the width of the attic was sealed and insulated with the open-cell product (Figures 110 – 113).

Figure 110 Insulation rig at site.


Figure 111 Insulation tech just finishing up kneewall and floor insulation/ air tightening.


Figure 112 Floor post retrofit has been completely sealed and insulated.

Figure 113 IR image from inside attic after repair.

11.5.4 House Testing Results

Changes in house test numbers as a result of wind washing repairs. Prior to repair, the house airtightness was 9.86 ACH50. After repair, the house airtightness was 9.19 ACH50. This result indicates a reduction in house envelope leakage of 6.8%.

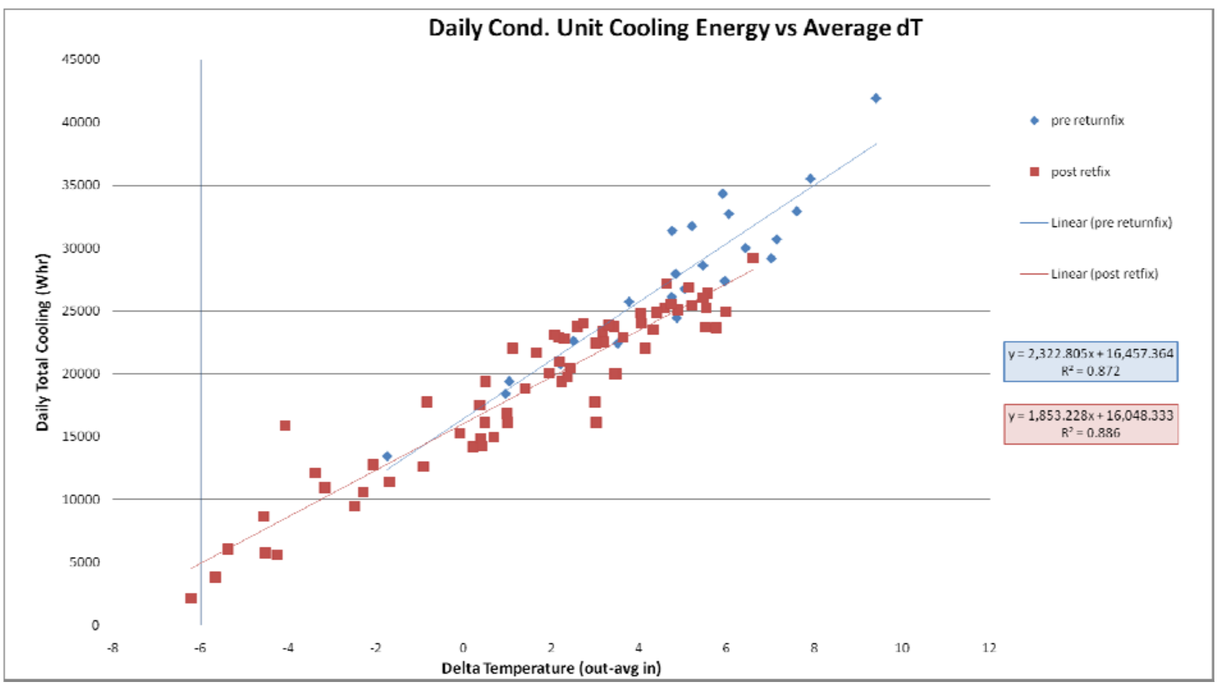
Wind washing repairs had little impact on duct leakage, except that the house infiltration rate (with the AHUs on) declined.

- Prior to these repairs, the return leak fraction (RLF) for the second floor system was 1.0%. After repair, the RLF remained essentially unchanged at 1.1%. The RLF for the first floor system remained unchanged at 5.3% for both pre and post tests.
- Prior to these repairs, supply pressure pan measurements for the first floor averaged 1.14 pascals. After repairs, the average supply pressure pan readings had declined to 0.30 pascals. Pressure pan results for the second story supplies remained unchanged at 1.02 pascals, on average.

The house infiltration rate with the AHUs running continuously decreased substantially as a result of the wind washing repairs. Prior to repair, the house infiltration rate was 0.26 ach. After repair, the house infiltration rate was 0.20 ach. These results indicate a 23% decrease in the house infiltration rate when the AHUs are operating.

11.5.5 Energy savings from repairs

The graph below shows the total cooling energy each day for this home versus the daily total average temperature difference between indoors and outdoors (dT).



Graph 5 H16B cooling energy versus temperature difference.

A linear regression best-fit analysis was used to develop the best fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida.

Annual cooling energy use was calculated using the pre- and post-repair best-fit equations. Wind washing repair resulted in annual energy savings of 682 kWh (13.4 %; $78.43).

11.5.6 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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). A linear regression best-fit was 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 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.

Based on this analysis, a reduction of 0.39 kW (from 2.25 kW to 1.86 kW) in air conditioning electrical demand occurred at House H16B as a result of the wind washing retrofit. This is equivalent to a 17.3% reduction in peak demand.

11.6 H11C

11.6.1 Description

This 2410 ft^2 split-level, block and frame home was constructed in 1967. It contains 1610 ft^2 on the first and second levels combined and 800 ft^2 on the top level (Figures 114 - 115). 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 eaves. This home was very difficult to repair since there was very limited access to open floor areas to be sealed on the north side of house.

Figure 114 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 115 Back of home (facing south) with top story floor space cantilevered and vented over patio.

11.6.2 Assessment of the Air Leakage Pathway (Series Leakage)

On the north side of the house, the exposed open area of floor cavity on the north side is about 5.5 ft^2 and the open area of the floor cavity from north attic to north soffit is about 11.6 ft^2. The total air pathway from north attic through soffit and ridge vents is about 2.3 ft^2. Therefore, the attic venting is the most restrictive opening.

On the south side of the house, the exposed open area of floor cavity is estimated to be about 4.1 ft^2. The total net free area of the nine south soffit vents that open into the floor cavities is about 1.4 ft^2. Therefore, the attic venting is the most restrictive opening. Figures 116 – 123 show soffit vents and interstitial floor cavities.

Figure 116 Cantilevered section of floor space on south side showing 2 of nine vent openings.

Figure 116 Kraft faced batts located inside cantilevered portion of floor deck in most bays. Most only partially block opening from vent space to floor area. View from inside looking out to patio south side.)

Figure 117 View from soffit vent looking inside towards floor space in area having no batt. This is a different floor space bay than previous picture.

Figure 118 Soffit vents down the south side of the house.

Figure 119 North attic section looking west from garage attic. North soffit vents are to the right. Felt paper being held up to view small kneewall area not insulated and floor space at bottom.

Figure 120 View of air leakage between batt and floor deck on north side facing South. Air leakage estimated to be about 2"x 22" in each bay.

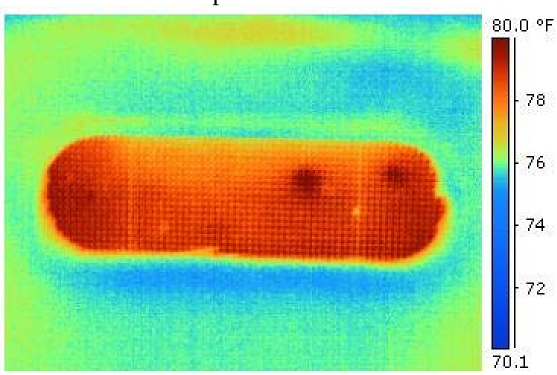


Figure 121 With 10 mph wind from the north, the north soffit vent shows interior surface temperatures about 78-80 ^{o}F. Outside air temperature =80.1 ^{o}F and interior air temperature=71.0 ^{o}F.

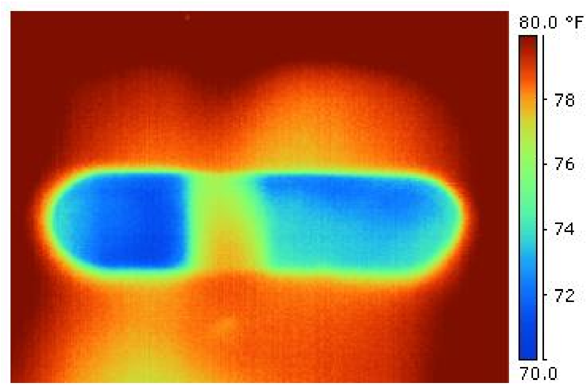


Figure 122 With 10 mph wind from the north, the south soffit vent shows average of 71.9 ^{o}F on interior surfaces in left bay and about 73.2 ^{o}F on right bay indicating cool house air being pushed through the house by means of the floor cavity and the force of the wind.

11.6.3. Description of the Wind Washing Repair

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 down through a very narrow attic space (above the front porch) having about 16" of vertical clearance. The problem with shooting foam down narrow areas is that the foam product spread is approximately 6" diameter at a distance of 8 feet. This means that you can only effectively reach about 10.5 feet away in a space with 16" clearance before product contacts surrounding surfaces and begins to expand and seal off further access. Figures 124 – 127 show wind washing repairs.

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 much narrower than usual spray stream to be projected through the small attic space, allowing better (further) than expected coverage. In spite of restricted access, foam could be applied to seal 75% to 80% of desired area. If wind washing repairs become a common application in the future, it will be valuable to have various nozzle sizes and wand lengths that can allow application extension.

Figure 123 Beginning of north side sealing.

Figure 124 Finishing up on north side by sealing garage attic off from north attic (with prayerful oversight by Mary)

Figure 125 Insulation tech applying insulation through soffit vent openings.

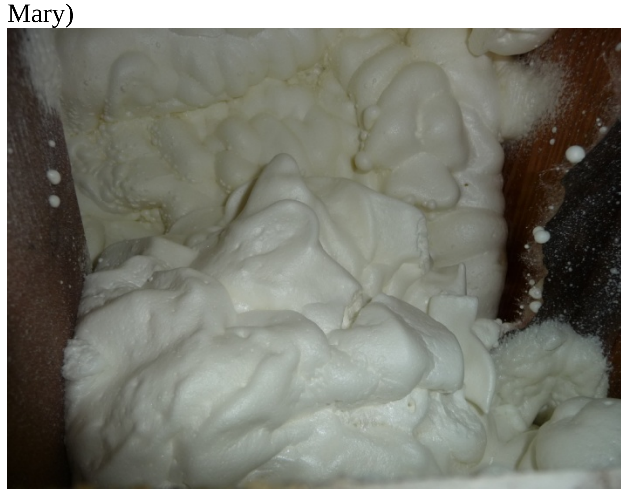
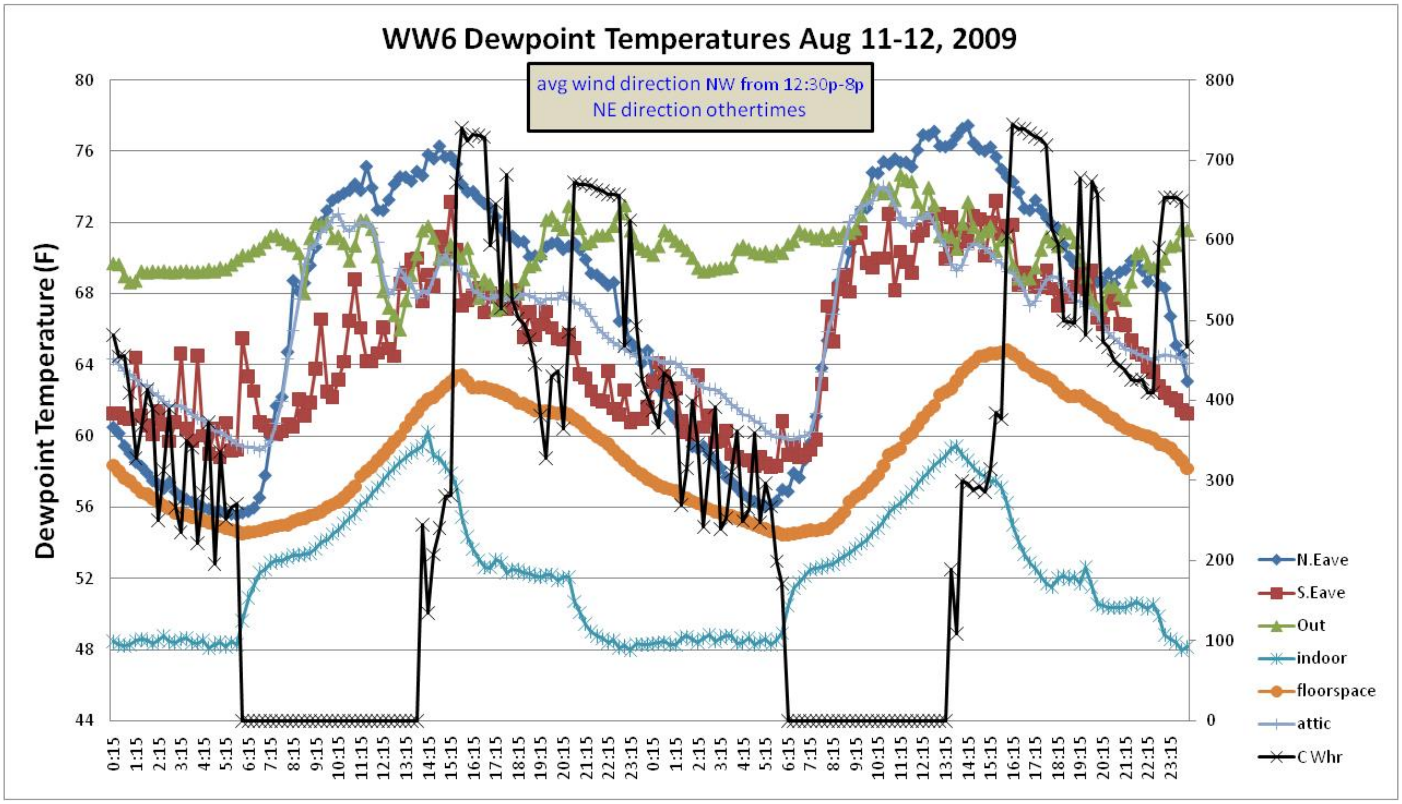


Figure 126 South side insulation applied over top of floor deck, then floor space vertically sealed off by foam wall from floor deck down to bottom of floor space.

Open cell foam was sprayed inside the south vents to separate floor space from vented area. The south side was sealed 100%. There was no direct access to north side open floor space, so the foam application was only able to seal about 75%-80% on this side. Average insulation thickness was about 3 inches. We estimate that overall, the repair effort resulted in sealing about 90% of openings to the interstitial floor cavities.

Chuck Withers noticed that very cool dry air was felt at the south soffits prior to sealing off floor space. HOBO loggers placed in both soffits also recorded dew point temperatures that were much lower than outside much of the time. The figure below shows dew point temperatures in six locations (including indoors, outdoors, eaves, attic, and floor cavities) over a two-day summer period. The figure also shows the power use of the AC system. Interesting patterns can be observed. The homeowner typically sets the thermostat up during the day, and then lowers it in the early afternoon (channel CWhr is the cooling system energy consumption). This causes the AC system to remain off for an approximate 7 hour period starting in the morning. While the outdoor dew point temperature is in the range of 70 to 72^{o}F throughout this two-day period, indoor dew point temperatures are at 48^{o}F when the AC has been operating for a consistent period, but then rises steadily to a spike of about 60^{o}F after the AC has been off for 7 hours.



Graph 6 H111C Dewpoint temperatures indoors, outdoors and in unconditioned spaces during two-day period.

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 drops substantially during the period that the AC system runs, declining from about 72^{o}F to about 60^{o}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, a research analyst has felt and measured with Vaisala HM34 (Figures 128 - 129) 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.

Figure 127 Evidence of cool, dry air emanating from the vented eaves on the south side of the house. (T)

Figure 128 Measurement of RH (%) showing low humidity air discharging from the soffit vent on the south side of the house.

11.6.4 House Testing Results

House test numbers changed as a result of wind washing repairs. Prior to repair, the house airtightness was 9.65 ACH50. After repair, the house airtightness was 9.40 ACH50, indicating a 2.4% decrease in building leakiness.

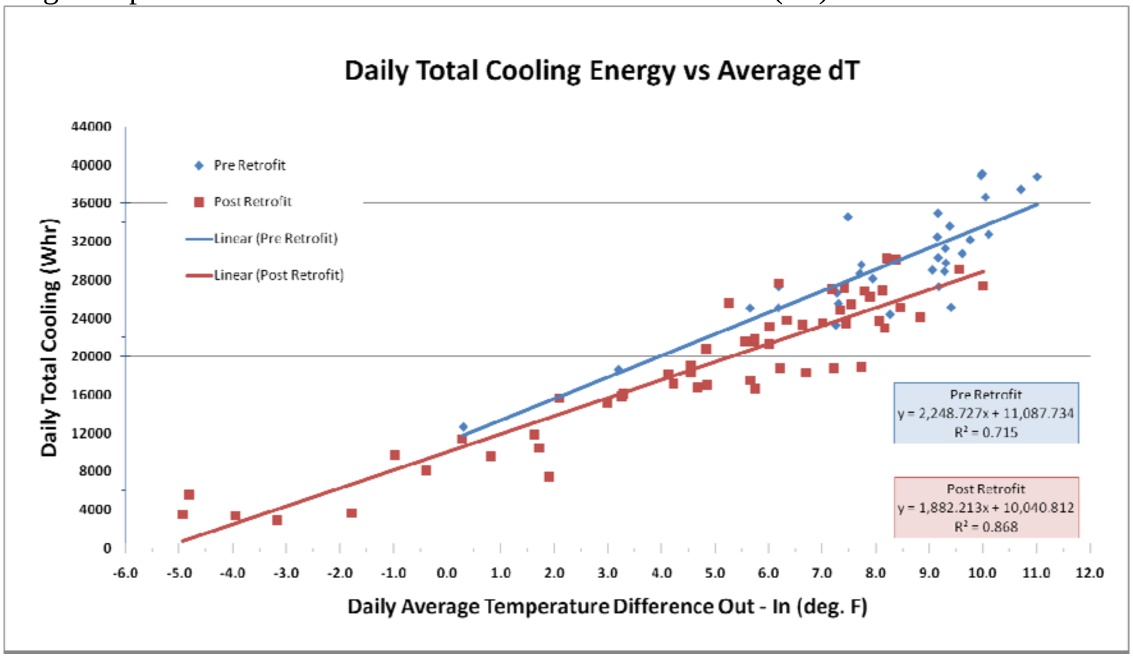
No duct repairs were done at this house. Wind washing repairs impacted duct leakage, but with mixed results.

- Prior to these repairs, the return leak fraction (RLF) for the single AC system was 11.5%. After repair, the RLF declined to 7.9%.
- Prior to these repairs, supply pressure pan measurements for the only AC system was 0.56 pascals. After repairs, the average supply pressure pan readings had increased to 0.89 pascals. The authors have no explanation for the increase in pressure pan numbers except for a difference of 0.33 is close to the amount of error that can occur in taking these values.

The house infiltration rate with the AHUs running continuously remained essentially unchanged from before to after the wind washing repairs. Prior to repair, the house infiltration rate was 0.73 ach. After repair, the house infiltration rate was 0.74 ach.

11.6.5 Energy Savings from Repairs

The graph below shows the total cooling energy each day for this home versus the daily total average temperature difference between indoors and outdoors (dT).



Graph 7 H11C cooling energy versus temperature differential.

A linear regression analysis was used to develop the best-fit lines shown in the graph. The linear equations from each period were then used with 10 year composite TMY data representing 4 major cities in Florida. Based upon the annual energy analysis, 565 kWh (12.0%; $65/year) would be saved each year from the wind washing repairs at this house.

11.6.6 Demand Savings from Wind Washing Repairs

In order to perform this peak demand analysis, five to ten of the hottest monitored days with comparable outdoor and indoor temperatures were chosen, for both the pre-repair and post-repair periods. 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). A linear regression best-fit was 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 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.

Based on this analysis, a reduction of 0.43 kW (from 2.02 kW to 1.59 kW) in air conditioning electrical demand occurred at House H11C as a result of the wind washing retrofit. This is equivalent to a 21.3% reduction in peak demand.

11.7 Summary of Energy Savings from Six Monitored Homes

As can be seen in Table 3, considerable energy savings were achieved as a result of wind washing repairs. The range of energy savings is large, ranging from 7.2% to 33.1%, and the average cooling energy use reduction was 15.3%.

It is worth noting that homes that were selected for repair and monitoring do not represent the greatest wind washing energy waste potential. (See Section 13 for additional discussion of the wind washing energy waste potential matrix, and how the houses that were selected for repair and monitoring do not in general represent a high level of energy waste potential.) Therefore, if additional research is performed and homes with greater wind washing potential are repaired, it is likely that higher savings will be achieved.

It is also worth noting that energy savings during the heating season have not been considered in this analysis. Therefore, actual savings from wind washing repairs would be greater than shown.

Table 3 Annual cooling energy savings from wind washing repair

	Pre-repair annual kWh	Post-repair annual kWh	Annual kWh savings	% savings	Annual savings (@11.5 cent/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*

As seen in Table 4, considerable energy savings were achieved as a result of duct leakage repair in two homes. On average, cooling energy use reduction resulting from duct repair in these two homes was 17.1%. (Analysis of peak demand reduction from duct repair has not been performed.) It is important to note that some of the energy losses caused by duct leakage would be eliminated by repair of wind washing. This is because some of the air exchange between indoors and outdoors produced by duct leakage would be eliminated as interstitial cavities of the house are moved more completely inside the house air envelope. Therefore, if we had not performed duct repair in these two homes, the annual energy savings from wind washing repair would have been greater than the 33.1% and 7.2% in homes H7G and H14Y.

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 cent/kwh)
H7G	8950	6743	2207	24.7%	253.80
H14Y	3102	2806	296	9.5%	34.04
Average			*1251.5*	*17.1%*	143.92

11.8 Peak Demand Savings from Wind Washing Repair in Six Homes

Peak demand reduction is not as great, on a percentage basis, as annual energy use reduction. On average, peak demand has been reduced by 12.6%, or 0.52 kW, as a result of wind washing repairs. Peak demand reduction from duct repair has not been determined.

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%*

Peak period analysis for August 15 from 3pm-6pm

12.0 Moisture Condensation Issues Associated with Insulation Materials in Contact with Ductwork

Dew point temperatures during the Florida summer are high, typically in the range of 73°F to 76°F throughout a four month period (June through September). Dew point temperatures can be even higher in the attic of homes, especially during the hottest hours of the day. It is not uncommon for light-to-moderate levels of condensation to occur on the exterior of ductwork in many homes in Florida, and in some cases moisture has dripped on to the ceiling causing staining and even mold growth.

Condensation on ducts can be accentuated when insulation materials come into contact with the exterior of the duct or duct insulation. This problem was observed in House H8Hd. The homeowner had become aware of the wind washing problem prior to our testing, monitoring, and repairs, and had taken steps to partially block openings into the floor cavity. Specifically, the homeowner had placed insulation batts with kraft paper backing into the floor cavity gap. In places where these batts came into contact with supply flex ducts (that were going from the attic space into the floor cavity), we found moisture condensation occurring (see photos in Figures 130 - 131). Because of our knowledge of this problem and because of what we observed at house H8Hd, we took steps to avoid moisture condensation problems.

To avoid condensation on the exterior of supply ducts where they would potentially contact the open-cell foam, we instructed the foam insulation contractor to apply (wrap) a layer of (3/8" thick) foil-faced insulation material around the flex duct prior to the application of the foam insulation (Figures 132 - 133). The insulation wrap has foil on one side of a closed-cell polyethylene foam center and a plastic membrane on the other. Thus, the spray foam insulation does not come into direct contact with the foil outer surface of the duct. There was no brand information available so we do not know exact performance specifications. Information was obtained on a product that appears to be identical to that used in the retrofits. The manufacturer claims an effective R value of 15.7 (no doubt by including a radiant barrier effect when facing into an air space) and vapor barrier resistance of 0.033 gr/m^2 kPa.

A second brand of insulation product was also used to wrap supply ducts in one house (Figure 134). This product has foil facing on both sides of a polyethylene air bubble. This product is about half the thickness of the flexible foam board product. The manufacture claims thermal resistance of R1.1 downward (R4.9 upward) and water vapor permeance of 0.000 perms.

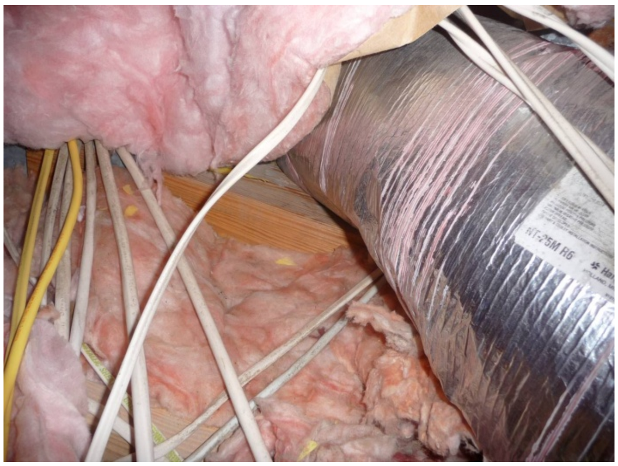


Figure 129 Batt placed against supply duct by homeowner at H8Hd.

Figure 130 Batt pulled away from duct shows it is soaked where dark areas are seen on paper facing.

Inspection in these four houses found that in all cases there was essentially no condensation occurring between the duct and the thin foil-faced insulation material or at any other location associated with the foam. The weather during these inspections had outdoor dew point temperatures in the 72^{o}F to 77^{o}F range, which is quite representative of full summer humidity conditions. The inspection for moisture condensation was performed in the following manner. Dry hands were inserted into the gap between the duct (typically flex duct) and the foil faced wrap material. In all cases no moisture was detected on the hands as they were withdrawn and in general a layer of dry dust was observed to be attached to the surface of the hands, indicating that the dust that had previously accumulated on the duct outer jacket had not become wet, even with outdoor dew point temperatures as high as 77^{o}F.

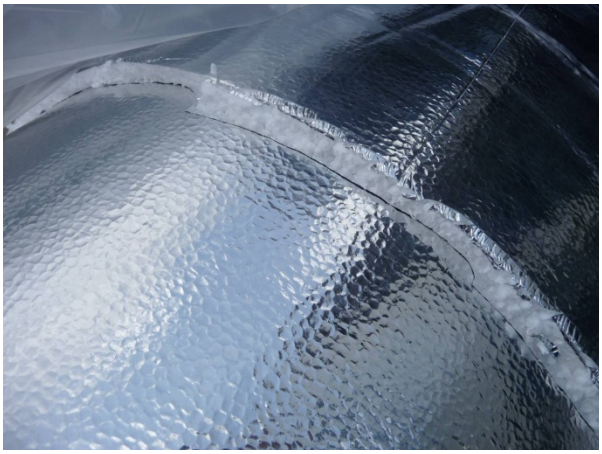


Figure 131 3/8 inch beadboard insulation with foil face on one side and plastic film on the other.

Figure 132 Supply duct from attic to floor space with insulation wrap around duct after foam applied.

The houses were visited one last time in late November to early December. While the outdoor air had much lower dew point temperatures at this time, we still looked for indications of moisture problems indicated by such things as water marks on ducts or nearby building materials. We found no evidence of moisture problems. We are cautiously optimistic that this duct wrap method and materials used will work to avoid condensation under most conditions. However, we do not know how well it will work under even more severe circumstances, such as when a homeowner might select a very low thermostat set point (such as 68°F for cooling) that would result in cooler exterior duct surfaces for extended periods of time.

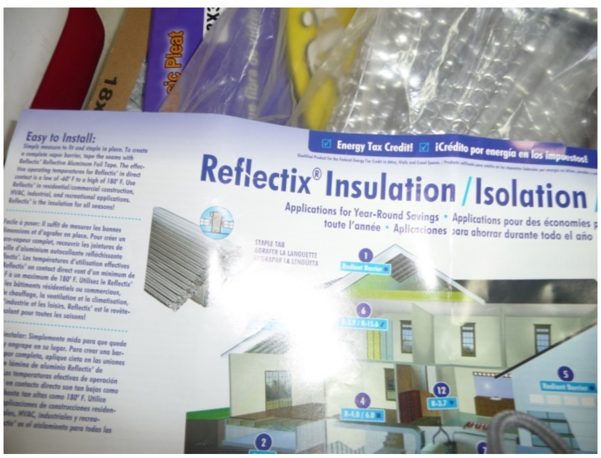


Figure 133 Second product used to wrap supply ducts has foil facing on both sides of a plastic air bubble pack.

13.0 Consideration of Wind Washing Repair Program Opportunities

Only a portion of two-story homes have substantial wind washing potential. Therefore, only a portion of all Florida 2-story homes are good candidates for wind washing repair.

Based on a limited sample size of only 32 homes it is not possible to say definitively how many homes are good candidates for repair. The six homes that were repaired were selected from a sample of 16 homes. Note that the first five homes had little or no wind washing potential, primarily because there were few or no openings between attics (or outdoors) and the interstitial floor cavities.

From our testing and monitoring we have identified six primary variables which determine the extent to which wind washing is likely to impact the cooling energy use of a house.

Factors which Affect the Energy Impact Potential of Wind Washing

There are a number of factors which contribute to the potential for energy losses and peak demand increases associated with wind washing. Those factors include the following.

1) The size (ft^2) of openings to the floor cavity located between the first and second story of the house.
2) The temperature of the air that flows into the floor cavity.
    a. In many cases, the air pushed into the floor cavity originates from an attic space, in which case the attic air temperature may be very high. Attic temperature depends upon the type of roofing material (tile roofs produce much cooler attics tan asphalt shingle roofs), the color of the roof surface (bright white reflects 70 to 80% of the sun's heat), the presence (or not) of a radiant barrier, and the degree of shading of the roof surface.
    b. In other cases, the air flowing into the floor cavity originates directly or almost directly from outdoors, flowing into the house cavities from the soffit. Generally, the air entering the floor cavity directly from outdoors is much cooler (on a sunny afternoon) than air originating from within an attic space.
    c. A taller attic will experience greater thermal stratification (temperature gradient from low to high). All other variables being held constant, attic air entering the interstitial floor cavity from a tall attic will be cooler than air entering from a shallow attic.
3) Complimentary holes.
    a. In some cases, the floor cavity is open to attic or outdoor spaces only on one side. In this case there are no complimentary openings on the other side of the floor space to allow air to easily flow through the floor cavity.
    b. In other cases, there are openings on the opposite side or adjacent sides of the floor cavity which would provide a "complimentary-pathway" for wind-driven air flow to occur. The presence of complimentary holes greatly increases the opportunity for air to flow freely through the building cavities.
    c. Even in the absence of complimentary holes, thermal buoyancy can transfer significant amounts of air between the interstitial floor cavity and the hot attic.

4) The degree of air leakage to indoors.
    a. In most cases, the wind washing air flow is isolated from the indoor conditioned air. In a typical scenario, the wind blows into an attic, the hot attic air is pushed into the interstitial floor cavity, and then this hot air passes through a complimentary opening to outdoors without entering the conditioned space. Heat passes into the conditioned space primarily by means of conduction, through the ceiling of the first floor and through the floor of the second story space.
    b. In other cases, there are openings from the floor cavity to the conditioned space. Air that is forced into the floor cavity may not have a complimentary path for the air to exit from the floor cavity to outdoors, but it may have pathways from the floor cavity into the house. Test House 24, for example, has 80 "canned" light fixtures in the ceiling of the first floor. Air flowing from outdoors into the floor cavities can pass into the first floor conditioned space through the leaks in the canned lights, thus adding heat and humidity directly into the space.
5) The strength of the wind and the orientation of the residence to the prevailing winds. Houses that are located at an ocean-front location, for example, will experience stronger winds and greater exposure to those winds, while those further inland and located in forested areas will experience much less wind exposure. Those adjacent to inland water bodies or golf courses, for example, will also experience more intermediate-strength wind forces.
6) The orientation of the wind washing openings in relation to the prevailing winds impacts the magnitude of the wind washing air flow. If the opening of the floor cavity faces toward the prevailing breeze, then air can more readily flow through the interstitial cavities, especially if there are complimentary openings at the other end of the house.
7) The size of the soffit venting which allows wind-driven air movement into the attic space and floor cavity.
    a. If the attic space has very little venting, then the wind can push only a limited amount of air into the attic and floor cavity. Test House 14 (Young) has very little attic venting, which in large part explains why energy reduction was only about 3%.

These factors are combined into a matrix shown in Table 6. This table is a first-attempt to identify wind washing factors which impact the cooling energy use of a house and attribute values to those factors. Columns 2 – 7 are wind washing potential factors. Each of these columns (with one exception) ranges from 0.0 to 1.0, where a value of 0 means no wind washing potential exists and ranges up to a maximum value of 1.0 meaning it has the highest potential. Column 8 is the calculated Wind Washing Potential, the result of multiplying columns 2 – 7. The larger the number, the greater the wind washing potential.

The six repaired houses are shown as rows 2-7 in Table 6. Additionally, we have inserted two hypothetical houses (rows 8 and 9 in Table 6) with maximized wind washing risk factors, one with a tile roof (cooler) and one with an asphalt shingle roof (hotter). These houses can be considered as worst-case. The reader can see that the calculated Wind Washing Potential (WWP) ratings for the six repaired homes are, on average, far from having the characteristics of a worst-case house. WWP ratings in Table 6 vary by two orders of magnitude. Note also that the WWP values are highly correlated with the percent energy savings which can be seen in Table 7. Table

7 shows that higher WWP ratings correlate in a consistent manner with higher Annual Cooling Energy Savings.

Table 6 Matrix of factors that indicate the Wind Washing Potential to introduce heat into a house

	Size of WW holes	Complimentary holes (no complimentary holes = 0.3) **	Size of soffit venting	Entering air temperature	Wind driving force	Orientation of openings to prevailing wind	WWP rating
H16B	0.7	0.3	0.3	0.7	0.4	0.7	0.012
H10H	0.7	0.5	0.3	0.7	0.4	0.7	0.021
H11C	0.3	0.8	0.4	0.3	0.5	0.7	0.010
H14Y	0.5	0.3	0.1	0.9 (low attic ht.)	0.4	0.3	0.002
H7G	0.9	0.5	0.8	0.7	0.4	0.3	0.030
H8Hd	0.9	0.9	0.9	0.3 (tile)	0.7	0.9	0.138
Worst case w/tile roof	1.0	1.0	1.0	0.3 (norm. attic ht.)	1.0 (on beach)	1.0	0.300
Worst case w/asphalt shingles	1.0	1.0	1.0	0.8 (norm. attic ht.)	1.0 (on beach)	1.0	0.800

** Range from 0.3 to 1.0, because even in the absence of complimentary holes, stack effect still continues to operate to move air between the attic space and the interstitial floor cavity.

Table 7 Wind Wash Potential Estimates Compared to Predicted Annual Cooling Energy Savings

	WWP rating	Annual Cooling kWh Saved	Annual Cooling % Saved
H14Y	0.002	201	7.2
H11C	0.010	565	12.0
H16B	0.012	682	13.4
H10H	0.021	836	18.1
H7G	0.030	2232	33.1
H8Hd	0.138	2771	8.2
Worst case / shingle roof	0.800	NA	NA

14.0 Conclusions and Recommendations

Wind washing problems in homes were found in approximately 40% of the two-story homes examined. Of the first 16 homes tested, six were selected for monitoring and repair. Annual cooling energy savings was found to be quite substantial in these six homes, averaging 15.3%. Peak demand reduction was 12.6%. 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 on average exceed 15.3%. Based on monitored cooling energy savings and likely reductions in foam insulation application costs, energy savings could pay for the retrofit costs in approximately four years. Wind washing diagnosis and repair appears, therefore, to be a cost-effective energy conservation measure and therefore a potentially viable utility energy conservation program.

An initial effort has begun to create a wind washing potential (WWP) evaluation matrix. The evaluation criteria include such things as the size of holes from attic to interstitial floor cavity, complimentary holes, attic temperature, exposure to wind, and size of soffit venting. Further refinement of this WWP evaluation matrix will be helpful in the implementation of a utility retrofit incentive program, by helping to identify homes with the greatest savings potential.

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.

When we first proposed this research project, we expected to be able to find houses with wind washing problems fairly readily. As it turned out, the first five houses that we tested had relatively little wind washing potential and in general, over the first 16 homes, we did not find many strong candidates. However, in the last 16 homes, we have found seven that had substantial wind washing issues, and two of those five had greater wind washing problems than any of the six that are currently being repaired and monitored (they were not included in the Phase 1 repair and monitoring because they were found too late in the summer).

Therefore, we feel that it is important to continue on into Phase 2 as there is need for additional field testing and monitoring of repair impacts. This would expand the sample size from 32 to 48 homes, including repairing additional homes. From this larger sample size we would expect to obtain a clearer picture of how wide-spread the wind washing issue is, what various forms that wind washing takes, and what potential exists from repair of these wind washing problems.

The following issues should also be considered in past and future work:

- The Phase 1 effort has examined only summer energy and peak demand effects. There are reasons for studying winter-time impacts. Cold winter days (and nights) are sometimes accompanied by strong winds (consider Christmas day 1989 when record cold temperatures occurred concurrent with 30+ mph winds with rolling brown-outs throughout much of Florida; it could be that wind washing was a significant contributor to the record peak demands experienced by electric utilities on that date). Wind washing on hot summer afternoons is typically driven by winds of 4 to 6 mph. On cold winter days, by contrast, winds of 15 to 20 mph (and greater) are not uncommon.
- Wind washing occurs in a variety of construction types and architectural configurations. From the Phase 1 study, we have learned a great deal about the types of building features and failures which lead to wind washing. For example, we have tested two split level homes in the first 30 homes. After the first of these homes, we concluded that perhaps wind washing does not commonly occur in split-level homes. However, testing in a second split-level home found significant wind washing, and that home has in fact become one of our six monitoring and repair homes (with 12.0% annual cooling energy savings and 21.6% peak demand savings from repair).
- Further research can also help to answer questions regarding the best diagnostic methods and the best repair methods.
    - Currently we have been performing a number of tests that include blower door, pressure pan, tracer gas decay infiltration, return leak fraction, pressure mapping, and AC system performance test. We also make the following inspection and observations; inspection in attic, inspection behind soffits, and feeling of cold air spilling out of interstitial cavities. Some of the testing is, of course, for research purposes, to provide a fuller understanding of the phenomenon and may not be necessary from a purely diagnostic perspective. But also, we are learning what tests are most important toward understanding and correctly diagnosing wind washing potential.
    - In our Phase 1 research, we implemented repairs by means of open-cell foam application. In Phase 2, we would consider additional repair techniques which could be appropriate to the specific types of wind washing problems that are found.

APPENDIX A

CASE STUDIES

The following three case studies are presented in order to give the reader a broader and deeper understanding of the nature of the wind washing phenomenon is several homes.

H23 House with a High Wind Washing Potential

House General Description:
H23 was tested in August 2009 and has high wind washing potential. This home 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 would readily allow the sea breeze to flow through the building cavities. An exterior view of the attic section over the garage on the east side of home can be seen in Figures 146 and 147.

H23 is a two-story home built in 2002 with a total of 2,500 square feet of floor area served by a 4.0 ton Goodman heat pump on the first floor and a 2.0 ton Goodman heat pump on the second floor. The second floor total area is 933 ft2. All of the second story floor space is over conditioned first floor and has two areas where floor space is next to attic space. The attic space will be very hot during summer periods since the roof is covered by black asphalt shingles and receives limited shading.

2nd Story Floor Space and Kneewall Air leakage Inspection:
Upon inspection in the garage attic, we observed that the floor space between the first and second floors was open to garage attic space and open to west attic space over the master bedroom (Figures 148 and 149). Evidence of the hot attic air that has flowed into the interstitial floor cavity can be seen in Figures 150-153. These infrared images show evidence of the hot floor space behind the gypsum board wall surfaces around the stairway and balcony areas. The 1st story ceiling and 2nd story floor surfaces also have elevated temperatures; infrared imaging indicates floor space surfaces of about 3- 6 degrees F warmer then interior air temperature of 77^{o}F at midday. This heat comes from outdoor air and attic air that are being pushed into interstitial floor cavities, adding considerable load on the AC system.Rrefer to Figures 154 and 155 for floor layout and orientation of open floor space. We expect that repair of this uncontrolled air flow (which we term wind washing) will considerably reduce AC energy consumption. The homeowner has indicated willingness to participate in the Phase 2 monitoring and repair (2010).

Figure 134 East and north side of house with attic over garage adjacent to open floor cavities.

Figure 135 Infrared image of the house during midday after mostly sunny conditions all morning.

Figure 136 Open floor cavity area in the east attic. (view looking toward the west into the floor space)

Figure 137 Open floor cavity area in the west attic. (west side is to the left)

Figure 13850 Open floor cavity area in the east attic.

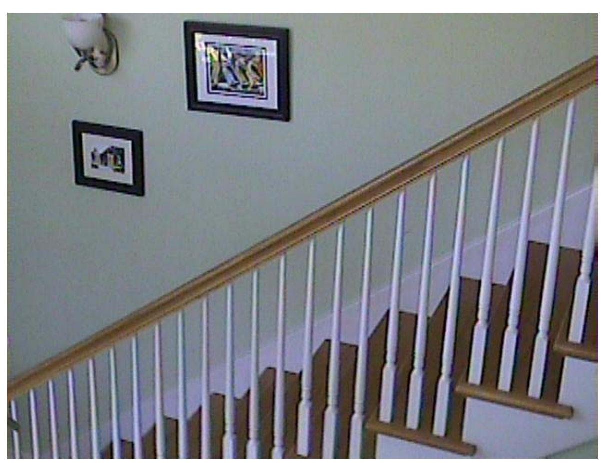


Figure 13951 Open floor cavity area in the east attic.

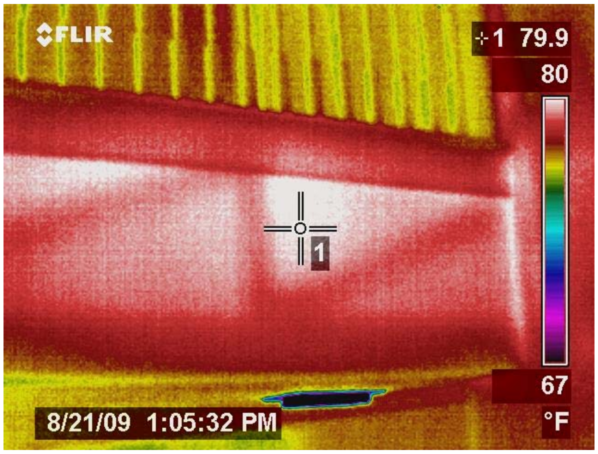


Figure 14052 Open floor cavity area in the east attic.

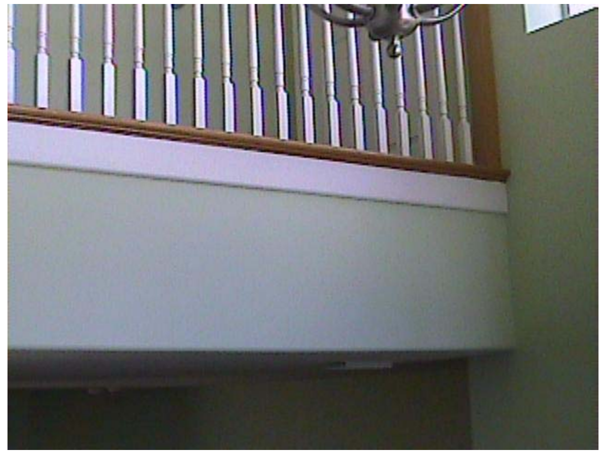


Figure 14153 Open floor cavity area in the east attic.

H23 floor plans of first and second floors shown below

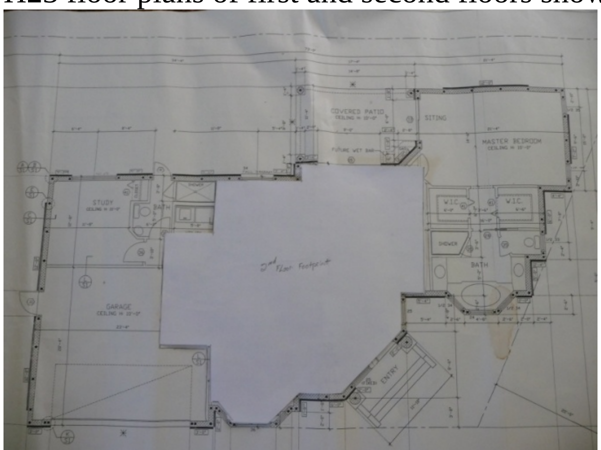


Figure 1424 First floor plan with 2nd floor plan footprint placed on top. Left side faces east.

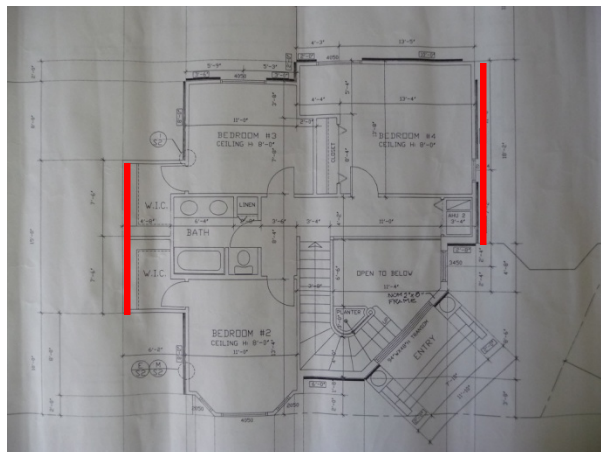


Figure 1435 Second floor plan. Red lines indicate areas of wind washing into floor space.

Windwashing is also an issue for some portions of kneewall on second floor. Figure 156 shows view upwards inside a wall section without insulation.

Figure 144**6** View looking up into open wall cavity from east attic shows no insulation in this wall next to walk-in closet.

House Tightness Tests

Blower Door Method

A house airtightness test (aka a blower door test) was performed according to ASTM E 779-87, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization", using a calibrated fan to draw air out of the house. When the house is tested at 50 pascals of pressure, the resulting measurement is called CFM50 (CFM = cubic feet per minute). This CFM50 number is a measure of the absolute airtightness at a standard test pressure. Increased building leakage results in a higher CFM50 value.

The CFM50 in this house was 2,854. For comparison to other houses, CFM50 is converted to ACH50 (air changes per hour at 50 pascals), which is a measurement of relative airtightness. This house has a relative airtightness of 7.45 ACH50. The average tightness for homes built after 2004 is about 6.1 ACH50, so this house leakage is about 22% leakier.

Tracer Gas Method

Another assessment of house air tightness was completed through test standard ASTM 741 “Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution”. This method makes a direct measurement of the rate of change of house air volume exchanged with outside air at the time of the test.

The air infiltration rate with the air handlers of both AC systems operating continuously was 0.45 air changes per hour. This means that 45% of the house air volume is replaced with outside air during a one hour period when both air handlers are operating.

Duct Leakage Diagnostics

Pressure Pan Method

With the house depressurized to -50 pascals with reference to outdoors by a blower door, pressure pan readings were taken at thirteen different air grill locations representative of various duct branches.

First floor system:

- The average of all supply readings was 0.3 pascals which indicate a modest amount of leakage. Readings greater than 2.0 pascals are generally considered worth repairing at today's energy costs.
- The average reading for the return side was 1.3 pascals.

Second floor system:

- The average pressure pan measurements of the second floor supply registers was 1.0 pascals. This is normal for newer homes and indicates a small to moderate amount of leakage.
- The average pressure pan measurement on the return side was 2.4 pascals.

Return Leak Fraction

During the tracer gas decay infiltration test, the gas analyzer measured the return leak fraction (RLF), the amount of the return air that originates from outside the conditioned space of the home. The RLF was determined by measuring the concentration of tracer gas entering the return and discharging from a supply register.

The RLF was measured on the both AC systems. The measured RLF on the first floor system was 8.1%. This means that about 8.1% of the total system airflow was being drawn from outdoors (or unconditioned space). The source of return leakage is primarily through air handler and support platform leakage in the garage. This test was not repeated on the second floor system.

H23 Summary

Based on our field testing, we found that H23 has two air conditioners that deliver far lower than expected capacity most likely due to a combination of things such as refrigerant charge, restricted return air flow from undersized duct and return duct leakage. The amount of supply duct leakage is about average for a home of this age and the first and second floor returns have less than average leakage.

The home has total of 5,178 in2 of 2nd story floor space open to attic space. The east side of home has about 3,856 in2 with 1,322 in2 of complimentary air pathway on the west side of home. Therefore, it has a very high wind washing potential into interstitial floor space. There was also a large area of east kneewall area with no visible insulation.

The R11 batts on all kneewall areas should be at least R19, but the practice of installing plywood over a 2x4 frame wall will only permit R11 insulation. This practice seemed to be sporadically used by a variety of builders in older and newer homes.

H19 House with Kneewall Wind Washing, Poor Cooling Efficiency, and a Hot Ceiling

House General Description:
H19 is a two-story home built in 2005 by a regional builder with a total of 3,024 square feet of floor area served by a 3.5 ton Bryant heat pump on the first floor and a 2.5 ton Bryant heat pump on the second floor. The second floor total area is 1312 ft2. All of the second story floor space is over conditioned first floor and has one area where floor space is next to attic space. The attic space will be very hot during summer periods since the roof is covered by brown asphalt shingles and receives no shading (Figure 157).

2nd Story Floor Space and Kneewall Air leakage Inspection:
This home only had 80 in2 of opening of second story floor space into attic areas. There were no other complimentary holes from floor space into other attic spaces opposite of the garage attic. Almost all the floor space was covered by plywood and house wrap (Figure 158). Most of the kneewall areas were also covered by plywood and house wrap except for a large area around the stairwell. This area only had R11 batt insulation that was sagging some with air space between the batt and interior drywall surface seen in Figures 159-160. The open air space between the batt and wall allow for a good potential of wind washing which can be seen in figures 161-162 that follow.

Figure 157 H19 Exterior view of home.

Figure 158 Portions of kneewall and floor space were covered with plywood and house wrap.

Figure 159 Stairway kneewall view from attic with batts away from wall.

Figure 160 Air space between R11 batts and wall allow hot air in contact with interior drywall.

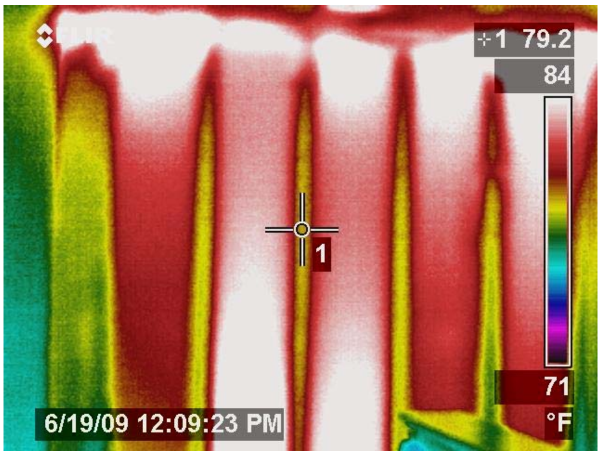


Figure 161 Infra red image of indoor kneewall at stairway

Figure 162 Photo of IR image to left.

Some ceiling areas also were not insulated well. Figures 163-166 below show very hot areas from inadequate insulation placement on 2nd floor ceiling.

Figure 163 Area of front left 2nd fl. bedroom with very hot ceiling due to inadequate insulation placement.

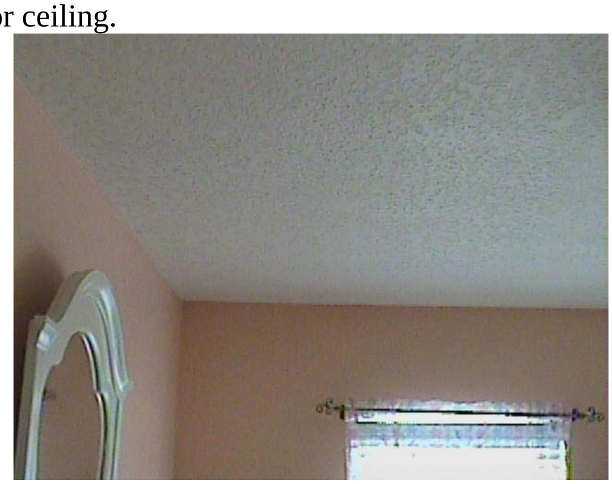


Figure 164 Photo of IR image to the left.

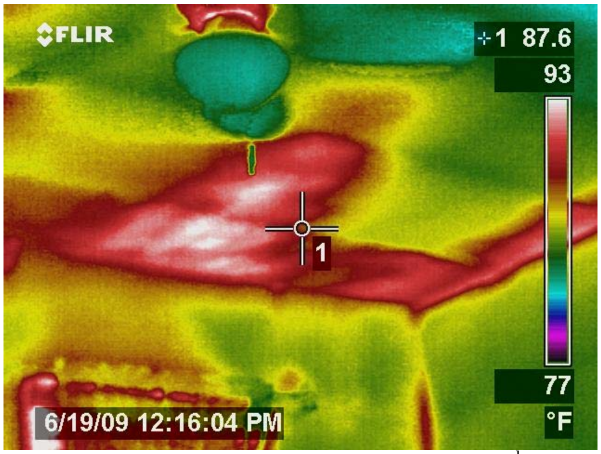


Figure 165 Another hot ceiling in front right 2nd floor. bedroom.

Figure 166 Photo of IR image to the left.

Cooling/Heating Systems:

H19 also has problems with delivered cooling capacity much lower than the nominal rating indicates. The house is served by two Bryant air conditioners zoned for 1st and 2nd floor separately. The first floor is served by air handling unit model number FX4BNF0420000 and outdoor unit model number BRYANT 633GJ042 (approx. 3.5 ton system cooling capacity). The second floor air handling unit model number is FX4BNF030 and the outdoor unit model number is 633GJ030-A (approx. 2.5 ton system cooling capacity).

Temperature and relative humidity were measured at the return grills and a supply register. The temperature differential from return to supply was 16.0 degrees F for the first floor system and only 13.5 F for the second floor system. The temperature differences of the first floor system are about 15% lower than what is expected and about 29% lower than expected for the second floor system. Airflow measurements were made at the air handlers using a Shortridge Flowhood.

The first floor system total air flow rate was 851 cubic feet per minute (cfm). We estimate that the airflow rate should be in the range of 1,120-1,400 cfm, therefore the airflow appears to be at least 24% low. The return plenum pressure is -49.7 pascals just at the bottom of the air handler which is about average. Based on our measurements; the delivered cooling output of the AC system is only 22,680 Btu/hr, or 46% lower than the 42,000 Btu/hr nominal expected output.

The most likely causes of lower than expected delivered cooling capacity is related to low air flow related to poor duct layout and improper refrigerant charge. We did not evaluate refrigerant charge, which can be done by a licensed contractor as part of a routine check-up service.

The second floor system flow rate was measured as 936 cfm at the air handler. We estimate that the airflow rate should be in the range of 800-1,000 cfm for a system with 2.5 tons of cooling capacity. The airflow of this system is about what is expected.

The calculated cooling output of the 2nd floor AC system is about 20,040 Btu/hr. This is about 33% lower than expected cooling delivered for a 2.5 ton system. The most likely cause of this poor delivered output is improper refrigerant charge as indicated by the very low temperature difference between the return and supply grills.

House Tightness Tests

Blower Door Method
A house airtightness test (aka a blower door test) was performed according to ASTM E 779-87, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization", using a calibrated fan to draw air out of the house. When the house is tested at 50 pascals of pressure, the resulting measurement is called CFM50 (CFM = cubic feet per minute). This CFM50 number is a measure of the absolute airtightness at a standard test pressure. Increased building leakage results in a higher CFM50 value.

The CFM50 in this house was 2,340. For comparison to other houses, CFM50 is converted to ACH50 (air changes per hour at 50 pascals), which is a measurement of relative airtightness. This house has a relative airtightness of 5.16 ACH50. The average tightness for homes built after 2004 is about 6.1 ACH50, so this house leakage is about 15% tighter.

Tracer Gas Method
Another assessment of house air tightness was completed through test standard ASTM 741 “Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution”. This method makes a direct measurement of the rate of change of house air volume exchanged with outside air at the time of the test.

The air infiltration rate with the air handlers of both AC systems operating continuously was 0.31 air changes per hour. This means that 31% of the house air volume is replaced with outside air during a one hour period when both air handlers are operating.

Duct Leakage Diagnostics

Pressure Pan Method
With the house depressurized to -50 pascals with reference to outdoors by a blower door, pressure pan readings were taken at thirteen different air grill locations representative of various duct branches.

First floor system:
- The average of all supply readings was 0.8 pascals which indicate a modest amount of leakage. Readings greater than 2.0 pascals are generally considered worth repairing at today’s energy costs.
- The average reading for the return side was 0.5 pascals.

Second floor system:
- The average pressure pan measurements of the second floor supply registers was 0.6 pascals. This is normal for newer homes and indicates a small to moderate amount of leakage.

- The average pressure pan measurement on the return side was 1.4 pascals.

Return Leak Fraction
During the tracer gas decay infiltration test, the gas analyzer measured the return leak fraction (RLF), the amount of the return air that originates from outside the conditioned space of the home. The RLF was determined by measuring the concentration of tracer gas entering the return and discharging from a supply register.

The RLF was measured on the both AC systems. The measured RLF on the first floor system was 2.5%. This means that about 2.5% of the total system airflow was being drawn from outdoors (or unconditioned space). The source of return leakage is primarily through air handler and support platform leakage in the garage. This test was also repeated on the second floor system and found the RLF to be 0.0%. Inspection of this return found that it was sealed well using duct mastic at seams and connections with an air handler located inside a second floor closet.

H19 Summary
Based on our field testing, we found that H19 has two air conditioners that are far from expected capacity most likely due to refrigerant charge. The amount of supply duct leakage is about average for a home of this age and the first and second floor returns have less than average leakage.

The home has only 80 in2 of 2^{nd} story floor space open to attic space on just one side of home with no complimentary air pathways. Therefore, it has very little wind washing potential into interstitial floor space. However, there was a large kneewall at the stairwell area where wind washing could occur around loose fitting R11 batts.

The R11 batts on all kneewall areas should be at least R19, but the practice of installing plywood over a 2x4 frame wall will only permit R11 insulation. This practice seemed to be sporadically used by a variety of builders in older and newer homes.

The last significant inefficiency discovered was related to inadequate insulation placement on the second floor ceiling above two bedrooms and over and attic hatch access. Approximately 25% of two bedrooms were barely insulated effectively. Ceiling surface temperatures were noted as high as 90 F.

H25 House with Large Open Floor Cavities and Restricted Return Air Flow

House General Description:
This home is a two-story home built in 2006 by a custom builder with a total of 2,973 square feet of floor area served by a 2.5 ton Bryant heat pump on the first floor and a 5 ton Bryant heat pump on the second floor. The second floor total area is 762 ft2. About 482 ft2 of second story floor space is 100% over conditioned first floor and has attic space surrounding three sides. The remaining 280 ft2 of second floor space area is under the bonus room floor located over the garage space and has attic space exposure on two sides. The attic space will be very hot during summer periods since the roof is covered by brown asphalt shingles and receives little shading (Figures 167-168).

Figure 167 Front northeast view of home.

Figure 168 Northwest corner of home shows bonus room over garage.

2^{nd} Story Floor Space Air Leakage Inspection:
There was one significant area where attic air could move into the main 2^{nd} story floor space creating a good potential for wind washing. The entire span of the north face of the floor space is open and can be seen in Figure 169. This is an area of approximately 20 ft^2. The east and west sides of this floor area are mostly blocked by batt insulation with some gaps visible. The floor space under the bonus room consists of solid floor joists running east to west with the open ends in attic blocked by R11 batts in most cases (Figure 170). There is also batt insulation inside the bonus room floor cavities.

Figures 171 and 172 show an infra-red image taken inside the attic space. Both images show cool floor space air displaced onto lower attic floor areas causing cooling of unconditioned attic. The attic was not nearly as hot as it is during summer weather, but the roof deck of an east exposed roof section shows interior roof temperature of about 93 degrees F in Figure 172.

Figure 169 North attic section with open 2^{nd} story floor space. Insulation batts are located inside the floor space on the ceiling of the first floor.

Figure 170 Open section of bonus room floor space near garage attic access.

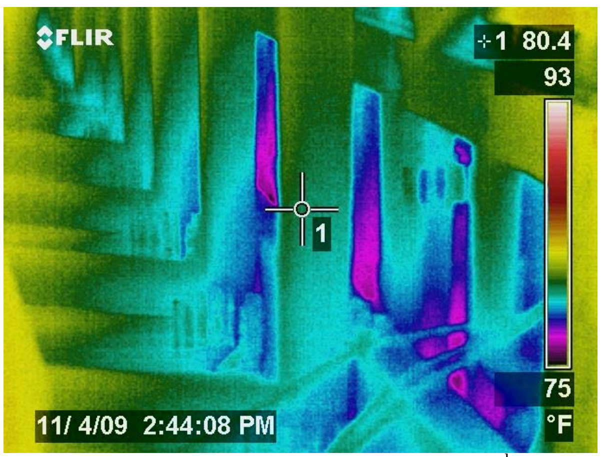


Figure 171 IR image of open floor space of 2^{nd} story in north facing attic section. Cool floor space air spillage resulting in cooling of unconditioned materials. Indoor temperature 75 deg °F.

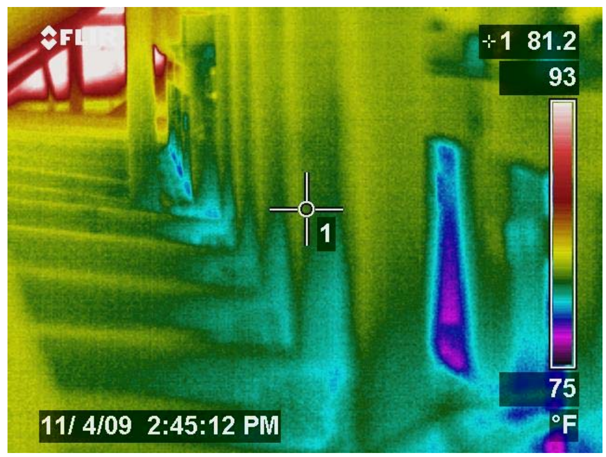


Figure 172 IR image of open floor space with east hip roof section in background shows roof deck only 93 deg. F. North attic section about 89 deg. °F.

Zone Pressures:

Using digital manometers, pressure differentials were measured in the house with the HVAC systems in various modes of operation. The basic approach is to characterize pressures in the building and various zones of the building with air handlers turned on, and with various doors open and closed. The primary objective is to characterize the effect of the air moving equipment on building and zone pressures. This is because negative pressure can draw pollutants from the soil, back draft vented combustion equipment, draw humid outdoor air into building cavities(such as floor space and walls), increase heating and cooling loads, and cause excessive ventilation rates.

Florida Mechanical Code requires that pressure differentials across closed interior doors be no greater than 2.5 pascals for houses permitted for construction after March 2002. The individual zones of the house were measured with respect to the main body with interior doors closed one at a time while both air handlers were on.

All rooms with closeable doors, except the 1st floor office, had pressures within the 2.5 pascals limit. The pressure differential in the office with reference to the central area was - 3.0 pascals. The negative value means that the return in this room pulls more air out of the room than the supply pushes into it. The differential could be brought closer to the 2.5 pascals limit by a few methods.

- The easiest is to first make sure the supply diffuser is 100% open. Open the supply fully if it is not already.
- Increase the opening of the large main return over stairway seen in Figure 173 (see recommendations section.)
- The next easiest is to cover a small portion of the office return until a neutral pressure across the doorway is measured.
- Increase the undercut of the door by another 1/4 to 3/8 inches.

Cooling/Heating Systems:
The house is served by two Bryant air conditioners zoned for 1st and 2nd floor separately. The first floor is served by air handling unit model number FY4ANB060000 and outdoor unit model number 213ANA060 (approx. 5 ton system cooling capacity). The second floor air handling unit model number is FY4ANF030000 and the outdoor unit model number is 213ANA030 (approx. 2.5 ton system cooling capacity).

Temperature and relative humidity were measured at the return grills and a supply register. The temperature differential from return to supply was 17.8 degrees F for the first floor system and 18.8 F for the second floor system. These temperature differences are near what is expected. A temperature drop around 18F is typical. Airflow measurements were made at the air handlers using an Energy Conservatory TrueFlow device.

The first floor system air flow rate was 1,466 cubic feet per minute (cfm). We estimate that the airflow rate should be in the range of 1,700-2,000 cfm, therefore the airflow appears to be at least 14% low. The return plenum pressure is -162 pascals just at the bottom of the air handler which is about 4 times greater than average. It indicates a flow restriction between the grills and coil. It appears that the higher static pressure is mostly related to undersized filter-backed return grill and perhaps somewhat to a very long run of 20" diameter flex duct main from the return plenum to the main 1st floor return. We estimate the total filter area to be about 700 in^2. This is about 30% less than 1,000 in^2 of total filter area recommended based on 2 cfm / in^2 of filter. Based on our measurements; the delivered cooling output of the AC system is approximately 45,840 Btu/hr, or 24% lower than the 60,000 Btu/hr nominal expected output.

There are a few factors that can diminish the delivered cooling capacity.

- Low airflow can be due to dirty filters, coils and blower fan blades or high frictional losses related to poor duct layout. Dirty components do not appear to be the cause for low airflow. In this case, the most likely cause for low airflow is related to an undersized main return grill in the central space (see Figure 173 below and Recommendations section on possible solution).

- Improper refrigerant charge will affect capacity. We did not evaluate refrigerant charge and do not suspect a charge problem, which can be done by a licensed contractor as part of a routine check-up service.
- Even if the airflow and refrigerant are within manufacturers' specifications, duct leakage on the return side can pull hot air into the returning air stream greatly adding large heat loads that diminish the cooling capacity of the system. Air leaking into return duct at the time of our test was mild with outdoor conditions at 80 F and 66% RH. However, A return leak as small as 5% that pulls in attic air at 120F will decrease the effective energy efficiency ratio (EER) by about 18%! If most the return leakage is from the garage (which will not be as hot as an attic) it could still lower the capacity by about 15% under peak summer conditions.

Figure 173 Main return for first floor with undersized opening into return junction. View inside box shows return ducts (from left to right) 20" diam. flex to main plenum, office, and master bedroom.

The second floor system flow rate was measured as 940 cfm at the air handler. We estimate that the airflow rate should be in the range of 680-800 cfm for a system with 2 tons of cooling capacity. The airflow of this system is about 18% higher than expected.

The calculated cooling output of the 2^{nd} floor AC system is about 30,000 Btu/hr. This is exactly the expected cooling delivered for a 2 ton system.

House Tightness Tests

Blower Door Method
A house airtightness test (aka a blower door test) was performed according to ASTM E 779-87, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization", using a calibrated fan to draw air out of the house. When the house is tested at 50 pascals of pressure, the resulting measurement is called CFM50 (CFM = cubic feet per minute). This CFM50 number is a measure of the absolute airtightness at a standard test pressure. Increased building leakage results in a higher CFM50 value.

The CFM50 in this house was 3,422. For comparison to other houses, CFM50 is converted to ACH50 (air changes per hour at 50 pascals), which is a measurement of relative airtightness. Your house has a relative airtightness of 7.4 ACH50. The average tightness for homes built after 2004 is about 6.1 ACH50, so this house leakage is about 21% leakier.

Tracer Gas Method
Another assessment of house air tightness was completed through test standard ASTM 741 "Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution". This method makes a direct measurement of the rate of change of house air volume exchanged with outside air at the time of the test.

The air infiltration rate with the air handlers of both AC systems operating continuously was 0.541 air changes per hour. This means that 54% of the house air volume is replaced with outside air during a one hour period when both air handlers are operating.

Air can enter a house by means of natural infiltration (driven by wind and temperature differential forces) and by means of mechanical infiltration (driven by the heating, cooling, and ventilation mechanical systems). Natural infiltration comes into the house from outside through a variety of pathways. In this house, air enters through some limited window and door leakage, but more so through wall (outlet and wire and plumbing at top of wall into attic) and ceiling penetrations (duct penetrations and recessed light fixtures). Air also enters through duct leakage under natural conditions when the air conditioner is off.

Mechanically induced infiltration is being driven by duct leakage. Duct leakage on the return side pulls air from unconditioned space into the return ducts or return plenums and distributes it to the conditioned space.

Duct Leakage Diagnostics

Pressure Pan Method
With the house depressurized to -50 pascals with reference to outdoors by a blower door, pressure pan readings were taken at thirteen different air grill locations representative of various duct branches.

First floor system:

- Measurements were taken at nine supply registers on the first floor. The average of all readings was 2.0 pascals which indicate a modest amount of leakage. Readings greater than 2.0 pascals are generally considered worth repairing at today's energy costs.

  First floor supply grills with pressure pan values greater than 2.0 pascals

	Bathroom	MBR bath	MBR toilet	Utility room
Pressure Pan	5.4	2.4	2.6	3.5

- The average reading for the return side was 0.7 pascals. This is about average for returns in newer homes. The leakage is partly through small leakage areas where flex duct connects to ductboard when no mastic is used (Figure 174). Figure 175 below shows what mastic looks like (grey sealant) when used on duct connections inside the second story support plenum box. There is also leakage in the air handler and possibly in the support plenum box under the air handler (Figure 176). Note that air leakage from a garage can introduce air contaminants from the garage, and it is important to never operate any gas combustion devices (such as car, generator, and cooking grill) for this reason.

Second floor system:
- The average pressure pan measurements of the second floor supply registers was 1.2 pascals. This is normal for newer homes and indicates a small to moderate amount of leakage.
- The average pressure pan measurement on the return side was 1.0 pascals.

Figure 174 Flex duct connection with no mastic on first floor return plenum. Flexduct is mechanically fastened, but not airtight.

Figure 175 Inside of 2nd story support platform sealed well with mastic on seams and duct connections.

Return Leak Fraction
During the tracer gas decay infiltration test, the gas analyzer measured the return leak fraction (RLF), the amount of the return air that originates from outside the conditioned space of the home. The RLF was determined by measuring the concentration of tracer gas entering the return and discharging from a supply register.

The RLF was measured on the both AC systems. The measured RLF on the first floor system was 8.5%. This means that about 8.5% of the total system airflow was being drawn from outdoors (or unconditioned space). The source of return leakage has been previously discussed. This test was also repeated on the second floor system and found the RLF to be 0.8%. Inspection of this return found that it was sealed well using duct mastic at seams and connections as seen in Figure 175.

Figure 176 Air handler in garage has typical panel leakage at seams and penetrations.

Recommendations

- Place an air and thermal barrier over the open floor space area in the north attic section (Figure 169). This can be done by simply using rigid board cut to fill in the opening within the same plane as the attic kneewall. Then add batt insulation over this for a total insulation value of at least R19. Another method is to have a contractor familiar with expanding spray foam come to foam insulate the open area on the north side and the east and west sides of the main 2nd story floor space. Have the contractor also spray the exposed ends of the bonus room floor cavity inside both attic sections on east and west sides of this room.
- Increase the opening from the main return grill into the return junction box. Remove the filter, cut the ductboard out around the existing open oval shape to increase the hole-size so that only a perimeter of about 2” is left (Figure 173). This will allow more air to be pulled from the central larger filter, and decrease some of the return pulled from master bed room and office space. It may be enough that the closed door pressure in office will become neutral to just slightly positive and eliminate the need to address previous discussed methods of pressure neutralization for the office in the Zonal Pressures section.
- Tape or putty all air handler panel seams and penetrations on first floor system in garage (Figure 176). The return leakage from the garage can draw dangerous fumes into the house. Note that air leakage from a garage can introduce air contaminants (including life-threatening carbon monoxide (CO)) from the garage.
- Consider arranging for FPL to do a duct system airtightness test to obtain a repair rebate. Have duct leaks repaired. The first floor system should be a higher priority than the second floor system.