MOISTURE RISK IN SPRAY POLYURETHANE FOAM UNVENTED ATTICS DUE TO AIR LEAKAGE PATHS

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ABSTRACT

IBACOS completed a high-level analysis of the moisture damage potential—caused by airflow leakage paths (cracks) to the outdoors—in unvented cathedralized attics insulated with closed-cell spray polyurethane foam (SPF) in cold climates. IBACOS began this preliminary analysis by collecting limited field data from three existing houses retrofitted from vented to unvented attics, focusing on a 2,050-ft^2 house in Minnesota that is insulated with closed-cell SPF at the roof deck. IBACOS then used computational fluid dynamics (CFD) analysis to quantify the airflow rates through individual leakage paths, used CONTAM software to simulate hourly flow rates through the leakage paths, correlated the CONTAM flow rates with indoor humidity ratios from Building Energy Optimization (BEopt) software, and finally used Wärme und Feuchte instationär Pro (WUFI) two-dimensional (2D) hygrothermal analysis modeling software to determine the moisture content of the building materials surrounding the cracks. The results indicate that localized damage from the high moisture content of the roof sheathing is possible under very low airflow rates. Although the study used existing houses, the results apply to new construction with similar leakage rates. Reducing the number of assumptions and approximations used in this project would produce more accurate understanding of the real-world moisture damage potential in unvented attics. This would include collection of more field data to better define the leak types, as well as laboratory measurements to characterize the flow and pressure relationships at attic leakage pathways.

Key words: Hygrothermal, CFD, CONTAM, unvented attics, closed-cell spray foam.

INTRODUCTION

The use of open-cell SPF and unvented cathedralized attics (i.e., attics within conditioned space, where spray foam is applied against the underside of roof sheathing) has been increasing over the last 10 years. However, the potential moisture risk caused by air leakage at small cracks in unvented attics is not fully understood yet, partly because any roof sheathing rot problems probably will not be realized until the roofing material is removed and replaced at the end of its useful life. This could take 5 to 50 years, assuming a 25-year shingle life and the fact that current codes permit a second layer of roofing to be applied over an existing layer of old roof shingles. The fact that a major systemic problem has not been reported may or may not indicate a widespread system failure now or in the future.

For this initial investigation, IBACOS first collected field data and then performed modeling to begin to understand the worst-case scenario of moisture problems related to small crack air leakage in unvented cathedralized attics in cold climates (climate zones 6 and 7). Condensation is more likely to occur in cold climates because warm indoor air has more moisture than the cold outdoor air and lower density; thus, that lower-density air moves to the highest point (i.e., the attic) and travels through cracks to the outdoors.

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IBACOS made conservative assumptions that maximized the water vapor available for condensation and the environment for condensation. The hypothesis was that unvented cathedralized attics insulated with closed-cell SPF on the roof deck have some level of airflow at roof penetrations and inherent cracks and gaps (e.g., wood-to-wood connections) and that the airflow from these leakage paths can cause moisture damage to building materials resulting from condensation and the inability of the system to dry.

Vented and Unvented Attics

A vented (conventional) attic has insulation placed on the attic floor, with intentional venting to the exterior. An unvented (cathedralized) attic has insulation placed at the roof deck, with no intentional venting to the exterior. In most houses retrofitted from vented to unvented attics, any pre-retrofitted attic insulation is allowed to remain on the attic floor.

Attic Moisture-Related Issues

Moisture in an attic space related to attic ventilation was first studied by Rowley et al. (1939). Several studies of vented attics found that attic ventilation reduced the condensation risk in heating climates but contributed to the condensation risk in southern humid climates (Rudd and Lstiburek [1998]; Lstiburek [1993]; TenWolde and Rose [1999]).

Fitzgerald (2010) completed studies of moisture damage in unvented attics for dense pack cellulose, which indicated that 20% of incorrectly installed (i.e., no air rafter ventilation built into the assembly to dry materials) dense pack cellulose in cathedralized attics failed within the first 10 years of installation. Schumacher and Lepage (2012) provided guidance for using dense pack cellulose in cathedralized attics; one of their strategies recommends the use of closed-cell SPF on the underside of the roof deck, with cellulose below it.

Straube et al. (2010) and Lstiburek and Shumacher (2011) used WUFI hygrothermal analysis modeling software to analyze various combinations of air-impermeable insulation (spray foam) and air-permeable insulations (spray fiberglass or cellulose) and drew conclusions about appropriate R-values and vapor control strategies. Straube et al. (2010, p. 8) indicated that spray foam in cathedralized attics effectively stops air leakage at cracks in the roof deck but does not stop air leakage at wood-to-wood joints.

Grin et al. (2013) studied the unvented attic moisture risk resulting from bulk water transport due to precipitation through damaged roofs. They concluded that an unvented attic can adequately withstand a limited water leakage event without damage to the building materials.

RESEARCH STRATEGY

Field Data

IBACOS first collected field-recorded attic leakage rate data on three existing houses that had been retrofitted from vented to unvented attics in a cold climate. Then IBACOS used numerical simulations calibrated against measured data to study the moisture potential in a hypothetical house: a two-story, 2,050-ft^2 house located in Minneapolis, Minnesota, having an unvented attic insulated with closed-cell SPF at the roof deck. In this house, the attic temperature and relative humidity were equal to those of the living space, and the house had an envelope leakage rate of 5 air changes per hour at 50 Pascals (ACH50). Attic leakage was included in the envelope leakage, but the volume of the attic was not used to determine the air changes per hour because the attic will not be used as living space.

Modeling Efforts

After gathering field data, IBACOS used numerical models to simulate physical phenomena. Figure 2 shows the project workflow and relationship of field data to the modeling effort. IBACOS used four software programs: ANSYS CFD[3], CONTAM Version 3.1[4], Building Energy Optimization Version 2.1.0.2[5] (BEopt), and WUFI Pro Version 5.0[6].

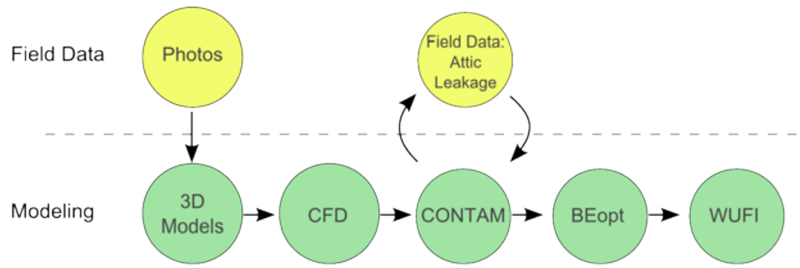

Figure 1: The study workflow combined field measurements with multiple numerical models

IBACOS used the field data to understand the appearance of the penetrations and cracks and to determine the attic airflow rates, the three-dimensional (3D) geometry of the airflow paths, and gross leakage of the attic. IBACOS reviewed photos of air leakage paths, made 3D models of those paths, and input the models into ANSYS. Then IBACOS drove ANSYS at steady state with approximately five different mass flow rates and recorded the pressure differentials between the interior and exterior of the crack. IBACOS used the power law equation—which is a continuous representation of airflow rate as a function of pressure across a crack—to develop the mathematical description of each airflow path (ASHRAE 2005, Chapter 27.12, Equation 32),

$$q = C\,\Delta P^{n},$$

where q is the airflow rate (CFM), C is the leakage flow coefficient (CFM/(Pa)^n, ΔP is the pressure difference across the leak (Pa), and n is the flow exponent (dimensionless). IBACOS determined C and n using ASTM E779 methods (ASTM 2010).

Once the flow rate was characterized, IBACOS entered the flow parameters (C and n) for each crack type into the CONTAM model using the field data of attic leakage rates to determine the hourly flow rate through the attic leakage paths. The two methods that create a pressure differential that results in airflow from the living space to the exterior through attic cracks are stack effect and wind-induced pressure differentials (Walker 1989). Then IBACOS drove the CONTAM model with Typical Meteorological Year 3 (TMY3) weather data for Minneapolis, Minnesota, to quantify the infiltration/exfiltration driven by stack and wind-induced pressure effects in an unvented attic. The building enclosure leakage, including attic leakage, of the CONTAM model was 5 ACH50, where the air changes per hour do not include attic volume.

Next, IBACOS used the BEopt model, which was equivalent to the CONTAM model geometrically and in envelope tightness, to determine the hourly indoor temperature and relative humidity. (The BEopt model does not account for leakage from the house into the attic space.)

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[3] ANSYS, Inc., Canonsburg, PA: http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics.

[4] National Institute of Standards and Technology, Gaithersburg, MD: http://www.nist.gov/el/building_environment/contam_software.cfm.

[5] Building Energy Optimization Software, National Renewable Energy Laboratory, Golden, CO: http://beopt.nrel.gov/.

[6] Fraunhofer Institute for Building Physics, Stuttgart, Germany.

The CONTAM airflow rates were matched with the humidity ratio from the BEopt model to determine the mass flow rate of water vapor through the attic cracks.

Finally, IBACOS input into WUFI the hourly mass flow rate of water vapor to perform a hygrothermal analysis to determine the moisture absorption and desorption in the attic materials.[7]

RESULTS AND DISCUSSION

Field Data

To simulate the leakage rate of SPF insulation on the roof decks of unvented attics, IBACOS characterized the airflow paths and quantified the unvented attic air leakage rates. The following two sections describe the approach IBACOS used to gather and analyze the field data.

Attic Airflow Path (Crack) Types. IBACOS reviewed photos from past building quality inspections done in-house and by others to determine that the following types of attic airflow paths might be found in a closed-cell SPF-insulated unvented attic: (1) plumbing roof penetrations, (2) spray foam delamination, (3) framing intersections, and (4) ridge vent sealing.[8] IBACOS then used Rhinoceros[9] Version 5 software to create 3D solid models of the cracks. Note, IBACOS focused on the plumbing vent for the final hygrothermal analysis, but the family of known airflow paths had to be modeled to quantify the gross house-to-attic airflow. IBACOS then converted the presumed leakage paths to 3D models to complete CFD analysis of the cracks. Figure 3 through Figure 6 show the four types of cracks.

Figure 2: Plumbing penetrations

Figure 3: Delamination at rafters

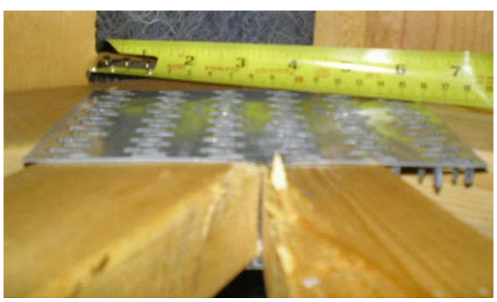

Figure 4: Ridge vent opening

Figure 5: Surface area openings at roof

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[7] Hygrothermal analysis quantifies the wetting and drying of building materials based on moisture available to the material at the current time-step as a function of moisture content of the material at the previous time-step, plus the addition or removal of moisture resulting from the conditions of materials and air surrounding the crack. It is useful in understanding physical phenomena and durability but is subject to assumptions and parameters input into model.

[8] Poor sealing of soffit vents was not included because further work would be needed to develop a more robust characterization of these leak types.

[9] http://www.rhino3d.com/.

Figure 7 shows the 3D models of the airflow paths for the plumbing, bath fan venting, or flue vent airflow path; the arrows illustrate the direction of airflow out of the attic space. With the surface and ridge vent cracks, IBACOS assumed that the closed-cell SPF would delaminate and that the preexisting opening was not completely sealed with foam because of improper closed-cell SPF installation practices.

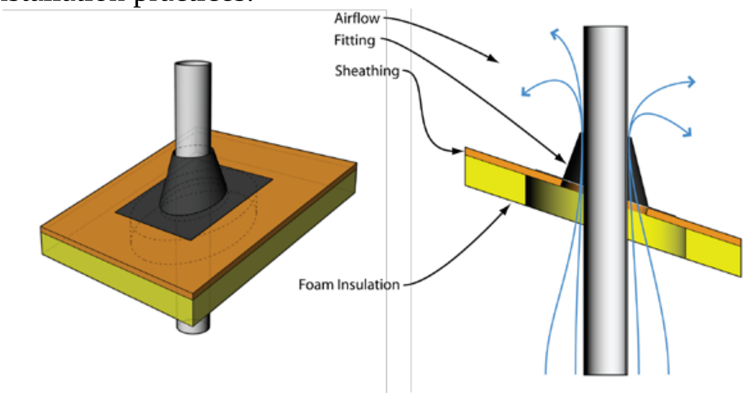

Figure 6: Plumbing, bath fan venting, or flue vent airflow path

As a starting point in understanding the potential airflow from a family of defined airflow paths, IBACOS did not include all building materials in the analysis because a properly installed roof system would have very little air leakage; however, the field data indicated otherwise.

Unvented Attic Air Leakage Rates for Field Data. IBACOS collected field data for three houses that were being retrofitted from vented conventional to unvented cathedralized attics with closed-cell SPF insulation. Data for the envelope and attic leakage for House 1 and House 2 were recorded both before and after the retrofits. Data for House 3 were recorded only after the retrofit. IBACOS analyzed the test results using TecTite 4.0 software[10] to determine airflow rates as a function of pressure. Table 1 presents the analysis results, where *C* is the flow coefficient and *n* is the flow exponent. With only two data points, Table 1 shows that attic leakage was reduced approximately 65% for two attics but remained relatively high, although the installation was completed by a competent crew. IBACOS calculated the total attic leakage at 4 Pa to help in developing the CFD and CONTAM models.

Leakage Metric	House 1 – Attic				House 2 – Attic				House 3 – Attic		
	Pre-Retrofit		Post-Retrofit		Pre-Retrofit		Post-Retrofit		Pre-Retrofit	Post-Retrofit	
C	196	±6.0%	91	±5.6%	186	±14.7%	53	±5.7%	Not available	126	±33.9%
n	0.632	±0.016	0.49	±0.015	0.69	±0.045	0.66	±0.015		0.65	±0.097

[10] The Energy Conservatory, http://www.energyconservatory.com/blower-door-test-software.

Leakage @ 4Pa	471±39 CFM	179±14 CFM	484±102 CFM	132±10 CFM		310±138 CFM

Table 1: Data Collected for Three Attics

Computational Fluid Dynamics Results

IBACOS used ANSYS to determine the airflow rate for dry air at a standard temperature at various pressure differentials across the airflow paths based on pressure. A mesh study was completed, which ensured that the results were not biased because of the mesh network. IBACOS used regression analysis to determine the flow coefficients and flow exponents for different types of airflow paths. Table 2 presents the airflow path regression analysis; *C* represents the flow coefficient, and *n* represents the flow exponent.

Airflow Path Type	CFM @ 4Pa	*C*	*n*
Plumbing	6.38	3.1900	0.5050
Surface	0.0405	0.0196	0.5228
Gable	2.0E-5	0.00001	0.50138
Ridge Vent	1.43	0.694	0.523

Table 2: Airflow Characteristics Relating Airflow Rate to Pressure

The CFD analysis results indicate that very low airflow rates will be achieved with surface and gable end airflow paths. As mentioned, IBACOS created 3D models from photos rather than from physical measurements of actual airflow paths. IBACOS chose to use completely dry air with no moisture because the variability of moisture moving through the airflow path would be added later using results from the BEopt model.

CONTAM—Airflow Rates for Unvented Attics

IBACOS created the CONTAM model with the airflow path characteristics determined by the CFD analysis. Several iterations were necessary to adjust the CONTAM model to have similar gross attic airflow rates as found with the field measurements. IBACOS reused the ridge vent airflow path as a soffit airflow path to achieve total attic airflows that were similar to field measurements. Table 3 indicates the number of airflow paths used in the CONTAM model.

Airflow Path Type	Number of Airflow Paths Used in CONTAM Model
Plumbing	2
Surface	120
Gable	16
Attic Ridge	57
Eave	57
Total for Airflow Path Family	252

Table 3. Airflow Path Type, Number, and Airflow at 4 Pa

The number of cracks indicated in Table 3 represents a surface crack at every roof sheathing intersection and rafter interface. Attic ridge and eave cracks were added at every rafter. Two plumbing cracks were included, and 16 gable cracks were included.

Once the cracks were added to the CONTAM model, IBACOS evaluated the airflow rate and pressure relationship curve by driving CONTAM with a range of interior pressures inside the house to simulate a multipoint blower door test without wind. The flow coefficient and exponent were 90.3 CFM/Pa^n and 0.5214 dimensionless, respectively.

Next, to produce hourly air leakage rates, IBACOS simulated the air leakage of the attic using a TMY3 weather file for Minneapolis, Minnesota, a constant indoor temperature of 70°F, and no airborne water vapor. The cumulative airflow entering the attic (the sum of all negative airflows) occurred less than 2% of the year because the dominant stack effect found in a two-story house in a cold climate essentially produces a constant airflow out of the attic.

The average airflow rate was 185 CFM, which is approximately equal to the family of the airflow paths when experiencing 4 Pa pressure differential. Based on this analysis, the CONTAM model produced results that were comparable to the field data.

BEopt—Mass Flow Rate of Water Vapor

IBACOS combined the hourly CONTAM airflow rates with the indoor temperature and humidity ratio from the BEopt model. The BEopt model was geometrically identical to the CONTAM model and used Building America House Simulation Protocols (Hendron and Engebrecht 2010) for occupancy, latent loads, and temperature set points (68°F heating and 71°F cooling). Each airflow rate was converted to a mass flow rate of water vapor, and the mass flow rate of water vapor passing through the attic airflow paths was calculated to be approximately 36,000 lb of water vapor per year.

IBACOS calculated the dew point temperature of air flowing out of the attic space for each hour and IBACOS compared the outdoor temperature to the dew point temperature of air flowing through the crack. Figure 8 shows the airflow rate for each hour using semi-transparent round yellow dots and grey vertical bars to indicate that a condensation event is possible (i.e., when the outdoor temperature equals or is less than the dew point temperature of the indoor air).

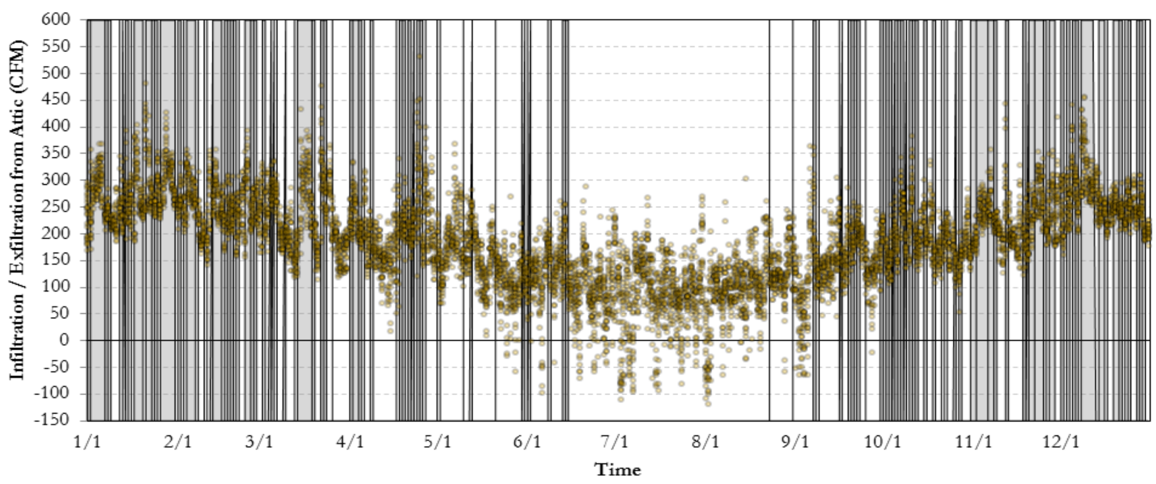

Figure 7: CONTAM attic airflow rates determined for Minneapolis, Minnesota. (Shading shows when the outdoor temperature was less than the dew point of air flowing through the crack.)

Although the dew point temperature was reached, condensation may not occur because of solar radiation and/or heat transfer of the warm air moving through the crack to the attic materials and/or condensation warming the building materials. WUFI results that include solar and night sky radiation are presented later in this paper.

WUFI—Hygrothermal Results and Moisture Content

IBACOS used WUFI modeling to calculate the moisture content of the building materials using the surface area of the penetrations/cracks, the water vapor in the air flowing through the penetrations/cracks, and the TMY3 outdoor weather file for Minneapolis, Minnesota. IBACOS determined the condition of the air flowing through the airflow path by merging the CONTAM mass flow rate with the BEopt-simulated indoor air conditions.

IBACOS also used WUFI to simulate the moisture content of the building material surrounding the airflow path and chose the plumbing vent for analysis. A small airflow path along the round plumbing vent allowed air to flow over the building materials (the foam and roof sheathing). Figure 9 illustrates the 2D model and shows the materials used in the simulation.

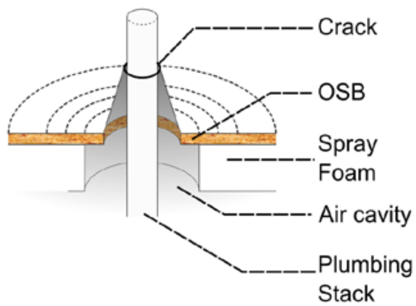

Figure 8: Schematic view of the WUFI 2D model for the plumbing airflow path.
(OSB is oriented strand board.)

Using the modeling results, IBACOS completed a sensitivity analysis of the WUFI simulation results representing the moisture content of the building materials by adjusting the gross vapor flow rate through the airflow path. Because the results are based on modeling results, the sensitivity analysis paints a more useful picture of the building material moisture absorption and desorption than running one instance of the model. Also, one-dimensional (1D) WUFI modeling was used but produced unrealistic results because the drying potential of the airflow was excluded.

To complete the sensitivity analysis, IBACOS held the airflow rate through the plumbing airflow path constant at 200%, 40%, 4%, and 0% (no airflow) of the CONTAM-predicted airflow at 4 Pa. Next, the airflow conditions were merged with the indoor air conditions from BEopt. Finally, IBACOS used the TMY3 outdoor conditions for temperature, relative humidity, and solar and night-sky radiation.

Figure 10 shows a spatial/temporal representation of the moisture content in the OSB sheathing. The red shaded areas show moisture content in the OSB above 20%. The axis moving toward the reader from the page indicates the time of year, and the horizontal axis indicates the distance away from the edge of the air leakage pathway.

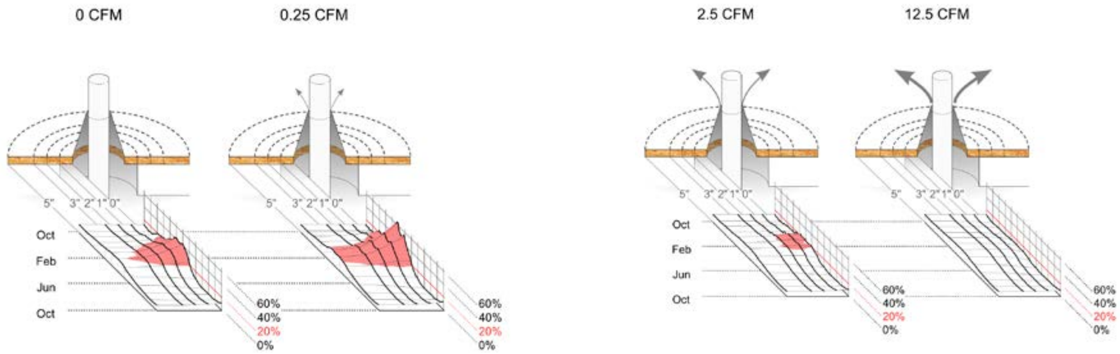

Figure 9: Hygrothermal results for plumbing airflow paths with airflows from 0 to 12.5 CFM

The 2D WUFI results indicate that drying occurs at higher airflow rates and that high moisture content in the sheathing is localized at the crack location. Based on the 2D analysis of a very low airflow rate, the area surrounding the plumbing penetration would have enough moisture to cause damage at a distance of 1.5 in. into the OSB sheathing. At higher airflow rates, the moisture risk lessens because of the drying nature of the heat energy in air moving through the crack. Thus, small-magnitude airflow paths may have higher risk than large-magnitude airflow paths. The results for the scenario with no airflow indicate that moisture risk occurs, although this may be unrealistic because WUFI is seeing the air moisture of a dynamic airflow although the condition is static; the air in the crack will be stagnant and will not have the same properties as the dynamic airflows calculated with CONTAM and BEopt.

CONCLUSIONS

To determine the potential for moisture-related issues in an unvented cathedralized attic and to quantify gross air leakage from the attic to the exterior, IBACOS measured the attic airflow leakage rate in three houses retrofitted from vented to unvented attics. IBACOS then used several modeling programs (3D modeling, CFD, CONTAM, BEopt, and WUFI), and analysis of the results indicated an average air leakage of 207 CFM at 4 Pa of pressure. Also, moisture can accumulate in building materials surrounding air leakage paths that have low airflows. Higher airflow rates have less moisture accumulation in winter because the drying potential of airflow across the crack warms the sheathing and eliminates it as a condensing surface. Converting a vented attic to unvented may result in reduced airflow through leakage pathways and possibly localized damage. Because the results are based on simplifying assumptions, future work should be undertaken to improve on this preliminary analysis, particularly collection of more field data to better define the leak types that are present and laboratory measurements to characterize flow and pressure relationships at attic leakage pathways. CONTAM modeled airflow rates from assumed airflow paths could be replaced with empirically measured airflow rates from actual airflow paths (cracks) in unvented attics.

Finally, the results presented here are based on numerical models that should be used only to *guide* decision making. To better understand the moisture risk in unvented attics, decision makers should collect actual field data.

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