Envelope Thermal Failures Due to Wind Washing in Two-Story Homes

James B. Cummings and Charles R. Withers, Jr.
Florida Solar Energy Center

ABSTRACT

This paper examines heat loss/heat gain mechanisms which occur in many two-story residences during hot and humid weather, when air coming either from attic spaces located above first-story sections of the house or air directly from outdoors, can flow into floor cavities positioned between the first and second stories of the house. Mechanisms which contribute to energy losses are examined and consideration is given to wind-driven, thermal buoyancy-driven, and mechanically-driven air transport. Heat and moisture flow into floor cavities during hot summer afternoons and cold winter mornings in particular, are discussed in the context of factors such as roof type/color, radiant barriers, prevailing wind direction, complimentary holes, leak pathways to indoors, and attic venting that affect attic temperature and sensible and latent heat transfer into the conditioned space. Field test data from 32 homes (including blower door, duct leakage, return leak fraction, tracer gas decay air infiltration, pressure mapping, and AC performance testing) and measured energy savings from repair in 6 homes are provided. Case studies that are presented here exemplify both the repair techniques and characterize the factors which cause wind washing. Furthermore this paper examines the relationship between wind washing and duct leakage.

BACKGROUND AND FIELD TESTING FINDINGS

Wind washing is a general term referring to diminished thermal control in buildings caused by air movement over or through thermal barriers. This paper focuses on a specific type of wind washing where wind (or other forces) can push exterior air from an attic space into the floor cavity between first and second stories of a home through ineffective (or missing) air barriers separating attic space from the floor cavity (Figure 1). In some cases, air can also be transported between the floor cavity and conditioned spaces above or below that floor cavity, especially through canned lights. Air transport between the attic and floor cavity can also be driven by thermal buoyancy, especially in cases where the wind is light or there are no complimentary pathways on the far side of the floor cavity. In some cases, mechanically-induced forces can drive air flow into and out of floor cavities.

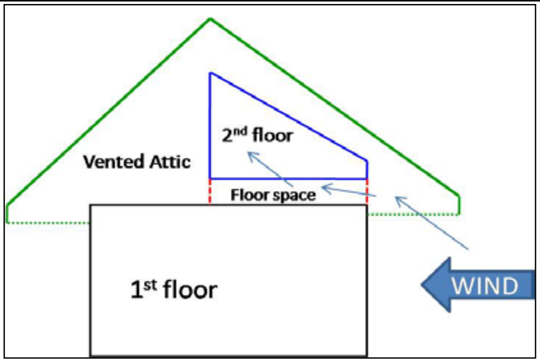

Figure 1 Wind-driven attic air is pushed into the space between floors. *(Withers)*

Field testing was performed in 2009 in 32 homes in central Florida. The homes were selected with pre-screening, namely by looking for building characteristics associated with wind washing potential (e.g., attic spaces that exist over first floor sections of the house – such as a garage – and are adjacent to conditioned portions of the second floor of the house). In some cases, the research team was able to determine from homeowners that some portion of the floor cavity was, in fact, open to an attic space.

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

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

During the tracer gas decay test, a return leak fraction (RLF) test with the AHU(s) operating was also performed. Concentrations are measured at the return grill(s) and at a supply register. RLF is calculated using the equation:

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

where A = tracer gas concentration entering the return grill, B = supply tracer gas concentration, and C = tracer gas concentration of the air entering the return duct leak site[1]. An AC system performance test was performed by measuring delta-enthalpy (based on supply and return temperature and relative humidity) and the AC system air flow rate measured with a flow hood (at the return) or calibrated flow plate device (internal to the air handler unit).

Field testing also included fairly detailed inspections of attic spaces, floor cavities, and other locations to identify the potential for wind washing. Infrared (IR) scans were used to identify thermal characteristics of various building cavities associated with wind washing. Since infrared thermography works best when the temperature difference between conditioned and unconditioned spaces is large, IR scans have the potential to provide useful information only within a specific range of weather conditions.

During the cooling season, infrared scanning was typically done during early-to-mid afternoon when the sun had heated the attic substantially. During winter, scans were performed as early as practically possible while the attic was still cool. While effectiveness of thermography is limited by mild or cloudy weather, high mass construction, reflective roofing, or radiant barriers, it is very useful in a variety of conditions. Figures 2 and 3 provide a good illustration of a strong thermal signal resulting from wind washing when the outdoor temperature was about 90^{o}F. In Figure 2, specifically, the thermal signature shows where hot air (from an attic space located above a one-story portion of the house) has been able to migrate throughout the interstitial floor cavity, between the first and second floors of the house. This pocket of hot attic air has been pushed into the inter-floor cavity where it delivers considerable heat, by means of conduction, convection, and radiation to the ceiling of the first floor, the floor of the second story, and a portion of the stairwell wall.

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[1] Cummings, J.B., "Tracer Gas as a Practical Field Diagnostic Tool for Assessing Duct System Leaks," Proceedings of 6th Annual Symposium on Improving Building Systems in Hot and Humid Climates, Dallas TX, October 1989. (FSEC-PF-195-90)

Figure 2 Infrared image at stairwell shows that floor space behind wall is very warm.
(Image credit C. Withers)

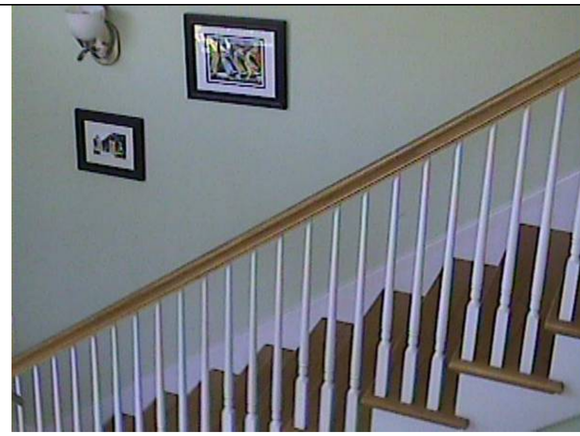

Figure 3 Visual image of stairwell. The location of the floor cavity can be referenced to the location of the pictures. *(Withers)*

Figures 4 through 6 illustrate a second form of wind washing. In this instance, hot air from an attic space behind the stairwell wallboard migrates behind insulation batts and against the wallboard. This air flow can occur when insulation batts are not held tightly against the wallboard. Figure 6 shows that the batts have not been properly positioned to maintain contact with the wallboard. As the hot attic air comes into contact with the cool wallboard, it cools, becomes denser, and falls toward the attic floor, only to be replaced by additional hot attic air. This convective loop, driven by temperature differential and air density differentials, continues throughout the day and peaks during the hottest hours of the day. This particular form of wind washing (in this instance driven primarily by convective looping), where the insulation is not tightly held against the wallboard, was found to produce a significant energy flow effect in only one of the 32 field-tested homes.

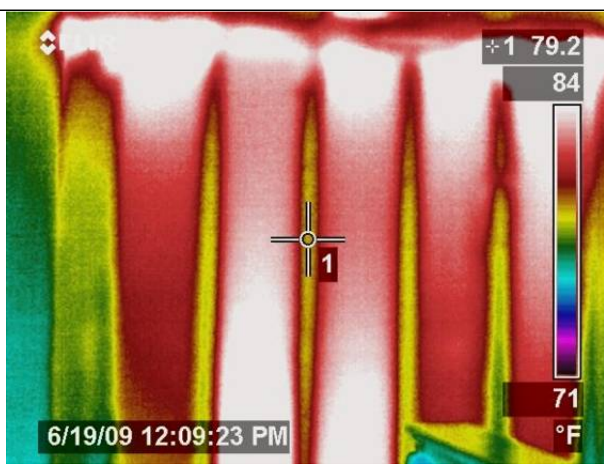

Figure 4 IR image of wood frame wall adjacent to unconditioned space. *(Withers)*

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


Figure 6 Insulation batts are not consistently in close contact with the wallboard, allowing considerable convective heat exchange between attic air and wallboard, as shown in Figure 4. *(Withers)*

Wind Washing Monitoring and Repairs

Repairs were performed in 6 of the 32 field-tested homes. All repairs involved sealing of the floor cavity-to-attic interface. No repairs involving repositioning of insulation batts, so that they would adhere closely to the attic wall, were implemented (as illustrated in Figures 4 - 6), because it was determined that the energy savings in this situation would be relatively small. These six repair homes were monitored for representative summer periods to characterize AC energy use and space conditions before and after repairs. Analysis was performed to characterize cooling energy and peak demand savings. No energy use data was available for the winter season.

Monitoring consisted of the following types of data.

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

Energy and Peak Demand Savings Analysis Method

All six central Florida homes were repaired in the same month (September 2009) and in all cases, open-cell foam was applied to seal openings of the between-stories floor cavities (Figures 7 and 8). In two homes, duct leak repairs were also separately implemented. The researchers decided to correct these large (return) duct leaks because they represented a large energy waste factor which could substantially impact the savings achieved by wind washing repairs. An energy monitoring period occurred before the duct repair and another monitoring period occurred before the wind washing repair. Because of this, cooling energy use was characterized in these two homes for three time periods; 1) before any repairs, 2) after duct repairs, and 3) after wind washing repairs.

Figure 7 Photo of IR image above. The floor cavity at the bottom of the wall is open to garage attic. *(Withers)*

Figure 8 Technician finishes up kneewall and floor cavity insulation/air tightening. *(Ian LaHiff)*

Energy savings analysis was performed for each home in the following manner. A linear regression (best-fit analysis) was used to develop equations 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 (weather normalization; Figure 9). The linear equations from each period were then used with 10 year composite typical meteorological year (TMY2) data representing 4 major cities in Florida. The TMY2 data has hourly outdoor dry bulb temperature for each day of the year representing a geographical weighting of Florida Power and Light's (FPL) residential consumers. Using the TMY data, daily energy use, for the pre-repair period and the post-repair period was calculated based on the daily temperature difference between indoors and outdoors. On cold days, the calculation results in negative cooling energy values, which have been excluded from the annual cooling energy consumption. Cooling energy savings for each day of the year is summed to yield annual energy savings.

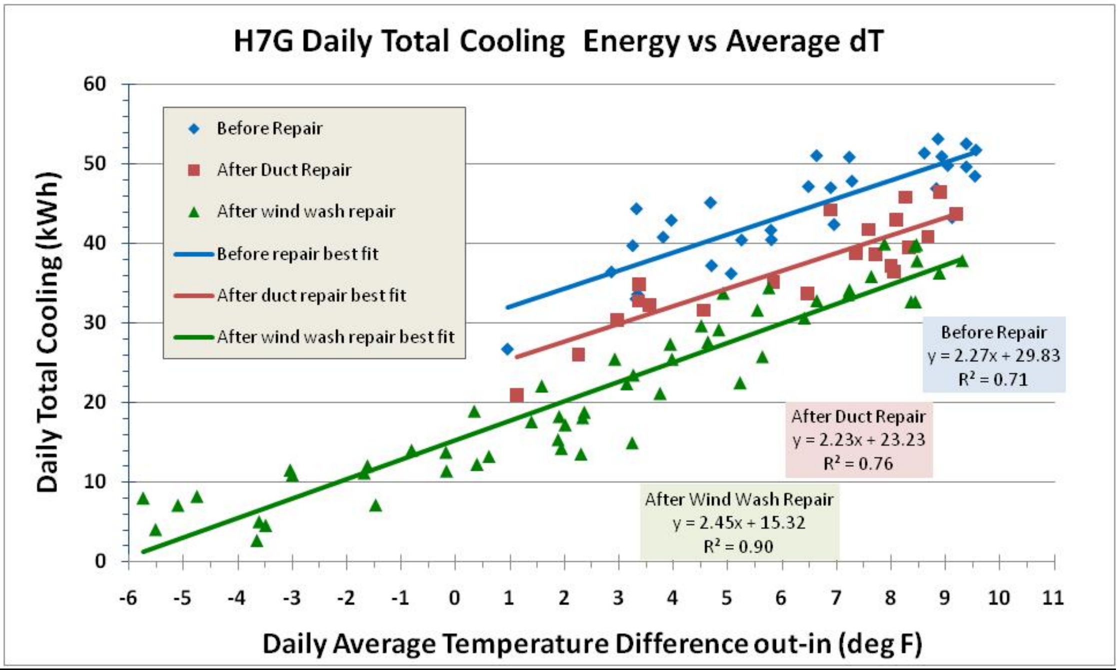

Figure 9 Cooling energy use versus measured temperature difference between outdoors and indoors before pre-repair, after duct repair, and after wind washing repair.

To perform the peak demand analysis, five to ten of the hottest monitored days were chosen with comparable pre-repair and post-repair outdoor and indoor temperatures. Only the hours from 3 PM to 8 PM were used for this regression analysis. Weather normalization was achieved as follows; hourly energy use was plotted against the hourly average delta-T (outdoor temperature minus indoor temperature) for those data for the hours of 3 PM to 8 PM on those hot summer days. 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 hottest TMY day (from 3 PM to 6 PM) of the year. The peak demand (kW) was calculated for the hours ending at 3, 4, 5 and 6 PM, and the average for this four-hour period was used to represent the peak. The peak demand reduction was obtained by subtracting the calculated peak from the pre-repair equation from the calculated peak from the post-repair equation for that hot TMY day.

Cooling Season Energy Savings

Annual cooling energy savings were found to be quite substantial in these six homes, averaging 15.3% or $140 per house. Energy savings resulting from wind wash repairs at each house are summarized in Table 1. Duct leak repairs (all leaks were on the return side) in two homes produced estimated average annual cooling savings of 17.1% or $144 (Table 2). Cooling season peak demand reduction was 12.6% or 0.52 kW on average (summarized in Table 3). Based on monitored cooling energy savings, cooling energy savings will pay for the retrofit costs in approximately four to five years. Diagnosis and repair of this form of wind washing appears, therefore, to be a cost-effective energy conservation measure and therefore a potentially viable utility (or other entity) energy conservation program.

Table 1 Annual cooling energy savings from wind washing repair, based on weather normalization and TMY3 data.

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

Table 2 Annual cooling energy savings from duct repair in two homes, based on weather normalization and TMY3 data.

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

Table 3 Peak demand savings from wind washing repair in six homes, based on weather normalization and TMY3 August data.

	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%***

It should be understood that this project evaluated only cooling season impacts of wind washing. Homes will, of course, experience seasonal and peak heating energy savings from wind washing repair that will be in addition to the cooling savings shown for each house in Tables 1 through 3. It is likely that heating energy and peak demand (kW) reductions in central Florida will be greater (on a percentage basis) than cooling season impacts since wind speeds and temperature differentials between indoors and outdoors are often greater during cold weather than during summer periods and because electricity is a common source of space heating in central Florida.

DISCUSSION OF WIND WASHING HEAT TRANSFER MECHANISMS

Wind washing transfers heat from unconditioned air that may originate from outdoors or from an attic space into the conditioned space, during the cooling season (Figure 10). During the heating season, heat flow is reversed, with heat being transported from indoors to cold air penetrating into the house (Figure 11). (For purposes of simplicity and clarity, the discussions that follow will examine heat transfer that occurs during hot (and humid) summer weather.)

Figure 10 An infrared image taken on a summer day illustrates wind washing heat transfer through wall and (tile) floor. Some floor surface temperatures are as much as 9°F warmer than the room air temperature.

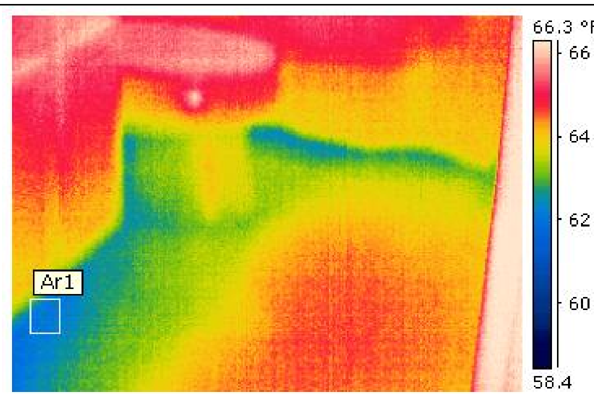

Figure 11 An infrared image taken on a winter day illustrates wind washing heat transfer through the floor. Some floor surface temperatures are as much as 8°F colder than the room air temperature in house H7G.

In a typical scenario, the process starts with wind blowing into the eave vents of a house. This attic ventilation air is then transported into an attic space located above a first-floor portion of the house. In the attic, the air is heated by various mechanisms related to the sun shining on the roof surface. The degree of heating depends upon a number of variables including the solar absorptivity of the roof surface, shading of the roof surface, the degree of contact between shingles and roof decking material, the presence or absence of insulation or a radiant barrier on the bottom of the roof decking, and the level of ventilation within the attic. The hot attic air then flows into the interstitial floor cavities of the house as a result of convection or wind-induced pressures. The degree of penetration depends upon the strength and direction of the wind, the size of the eave vent openings, the size of openings between the attic space and the interstitial floor cavities, and the extent to which there are complimentary openings on the far side of the floor cavity.

Figure 12 Shallow attic at front of house H11C. Oval vents allow air from outside into attic. No peak or off-peak vents were used.

Figure 13 View inside shallow attic eave; vents are to the right and floor cavities are to the left. Attic ventilation air could flow from right to left, under the tar paper, over the batts, and into the floor cavities.

In some cases, the attic space is small and the eave vents are in close proximity to the floor cavity (typically inaccessible to people), so the air is heated to a lesser degree (as in Figures 12 and 13). Figure 13 is an image obtained by moving into the attic space over the garage at the front of the house. The exterior of this area is seen in Figure 12. In other cases, there is no attic space at all, in which case the temperature of the entering air is similar to that outdoors (Figures 14 and 15). This can be seen in Figure 14, where the second story is cantilevered over the first floor, and the vents enter directly into the floor cavities without passing through an attic space.

Figure 14 Cantilever floor has eave vents underneath (elongated ovals) which open directly into the floor cavities, as shown in Figure 15. This means that the floor cavities are open to outdoors.	Figure 15 View inside one floor cavity which is open to one of the vents shown in Figure 14 (looking toward vented eave). Air from vent (below batt) bypasses the batt and flows into the floor cavity.

An interesting variation (which has been observed in two houses) involves the location of the air conditioning system outdoor units under the eaves. When the AC system(s) operate(s), the discharge air flow of the outdoor units blows upward into the eave soffits, forcing incrementally heated air into the attic space (this air may be 10^{o}F warmer than the outdoor air). This "mechanically forced wind" both enhances the driving force and elevates the temperature of air being pushed into the attic and the interstitial floor cavities.

Once this air has penetrated into the interstitial cavities of the house (e.g., the inter-story floor cavity), it has now bypassed the air and thermal boundaries of the building. At this point, it can readily transfer heat into the house by a combination of a number of mechanisms; 1) conduction, 2) air transport (convection), and 3) radiation.

Wind Washing Air Flow Rates

The magnitude of wind washing energy impacts depends in large part upon the rate at which wind washing air flow can penetrate into the interstitial cavities of the building. This wind washing air flow rate is determined by a number of variables. First is the strength of wind and the orientation of the house (specifically the wind washing openings) to the prevailing wind. Second is the size of the soffit vent openings. Larger eave vent openings allow a greater amount of air flow into the attic space. Third is the size of the openings from the attic space to the floor cavity. Fourth, and last, is the presence and size of complementary openings. These complementary openings could be on the far side of the interstitial floor cavity or they could be leaks from the floor cavity to indoors, or some combination of the two.

Heat Transfer Rates

Conduction can occur downward through the ceiling of the first floor, upward through the floor of the second story, or laterally through walls of an adjacent stairwell or other building space. Since the hot air that has penetrated the floor cavity has already bypassed the thermal boundary of the building, the only barrier to conductive heat flow is the gypsum board of the first floor ceiling (or adjacent walls) and the floor materials of the second story floor. The R-value (units here are hr-ft^2-^{o}F/Btu) of the ceiling is approximately 1.7, consisting of 0.45 for the ½" gypsum board and 0.61 for an air film on the top and bottom of the gypsum board (0.45 + 0.61 +0.61 = 1.67). The R-value of the floor (assuming carpeting) is approximately 5.4, consisting of 0.77

for the 5/8th inch plywood, 3.31 for carpet and pad, and 0.61 for an air film on each side of the floor assembly (0.77 + 3.31+ 0.61 +0.61 = 5.30). A tile, linoleum, or wood floor would have an R-value about half as great. Adjacent wall R-value is approximately 1.8, consisting of 0.45 for the ½" gypsum board and 0.68 for an air film on each side of the gypsum board (0.45 + 0.68 +0.68 = 1.81).

The rate of heat transfer depends upon the temperature of the air penetrating the interstitial cavities, the rate of air entry, and the surface area of the interstitial floor cavity. If we assume that the air penetrating the cavity has a 24-hour average temperature of 90°F, and that the average temperature within the cavity is 84°F, that the indoor temperature is 76°F, that the ceiling and floor surface areas are 800 ft^2 each, and that the adjacent wall surface is 110 ft^2, then the total calculated heat penetration into the space is 5464 Btu/hr (Table 4). If we assume that the air conditioning system is operating at a sensible heat ratio (SHR) of 0.75, then the heat entering the space represents approximately 0.6 ton of cooling load operating continuously throughout the cooling season. If the cooling season is considered to be 150 days in length, then the added cooling load is 21600 ton-hours. Assuming a SEER rating of 10 and electricity cost of $0.10/kWh, then the added cooling energy cost of this wind washing phenomenon would be about $216 per year.

Table 4 Calculation of typical conductive heat transfer rate from interstitial floor cavity to conditioned space, assuming 8°F daily average delta-temperature.

	Surface area (ft^2)	R-value (hr-ft^2-°F/Btu)	Heat transfer rate (Btu/hr)
Ceiling	800	1.67	3832
Floor	800	5.30	1146
Wall	110	1.81	486
Total			5464

Convection is a complementary heat transfer mechanism that occurs within the wind washing phenomena. It can increase the heat transfer rate as air flows across the surfaces within the interstitial floor cavity, thereby enhancing the rate of conduction across various surfaces of the floor cavity.

Radiation is also a complementary heat transfer mechanism. It allows radiative transfer of heat from surfaces that are warmer to surfaces that are cooler. Warmth that is delivered by conduction and convection to the ceiling of the first floor and the floor of the second story can then be transferred by radiative exchange to cooler surfaces within view of the warm ceiling and floor. This radiative exchange also causes house occupants to experience (perceive) a warmer or hotter indoor environment, as these warm surfaces exchange radiation with the individual's body. In many circumstances, the radiant temperature of a space represents 50% or more of the effective temperature sensed by the human body.[2]

Water Vapor Transport

The air penetrating the house interstitial cavities often has significantly elevated vapor pressures or dew point temperatures (often 70^{o}F and higher). The water vapor can enter into the conditioned space by means of vapor diffusion through the ceiling and floor materials, or by air transport into the conditioned space through pathways from the interstitial cavity to the room.

Vapor diffusion through building materials typically represents a relatively small transport rate relative to air transported moisture (water vapor). Consider the following example based on one of the six repair homes where the average indoor space conditions were 78^{o}F drybulb and 58^{o}F dew point. The average conditions inside the floor cavities were 84^{o}F drybulb and 67^{o}F dew point. The resulting vapor pressure difference was 0.181 In HG (612 Pa). Vapor permeability through the floor assembly has been calculated. From these numbers, the rate of vapor diffusion through the plywood floor and carpet into the upstairs conditioned space is calculated to be 0.181 gr (0.0117 g) per hour per ft^2. For an 800 ft^2 floor area, the calculated moisture entry rate would be 3475 gr (224.6 g) (0.495 lb) of water vapor transport per day. This represents a (latent) space cooling load of approximately 520 Btu/day.

Vapor diffusion would also occur downward through the ceiling of the first floor which is simply drywall finished with latex paint. Assuming a permeability of 8 perms across this plane, the vapor transfer rate is calculated to be 1.446 gr (0.094 g) per hour per ft^2, or about 8 times the rate through the floor assembly. For an 800 ft^2 floor area, the calculated moisture entry rate would be 27,763 gr (1805 g) (3.98 lb) of water vapor transport per day. This represents a (latent) space cooling load of approximately 4179 Btu/day. Combined, water vapor transfer across both planes results in about 4.5 lbs (2030 g) of water per day representing about 4700 Btu/hour of latent cooling load.

While the cooling load and indoor humidity impacts of vapor diffusion can be considered modest, vapor transport by means of air flow can be very large particularly during periods when attic temperatures are hottest. There are several potential pathways that can allow air to travel directly from the floor space into the conditioned space. Recessed can light fixtures, supply and return air duct penetrations, as well as electrical and plumbing penetrations are some examples. If the air flow rate from floor cavity to conditioned space is say 100 cfm (450 lb/hr dry air), on a daily average, and the air conditions (drybulb and dew point temperatures) in the interstitial cavity and indoor space are 84^{o}F/72^{o}F and 76^{o}F/57^{o}F, respectively, then the total

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[2] Edward Mazria, "Passive Solar Energy Book", August, 1979.

amount of water vapor and total heat, respectively, entering the conditioned space would be 3.16 lb/hr (450 lb/hr x (118.75 gr - 69.52 gr) / 7000 gr/lb = 3.16 lb/hr) and 4356 Btu/hr (450 lb/hr x (38.79 Btu/lb – 29.11 Btu/lb) = 4356 Btu/hr), respectively.

In addition to adding latent cooling load to the house, the elevated dew point temperature in the interstitial cavities introduces the opportunity for moisture condensation to occur on cool surfaces within the building. In some cases, moisture condenses on cool supply duct surfaces which can then drip onto ceiling materials and create damage. In one house, elevated humidity entered a wall cavity containing a pocket door, causing mold growth and warping of the door panel. In that same house, wooden stair risers in contact with the floor cavity experienced cracking of the wood in contact with the wind washing air. After the repairs were completed, the cracks pulled shut and the expanded wood returned to normal.

Figures 17 and 18 show floor cavity temperatures on hot days at house H7G before and after wind washing repair. The line graphs show drybulb and dew point conditions inside the floor space as well as indoor and outdoor conditions. With outdoor dew point averaging about 74^{o}F during pre- and post-repair periods, the daily average floor cavity drybulb temperature declined noticeably after the wind washing repairs, from 82.9^{o}F to 77.8^{o}F. The daily average dew point temperature declined from 72.5^{o}F to 65.3^{o}F.

Examination of dew point temperatures outdoors, in the floor cavity, and indoors allows us to determine whether the floor cavity is mostly indoors or mostly outdoors. Based on dew point temperature, the floor space changes from being most like the outdoors to being most similar to indoors as should be expected. Before repair, the floor cavity could be considered to be 83% outdoors. After repair, the floor cavity can be considered to be 25% outdoors. This determination is made based on the ratio of dew point temperature differentials between the floor cavity and the indoor space.

The before repair calculation is made as follows:

72.5^{o}F - 62.0^{o}F/74.6^{o}F - 62.0^{o}F = 83.3%.

The after repair calculation is made as follows:

65.2^{o}F - 62.0^{o}F/74.6^{o}F - 62.0^{o}F = 25.4%.[3]

It is also noteworthy that the drybulb temperature in the interstitial floor cavity declined precipitously as a result of the wind washing repair. Before repair, it can be observed that the

[3] C.Withers, Jr., Neil Moyer, Dave Chasar, and Subrato Chandra. "Performance and Impact from Duct Repair and Ventilation Modifications of Two Newly Constructed Manufactured Houses Located in a Hot and Humid Climate" Proceedings of the 13th Symposium on Improving Building Systems in Hot and Humid Climates May 20-23, 2002 in Houston, TX

drybulb temperature in the floor cavity peaks at about 87°F (8°F warmer than indoors) on a day that reaches 98°F outdoors (Figure 17). After wind washing repair, it can be observed that the drybulb temperature in the floor cavity peaks at only about 79°F (only about 1°F warmer than indoors) on a day that reaches 101°F outdoors (Figure 18). This illustrates that the wind washing air flow penetration into the interstitial cavities of the house has been largely or perhaps completely eliminated as a result of the foam sealing of the wind washing openings.

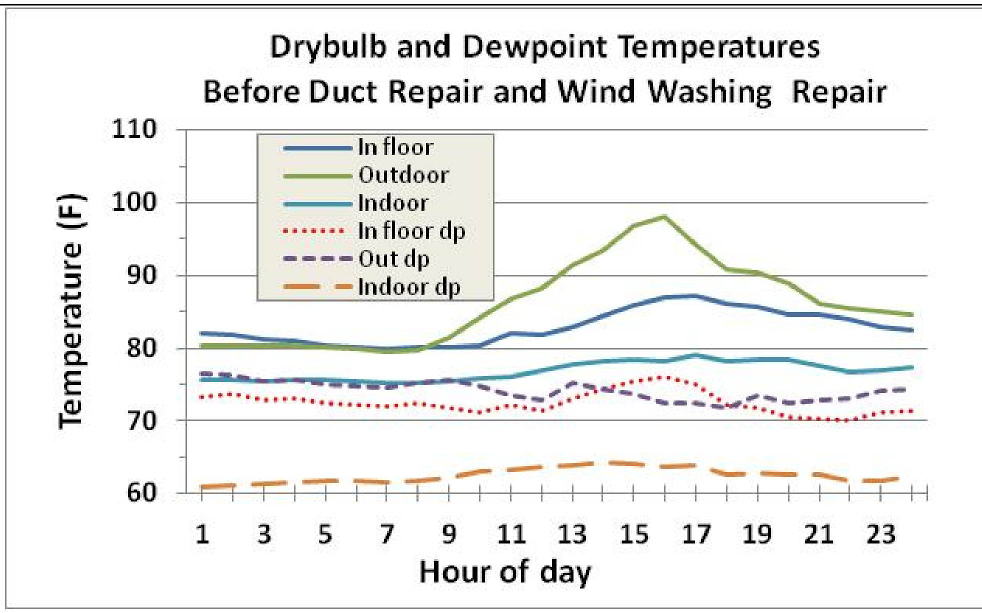

Figure17 Temperatures inside floor space, inside conditioned space and outdoors.

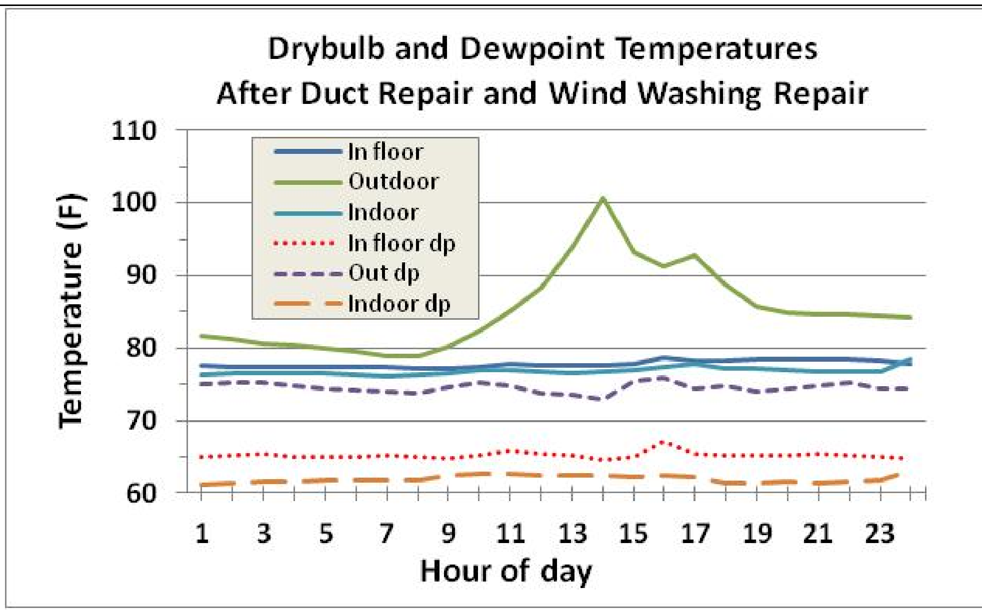

Figure18 Temperatures inside floor space, inside conditioned space, and outdoors.

Wind Washing Configurations and Discussion of Applicable Heat Transfer Mechanisms

The magnitude of the heat transfer into the house (creating cooling load) depends upon a number of factors, including the air flow rate into the interstitial floor cavities and the extent to which that air can leak into the conditioned space. Following is a discussion of three different wind washing configurations and how they impact transport of heat into the house.

Wind Washing with complimentary pathways. This may be the most potent form of wind washing, when there is an attic space, a wide open floor cavity, and complimentary pathways. The complementary pathways allow a fairly large and steady flow of hot air into the floor cavity. In this circumstance, the air temperature in the floor cavity can approach the air temperature which exists at the floor level of the attic space itself. At peak conditions, this temperature could be 115^{o}F or higher depending upon various characteristics of the roof and attic. The energy impacts are determined, in large part, by the temperature of the attic space, which in turn is controlled by the solar absorptivity of the roof surface, whether the roof is asphalt shingles or tile, the presence of a radiant barrier, etc.

Wind washing with no complimentary pathways. The impact of wind washing is considerably lessened when there are no complementary pathways. In this circumstance, the attic air does not readily enter the floor cavity because the through-flow is restricted by the air barriers at the far side of the interstitial floor cavity. In the absence of ready through-flow, thermal buoyancy becomes a significant driver. The air in the attic is hotter and the air in the floor cavity is cooler. Therefore, air in the attic is less dense and the air in the floor cavity is more dense. Because of differences in air density, the cooler floor cavity air flows from outward into the attic, and the lighter attic air replaces the displaced floor cavity air. The rate of this air exchange between attic and floor cavity depends upon the height of the floor cavity opening and the temperature differential between the attic air (at the attic floor level) and the floor cavity air. Figures 19 and 20 show the floor cavity-to-attic interface and thermal stratification within the floor cavity of a home with no complimentary pathways.

Figure 19 View inside floor cavity taken from opening to attic space. (Withers)

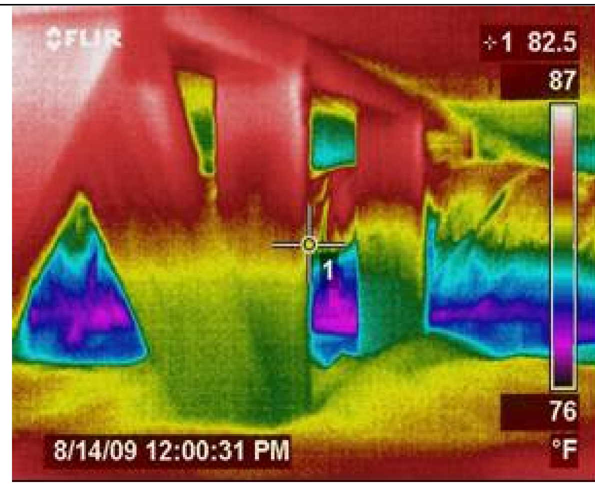

Figure 20 A thermal image of the floor cavity shows temperature variation of about 5^{o}F from top to bottom of the floor cavity. (Withers)

Wind washing with air flow into conditioned space. In this configuration, there is no complementary pathway at the other side of the floor cavity, but there are significant air leak pathways from the interstitial floor cavity to the indoor space. Air flow pathways in the ceiling could include penetrations at duct registers and grills, speakers, ceiling fans, canned lights, and other light fixtures. Wind washing flow into the conditioned space can be a very potent form of wind washing because the total heat (including sensible heat and latent heat) can flow directly into the conditioned space. The impacts are more focused on indoor RH than on total cooling energy use because of the low load SHR associated with the wind washing infiltration. When infiltration air has drybulb and dew point temperatures of 84^{o}F/72^{o}F (and indoor conditions are 76^{o}F/60^{o}F), 76% of the imposed cooling load is latent and only 24% is sensible. The degree of energy impact depends upon the drybulb and dew point temperatures of the entering air, the driving force of wind washing, and the size of the opening between the floor cavity and the conditioned space.

In one extreme example, the first floor of a 4090 ft^2 house located in east central Florida (2954 ft^2 on the first floor) had 80 recessed (canned) lights with estimated air leakage opening of 80 in^2. The house had an ACH50 of 11.1, which indicates a very leaky envelope. The homeowners reported that indoor RH was always high throughout the hot and humid summer months. The penetration of the wind washing air flow was enhanced because the leak openings at the exterior, where motorized hurricane shutters (the attic above the garage was not involved in the wind washing in this house) had been installed and were not sufficiently sealed, faced an open expanse of open river and a strong prevailing sea breeze. While no repairs were implemented and the energy impacts have not, therefore, been monitored, ballpark energy impacts can be calculated. Blower door testing indicated a natural air infiltration rate of 0.28 ach (based on a “divide by 40” method presented in Cummings et al, 1990[4]. Given a volume of 32,720 ft^3, and assuming that ½ of the house air infiltration originates from the wind washing and that the conditions (drybulb and dew point temperatures) in the interstitial cavity and indoor space are 84°F/72°F and 76°F/60°F, respectively, then the calculated wind washing cooling load associated only with air infiltration (calculated to be 76 cfm based on the stated assumptions) was introducing water vapor and total heat (enthalpy) into the house at a rate of 2.02 lb/hr (344 lb/hr x (118.75 – 77.56) / 7000 gr/lb = 2.02 lb/hr) and 2896 Btu/hr (344 lb/hr x (38.79 – 30.37)), respectively. Additional heat would enter the space through conduction from the floor cavity to the ceiling of the first floor and the floor of the second story.

In this house with the 80 canned lights, the wind washing air flow did not originate from an attic space, so the drybulb temperature of the infiltrating air was moderate (essentially the same as outdoors). If the circumstances were altered, so that the air entering the floor cavity was originating from a hot attic, then the sensible loads associated with this type of wind washing would have been much greater. The entry of hotter air would have caused a substantial increase in AC system runtime (because it is sensible load that raises indoor temperature and activates the thermostat) and a proportional lowering of indoor RH, since the air infiltration load SHR would have been considerably higher.

Interactions Between Wind Washing and Duct Leakage

Wind washing results in unplanned thermal transfers between conditioned and unconditioned spaces as a result of natural driving forces such as wind and temperature differences. By contrast, duct leakage (especially return leaks) can also drive air flow through wind washing pathways, creating additional unplanned thermal transfer. There is almost always ductwork located in the floor cavity of two story homes. The thermal transfer between inside and outside can occur in this space as long as the floor space has a means of exchange with unconditioned space.

Wind washing pathways into the floor cavity create the connectivity to outdoors through which duct leakage can flow. Consider house H11C (previously shown in Figures 12-15) which has more duct leakage on the return side than the supply side. Return leaks were drawing air from

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[4] 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, page 42 (http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-370-90.pdf).

the garage, attic, and floor cavities. When the air conditioner turned on, the house pressure increased about 1.2 Pa. During site testing, research staff noticed that very cool dry air was felt at the south soffits of this house prior to the wind washing repairs, which included sealing off of the floor cavity. Data loggers recorded temperature and humidity in the north and south eave vents (within the interstitial floor cavity). As can be seen in Figure 21, dew point temperatures within the floor cavity were much lower than outdoors much of the time. In most homes, the floor cavity (near the eave vents) would have a dew point temperature that is similar to outdoors. In this house, however, a daily pattern occurred where the floor cavity dew point temperature would rise during a 7-hour period when the AC system was off (the black line in Figure 21 is the AC system 15-minute energy consumption), from about 55^{o}F to about 64^{o}F, and then decline during an extended period when the AC system was again turned on. Indoor conditions also fluctuated. While the outdoor dew point temperature was in the range of 70 to 72^{o}F throughout this two-day period, indoor dew point temperatures were 48^{o}F when the AC system had been operating for an extended period, but then rose steadily to a spike of about 60^{o}F at the end of the 7 hour off period.

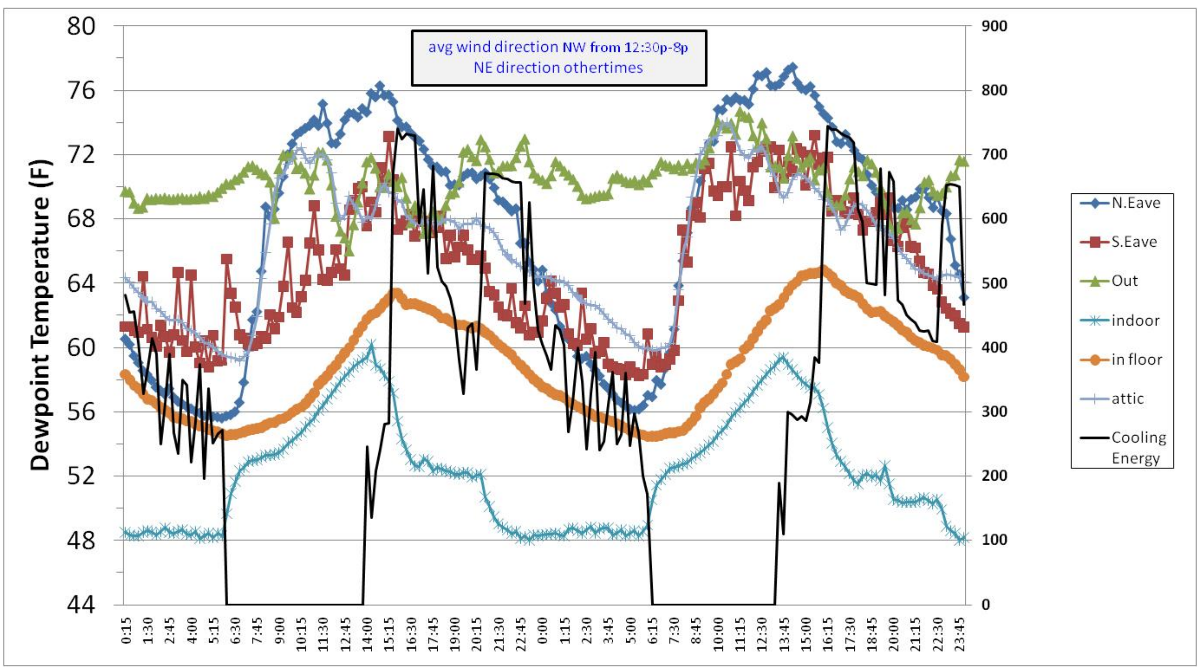

Figure 21 Plot of dew point temperatures and AC system energy use shows that both indoor and floor cavity dew point temperatures decline when the AC system operates, and then rise substantially when the AC system is off (typically for about 7 hours). Right Y-axis is cooling energy in Wh/15 minutes.

It is also interesting to note that the attic dew point temperature exhibits a similar daily pattern. One can observe that the attic dew point temperature drops substantially during the period that the AC system runs, declining from about 72°F to about 60°F.This indicates that the attic space is also well connected to the conditioned space.

It appears that duct leakage is creating a mechanical driving force that displaces air through the floor cavities into the eaves and attic spaces. Measurements found that turning on the air handler unit produced a positive pressure in the house of 1.2 Pa, indicating dominant return leakage. This positive house pressure allows air from the conditioned space to be driven into the attic and the floor cavities.

Additionally, it is known that the wind pushes air from the floor cavities into the eaves. On three different occasions, a research staff member felt (by hand) and measured (with a temperature/RH probe) cool and dry air conditions in the south eaves. These pulses of cool, dry air coincided with significant wind from the north at times when the air handler was off. Infrared images taken at the time also show a difference in temperature between the windward and leeward soffit vents (Figures 22 and 23).

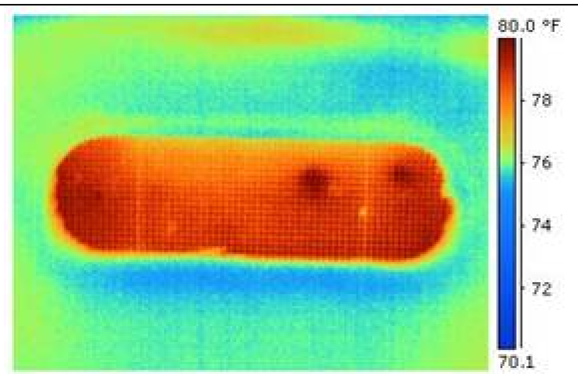

Figure 22 With 10 mph wind from the north, the north soffit vent shows interior surface temperatures about 78-80°F. Outside air temperature = 80.1°F and interior air temperature = 71.0°F. *(Withers)*

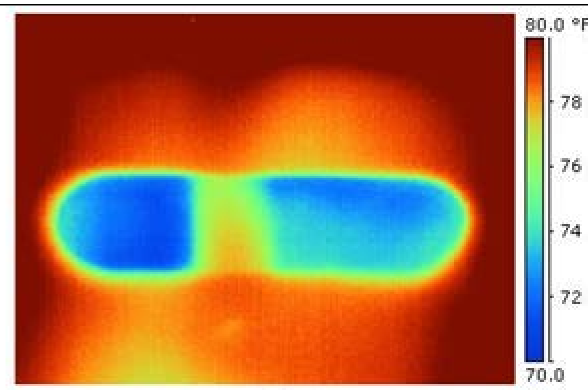

Figure 23 With 10 mph wind from the north, the south soffit vent shows average of 71.9°F on interior surfaces in left bay and about 73.2°F on right bay indicating cool house air being pushed through the house by means of the floor cavity and the force of the wind. *(Withers)*

Based on blower door testing, house envelope leakage (CFM50) was reduced by only 2.3%. While this is only a small reduction, it is leakage that has a significant impact because of the location and the interaction of duct leakage within the house. While some of the return leakage draws from the floor cavity, most of the return duct leakage originates from the attic space above the top story of this split-level home. Return duct leakage was measured by means of tracer gas testing. While return leakage was measured to be 11.5% before wind washing repairs, it has declined to 7.9% after wind washing repairs, even though no duct leakage was directly repaired. We conclude that the wind washing repair reduced or eliminated some pathways for the return leaks to draw air from outdoors. The measured airflow of the AC system was 1256 cfm. This equates to return leakage of 144 cfm before repair (1256 cfm *

0.115 = 144 cfm) and 99 cfm after repair. The change results in a 45 cfm reduction in return leakage from outside space.

CONCLUSIONS

Inspection and testing found substantial openings into interstitial floor cavities from either outdoors or adjacent attic spaces in a substantial number of two-story homes. Based on the study of thirty-two homes, wind washing may affect as many as 30-40% of two-story homes in Florida and can be found in old and new construction.

The penetration of hot and humid air into interstitial floor cavities creates significant increases in space cooling loads. In some homes, the presence of high dew point air within the “bowels” of the building cause moisture problems that include moisture condensation on ducts, registers, and canned lights, and moisture adsorption (with resulting cracking) into wood stairway materials.

Wind washing repair appears to be cost effective, with cooling energy savings typically paying for repairs in 4 to 5 years, without considering heating season savings (which were not monitored) or any incentives which may be implemented as part of utility or government programs. Repair of wind washing, achieved in six homes by application of open-cell foam, reduced cooling energy use by an average of 15.3%, equal to about $140 per year. Peak cooling energy demand was reduced by 12.6%, or 0.52 kW. Wind washing repair also reduced measured duct leakage even when no duct leaks were sealed, because those duct leaks had, as a result of the wind washing repair, less access to air from outdoors by means of the interstitial floor cavity (which was now mostly inside the house air boundary).

The degree of wind washing impacts depends upon the thermal conditions of the air penetrating the interstitial floor cavity (related to roof color and other factors), the wind washing flow rate, whether there are complimentary pathways on the opposite side of the interstitial floor cavity, and whether pathways allow air flow from the floor cavity to the conditioned space. In addition to reducing sensible cooling loads (and heating loads in the winter), repair of wind washing also reduces the entry of latent cooling loads into the space, by means of vapor diffusion through building materials or by air transport through openings in the ceiling of the first floor and the floor assembly of the second story. Wind washing repair can also reduce or eliminate moisture condensation problems that commonly damage building materials or create mold growth during hot and humid weather.

The findings of this research have implications for new construction. Designers should provide clear documentation to contractors on how to maintain continuity of the thermal and air barrier intended to separate floor cavities from unconditioned spaces. In cases of simple construction and simple building geometries, adequate thermal control may be as simple as carefully installing kraft-faced batts. Complex structural framing or other obstructions around open floor cavities may require application of a blown insulation product or possibly the application of custom fitted rigid insulation board with caulked seams.

Determining the potential for wind washing to occur in existing construction is best accomplished by a visual inspection in attic spaces. Other diagnostic assessments can also be useful to identify wind washing problems and determine necessary repairs to correct those problems. Performing building airtightness testing, pressure mapping, using smoke pencils, moisture meters, and infrared cameras are useful diagnostic tools that aid an inspector in determining the potential severity of wind washing impacts. A successful repair requires a contractor that understands the importance of maintaining an effective air and thermal barrier and the skills and determination to install such in a difficult working space.

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