

Cold-Weather Condensation Problems in Fully Insulated Low-Slope Roof Systems to Meet NFPA 13 Requirements

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INTRODUCTION

The authors have investigated numerous failures in low-slope roof systems installed over insulated framing spaces. In many cases, these failures are severe, involving decay and structural failure of the roof sheathing and top chords of wood roof trusses (**Fig. 1**), even in climate zones with relatively moderate winter temperatures. A recent increase in the number of requests to investigate failures of these systems indicates to the authors that the issues causing these failures are not well understood by the building community. A significant percentage of these failures involve multistory, multifamily buildings where the roof framing spaces are filled with noncombustible, air-permeable insulation to avoid the use of sprinklers within concealed spaces in buildings governed by NFPA 13.¹

In 2021, we investigated a failure of this type in the Midwest (Climate Zone 5). The four-story wood-framed apartment building, completed in 2017, has wood floor and roof trusses spanning the 60 ft width of the building. The top chord of the roof trusses sloped from 36 in. to 20 in., creating a roof slope of 1/4 in. per ft (**Fig. 2**).

The building height exceeds 60 ft, triggering NFPA 13¹ sprinkler requirements. To omit sprinklers from the roof framing space, the roof framing space was filled with non-combustible insulation. Although the fiberglass batt insulation was specified to be slightly compressed by the roof sheathing, the actual construction typically has a small gap between the insulation and the sheathing. No vapor retarder was required or provided above the ceiling below the insulation. However, installing a vapor retarder in this location in an unvented assembly can increase the potential for moisture issues by trapping any moisture that is introduced into the truss space between two vapor retarders (the roof membrane at the top side and the vapor retarder at the bottom side). Each apartment unit includes a 1.5- or 2-ton heat pump unit with ductwork (both flexible and rigid) located in the roof framing space (**Fig. 3**).

As is common, the flexible ductwork was connected to the main rectangular ducts and ceiling diffusers with plastic zip ties (**Fig. 4**).

We will review the causes of this type of failure and how it can be avoided. Our analysis focuses on multistory, multifamily residential buildings conforming to NFPA 13.¹

BACKGROUND

Code Changes That Increase Condensation Risk

Increases in Required Thermal Performance

Low-slope wood-framed roof assemblies are common in multistory, multifamily buildings due to their familiarity, simplicity, and cost effectiveness. Historically, these assemblies were often insulated with a relatively thin layer of rigid insulation on the top side of the sheathing or a small amount of insulation above the ceiling. Even with insulation in the framing space, the potential for condensation was low since the temperature differential



Figure 1. Sheathing and truss failure in insulated roof framing system (insulation removed to show distress).

across the minimal thickness of insulation was relatively small. As prescriptive requirements for thermal performance increased, placing all the insulation within the framing space became a practical and economical method for achieving code-required roof thermal performance. However, this approach can increase the potential for condensation since the large temperature differential across the insulation thickness causes the sheathing temperature to approach the exterior temperature during winter months. Any interior air that enters the framing increases the moisture content of the air in that space. This moisture will condense on surfaces that are below the dew point temperature of this air, such as the sheathing. Prolonged exposure to condensation can contribute to conditions such as apparent water leakage to the interior (from condensation dripping to the space below), biological growth, corrosion of metal components and fasteners, and, in severe cases, wood decay.² Researchers have estimated that as many as 20% of assemblies insulated with only air-permeable insulation within the framing space fail within the first 10 years,³ particularly in cooler northern climates.^{4,5}

NFPA 13

Another important code issue that is increasing the frequency of condensation problems in low-slope roof systems relates to sprinkler requirements. In the past, codes often did not require sprinklers. However, sprinklers are currently required in most parts of the US, governed by the requirements of either NFPA 13¹ or NFPA 13R.⁶ While the more stringent NFPA 13 is intended to provide property protection in addition to life safety, NFPA 13R is limited to providing life safety.⁷ NFPA 13R is only permitted for residential occupancy buildings with four stories or fewer that do not exceed 60 ft above grade.⁶ The 2021 *International Building Code* (IBC) also includes provisions to allow taller multifamily residential buildings with podium construction and sprinklers per NFPA 13.⁸

NFPA 13 incentivizes designers to fill the wood-framed roof spaces with noncombustible insulation to avoid the need for costly sprinkler protection.⁴ Since air-impermeable insulations such as polyurethane and polystyrene foams are combustible, air-permeable noncombustible insulations, such as fiberglass batt, loose fiberglass fill, and cellulose fill, are typically used. As the amount of insulation

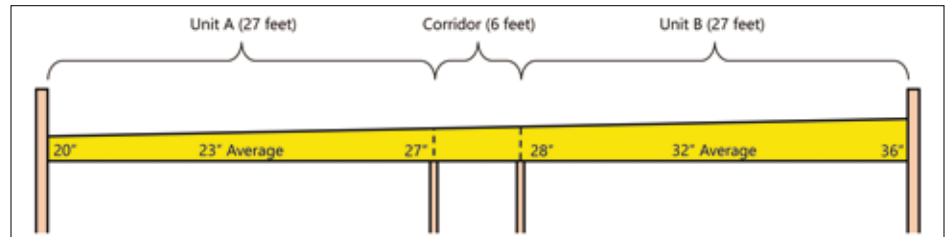


Figure 2. Diagram of truss.



Figure 3. Ductwork within insulation.



Figure 4. Zip tie connection of flexible duct to ceiling diffuser.

added to fill the framing space is often far greater than that required by energy code, the surface temperature of the roof deck and portions of the framing will approach exterior temperatures during winter weather, increasing the potential for condensation.

Reflective Roof Surfaces

The potential for condensation problems in these systems during cold weather is further increased by code-required reflective roof membranes. Roof membranes with high reflectivity result in cooler roof decks and consequently higher

moisture contents, since the roof, by design, will absorb less solar radiation.

Code Changes That Reduce Condensation Risk

Until recently, the design and construction of low-slope, insulated framed roof assemblies was not clearly addressed in the building codes. Whereas some designers and code officials have applied the ventilation requirements for steep-slope roofs to these low-slope roofs, these ventilation requirements are generally not appropriate in this application, often making condensation problems worse by drawing interior air into the framing space. A viable approach was not provided in the building codes until the 2015 IBC, which added guidance in Section 1203.3 (1202.3 in subsequent editions).⁹

The code revisions to address condensation in low-slope and unvented roof assemblies primarily consider: (1) airflow and air leakage via air barrier placement and detailing,¹⁰ (2) the appropriate ratio and placement of air-impermeable versus air-permeable insulation,¹¹ and (3) exterior design temperatures which provide an appropriate balance between practicality and conservatism.¹² Based on field studies and analyses by the authors, the options for insulation selection and placement can significantly reduce the potential for condensation. However, pressurized ductwork located within the roof framing, which can be a significant source of air leakage, is notably absent from the code provisions.⁸

CONDENSATION FORMATION

Moisture within the air of the roof structure (and thus, condensation risk) increases due to airflow from the interior in combination with ineffective ventilation of the framing space with exterior air.

Sources of Interior Air

Assuming that the roof membrane and adjacent wall interfaces are watertight, moisture typically enters the roof framing space via interior air leakage driven by positive pressurization of the occupied space relative to the framing space. Although vapor diffusion can also contribute to moisture in these roof framing spaces, it is generally only a small fraction of the moisture delivered by airflow.^{12,13} In typical construction, there are numerous potential airflow paths between the interior and the unconditioned framing space. These include partition walls interrupting the plane of the ceiling; mechanical, electrical, and plumbing penetrations (including exhaust fans for

spaces with high moisture generation such as bathrooms and kitchens); sprinklers; and recessed light fixtures. Vapor barriers beneath the framing spaces, when provided, are rarely airtight. Such incomplete barriers allow interior air to flow into the framing space. As noted previously, vapor retarders placed both above and below the framing space increase the potential for damage.

Although interior air flowing into the framing space adds moisture, perhaps the most significant source of air and moisture is the presence of pressurized heating, ventilating, and air conditioning (HVAC) ductwork above the ceiling. The air within the ductwork will either have approximately the same moisture content as the room air, or greater if humidification is supplied by the HVAC system. Therefore, the amount of moisture within the ductwork that may be added to the framing space via duct leakage can be significant. For sound transmission, space savings, and maintenance accessibility, ductwork for each dwelling unit is typically placed in the ceiling of the unit served, rather than within the ceiling of the unit below. As in the example discussed earlier, the ductwork at the top floor occurs within the roof structural system. Even reasonably well-sealed ductwork is not airtight, with unsealed crimped seams and connections commonly formed with zip ties. Based on infrared thermography and other studies by the authors, most duct leakage occurs at connections with ceiling diffusers and at joints and connections with sheet metal ducts. Since the air is under pressure, even small voids and joints can allow significant leakage. Based on research by others, "low leakage" can be characterized as less than 5% of duct

inlet flow.¹⁴ This characterization is supported by measurements of 11 residential sites in California, Nevada, and Texas constructed circa 2000¹⁵ and 19 residential sites in Wisconsin constructed circa 2008.¹⁶

Ineffective Ventilation

Steep-slope framed roof systems are typically vented to dissipate moisture via natural convection and wind. This is accomplished by providing lower (soffit) and upper (ridge) vents, as required in the IBC. Although attic ventilation is often attributed primarily to natural convection (warm air rising out of upper vents is replaced by cool air entering lower vents), studies have shown that ventilation by convection is typically an order of magnitude less than that provided by wind.^{17,18} To be effective, wind must enter on the windward side and leave on the leeward side. This type of cross-ventilation is typically not practical in low-slope roof systems. This is especially difficult to achieve in framing spaces with draft stopping per the IBC and NFPA 13R, or those filled with insulation per NFPA 13, to avoid sprinklers in the framing space. When roof vents are placed on the top surface of the roof to ventilate the system, wind blowing across the roof creates negative pressure that will draw air out of these vents. Natural convection can also provide a small additional contribution to the negative pressure, with solar radiation heating the roof surface and causing the adjacent air to flow out the topside vents.

The air drawn from the topside roof vents is replaced with interior air, increasing the potential for condensation within the framing space. This risk is further increased with turbine roof vents (Fig. 5), whose spinning action moves more air.



Figure 5. Turbine-style roof vent.

Most insulation products applied within the wood framing space (for example, fiberglass or cellulose) are not airtight, regardless of how densely packed the assembly may be.³ Whereas heat from leakage sources such as ducts, pull-down attic access ladders, or recessed light fixtures will not uniformly heat surfaces throughout the roof assembly because of the insulation, air and moisture from these sources will flow throughout the assembly. This can contribute to unique distributions of condensation, with the most severe damage counterintuitively located at surfaces away from the leakage source which are not effectively warmed above the dew point temperature.

ANALYSIS OF UNVENTED ROOF ASSEMBLY OPTIONS PER IBC

Options for Insulation Placement per 2021 IBC

For the purposes of this study, the 2021 IBC⁸ was considered. (For Climate Zones 5, 6, 7, and 8, Section 1202.3—formerly 1203.3 in 2015—is essentially unchanged since its first adoption in 2015.) This section outlines requirements for unvented roof assemblies, including four basic options for insulation placement: (1) 1202.3.5.1.1—only air-impermeable insulation, in direct contact with the underside of the sheathing, (2) 1202.3.5.1.2—air-permeable insulation in direct contact with the underside of the sheathing, with a prescribed *R*-value of rigid insulation above the roof deck for condensation control, (3) 1202.3.5.1.3—a prescribed *R*-value of air-impermeable insulation in direct contact with the underside of the sheathing and air-permeable insulation directly beneath (no insulation above the deck), and (4) 1202.3.5.1.4—air-permeable insulation beneath the sheathing, with rigid insulation above the roof deck in sufficient thickness to maintain the monthly average surface temperature of the underside of the sheathing above 45°F (7°C), given an interior temperature of 68°F (20°C) and an exterior temperature equal to the monthly average air temperature for the coldest three months of the year.⁸ Each of these options has subsequent impacts on fire protection, assembly thickness and detailing, and other project requirements, which must be considered.

Options #2 and #4

Only Option #2 and Option #4 above comply with the NFPA 13 exception to avoid the need for sprinklers in the framing space (provided insulation fills the space), since the materials that are typically used for air-impermeable insulation included in Option #1 and Option #3

are combustible. Option #2 and Option #4 describe the same basic type of construction, but with different criteria for determining the amount of insulation above the deck. Option #2 prescribes a minimum insulation thickness above the deck based on climate zone,¹¹ while Option #4 employs a practice for selecting an exterior design temperature and corresponding insulation thickness.¹² Overall assembly thickness must also be considered, as adding insulation above the roof deck increases the thickness (and cost) of the assembly and may require modifications to drainage and flashings.

Filling the framing space with air-permeable insulation to meet NFPA 13 requirements increases the potential for condensation in Option #2 for deep roof framing by placing a large percentage of the total insulation below the sheathing, decreasing the sheathing temperature. The authors have encountered buildings where wood trusses exceeding 40 in. (101.6 cm), needed for structural support and to accommodate ductwork and equipment, were filled with noncombustible insulation to meet the requirements of NFPA 13. In such cases, the thickness of insulation above the sheathing is not increased in Option #2; however, significant additional insulation must be added in Option #4 to maintain the sheathing temperature above 45°F (7°C). Therefore, projects that use Option #2 and omit sprinklers may be vulnerable to condensation problems depending on the insulation thickness above the deck.

Note that NFPA 13 allows a maximum 2 in. air gap between the insulation and sheathing. Therefore, the insulation may not be in “direct contact” with the sheathing, as required in Option #2. However, since the insulation is air permeable, this small gap is unlikely to significantly alter the behavior related to condensation formation. As noted above, Option #2 and Option #4 do not include consideration of pressurized ductwork within the framing space. Leakage from ductwork moves interior air into the insulation filled roof framing, increasing the risk of condensation formation.

Other Considerations for Options #1 and #3

Both Option #1 and Option #3 require costly sprinkler systems in the roof framing space to meet NFPA 13 since the concealed spaces are not filled with noncombustible insulation. By not requiring additional rigid insulation above the roof deck, Option #3 reduces the overall thickness of the assembly and simplifies detailing for drainage and flashings. However, for both options, installation of ductwork and

other components within the framing space may be impeded by the impermeable insulation beneath the roof deck. Further, in the event of potential future roof leakage, the impermeable insulation applied directly to the underside of the deck can hold moisture against the sheathing, concealing leakage and associated damage until the problem becomes advanced.

Hygrothermal Analyses of Code-Prescribed Options

For this study, the researchers focused on Options #2 and #4, which meet NFPA 13 requirements, as discussed above. The roof assembly described in the introduction with 32 in. (91.44 cm) deep trusses was modeled, with a 2 in. air space between the insulation and sheathing (reducing the insulation thickness to 30 in. [76.2 cm]), per NFPA 13 allowances. Assessments were made for four different major cities in the US, corresponding to northern and mixed climate zones:¹⁹ Minneapolis (Zone 6A), Chicago (Zone 5A), Baltimore (Zone 4A), and Atlanta (Zone 3A). A series of WUFI simulations were performed to evaluate the hygrothermal performance of the assembly and assess the impact of air leakage from pressurized ductwork within the framing space. The simulation results were evaluated according to commonly accepted criteria regarding the potential for biological growth and water content of the wood roof deck.

Comparison of Option #2 and Option #4

Tables 1 and 2 compare Option #2 and Option #4, with insulation above the sheathing as determined in each of these options. Table 1 below shows the minimum *R*-value for each climate zone as specified in Section 1202.3.5.1.2, along with the corresponding thickness of rigid insulation. Table 1 also includes the average temperature for the three coldest months of the year for each location, per Section 1202.3.5.1.4.^[8]

To calculate the temperature of the underside of the structural roof sheathing in accordance with Section 1202.3.5.1.4, a temperature factor calculation was applied in accordance with ISO 13788.²⁰ This methodology was used for the modeled assembly in all four climate zones, with the calculation carried out for various *R*-values of rigid insulation above the deck. In this way, the rigid insulation requirements from Sections 1202.3.5.1.2 and 1202.3.5.1.4 could be compared, as shown in Table 2.

Table 2 reveals two issues with the current code. First, the cases which satisfy Option #2

Table 1. Minimum R-values and design temperatures for each climate zone

Climate Zone	Minimum R-Value of Air-Impermeable Insulation ^(a)	Corresponding Thickness of Rigid Insulation, in. ^(b)	Monthly Average Outside Air Temperature for Three Coldest Months, °F ^(c)
6A	R-25	4.25	20
5A	R-20	3.5	24
4A	R-15	2.5	33
3A	R-5	1	41

(a) Source: 2021 IBC, Table 1202.3.8.

(b) Source: Calculated based on R-value of 6 per in.

(c) Source: Calculated from the climate data file from the WUFI database using the representative location for each climate zone.

(minimum prescriptive R-value) but do not satisfy Option #4 (maintaining the underside of the deck above 45°F) indicate that the prescribed insulation options do not provide equivalent levels of protection against moisture problems, although their offering as alternatives suggests otherwise. Second, the magnitude of insulation required above the deck to achieve 45°F sheathing when deep framing spaces are filled with insulation is impractical, suggesting this may not have been considered by the code authors.

Note, further calculations revealed that 7.1 in. (18.03 cm) of air-permeable insulation, without a 2 in. air layer, is the thickness for which all values satisfy both Option #2 and Option #4, suggesting that the authors of the code likely did not consider more than 7.1 in. (18.03 cm) of loose fill or batt insulation in these assemblies. See **Table 3**.

Hygrothermal Simulation: Modeling Assumptions

To assess the impact of air leakage from pressurized ductwork in the framing space, a series of WUFI simulations were performed and evaluated according to commonly accepted criteria regarding the potential for biological growth and water content of the wood sheathing. The studied roof assembly consisted of (from exterior to interior): white EPDM roof membrane, air-impermeable insulation (thickness selected per Option #2 by climate zone, see **Table 1**), 5/8 in. (1.6 cm) plywood sheathing, 32 in. (81.3 cm) roof framing space with 30 in. (76.2 cm) fiberglass insulation, optional vapor retarder, and 1/2 in. (1.3 cm) interior gypsum board coated with latex paint (7 perm). Material properties were obtained from the WUFI database.

Simulations were performed for each of the four selected climate zones, with and without pressurized ductwork in the framing space,

with and without a Class II (1 perm) vapor retarder (which also functions as an air barrier), and with two variations on roof membrane color and solar reflectivity: white membrane (70% reflectivity) and black membrane (10% reflectivity), resulting in a total of 32 simulation cases. Nighttime overcooling effects were considered using the built-in long-wave radiation exchange model with the surrounding sky, using a long-wave emissivity of 90%, which represents opaque materials.²¹

The outdoor climate conditions for each simulation were obtained from the WUFI database for the selected locations. Indoor climate conditions have been assumed to be 72°F (22°C), with indoor relative humidity modeled as an annual sine curve.²² See **Fig. 6**.

Simulating Moisture Load from Air Duct Leakage

For the presented example, the airflow from the 2-ton heat pump unit is 800 cfm in a 1,200 ft² dwelling. With a 32 in. framing space, 95% air

within the batt insulation, and presuming a "low" duct leakage level of 5%, this amounts to one air change every 45 minutes. However, since modifying the software to simulate one air change every 45 minutes was considered neither practical nor reliable, a different approach was selected.

The moisture impact of air leakage from the pressurized ducts has been modeled such that whenever the HVAC system is running, the moisture associated with air at the indoor absolute humidity level is available at the interior surface of the plywood to be absorbed during winter weather conditions. For the analysis, 5% of the excess moisture (the difference between the vapor pressure of the interior air and that of the air within the sheathing) is assumed to be available for this moisture transfer, with the other 95% assumed to dissipate via convective flow. Similarly, moisture in the plywood can be dried by the simulated air leakage during summer weather conditions. This approach was selected since it produced results that closely

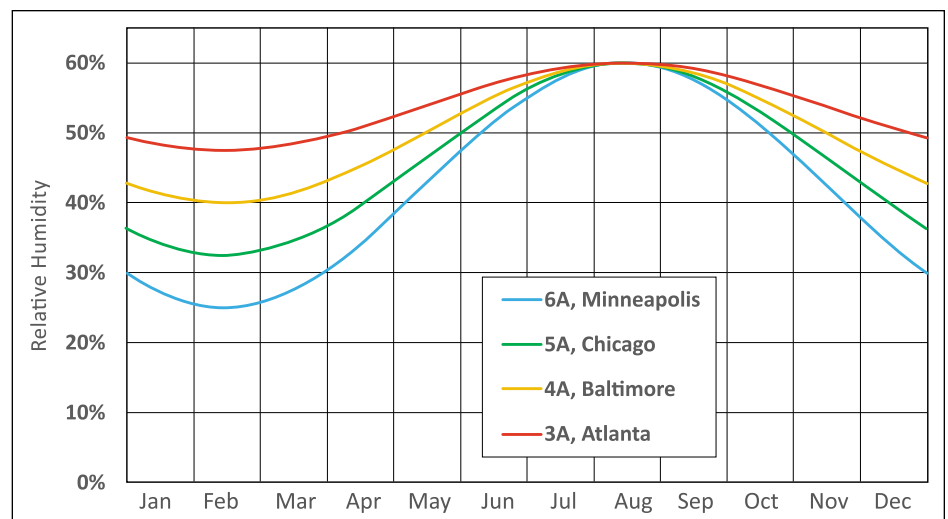


Figure 6. Seasonally assumed indoor relative humidity used within the simulations.

Table 2. Temperature at underside of structural roof sheathing (°F) for various locations with code-prescribed rigid insulation thicknesses above the sheathing and 30 in. (76.2 cm) deep roof framing space filled with batt insulation

R-Value of Rigid Insulation	Climate Zone			
	6A, Minneapolis	5A, Chicago	4A, Baltimore	3A, Atlanta
R-4	21.8	26.1	34.4	41.7
R-5	22.3	26.5	34.7	42.0
R-10	24.5	28.6	36.3	43.3
R-15	26.6	30.4	37.8	44.4
R-20	28.4	32.1	39.2	45.5
R-25	30.1	33.6	40.4	46.5
R-30	31.7	35.1	41.6	47.3
R-35	33.1	36.4	42.6	48.2
R-40	34.4	37.6	43.6	48.9
R-45	35.7	38.7	44.5	49.6
R-50	36.8	39.7	45.3	50.3
R-55	37.9	40.7	46.1	50.9
R-60	38.9	41.6	46.8	51.4
R-65	39.8	42.4	47.5	52.0
R-70	40.7	43.2	48.1	52.5
R-75	41.5	44.0	48.7	52.9
R-80	42.3	44.7	49.3	53.4
R-85	43.0	45.3	49.8	53.8
R-90	43.7	46.0	50.3	54.2
R-95	44.3	46.5	50.8	54.5
R-100	44.97	47.1	51.2	54.9
R-105	45.6	47.6	51.7	55.2

■ Cases that satisfy neither 1202.3.5.1.2 nor 1202.3.5.1.4.

■ Cases that satisfy 1202.3.5.1.2 but not 1202.3.5.1.4.

■ Cases that satisfy both 1202.3.5.1.2 and 1202.3.5.1.4.

matched observations by the authors in building failure investigations. For these calculations, a moisture transfer coefficient was assumed from previous research.²³

The HVAC system is assumed to operate in heating mode when the exterior temperature

falls below 65°F (18°C) and in cooling mode when the exterior temperature is above 70°F (21°C). The stated set points include indoor thermal gains which result in a 5°F shift of the indoor temperature according to ASHRAE 160,²⁴ resulting in actual thermostat set points of 70°F

(21°C) and 75°F (24°C) for heating and cooling, respectively.

The percentage of heating time in an hour is assumed to be at 100% at the coldest hour of the year, two minutes at times where the exterior temperature falls minimally below the set point of 65°F (18°C), and linearly interpolated for all points between.

An analog procedure was used to determine the percentage of cooling time during summer conditions.

Evaluation Criteria

The hygrothermal simulations were evaluated based upon the mold growth index (MGI), per ASHRAE 160,²⁴ as measured at the interior surface of the sheathing. The MGI, whose calculation depends on the sensitivity class of the substrate, relative humidity, temperature, and time shall stay below 3.0, per ASHRAE 160 (see **Table 4**). The simulations were also evaluated based upon the simulated water content of the sheathing, which must remain below 20% by weight to prevent decay.²

Simulation Results

Each simulation case and its corresponding final MGI value and maximum sheathing water content in the last year of the calculation are listed in **Table 5**. Note that MGI and water content values indicative of biological growth or decay are shaded.

The results above show that even with significant insulation below the sheathing, the minimum insulation provided by code is sufficient to minimize the risk of condensation, if ductwork is not present and the flow of interior air into the roof framing space is low. This also suggests that Option #4 in the building code may be more conservative than necessary to avoid condensation-related moisture problems, provided significant flow of interior air into the roof framing space can be avoided. However, the results show elevated values for MGI and plywood water content for cases which include the effect of air leakage from pressurized ductwork in the framing space. As such, biological growth and/or wood decay may be expected to occur in these cases.

The influence of the roof membrane color is significant, with a black membrane leading to increased solar gain, drying the roof assembly better than a white surface. This effect has been studied many times.^{26,27,28,29} However, the impact of the black membrane alone is not sufficient to result in a moisture-safe design.

The influence of the vapor retarder is minor for cases with ductwork in the framing space because wetting and drying occurs primarily

Table 3. Temperature at underside of structural roof sheathing (°F) for various locations with code-prescribed rigid insulation thicknesses above the sheathing and with 7.1 in. (18.0 cm) deep roof framing space filled with batt insulation

R-Value of Rigid Insulation	Climate Zone			
	6A, Minneapolis	5A, Chicago	4A, Baltimore	3A, Atlanta
R-4	27.5	31.3	38.5	44.96
R-5	29.0	32.6	39.6	45.8
R-10	35.0	38.0	43.9	49.2
R-15	39.4	42.0	47.2	51.7
R-20	42.7	45.1	49.6	53.6
R-25	45.4	47.5	51.5	55.1

- Cases that satisfy neither 1202.3.5.1.2 nor 1202.3.5.1.4.
- Cases that satisfy 1202.3.5.1.2 but not 1202.3.5.1.4.
- Cases that satisfy both 1202.3.5.1.2 and 1202.3.5.1.4.

Table 4. Mold growth index (MGI) for experiments and modeling²⁵

MGI	Description of Growth
0	No growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, <10% coverage, or <50% coverage of mold (microscope)
4	Visual findings of mold on surface, 10%–50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

through the leaking air from the ducts, bypassing the vapor retarder. For cases without ductwork, a Class II vapor retarder provides slightly improved performance.

The influence of climate zone is minor, since colder climate zones are also associated with lower winter indoor relative humidity values, as shown in Figure 6. However, this effect will be negated with the use of humidifiers to raise the indoor relative humidity above levels assumed in this study, especially in northern climates.

CONCLUSIONS

The recent revisions to the IBC greatly reduce the potential for condensation in roof framing systems, provided that these spaces do not include ductwork or other significant sources of airflow from the interior.

This is true even when considering a high percentage of air-permeable insulation below the sheathing to meet NFPA 13 requirements. The approach listed in Option #4 is significantly more conservative than the approach listed in Option #2 for air-permeable insulation thicknesses greater than 7.1 in. If ductwork is placed in the framing space, the potential for condensation greatly increases. The amount of risk is dependent on the amount of duct system air leakage and the ratio of air-permeable insulation to total insulation. Although the roof membrane color is significant, use of a dark membrane by itself is not sufficient to reduce the condensation risk. The influence of a vapor retarder is minor for cases with ductwork in the framing space but can offer modest protection for assemblies without ductwork.

RECOMMENDATIONS

Additional study is needed to develop computer simulation procedures to reliably predict these failures. The authors plan to construct roof systems with controlled values for simulated ductwork leakage to calibrate computer models. However, until such refined models are available, we suggest the following approaches for low-slope systems with insulation in the framing space complying with NFPA 13:

- A. Do not place pressurized ductwork in the insulated framing space.
- B. If ductwork is located in the framing space, place ductwork below the air permeable insulation and use Option #1, Option #3, or Option #4, with sprinklers in the roof framing space per NFPA 13.

Table 5. Summarized WUFI simulation results

Case No.	Climate Zone	Ducts in Trusses	Roof Color	Vapor Retarder	Final MGI, Plywood Sheathing	Max. Water Content, Plywood Sheathing, by Weight
1	6A	No	White	None	0	15%
2				Class II	0	16%
3			Black	None	0	12%
4				Class II	0	11%
5		Yes	White	None	3.9	39%
6				Class II	3.9	40%
7			Black	None	0.6	27%
8				Class II	0.3	27%
9	5A	No	White	No	0	15%
10				Class II	0.1	16%
11			Black	None	0	12%
12				Class II	0	11%
13		Yes	White	Yes	4.3	39%
14				Class II	4.2	40%
15			Black	None	2.9	31%
16				Class II	2.4	30%
17	4A	No	White	None	0.1	15%
18				Class II	0.3	16%
19			Black	None	0	11%
20				Class II	0	11%
21		Yes	White	None	4.5	46%
22				Class II	4.5	47%
23			Black	None	3.1	34%
24				Class II	2.6	33%
25	3A	No	White	No	0	15%
26				Class II	0	15%
27			Black	None	0	11%
28				Class II	0	9%
29		Yes	White	Yes	4.3	40%
30				Class II	4.3	39%
31			Black	None	1.0	25%
32				Class II	0.5	24%

C. To include ductwork and omit sprinklers, use Option #2 in conjunction with extremely low-leakage high-speed ductwork (for example, PVC piping or metallic tubing with airtight joints) with sealed connections (for example, at diffusers).

In all cases, hygrothermal analysis is recommended if the air permeable insulation thickness or interior relative humidity will exceed those included in this study. 

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